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Zero-net energy management for the monitoring and control of dynamically-partitioned smart water systems[★]

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ABSTRACT

The optimal and sustainable management of water distribution systems still represent an arduous task. In many instances, especially in aging water net-works, pressure management is imperative for reducing breakages and leakages. Therefore, optimal District Metered Areas represent an effective solution to decreasing the overall energy input without performance compromise. Within this context, this paper proposes a novel adaptive management framework for water distribution systems by reconfiguring the original network layout into (dynamic) district metered areas. It utilises a multiscale clustering algorithm to schedule district aggregation/desegregation, whilst delivering energy and supply management goals. The resulting framework was tested in a water utility network for the simultaneously production of energy during the day (by means of the installation of micro-hydropower systems) and for the reduction of water leakage during the night. From computational viewpoint, this was found to significantly reduce the time and complexity during the clustering and the dividing phase. In addition, in this case, a recovered energy potential of 19 MWh per year and leakage reduction of up to 16% was found. The addition of pump-as-turbines was also found to reduce investment and maintenance costs, giving improved reliability to the monitoring stations. The financial analyses to define the optimal period in which to invest also showed the economic feasibility of the proposed solution, which assures, in the analysed case study, a positive annual net income in just five years. This study demonstrates that the combined optimisation, energy recovery and creation of optimized multiple-task district stations lead to an efficient, resilient, sustainable, and low-cost management strategy for water distribution networks.

1. Introduction

The United Nations Sustainable Development Goals (especially Goal 6, 11 and 12) define actions aiming to ensure improved access to safe water, improved resource efficiency in water systems through sustainable consumption patterns (Nations, 2015). As cities grow, water systems are becoming larger and more complex interconnected networks, which is not trivial to manage. Thus, the efficient and effective management of large-scale, complex, and dynamic water distribution systems (WDSs) still represent an arduous task for water utility managers. Nowadays, in addition to supplying water to the users and satisfying the minimum service levels, the main goals for water utilities range from managing abnormal conditions (such as burst pipe scenarios, peak demand variability) to dealing, at near real-time, with accidental or intentional contamination (Herrera et al., 2018) and leakage detection (Wu et al., 2016). Whilst respecting economic, social and environmental sustainability requirements and operation within affordable energy costs. The energy mainly in the form of electricity, associated with water systems worldwide was 120 Mtoe in 2014. This corresponds to 4% of the total global electricity consumption (Luna et al., 2019). Water distribution represents the largest share

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of energy consumption in the sector (IEA, 2016). The necessary use of new sensors, technologies and their associated cyber-physical systems (CPSs) to manage assets, gather and analyse data across a smart city, further increases the use of energy. The climate and environmental impact of water processes as well rising energy tariffs mean than systemic and operational practices need to be more resource efficient.

The efficient management of water systems, in terms of energy and resource, thus represent a crucial task towards the more sustainable and efficient use of water. Further, the energy potential in water networks can be used to deliver social good especially in peri-urban and rural areas where water and energy infrastructure may be costly or lacking (Bere et al., 2017). Previous studies of micro hydropower (Bhandari et al., 2018) have demonstrated the comparative social value of such renewable schemes, in addition to financial and environmental value. Further, smart water system solutions with the improved efficiency, longevity, and reliability of WDSs are imperative for better identification, monitoring and acting on a wide range of water system events. This approach can be implemented in the different phases of the water distribution process, such as real-time monitoring and automation, operational readiness, or network planning, leading to an integrated water-energy framework and overall system efficiency. In this regard, smart actions devoted to safe/energy recovery and leakage reduction contribute to reductions in cost and the environmental impact associated with the operation, and the diversification of electric energy production. To this aim, this study combines the optimal positioning and installation of micro-hydropower systems (Gallagher et al., 2015), with the optimisation strategy of the water network partitioning to deliver a pro-active, efficient and cost-effective management of WDSs. The need of a holistic approach to create sustainable systems was strongly highlighted in Urbaniec et al. (2017).

1.1. Literature review

One of the main challenges faced by water companies is how to minimise water losses and the wastage of finite water resources whilst protecting the natural environment and its ecosystems. Pressure management, among others, represents a proactive measure to reduce water loss in WDSs (Boulos and Aboujaoude, 2011). This involves using Pressure Reducing Valves (PRVs) to reduce pressure to the minimum level whilst maximising the service level to meet consumer demands (Hindi and Hamam, 1991). Water network partitioning (WNP) is another approach that can be used to achieve pressure management. WNP is the process of splitting a water distribution system into a set of independent District Metered Areas (DMAs) (Ltd, 1999). DMAs are formed in WDNs by placing gate valves along some boundary pipes connecting one DMA to another and placing a flow meter in the remaining connecting pipes (Fig. 1). In addition to providing an overall head drop which leads to a reduction in water losses, leakage can be more easily quantified in each DMA by measuring minimum night flows. It is important to highlight that the design of permanent DMAs (with the insertion of gate-valves) could significantly reduce the head pressure over the WDS and, consequently, the energy resilience. Therefore, the optimal WNP design always represents an arduous task for the water utilities and limits their capacity to improve the system's hydraulic performance. This is the reason why, WNP is not typically tailored for water leakage reduction, but this aspect is considered as a secondary advantage to exploit during the night. When the request and variability of water demand strongly reduce, pressure reaches higher values, and lower values of energy resilience are acceptable. Over the years, working with DMAs has helped water utilities to carry out leakage control (Taillefond and Wolkenhauer, 2002; Feng and Zhang, 2006), pressure management (Ltd, 1999), monitor water quality (Chianese et al., 2017; Ciaponi et al., 2019), and speed up repairing interventions (Campbell et al., 2016). In this way, water utilities can efficiently plan management programs by reducing the complexity of the network layout into smaller monitored areas. WNP has become one of the most attractive and studied strategy for the improvement of WDS management.

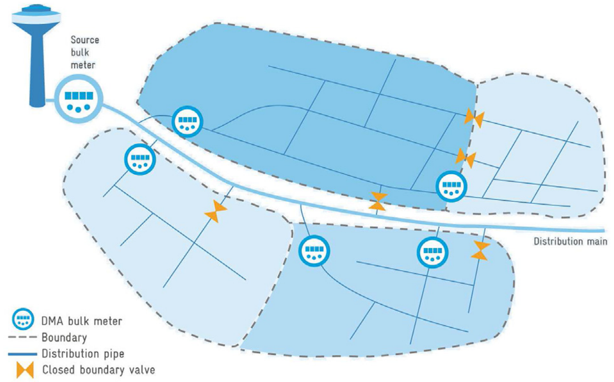


Fig. 1. Water network partitioning.

