Combining pressure management and energy recovery benefits in a water distribution system installing PATs

M. Patelis, V. Kanakoudis and K. Gonelas

ABSTRACT

Gravity can play a beneficial role in certain water distribution networks (WDNs), although sometimes high nodal pressures occur. Excessive pressure may lead to several negative effects regarding the network's operation and life. Thus water utilities are obliged to implement pressure management (PM) policies. Instead of just 'destroying' energy using conventional measures, there are other PM options, like installing pumps working as turbines (PATs) that can recover energy at the same time. Hydro-turbines are widely used in small water energy production plants that produce electricity utilizing the water's kinetic energy. PATs are micro-turbines (compared to the usual ones) used in reverse mode to ordinary pumps. Installing a PAT aims to not only produce energy but also keep the pressure of the downstream pipe to a desired level. Pressure reducing valves (PRVs) are able to decrease pressure too, thus reduce also water losses. This study attempts to exploit every possibility of replacing a PRV with a PAT and check a PAT's ability to reduce pressure to acceptable levels as well as produce a significant amount of energy. Kozani's (Greece) WDN is used as the case study. Various scenarios were checked, utilizing the network's calibrated hydraulic model with intriguing results.

Key words | pressure management, pressure reducing valves, pumps working as turbines, water losses

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INTRODUCTION

The kinetic energy of water has been a power source for humankind since ancient times. In recent years, a great opportunity has unfolded for green energy production via turbines. Hydro-turbines have been used in small water energy production plants to turn kinetic energy of water into electricity. Pumps working as turbines (PATs) are micro-turbines working in 'reverse mode' compared to the usual pumps. As far as water distribution networks (WDNs) are concerned, PATs can be installed to recover a significant part of the available kinetic/flow energy inside a pipe and convert it to electricity (Paish 2002). The power of the electricity produced can be both high or low voltage and it can vary from 1 to 200 KW. Water utilities in charge of either small or greater networks try to exploit this new opportunity in order to cover part of the energy needs of their systems, or sell electricity to bring back revenues. Oil prices are on the rise once again and environmental friendly options of energy production seem to be a cost-effective alternative. Energy produced from PATs has a higher importance as it is a renewable form of energy. PATs also contribute to a more self-sustainable environment and decrease the dependence of water utilities on other energy sources, such as fossil fuels.

Although energy recovery is one of the main advantages of PATs, it is not the only one. An additional great advantage of a PAT is its ability to reduce the downstream pressure, even close to zero. After certain modifications and operation patterns, some PATs, depending on site characteristics and

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availability of excess pressure, are capable of maintaining a desired level of pressure control. As the above-mentioned modifications have a mechanical character and determine energy production as well as pressure management (PM) of a PAT, they are not part of the present study. If a PAT's energy production is combined with controlling the downstream pipe's pressure, energy production is reduced, along with additional benefits achieved. The selection (but not the installation) of the most appropriate mechanical equipment and operation mode of a PAT demand thorough evaluation, as a poorly selected PAT can bring devastating results to the network's service levels and its energy production outcome as well. Thus, although installing a PAT is a reliable way to produce energy, it requires thorough study prior to its adoption (Jafari *et al.* 2015). The installation of a PAT in a WDN must comply with all the WDN's operational constraints.

Although non-revenue water (NRW) level reduction in a WDN may be achieved utilizing several possible solutions, the most reliable one is PM. Most PM strategies start by forming district metered areas (DMAs) followed by installation of pressure reducing valves (PRVs) in the DMAs' entry points (or at least in some of them). The alternative to PRVs (which may not pose as alternatives but can cooperate for optimal results in pressure and energy terms) are PATs used to perform PM as well as recover 'green energy' from the WDN itself. PATs are simple mechanical devices that have the same operational mode as a common pump but instead of consuming energy to boost water, it takes advantage of water flow to produce electricity. Since a PAT operates like any other regular pump, it requires no expert adjustment during its installation and no significant modifications are needed for it to be placed in the network. Maintenance can be easily carried out by the utility's personnel as no specialists are needed for this work. Additionally, spare parts for PATs are easy to find in the market. Acquisition and implementation costs are not low but they are comparable to those of regular pumps. The one and only requirement is the existence of a naturally produced energy surplus. There have been several examples of PAT implementation around the world during the last two decades (Williams 1996; Williams & Simpson 2009). Although, the potential of a network to recover energy is not something novel, few water utility managers have adopted this policy. The majority of PAT installations have taken place in the water supply mains of WDNs (Arriaga 2010), where water from springs or bore holes is being supplied through large diameter pipes. The main reason is that such pipes have high flow rates and sometimes also cover long distances and develop high pressures from the altitude difference. Except for a minimum of pressure and flow inside a pipe, the energy produced must have a purpose to serve. Energy production usually takes place near the energy consumption/demand sites; otherwise a power transmission network is required.

Although the use of PATs may seem promising (Agarwal 2012), a thorough study is needed before equipment selection and installation. It is a problem of high complexity which needs extreme care; otherwise such a promising investment can easily turn into a failure. In order to implement PATs successfully, water utility managers need to cooperate with experienced researchers and equipment providers. Kozani city was selected as a case study in order to present an example of a PAT implementation project in a city's WDN.

CASE STUDY AND METHODOLOGY

In order to test the possible implementation of PATs, the WDN of Kozani city (capital of Kozani County in West Macedonia Region, Greece) was selected as the case study, as it operates completely with gravity and has a need for PM due to considerable altitude differences between the water tanks and the lowest parts of the city. Several nodes of the network suffer from pressures higher than 10 atmospheres. The hydraulic model of the WDN was developed using the WaterGEMS v8i software tool. Kozani city lies 710 metres above sea level (asl). The local municipal water utility (called DEYAK) serves almost 50,000 people, through a well-designed water network widely spread to cover a huge area (Figure 1), including the entire city and more than ten suburbs. The total daily water volume supplied by the WDN reaches its peak (22,744 m^3) in July, while dropping to 18,584 m^3 in January. These figures equal a per capita daily water use ranging between 370 and 455 litres, both are extremely high, indicating a possibly high level of NRW (Patelis *et al.* 2016). Kozani is supplied by the Ermakia springs (to the north) in winter and by the Vathylakkos boreholes

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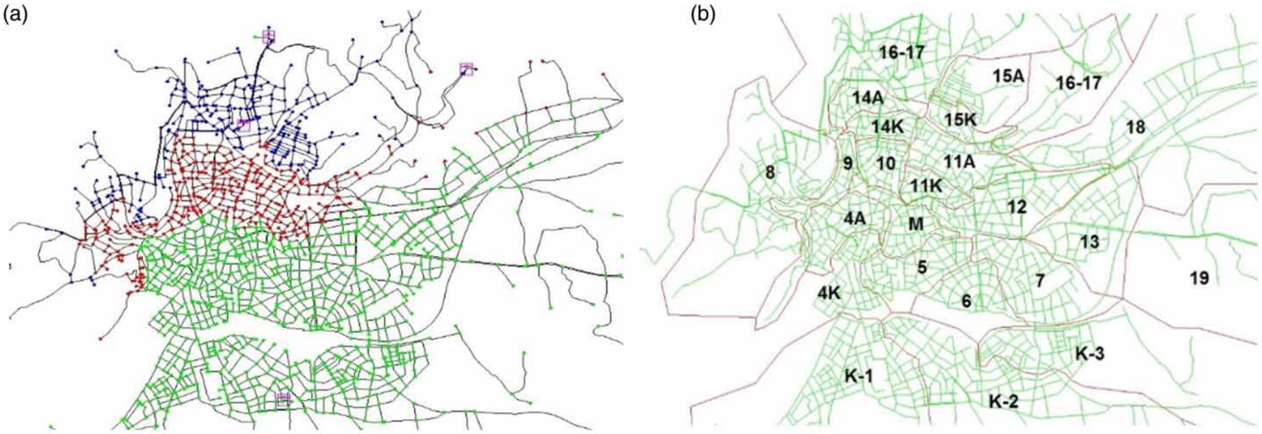

Figure 1 | Kozani's WDN: (a) water tanks and pressure zones; (b) DMAs. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/aqua.2017.018.