Although working with DMAs has the fore-described advantages, it comes with important associated inconveniences. As mentioned above, these are mainly related to the energy efficiency for supply and water quality, especially in the case of non-contemplated functioning conditions (Di Nardo et al., 2018). Traditionally, WNP is a static solution for urban water distribution operation and management. Therefore, a dynamic/adaptive approach to WNP represents an innovative and efficient approach to dealing with these drawbacks, making it possible to achieve simultaneous management goals. The advantages of an adaptive WNP are demonstrated in Wright et al. (2014). Further, several studies have been carried out to develop alternatives to reducing energy consumption in the water sector (Fecarotta et al., 2018). In this regard, pressure control represents an important issue for energy efficiency improvement. In that, it reduces both the energy consumed in pumping stations and the pipe leakage (which also reduces indirect energy consumption owing to the reduction of the total flow). Indeed, water and energy efficiency can be improved through the diminishing of head losses, the reduction of the flow velocity in gravity pipes systems, as well as the reduction of the pressure and consequently the leakages in the water distribution systems (Araujo et al., 2006). Thus, the use of pumps working as turbines (PATs), by replacing or in conjunction with the pressure reduction valves, was proposed by Ramos and Borga (1999), as an alternative solution for reducing the pressure in pipe systems. This energy recovery system has the advantage of energy generation in addition to pressure control regulation. This renewable energy system can also lead to the improvement of the future sustainability of existing WDS (Pérez-Sánchez et al., 2017). Hence, in water systems with excess energy, it is possible to install PATs which produce electric energy from the available excess of hydraulic energy, which would normally be dissipated through the PRV, turning transmission pipelines into potential energy sources.

Typically, pumps convert mechanical energy of the impeller into pressure and kinetic energy of water. When the pump works in reverse mode, it converts pressure and kinetic energy of water into mechanical energy of the runner (Fig. 2). Pumps as Turbines represent a viable solution for electric energy production due to

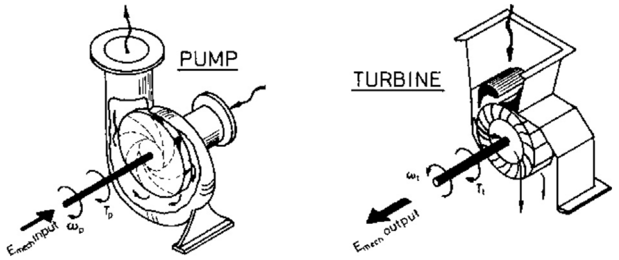


Fig. 2. Difference between pump and pump as turbine.

low maintenance, investment and repairing costs, and good efficiency. Finally, it has been demonstrated that, in many cases direct pumping could be less convenient than pump to a storage tank and recover energy with a PAT (Morani et al., 2018). Furthermore, PATs as a continuous clean source of energy, with low environmental impacts, represent an alternative opportunity to control pressure in WDSs whilst increasing the flexibility of the system (Fecarotta et al., 2015).

1.2. Contributions

The work in this paper contributes to the broader research on smart and resilient cities (De Jong et al., 2015). From an efficient urban water supply point of view: it investigates the integrated benefits of capturing the renewable energy generated during water distribution whilst controlling and monitoring leakage. This is possible due to an efficient WNP management and the potential for energy recovery from the boundary pipes between the DMAs. These are shown to be the points where kinetic energy increases even when the overall WDS energy decreases when combined with network partitioning. In fact, lower number of connections between districts causes a higher volume of water conveyed along them (because of the velocity). This study also pioneers an automated and practical approach to effectively achieve the dynamic water network partitioning (DWNP) related to an adaptive DMA configuration. The research develops a generic framework for the dynamic top-down/bottom-up partitioning of WDSs for a smart, efficient and sustainable management in response to the different goals of saving energy (and CO_2 emissions), water and costs. This is achieved by a novel multiscale abstraction of the original water network layout (Giudicianni et al., 2019) on which the clustering algorithm is applied. Consequently, DMAs are dynamically:

- *aggregated*: into bigger areas during the day (when the water flows reach higher values), to assure the network resilience and to recover energy; and periodically
- *desegregated*: during the night (when pressure heads assume higher values) for a better detection and reduction of leakages.

Thus, the disadvantages of a closed topology are significantly reduced without losing the possibility to exploit the strengths of the water network partitioning. From a computational point of view, the proposed framework assures a significant reduction of time and complexity during the clustering phase (working on the reduced MS network layout) and the dividing phase (defining a sub-set of the boundary pipes to optimise at each level of the management). Another innovative aspect of this paper is the installation, along the boundary pipes at the same monitoring station, of flowmeters as well as PATs for micro hydropower generation. This leads to a reduction in both the investment and maintenance costs, a simplification of the management, and an energy-neutral automation of the monitoring systems (electrical devices with power directly supplied from the recovered energy). This gives improved reliability to the monitoring stations, since they keep working in case of any failure of the local power grids. Finally, a simplified decision support system is proposed to help define the optimal period for investment and inform implementation decisions.

2. Methods

The novel concept of multiscale (MS) water network layout informs the dynamic/adaptive water network partitioning approach. The MS is useful for automating the creation of dynamic DMA through semi-supervised MS clustering, according to the variability of the function conditioning in the WDS.

2.1. Semi-supervised multiscale clustering

The novel concept of multiscale (MS) water network layout is based on the extraction of key elements from the original layout: a) *boundary node* (inlet/outlet of a partitioned network); b) *boundary links* (connecting boundary nodes belonging to different DMAs); c) *internal links* (connecting each pairs of boundary nodes belonging to the same DMAs with the shortest path linking them).

The aggregation process is done by applying semi-supervised clustering (Kulis et al., 2009) overlaid on the MS network, considering the boundary nodes membership and internal cluster connectivity as constraints. This structural background knowledge comes in the form of pairwise must-link (boundary links) and cannot-link (internal links) constraints (Herrera et al., 2010). In this case, the algorithm assures that:

- the new aggregate DMAs include the former districts without splitting them (to better manage the aggregation/desegregation phases);
- the set of new boundary links is included in the set of boundary links of the original partitioning (to reduce the computational burden of the whole procedure)

MS network of the original WDS implicitly considers the structural knowledge and simultaneously respects constraints, without the necessity to build additional vector or matrix features. Indeed, after the size reduction provided by the MS algorithm, each cluster of the MS network becomes a fully connected layout (whose links are the *internal links*) connected to each other by fewer links (*boundary links*). With this topological property, the clustering algorithm is assured to always provide a solution in which the novel set of boundary links is a sub-set of the boundary links of the original cluster layout, and the new cluster layout will certainly cross the former boundary links and will not split the original DMAs. Finally, the community detection algorithm introduced by Girvan and Newman (2002) (based on the search of the edges (links) that are most “between” communities) is used.

2.2. Optimisation objectives: recovered energy and leakage reduction

The combination of WDS partitioning with DMAs reduces the overall energy in the system when compared with a completely open WDS. However, this is a global result and it occurs that certain elements, such as the boundary pipes between DMAs, gain local energy with respect to their associated energy in the completely open WDS. This is one of the main opportunities for harvesting energy at specific points of the WDS. This is added to the better monitoring and control benefits of the WDS management via

DMAs.

The clustering phase for the WDS partitioning provides the size and shape of each cluster, and the set of boundary link N_{ec} between them (the set of pipes along which gate valves and flow meters must be installed). If N_{fm} is the number of flowmeters, then the number of gate valves (e.g. closed pipes) $N_{gv} = N_{ec} - N_{fm}$. The number of all the possible dividing configurations N_{dc} is expressed by the binomial coefficient at Equation (1):

$$N_{dc} = \binom{N_{ec}}{N_{fm}} = \frac{N_{ec}!}{N_{fm}!N_{gv}!} \tag{1}$$

Due to the large number of possible configurations, a heuristic optimisation approach was adopted to find the optimal positions of flow meters and gate valves at the boundary links. In this case, a Genetic Algorithm (GA) (Goldberg and Holland, 1988) was developed and specifically tailored for this problem.

In this study, the management of the WDS was split in two main temporal parts, Day (from 6 to 24, to maximise the potentially recovered energy) and Night (from 24 to 5, to better manage pressure and reduce water leakage). According to these main goals of the dynamic DMAs management, two different Objective Functions (OF) were defined:

$$E_{rec} = 9.8\eta \sum_{j=1}^{n_{PAT}} \sum_{i=6}^{24} q_{j,i} h_m \Delta t \tag{2}$$

Equation (2) corresponds to the potentially recovered energy E_{rec} (kWh) for the Day phase, where η is the mechanical efficiency, $q_{j,i}$ is the hourly flow through the j-th PAT (m^3/s), n_{PAT} is the number of installed PAT, Δt (unity), because hourly simulations were carried out, h_m (m) is the head drop through a micro hydropower PAT.

Modelling a PAT along a pipe provide the means to compute the dissipated energy in such a device which is equal to the potentially recoverable energy. In EPANET (Rossman, 2000), the head drop h_m (m) through a PAT can be computed by the equation of the local head losses through the pipe on which PAT is installed (Fontana et al., 2011). This can be written in terms of the flow rate $q_{j,i}$ and the valve/pipe diameter D_j:

$$h_m = K_m \frac{8}{\pi^2 g} \left(\frac{q_{j,i}}{D_j^2} \right)^2 \tag{3}$$

where K_m corresponds to the local loss coefficient (the higher K_m, the higher the head drop and thus the potentially recoverable energy). In the first optimisation step, the value of K_m was assumed constant for all the PATs.

The novel idea of this dynamic framework is to locate flowmeters and PATs in the same monitoring stations, which further simplifies the system management and reduces the investment cost. In this way, the optimal position of flowmeters (which is generally carried out by minimising the hydraulic performance deterioration) is shifted to find the most adequate site for the PAT scheme which maximises the potential for recovered energy.

A refinement of the optimal solution is carried out by searching for the optimal value of the local loss coefficient K_m using GA to further maximise the management efficiency. Such optimisation problem can be mathematically described through Equation (3) in which h_m varies according to the variation of K_m. The value of K_m was inferred from a conventional needle valve chart (Fig. 3).

The local head-loss coefficient initially attributed to all the PAT is $K_m = 1000$; in this subsequent refinement phase, it is varied with a step of 500.

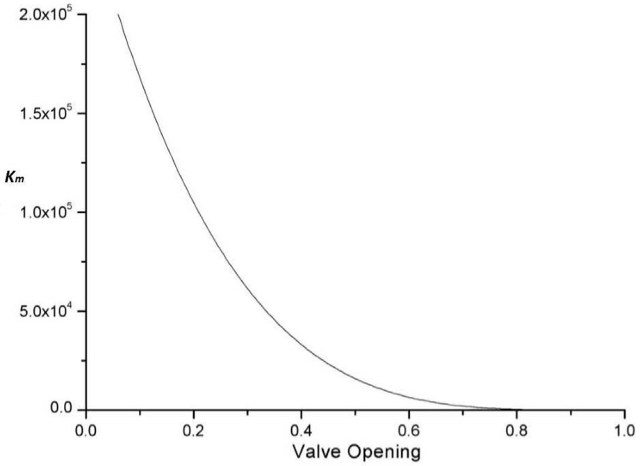


Fig. 3. Resistance coefficient for needle valve used in simulations.

For the Night phase, the leakage reduction function (%) was maximised:

$$L_{red,norm}(\%) = \left(\frac{q_{leak,N} - q_{leak,N^*}}{q_{leak,N}} \right) * 100 \tag{4}$$

Physical loss was concentrated in one node (*emitter*) in the northern part of the WDS; $q_{leak,N}$ is the leakage flow during the Night phase in the original WDS, while q_{leak,N^*} is the leakage flow during the Night phase in the managed WDS. Leakage was modelled through nodal emitters, using the orifice equation $q_{leak} = k\sqrt{h}$ (De Paola and Giugni, 2012), in which k $(L/s/m^{0.5})$ is the emitter coefficient representing the flow (L/s) that occurs at a pressure drop of 1 m (in this case study $k = 1$, simulating a round nozzle for the occurrence of a leak). H (m) represents the pressure head.

The GA was carried out with 200 generations of a population consisting of 50 individuals. Each individual is a sequence of a number of binary chromosomes equal to, and corresponding to the number of boundary links N_{ec}. Each chromosome assumes value 0 if a gate valve is inserted in the j-th pipe, value 1 otherwise if a flow meter/PAT is installed. The crossover percentage is settled $P_{cross} = 0.8$, and the mutation rate $P_{mut} = 0.02$. The optimisation was done by linking the EPANET hydraulic simulator and the programming language Python 3.7.

2.3. Constraints

Two types of optimisation constraints were considered for both Day and Night phases:

a) satisfaction of hydraulic performance of the system;
b) management simplification and cost reduction

Regarding the first group, the *OFs* defined in subsection 2.2 are constrained by equations (5) and (6), which imposes a minimum service level for all the users and a minimum resilience to the WDS as follows:

$$h_{min} \geq h^* \tag{5}$$

where h_{min} is the minimum nodal head pressure, and h^* is the design pressure head of the network (i.e. the minimum required pressure to guarantee the minimum service level to the users).

$$I_r = \frac{\sum_{i=1}^{n_n} Q_i(h_i - h^*)}{\sum_{r=1}^{n_r} Q_r H_r - \sum_{i=1}^{n_n} Q_i h^*} > I_r^* \tag{6}$$

where I_r is the resilience index (Todini, 2000), n_n is the number of demand nodes, n_r is the number of reservoirs, Q_i and h_i are the water demand and the pressure head of the i-th node, Q_r and H_r are the water discharge and the total head of the generic r-th source point. I_r^* is the minimum resilience value fixed for the WDS.

For the second group of constraints, the number of flowmeters N_{fm} were kept as low as possible, since, the smaller the number of flowmeters, the simpler the water budget computation and the WDS management (Di Nardo et al., 2017b). This aspect also leads to a reduction of the investment cost, as better shown in the following subsection. Finally, the passage from the Day to Night phase is carried out by a further selection of the partitioning configurations that completely consider the assets already installed over the WDS. Thus, the optimal device placement for the Day phase (with 4 DMAs) are preserved also for the Night phase. It allows to speed up the computational operation for finding out the optimal solution (by reducing the possible dividing configurations N_{dc}), and to simplify the management of the WDS.

2.4. Financial analysis

The financial feasibility analysis aims to determine whether the balance of costs and savings/benefits of a project is attractive. The adopted model considers year 0 as the initial investment year and the occurrence of an annual cash flow at the end of the year. In this work, a preliminary financial analysis was carried out by including the following factors:

- *investment cost*, PAT cost C_{PAT}, flowmeter cost C_{fm}, gate-valve cost C_{gv}, civil work cost C_{cw};
- *annual cost*, maintenance cost C_m;
- *annual income*, depending on the leakage reduction (so on the water costs C_w) and the recovered energy (so, on the electricity selling price C_e).

Civil work cost C_{cw} was estimated at 30% of device costs (20% if flowmeters and PAT are installed in the same monitoring station); maintenance cost C_m was estimated at 10% of total installation cost (sum of all device costs and civil work cost).