(to the south) in summer. There are three pressure zones formed: (a) a limited higher (BLUE) zone in the north (altitude ranging from +750 to +800 m asl); (b) a medium (RED) zone in the middle (altitude ranging from +710 to +750 m asl); and (c) a low (GREEN) zone in the south (altitude ranging from +610 to +710 m asl), covering 60% of the total water demand (Figure 1(a)) (Kanakoudis *et al.* 2014; Kanakoudis & Gonelas 2016). There are two main water storage tanks and also a tank system supplying only the middle zone.

Kozani's WDN was chosen for this study due, in part, to the large altitude differences observed (Patelis *et al.* 2016). Thus, as already mentioned, DEYAK operates the network by supplying water into three pressure zones. Due to the large altitude difference, the network works sufficiently by gravity. High nodal pressures cause major problems to the network's operating status and life expectancy. Furthermore, water losses are increased and NRW reaches 58% of the system input volume (SIV) (Kanakoudis & Tsitsifli 2014; Kanakoudis *et al.* 2015). Utilizing the water network's model, 24 DMAs were formed (Kanakoudis *et al.* 2014) (Figure 1(b)). The borders of the DMAs formed were figured by virtually installing isolation valves in the respective pipes. Although several pipes had the potential to be sites where PATs could be installed, only a few were selected for the present study. Specifically, the pipes considered were only those supplying water to one or more DMAs. Only DMA entrance pipes were checked simply because they are the water mains of the network and are capable of managing pressure downstream (controlling one or more DMA). The aim of the current study was twofold: not only to produce energy through PATs but also to reduce the operating pressure like the PRVs do, when installed in the same pipes at the DMAs' entrance points. To test a possible PAT site, a pipe with excessive pressure potential must be pinpointed. In order to reach a reliable solution, all DMAs were examined despite their high complexity. Some DMAs may be supplied by one pipe but still have more than one exit. This fact made the entire attempt even more complex as the impact of one DMA does not end within its limits but extends to all downstream DMAs. DMAs that supply water downstream (meaning that they are not the last downstream DMAs) affect other DMAs when upstream pressure is reduced. Although every possible position was checked, most times not all pipes could support a PAT efficiently. In order to estimate the energy potential of a pipe, Equation (1) was selected to calculate the power of a hypothetically installed PAT. This equation has been used in the past by researchers for similar purposes (Singh 2009; Nasir 2013) and is used by many manufacturers to calculate energy production.

$$P_{\mathrm{el}} = \Delta h \times Q \times \mathrm{g} \times \rho \times \mathrm{n}_{\mathrm{turb.}} \times \mathrm{n}_{\mathrm{gen.}}\ (\mathrm{watt}) \tag{1}$$

$$P_{\mathrm{el}} = (\mathrm{m}) \times \left(\frac{\mathrm{m}^3}{\mathrm{s}}\right) \times \left(\frac{\mathrm{m}}{\mathrm{s}^2}\right) \times \left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right) = \left(\mathrm{kg} \times \frac{\mathrm{m}^2}{\mathrm{s}^3}\right) = \frac{\mathrm{J}}{\mathrm{S}} = \mathrm{W}$$

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where P_{el} is the power produced through a turbine (watts); Δh is the hydraulic head difference (m); Q is the water flow (m^3/s); g is the acceleration of gravity ($9.81\,m/s^2$); ρ is the water density ($1{,}000\,kg/m^3$); $n_{turb.}$ is the turbine's efficiency factor (usually 0.8–0.9); $n_{gen.}$ is the generator efficiency factor (usually 0.8–0.9).