A cash-flow analysis during the first 10 years is carried out (this was considered a reasonable period to evaluate investment by a water company). The investment costs were actualised to the year 0 through the depreciation rate:

$$r_d = \frac{r(1+r)^t}{(1+r)^t - 1} \tag{7}$$

where t is the number of years considered, and r the discount rate.

According to the above-mentioned factors, the Annual Net Income (ANI) was defined as:

$$ANI = C_w W_{red} + C_e E_{prod} - r_d * \left[\sum_{j=1}^{n_{PAT}} C_{PAT} + \sum_{f=1}^{n_{fm}} C_{fm} + \sum_{g=1}^{n_{gv}} C_{gv} + \sum_{c=1}^{n_{fm}} C_{cw}\right] - \sum_{m=1}^{n_m} C_m \tag{8}$$

where W_{red} is the annual water leakage reduction, E_{prod} is the annual recovered energy potential. The product of C_w and W_{red} is the annual water benefit B_{water}, while the product of C_e and E_{prod} is the annual energy benefit B_{energy}.

The assessment of the cost of water C_w, of selling price of energy C_e, and discount rate r (which can be considered as the opportunity cost of capital) are fundamental for the evaluation of the annual income produced by leakage reduction and recovered energy.

Constant values for C_w, C_e, r were utilised, making reference to the values reported in Fecarotta et al. (2015) for Italy. The unit cost of PAT is estimated as a function of installed kW, as reported in McNabola et al. (2011). Table 1 shows the values adopted in this study.

In Table 2 the average cost of flowmeters and gate-valves are reported according to the diameter of the pipe on which they will be installed.

It is worth highlighting that all pipes are assumed to be equally good candidates for devices (they are considered equally desirable from a cost and accessibility standpoint). This simplification does not compromise the proposed methodology, since it can also be applied after the selection of highly desirable/undesirable locations. Indeed, a field survey should be performed after a potential device location (gate-valves, flowmeters, PATs) has been identified, to ensure that the selected site has features and characteristics that make the installation viable, among which includes:

- protected space for housing the instrumentation and the devices;
- easy access for installation and maintenance activities;
- electric power supply;
- wired or wireless connection for transmitting the acquired data.

All these aspects should be taken into account for a deeper economic analysis, performed during the subsequent phase of the design and before the realisation of the DMAs, in order to better define the optimal strategy to adopt.

After the final optimal solution is defined, which maximises *ANI*, the optimal investment period (the time on which it is worthy to invest for a water utility) is computed. This is defined as the period ranging between the year when the *ANI* becomes positive and the year when the increment in *ANI* becomes less than 10%. The analysis was done by varying the number of years t (from 1 to 20 years) and the depreciation rate r_d of the cash-flow analysis.

The overall process of the proposed management framework is summarised in Fig. 4.

3. Case study

The method described above was tested on the WDN of Parete

Table 1
Cost of water C_w, selling price of energy C_e, discount rate r, and unit cost for PAT.C_{PAT}

C_w [€/m^3]	C_e [€/kWh]	r [-]	C_{PAT} [€/kW]
0.30	0.22	0.05	1200

Table 2
Unit cost of flowmeters and gate-valves as function of the diameter.

Diameter	60 [mm]	80 [mm]	100 [mm]	125 [mm]	150 [mm]	200 [mm]
Flow-meter [€]	1693	1727	1771	1864	1940	2244
Gate-valve [€]	107	130	161	251	274	407

(Di Nardo et al., 2017a), a small town located in a densely populated area in the South of Italy, with a population of around 11,000 inhabitants. This WDN is composed of 182 demanding nodes (with ground elevations ranging from 53 m a.s.l. to 79 m a.s.l.), 282 pipes and 2 sources with fixed head of 110 m a.s.l. A unique design pressure head $h^* = 19$ m was assumed for the demanding nodes (equal to the sum of the maximum building height in the town, 9 m, and 10 m, as prescribed by the Italian guidelines). The value of the minimum resilience $I_r^* = 70\% \, (I_r, min) = 70\% \, (0.679) = 0.475$ is fixed, where (I_r, min) is the minimum resilience index during the day of the un-partitioned WDS. Reference was made to the day of maximum consumption in the year when the total nodal demand ranges from 14.1 L/s at night time to 83.2 L/s in the morning and midday peaks, with an average value of 58.3 L/s. The leakage volume of the networks during the day of maximum consumption is up to 553 m^3 (about 11% of the total outflow from the sources). For the analysis, leakage flow was split in two rates: a) $q_{leak,N} = 121 \ m^3$ during the Night phase, and b) $q_{leak,D} = 432 \ m^3$ during the Day phase. All the pipes are assumed to feature a Darcy-Weisbach roughness coefficient of 0.85 *mm* (typical value for cast iron), the diameter ranging from 60 mm to 200 mm and the length from 10.4 m to 542.3 m.

A pattern was used for the hourly demand multiplier to represent the daily variation in the users' demand in the system (with multiplier values ranging from 0.20 to 2.10).

4. Results

The first step was to define the clustering layout for the Night and Day phases according to the novel dynamic MS framework. The WDS of Parete was clustered in $C = 9$ DMAs during the Night phase (see Fig. 5a); the number of boundary links $N_{ec} = 33$. After this, the corresponding MS network was built. Fig. 5b shows the size reduction of the Parete WDS after its transformation into a MS network, and the key elements: a) boundary nodes of each cluster (highlighted by their corresponding DMA colour), boundary links (bold black line), and internal links (thin dashed grey line).

For the Day phase, the number of clusters for Parete's WDS was set to $C = 4$ (see Fig. 5c). The first step of the proposed method was to aggregate the previous DMAs in the MS network. The Girvan-Newman algorithm was applied to the MS network to provide the new clustering layout which suitably balances the new bigger 4 DMA (in terms of number of nodes) and minimises the number of boundary links between clusters. These are two crucial aspects for the definition of the new clustering configuration, since they ensure better management (district with the same size), reduce the computational burden in the subsequent dividing phase (a lower number of boundary links N_{ec} reduces the number of dividing configuration N_{dc}, as evident by Equation (2)), and reduces the device costs.

Fig. 5d shows that the four new, bigger clusters perfectly include the entirety of the former clusters within the new network partitioning (without splitting them). The new set of boundary links $N_{ec}^* = 14$ constitutes a subset of the previous set $N_{ec} = 33$ for the configuration $C = 9$ DMAs. This feature of the dynamic aggregation/desegregation process ensures that the DMAs in each phase