Out of 18 pipes/sites checked as potential PAT installation sites only 11 could support a turbine of 2 kW or more. Seven pipes were excluded as their flow and head differences were found to be insufficient for energy production. According to what the international market offers, suitable equipment was selected and virtually implemented (through the WDN's hydraulic simulation model) in each site. Each PAT was hydraulically simulated and tested in the model. The results showed that, in some cases, a PAT was able to control the downstream pressure in more than one DMA at the same time. Thus, some PATs were 'set to off' as both water pressure and flow had already been decreased due to a PAT installed upstream. Figure 2 presents the actual sites (pipes) of the seven turbines that were able to produce considerable energy. It has to be mentioned that technically in all PRV positions, a PAT has to be installed after the PRV (most of the time). The PRV is not removed when a PAT is installed. On the contrary, it continues to serve two purposes: (a) a PRV is required to control the flow before the PAT to avert damage due to rapid fluctuations of flow and pressure, so the PRV offers the necessary pressure and flow stability by slightly reducing pressure and flow level as well as keeping them steady; (b) in some cases flow and pressure may be reduced below a PAT's design point. This leads to no energy production or even worse may hamper a pipe's flow. In such cases the system must be able to by-pass the PAT and let the PRV alone control any excessive pressure.

Although combining energy recovery and PM using PATs is of high value, the results must be compared to those of installing just PRVs. Thus, three scenarios were crosschecked in this study; all took place in the seven DMAs (4 K, M, 5, 12, 7, K-2, 18) where the seven pipes that are potential PATs sites have their entry points. Scenario 1 includes the formation of the DMAs, without installing any PRVs or PATs. Scenario 2 includes the installation of a PRV at the entry point of each DMA. Each PRV is selected according to the diameter of the pipe and is regulated to operate on a steady initial minimum pressure value. This value is defined by the network's model in order for the crucial node in the DMA to be kept over 200 KPa (this minimum required nodal pressure is defined

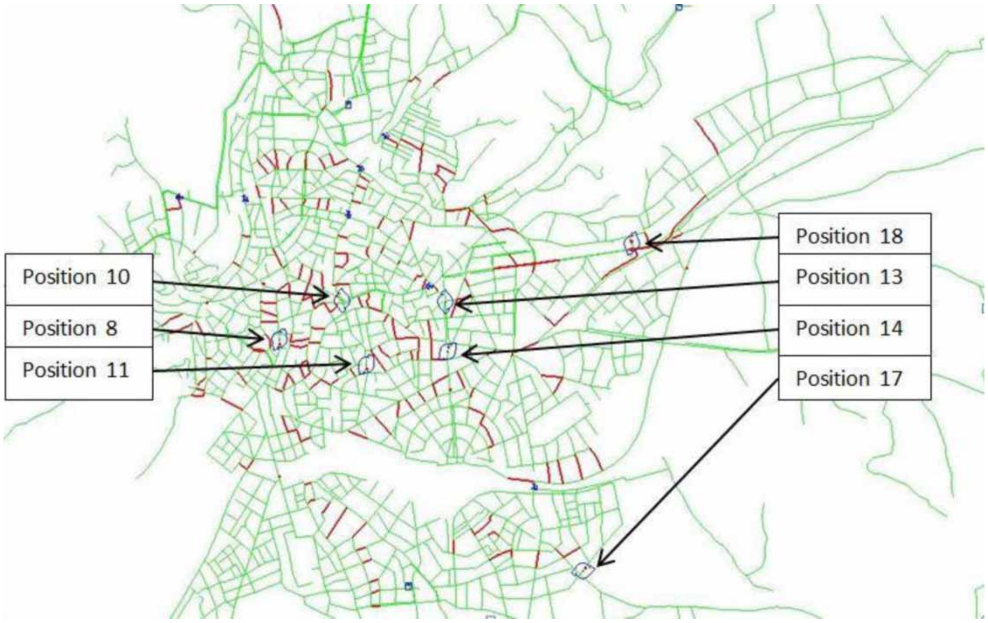

Figure 2 | Actual sites of PATs inside Kozani's WDN.

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by Greek legislation). Scenario 3 exploits the possibility of replacing every PRV with a proper PAT. The PATs are installed in the exact same position where the PRVs of Scenario 2 were put. Each PAT has a different power value (Table 1). Turbine power is limited due to the restriction of minimum nodal pressure (200 KPa) in every node of the DMA. Both the PRV and PAT selected have no daily pattern regulators, thus operate on a steady-state condition. The other factors that define a PAT's type are market availability and cost.