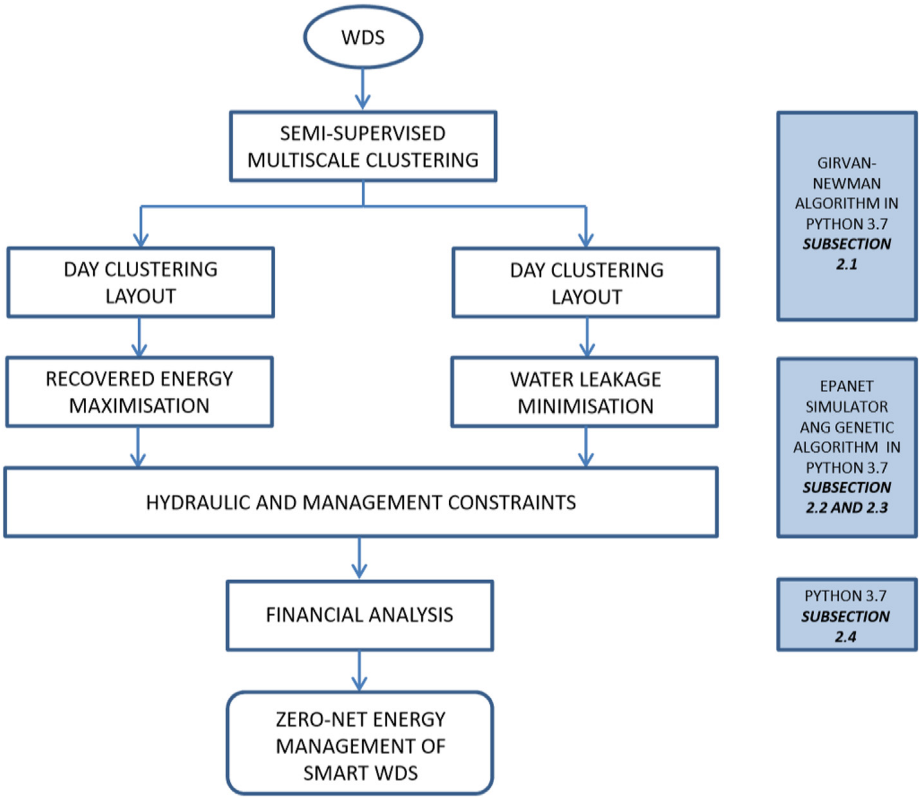
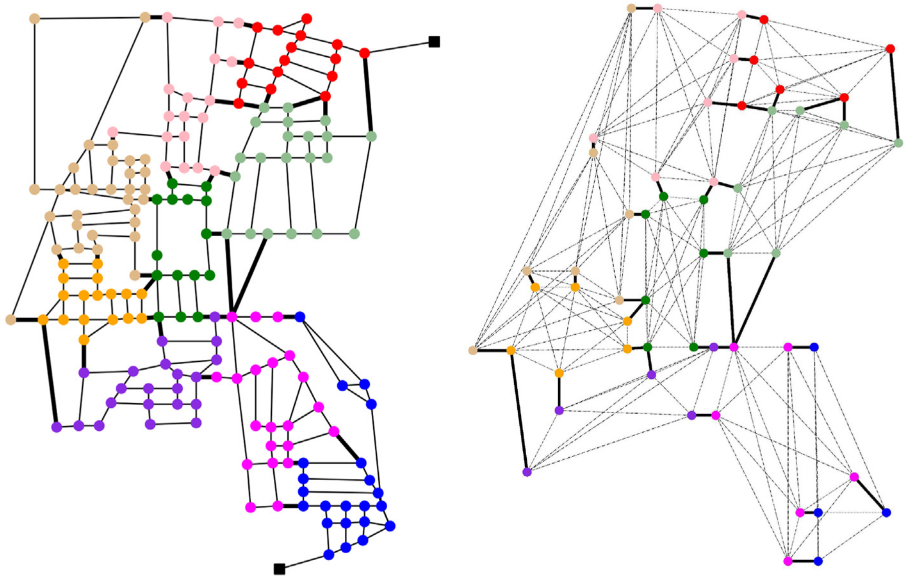
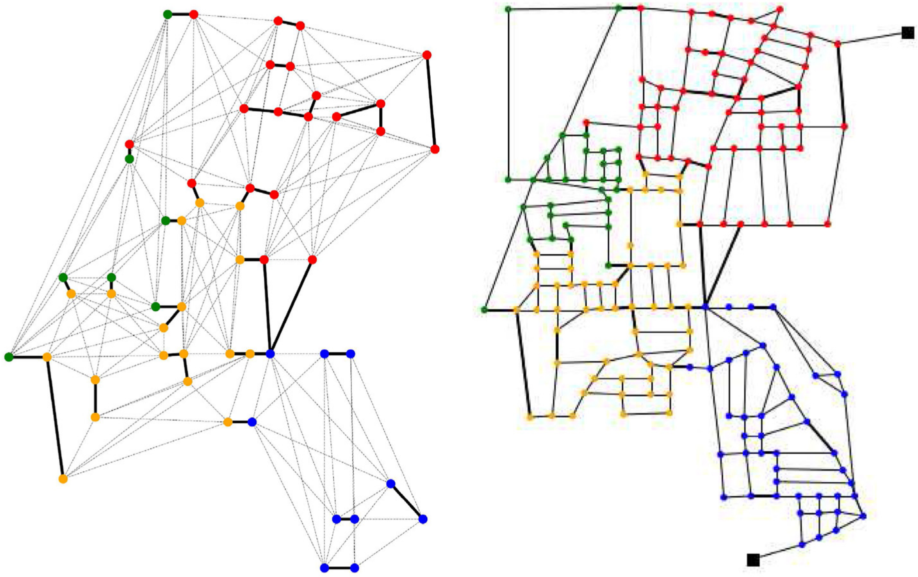


Fig. 4. Flowchart of the study.



(a) 9 DMAs for Parete WDS during the Night phase

(b) MS layout for 9 DMAs



(c) MS layout for 4 DMAs

(d) 4 DMAs for Parete WDS during the Day phase

Fig. 5. Graphical explanation for the creation of Parete MS layout.

are kept in control, by using the physical assets that are already installed in the WDS.

The optimisation of the device placement was carried out after the definition of the optimal clustering layouts for both Night and Day phases. The results of the dividing step for the Day phase are reported in Table 3, in which the dividing solutions are listed from $N_{fm} = N_{PAT} = 6$ to $N_{fm} = N_{PAT} = 14$. Layouts with a number of $N_{fm} = N_{PAT} < 6$ are not reported since they do not respect the constraints. Values of the un-partitioned network are also reported in the first row.

As evident in Table 3, all the listed solutions satisfy the hydraulic constraints, and are suitable for an efficient WDS management. The financial analysis was then carried out (see Table 4) to define the most cost-effective option. The layout with $N_{fm} = N_{PAT} > 10$ showed a negative *ANI*, so they are not valid solutions from an economical point of view. For this case study, for the Day phase, the dividing layout with $N_{fm} = 6$ (which simultaneously maximised the *ANI* and minimised the number of flowmeters N_{fm}) was chosen as the best option, but the water utility could choose any of the other solutions in the range $6 < N_{fm} = N_{PAT} < 10$, to suit specific needs.

In Fig. 6, the relationship between the different parameters were also investigated. As expected, the resilience index I_r increases as

Table 3
Optimal partitioning solutions for the Day phase; number of boundary pipes N_{ec}, number of flowmeters/PAT N_{fm}, number of gate-valves N_{gv}, recovered energy E_{rec}, water leakage $q_{leak,D}$, minimum resilience index $I_{r,min}$, minimum pressure.h_{min}

N_{ec} [-]	N_{fm} [-]	N_{gv} [-]	E_{rec} [kWh]	$q_{leak,D}$ [m^3]	$I_{r,min}$ [-]	h_{min} [m]
_	–	–	0.00	431	0.68	26.87
14	6	8	43.54	366	0.48	20.58
14	7	7	43.02	378	0.49	19.36
14	8	6	43.20	377	0.49	19.16
14	9	5	43.36	379	0.49	19.06
14	10	4	43.41	380	0.49	19.03
14	11	3	39.39	385	0.51	20.15
14	12	2	39.29	384	0.51	20.04
14	13	1	35.72	389	0.51	21.06
14	14	0	35.39	389	0.52	20.89

Table 4
Financial analysis for the optimal partitioning solutions for the Day phase (C = 4 DMAs); number of flowmeters/PAT N_{fm}, total cost of PAT, total cost of flowmeters, total cost of gate-valves, civil work cost, maintenance cost, annual energy benefit, annual water benefit, annual income.

N_{fm} [-]	C_{PAT} [€]	C_{fm} [€]	C_{gv} [€]	C_{cv} [€]	C_m [€/year]	B_{energy} [€/year]	B_{water} [€/year]	ANI [€/year]
6	7200	12,079	1131	4195	2460	3496	7180	4964
7	8400	13,559	1168	4742	2786	3454	5887	2871
8	9600	15,330	1007	5288	3122	3469	5935	2155
9	10,800	17,023	900	5834	3455	3482	5741	1200
10	12,000	18,716	793	6381	3789	3486	5662	352
11	13,200	20,580	542	6918	4124	3163	5119	−1292
12	14,400	22,351	381	7464	4459	3155	5183	−2016
13	15,600	24,213	161	8010	4798	2869	4678	−3593
14	16,800	25,984	0	8556	5134	2842	4680	−4397

the number of flowmeters/PAT (Fig. 6a) resulting in less dissipation of hydraulic energy. Contrariwise, the potentially recovered energy E_{rec} shows a decreasing trend with the number of flowmeters/PAT (Fig. 6b). This could be due to the fact that, the lower the number of open connections between districts, the higher the value of hourly water flow $q_{j,i}$ along them, and as a consequence, the higher the value of recovered energy (see equations (2) and (3), in which the water flow is raised to the power of one and two). Regarding the water leakage, the higher the number of flowmeters/PAT, the lower its reduction L_{red} (see Fig. 6c), since the head drop caused by the PAT is lower than that caused by the complete closure of pipes. Due to the previous decreasing trends of potentially recovered energy and leakage reduction, *ANI* itself showed a decreasing trend reaching its maximum value for $N_{fm} = 6$ (Fig. 6d).

In Fig. 7a and Fig. 7b the relationship between the three performance indices are reported: the dot label indicates the number of flowmeters/PATs adopted for the corresponding solution. In particular, Fig. 7a shows the trend between leakage reduction L_{red} and recovered energy E_{rec}; reduction of leakage resulted in maximum energy recovery. This corresponds to the case of $N_{fm} = 6$, making this the best solution for the system management. However, the trade-off between the resilience index I_r and the recovered energy E_{rec} (see Fig. 7b) led to a non-univocal choice, since solutions that maximise the recovered energy have the smallest values of resilience index (as the case of $N_{fm} = 6$). This makes the use of the financial analysis a crucial tool for the definition of the optimal management solution (or the best compromise solution).

The adopted dividing layout for the Day phase ($N_{fm} = N_{PAT} = 6$), was further refined to recover energy and reduce leakage. For 2 of the 6 PATs (located in the Northern part of the WDS in which the pressure head were much more higher than the design pressure h^*), the local loss coefficient was set $k_m = 2000$. Results are reported in Table 5, the second row reports the difference in percentage with respect to the solution with $k_m = 1000$ for all the PAT.

For the definition of the optimal dividing layout for the Night phase (9 DMAs), the number of boundary pipes are $N_{ec} = 33$; for 14 of them, the optimal device positioning is already defined in the Day phase ($N_{fm} = N_{PAT} = 6$, and $N_{gv} = 8$).The first attempt was to close all the new boundary pipes and check the hydraulic performance. Since the hydraulic constraints were not satisfied, a new optimisation was carried out using Equation (4) but focusing only on $N_{ec,red} = N_{ec}$ - $N_{ec}^* = 33-14 = 19$ boundary pipes. Due to the low value of the water flow during the Night phase, no other PAT was adopted (since the potentially recovered energy would be very low). The optimisation only defines which pipes are closed and which are left open. After that, the optimisation of the local loss coefficient is carried out for the PAT already installed during the Day phase.

Table 6 reports the results of the simulations: the number of assets that are located with the optimisation of the Night phase, for which the financial analysis is done, are shown in parentheses (Table 7). The value of the local loss coefficient after the refinement is $k_m = 1500$ (for 4 PATs), and $k_m = 2500$ (for 2 PATs), following the same layout defined for the Day phase.

Table 8 lists the cost/benefit for the Day and Night phases; the total Annual Net Income for the adopted solution is $ANI = 4906$ €.

Finally by varying the investment year from $t = 1$ year to $t = 20$ years, the optimal payback period for the adopted partitioning layout is defined. Results are plotted in Fig. 8; the labels report the percentage of relative increment between two consecutive years.

The trend of the *ANI* starts with negative values and increases as the investment period becomes longer. There is positive return on investment from $t = 5$ years (since $ANI > 0$). According to the adopted criteria (time to which the increment of *ANI* becomes less than 10%), the upper bound for the investment period is $t = 10$ years (increment of *ANI* is 12.2% for $t = 9$ years and 8.9% for $t = 10$ years).

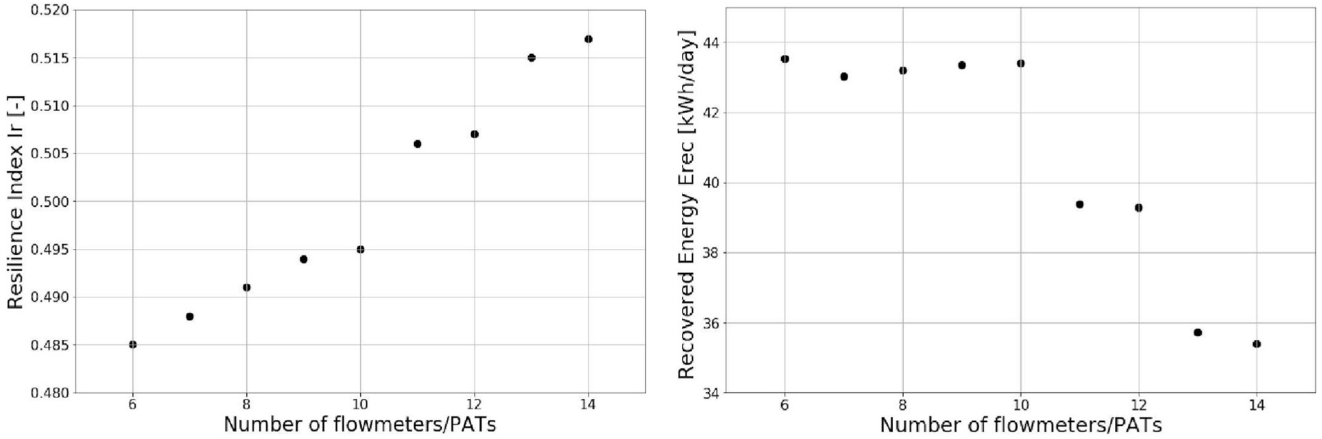
Fig. 9a and Fig. 9b report the optimal partitioning layout for the Day and the Night phases. The boundary pipes (and the installed assets) of the former layout constitutes a sub-set of the boundary pipes of the latter. This constitutes an efficient and sustainable management strategy, which simplifies network monitoring and maintenance. In fact, only the opening/closure of some pipes is required (15 gate-valves) and the setting of the 6 PATs from Night to Day phase.