Those three scenarios described above were separately tested using the Bentley WaterGems v8.i software tool. The hydraulic model of Kozani's WDN was calibrated and validated first in order to offer reliable results. Each scenario was tested regarding reduction of DMAs' water input volume, annually recovered energy (in Scenario 3 only), equipment purchase cost, maintenance costs, value of energy recovered and water volume being saved.

RESULTS

The results of each scenario clearly revealed, after several tests, certain advantages and disadvantages regarding each alternative. Specifically, it can be observed (Table 2) that in Scenario 2 better PM is achieved than in Scenario 3. On the other hand, Scenario 3 is the only one that results in some energy being produced, that can be used to cover several needs of the WDN. Reduction of the SIV greatly

Table 1 | Power of each PAT in each possible installation site

Possible site for a PAT that produce more than 2 kW		
Position numbering	**Estimated power**	**PAT (kW) Nominal power of selected equipment**
8	6.14	5
10	12.38	10
11	5.65	4.5
13	6.68	5
14	4.93	4
17	4.06	3
18	7.78	6

Table 2 | Pressure, flow, saved water, recovered energy in Scenarios 2 and 3

	Scenario 1 (just forming DMAs) – base Scenario				**Scenario 2 (DMAs formed and PRVs installed)**				**Scenario 3 (DMAs formed and PATs installed)**			
DMAs	**Average pressure (Kpa)**	**Annual average water flow (L/s)**	**Annually saved water (m^3)**	**Annually recovered energy (kWh)**	**Average pressure (Kpa)**	**Annual average water flow (L/s)**	**Annual water savings (m^3)**	**Annually recovered energy (kWh)**	**Average pressure (Kpa)**	**Annual average water flow (L/s)**	**Annual water savings (m^3)**	**Annually recovered energy (kWh)**
4 K	588.26	28.73	0	0	277.08	22.06	210,244.87	0	316.24	23.46	166,009.7	43,800.0
M	536.80	73.62	0	0	324.61	55.84	560,469.56	0	345.18	59.04	459,654.4	87,600.0
5	669.76	18.68	0	0	248.19	12.60	191,688.47	0	284.02	13.46	164,376.2	39,420.0
12	548.81	32.86	0	0	359.46	24.07	277,240.82	0	390.11	26.56	198,799.7	43,800.0
7	633.66	19.00	0	0	250.90	13.12	185,197.00	0	328.73	15.11	122,505.4	35,040.0
K-2	710.39	13.58	0	0	310.60	10.23	105,550.35	0	316.51	10.32	102,613.5	26,280.0
18	644.62	30.71	0	0	340.11	8.26	707,926.62	0	391.16	11.08	618,989.8	52,560.0

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depends on PM, thus Scenario 2 results in a slightly greater reduction of the SIV compared to Scenario 3.

Table 2 presents the results of all three scenarios in terms of pressure reduction, water volume entering each DMA, saved water volume, and recovered energy. It must be clear that in all three scenarios, the nodal pressure at the crucial nodes of each DMA is kept above the threshold set (200 Kpa). The PM achieved in Scenarios 2 and 3 differ by 0.83% (for DMA K-2) to 12.28% (DMA7). PM in both scenarios was very efficient and pressure reduction achieved ranged between 34.50% to 62.94% for Scenario 2 (PRVs) and 28.92% to 57.59% for Scenario 3 (PATs). Both PM strategies managed to control pressure efficiently compared to Scenario 1. Although PM achieved in Scenarios 2 and 3 is not identical, it is crystal clear that PATs do control pressure too. Figure 3 presents the pressure reduction rate achieved for in Scenarios 2 and 3.

Apart from reducing burst and leak incidents, PM measures reduce the NRW levels too as well as pressure-dependent consumption and other uses (Kanakoudis *et al.* 2014). All the above result in the reduction of the SIV. Saving water is vital for water utilities now as it is very hard to find new sources of water appropriate for drinking purposes in many locations. The total annual water saving in Scenario 2 was 2,238,318 m^3 and in Scenario 3 was 1,832,948.7 m^3 (i.e. 405,000 m^3 less). PATs' major advantage though is the energy being produced despite their inability to control pressure as efficiently as PRVs do. Scenario 3 is unique as there is energy recovery from the network itself. Significance of energy recovery is twofold, as the energy recovered would be otherwise wasted instead of offering the opportunity to the water utility either to directly cover part of its WDN energy needs or produce revenue if sold to the power utility. Figure 4 presents the energy recovery and water savings for Scenarios 2 and 3 for each DMA separately.

Results revealed that PATs should be considered by water utilities as a valuable investment, but their implementation requires careful study. Other than excessive energy, another prerequisite for PAT installation is energy requirement near the recovery site. In the situation where no energy requirement can be satisfied nearby, PATs are not the optimal solution for pressure reduction as power transmission must take place and this means additional costs. PRVs are more accurate and effective in reducing pressure and are easier to implement. Also equipment and maintenance costs differ for each scenario. A PAT may cost twice as much or more than a PRV, as a PAT usually needs a stabilization PRV to be installed too to protect the PAT. PATs require more advanced knowledge and personnel to monitor them. Nevertheless, installing PATs in a WDN making the best out of their dual beneficial role may prove

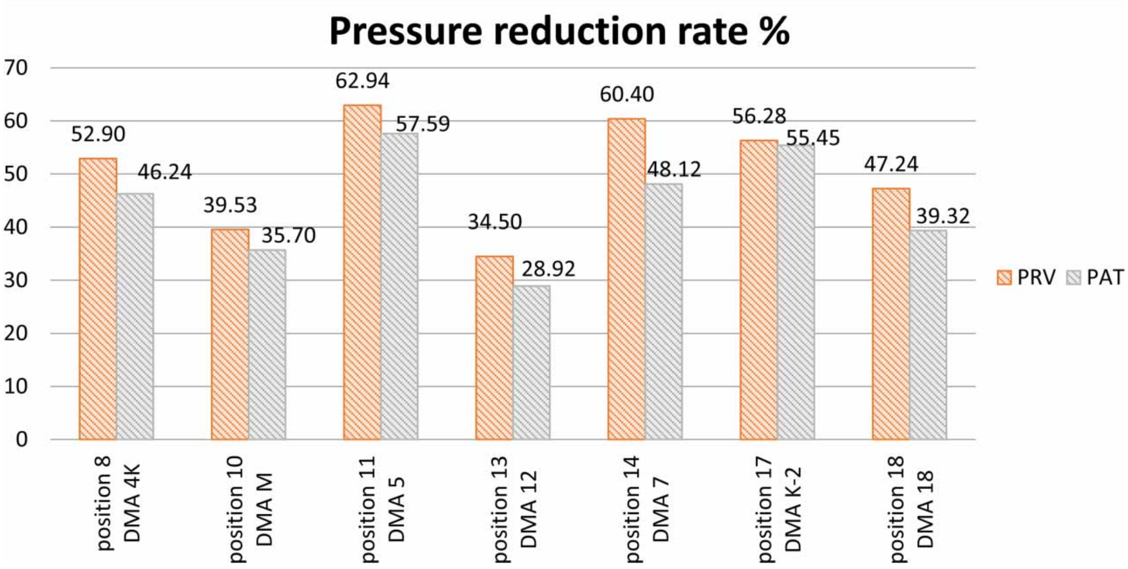

Figure 3 | Comparing the pressure reduction rate installing PRVs or PATs.