With the proposed MS layout and the installation of the same monitoring stations for both the flowmeters and PATs, the multiple-use of the partitioning is attained.

5. Discussion

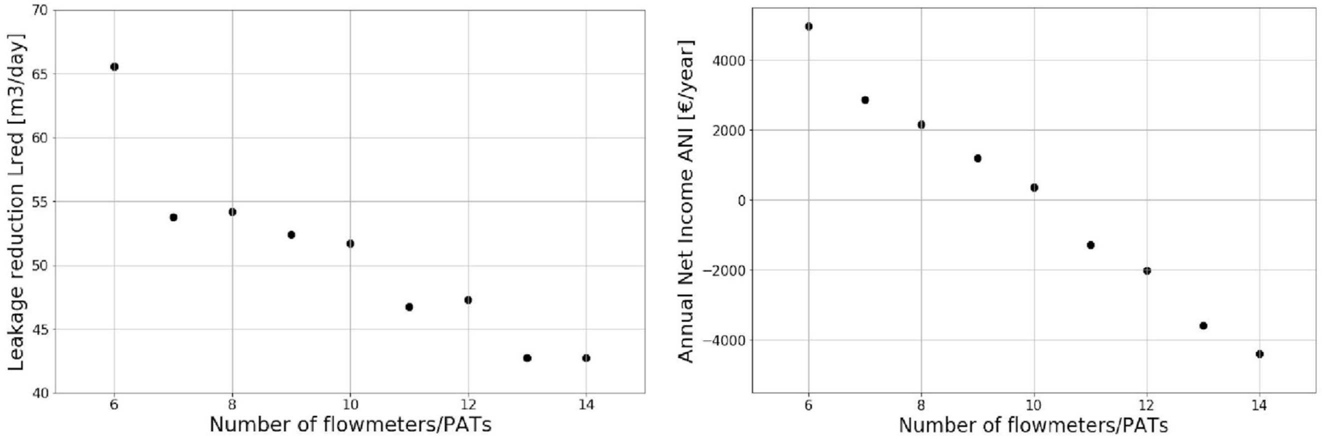
A smart city can be defined as a city in which an investment in human and social capital is performed, by encouraging the use of “Information and Communication Technology” (ICT) as enabler of sustainable economic growth, providing improvements in the quality of life of consumers, and consequently, allowing better management of water resources and energy. This represents the main goal of this work, whose results can be summarised in two groups:

- *Technical and computational aspects*:
  - the dynamic water network partitioning permitted the variability of the conditions of a WDS making the system, making



(a) Resilience index I_r versus Number of flowmeters/PATs

(b) Recovered energy E_{rec} versus Number of flowmeters/PATs



(c) Leakage reduction L_{red} versus Number of flowmeters/PATs

(d) Annual net income ANI versus Number of flowmeters/PATs

Fig. 6. Relationship between performance parameters and number of installed PAT.

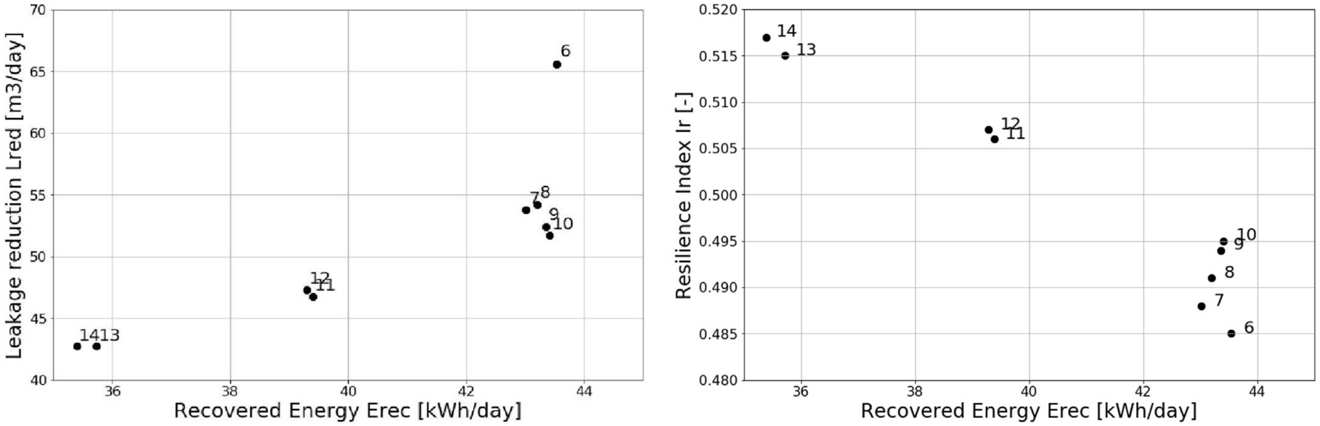
it more adaptive to addressing different management tasks such as pressure management and leakage control;

- the installation of PATs and flowmeters in the boundary stations simplifies the network management and reduces the investment and maintenance costs;
- flowmeters and sensors can then be powered through the recovered energy, conferring greater reliability to the monitoring systems;
- the application of the multi-scale layout reduces the computational complexity during the definition of the optimal partitioning and simplifies the aggregation/desegregation of the districts at each level;

- *Environmental and social aspects*:
  - by utilizing the systems inherent renewable energy, the combined use of water network partitioning and PATs simultaneously permit the simplification of the WDS management, reduces water wastage through leakage, and reduces the environmental impact (CO_2 emissions);
  - the surplus of the recovered energy can be used to power monitoring systems but also electrical charging stations e.g. for electric cars and mobile phones, or provide street lighting especially in off-grid areas;
  - the smart management of WDSs through multiple-use monitoring stations advances the zero-net cost control of water systems, reduces the economic impact on the water utility budget without negative cost and quality impact on end-users;

All these aspects deliver a Smart Water System (SWS) characterised by smart water management, with innovative information, control and monitoring technologies.

From a computational point of view, the proposed multi-scale layout used for the definition of districts represents a positive move towards the scalability of the proposed strategies and the adopted tools. It is also worth highlighting that the approach proposed in this paper can be effectively scaled to bigger water



(a) Leakage reduction L_{red} versus Recovered energy E_{rec} (b) Resilience index I_r versus Recovered energy E_{rec}

Fig. 7. Relationship between performance parameters.