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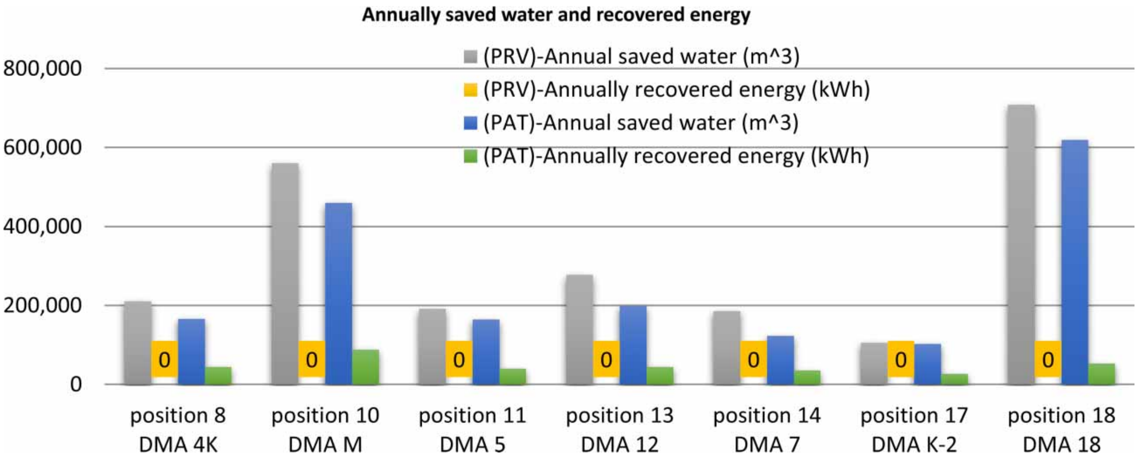

Figure 4 | Annually saved water and recovered energy volumes for Scenarios 2 and 3 (values from Kozani's WDN hydraulic simulation model).

to be the most valuable combined PM and energy recovery solution. Newer developed types of turbines make matters even more promising for PATs as recent models are capable of measuring downstream pressure and being self-adjusting to keep the pressure at the level required. More improvements are necessary in order to increase efficiency of mechanical equipment and limit other implementation risks as well as to minimize complexity of implementation and automate operation. If the differences in PM compared to PRVs are reduced and the energy recovery rate is increased then PATs would beyond any doubt be more appealing than PRVs.

CONCLUSIONS

Increased level of the NRW (mainly of real water losses) is a considerable problem for water utilities as it is considered responsible for additional problems to the existing infrastructure (e.g. increased pipe breakage rates). DMA implementation and PRV installation are considered as the most effective PM strategies today. PM tactics manage to reduce pressure along with all its negative effects but do not take advantage of water's surplus kinetic energy. PATs unfold a new opportunity for WDNs: energy recovery combined with effective PM. PATs, implemented properly, can produce a useful amount of energy, along with reduction of DMAs' excessive pressure. Water utilities can combine PATs inside a WDN with bigger PATs in the water supply mains (before the main water tanks outside the city limits). In this way water utilities could be self-sufficient in terms of energy needs. Pressure control through PATs is not yet as efficient as in the case of PRVs which leads to an inevitable dilemma: energy production or optimum PM? Experts must study and define whether there is adequate energy surplus in a network and find the most suitable sites for PATs to be installed. WDNs need certain characteristics to pose as possible hosts of PATs. For an efficient and cost-effective PAT, water must flow inside the WDN only by gravity. Furthermore, energy must be produced near to an energy-need site; otherwise energy must be transported for long distances or sold which might be impossible or quite expensive.

In the current study, three scenarios were tested to compare PRV and PAT implementation after the segmentation of a WDN in DMAs. Results for PRV installation met their expectations, but PAT implementation also provided very promising results. The 24 DMAs in the WDN of Kozani were evaluated but only seven of them would benefit from the installation of a PAT at their entrance. The rest of the DMAs lacked excessive pressure and flow. Finally, after hydraulic simulation, the entry points of the seven DMAs were proven capable of producing power greater than 2 kW and PATs were selected carefully in order to calculate PM too. Although the PM results through the PATs were good, they fell short of PRV implementation. PATs can be very valuable providing dual benefits but need extra care, cost more and require expertise in assessment before implementation. Improper selection of equipment, wrong

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installation sites and calibration may harm the WDN instead of reducing the pressure and recovering energy. Every test carried out was always performed according to certain restraints. PRV and PAT implementation in every scenario maintained the minimum pressure level requirements downstream in order to keep consumers satisfied. PATs may be promising up to now but need further research in order to produce a safe and cost-effective solution for water utilities.

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