Table 5
Performance after the optimisation of the local loss coefficient for the dividing layout with $N_{fm} = N_{PAT} = 6$ during the Day phase; recovered energy E_{rec}, water leakage $q_{leak,D}$, minimum resilience index $I_{r,min}$, minimum pressure h_{min}, Annual Net Income.*ANI*

E_{rec} [kWh]	$q_{leak,D}$ [m^3]	$I_{r,min}$ [-]	h_{min} [m]	*ANI* [€/year]
46.14 + 5.9%	361 − 1.3%	0.48 − 1.4%	19.46 − 5.4%	5638 + 13.6%

Table 6
Optimal partitioning solutions for the Night phase (C = 9 DMAs); number of boundary pipes N_{ec}, number of flowmeters N_{fm}, number of gate-valves N_{gv}, recovered energy E_{rec}, water leakage q_{leak,N^*}, minimum resilience index $I_{r,min}$, minimum pressure.h_{min}

N_{ec} [-]	N_{fm} [-]	N_{gv} [-]	E_{rec} [kWh]	q_{leak,N^*} [m^3]	$I_{r,min}$ [-]	h_{min} [m]
33 (19)	10 (4)	23 (15)	5.22	101	0.52	19.15

Table 7
Financial analysis for the optimal partitioning solutions for the NIGHT phase (C = 9 DMAs) for the WDN of Parete; total cost of flowmeters C_{fm}, total cost of gate-valves C_{gv}, civil work cost C_{cv}, maintenance cost C_m, annual energy benefit B_{energy}, annual water benefit B_{water}, annual income.*ANI*

C_{fm} [€]	C_{gv} [€]	C_{cv} [€]	C_m [€/year]	B_{energy} [€/year]	B_{water} [€/year]	*ANI* [€/year]
8199	2882	3324	1441	420	2193	−731

Table 8
Financial analysis for the optimal partitioning solution; total annual net income, total cost and annual energy and water benefits during the Day phase, total cost and annual energy and water benefits during the Night phase.

ANI [€/year]	Day			Night		
	C_{TOT} [€/year]	B_{energy} [€/year]	B_{water} [€/year]	C_{TOT} [€/year]	B_{energy} [€/year]	B_{water} [€/year]
4906	5712	3705	7645	3344	420	2193

distribution systems, where high value of water flow exist or are expected, thus a higher value of potential recovered energy. Furthermore, the strategy to implement districts (DMAs) is particularly tailored for large water systems, since it improves the management protocols and simplifies the detection of leakages. Moreover, multiple-task stations represent an appealing strategy when working with large water networks since these results in significant reductions in operation and management costs and a simplification of the monitoring and maintenance processes, of crucial importance in these cases.

6. Conclusion

This paper discusses the benefits and advantages of WDS partitioning into DMAs. It is accepted that energy decreases in a WDS with the creation of DMAs. However, it locally increases (compared to widely open WDS layout) at certain points such as the boundary pipes between DMAs. These points are therefore good for locating energy recovery devices with two regulating operations (night and day). The significant finding is that the potential for recovered energy reduces as the number of flowmeters/PAT decreases, due to the fact that, the lower the number of open connections between districts, the higher the value of hourly water flow, so it is possible to *produce more with less*. Beyond the novel applications of dynamic network partitioning, the improvement on the monitoring and control of a WDS divided into DMAs was also demonstrated. Both characteristics were proposed and applied in the novel framework of dynamic DMA partitioning based on a multiscale approach for a water network. Dynamic DMAs adapt themselves to a range of scenarios that occur in the water distribution network, boosting both the energy harvesting potential and the monitoring and control of a WDS. The recovered energy, along some of the boundary pipes between districts, can be used to supply the electrical needs of the station (or water quality sensors). Through effective integration, only one management strategy is needed to deliver better system control, reduce leakages, recover energy, and monitor water quality, therefore minimising the overall cost, by creating multiple-task monitoring stations along the boundary pipes between each DMA.

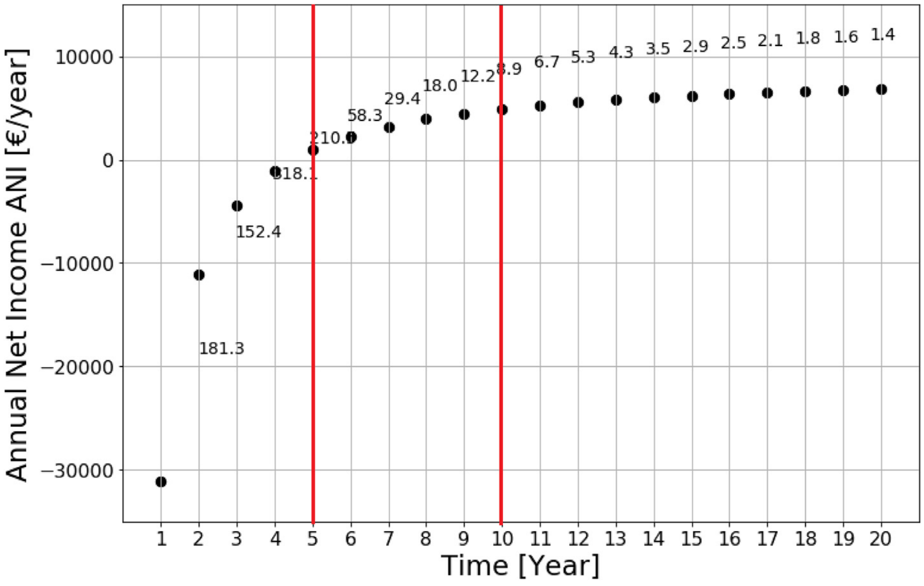
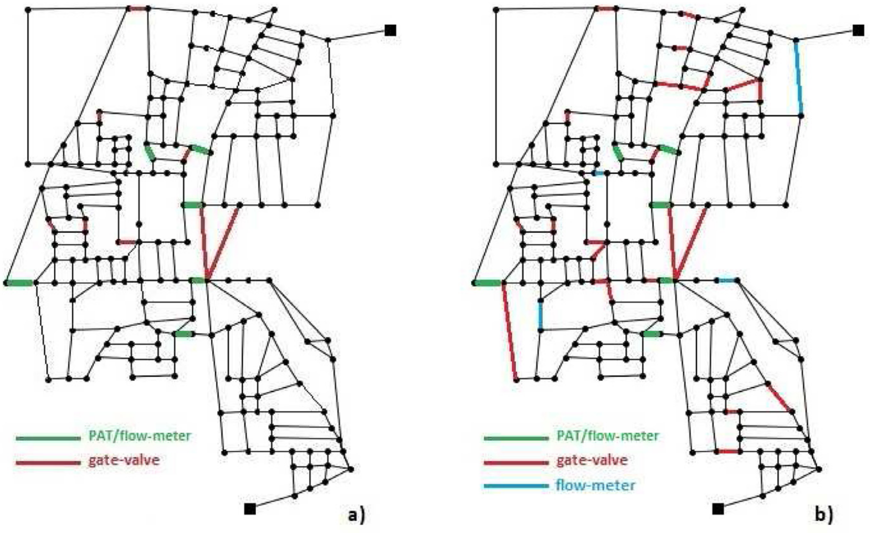


Fig. 8. Optimal payback period analysis.



(a) Optimal partitioning layout for the Day phase (4 DMAs)

(b) Optimal partitioning layout for the Night phase (9 DMAs)

Fig. 9. Optimal management strategy for the WDS of Parete.

Credit author statement

Conceptualisation: **CG, MH**. Software **CG, MH.** Visualisation: **CG, MH.** Writing Original Draft: **CG, MH, KA.** Methodology: **CG, MH.** Formal Analysis: **CG, MH.** Data curtion: **CG, ADN**. Validation: **CG, ADN, AC, HMR.** Writing and Reviewing: **ADN, KA.** Reviewing and Editing: **ADN, AC, HMR, KA.** Writing, Reviewing and Editing: **KA.** Supervision: **ADN, KA, AC, HMR**.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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