

# Excess Pressure in Municipal Water Supply Systems as a Renewable Energy Source: Antalya Case Study



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**Abstract** Pressure management is one of the most effective methods for water loss reduction. Pump used in turbine mode (pump as turbine, PAT) is a viable option for reducing excess water pressure, water losses, and pipe failures in water distribution networks in addition to energy production at microscale. In this study, a PAT system recently installed in Antalya City of Turkey is presented, and its performance is evaluated for its initial operational period of approximately 5 months. This full-scale PAT system was implemented in a parallel pipeline with a pressure-reducing valve (PRV). The operation of the PAT system was continuously monitored online for flow rate, power, and pressure levels. The PAT system proved to work efficiently in a wide range of inflows (130–300 m<sup>3</sup>/h) where the produced energy varied between 0.7 and 8.4 kWh for a reduction of approximately 1 bar pressure head with an average efficiency of 60%. Environmental benefits of green energy production, reduction in physical water losses, and carbon dioxide emissions were evaluated. The payback period of the PAT application was computed as 53 days based on the costs and revenues of the PAT application.

**Keywords** Energy recovery · Water supply · Urban network · Pump

## Introduction

Safe water supply is among the priority tasks of municipalities and water utilities. However, sustainability of water supply systems (WSSs) is an important issue besides continuous and hygienic supply of water. Within the context of sustainable WSS, improvement of energy efficiency, reduction of energy, and water losses in addition to reduction of greenhouse gas (GHG) emissions are of great concern. High amounts of energy are consumed and GHG emissions are encountered during

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water abstraction, treatment, transmission, and distribution stages. Pressure in water pipes is one of the main design parameters for WSSs where it is controlled by upper and lower limits. Excess pressure usually occurs during water transmission from high elevations of water resources to low elevations, and this high water pressure has to be reduced. Excess pressure at transmission lines is commonly reduced using traditional techniques including break pressure tanks, water storage tanks, or pressure-reducing valves (PRVs). However, a more sustainable technique of energy recovery from excess pressure is possible by using turbines. Applications of turbines for energy production at water transmission lines are available at many countries such as the United States, Canada, Honduras, Switzerland, Austria, and Italy.

One of the main factors causing leakage and pipe failure in water distribution networks (WDNs) is the excess pressure. An increase in the water pressure always implies an increase of leakage from the holes and cracks of the network. Consequently, pressure management is the most important and commonly applied action for physical water loss reduction [1–4]. Commonly, the excess pressure in WDNs is controlled and reduced to optimum operational levels by the use of PRVs at selected locations without any power generation. However, both pressure reduction and energy production from the available excess water pressure could be achieved by the use of turbines or pumps as turbines (PATs). In the literature, mainly two alternative schemes were proposed for hydropower generation in WDNs: only PAT [5] or combined PAT and PRV [6–8]. The PAT systems mainly include a centrifugal water pump, operated in reverse mode, and a synchronous electrical generator with constant rotational speed to produce energy. There are several advantages for using PATs instead of turbines: (1) PATs are usually cheaper than turbines, (2) turbines are usually designed specifically for application sites, (3) PATs are usually maintained easily from the market for different power and flow rate requirements, and (4) spare parts of PATs are easily available. The main reported disadvantage of PATs is the lower efficiencies compared with turbines. PATs contribute to water saving in WDNs by reducing leakage due to pressure reduction, besides energy production and reduction of GHG emissions [6]. In this respect, energy production in WDNs is widely discussed in the literature [9–12]. Energy production potential in WDNs is usually at microscale (<100 kW). Due to their low operational and capital costs, use of PATs is commonly advised [13, 14].

Due to the increasing global awareness on the adverse impacts of high energy consumption and GHG emissions on climate change, all sectors are usually forced to reduce their energy consumptions and GHG emissions. Metropolitan cities have priorities to accomplish sustainable WSSs and to take precautions to limit the GHG emissions [15]. Consequently, optimization of energy in water supply sector has gained an increasing interest [16], and several research studies were conducted to evaluate the technical and economic feasibilities for energy recovery in WSSs. Some of the presented cases for leakage reduction and energy production indicate good opportunities for actual implementations with relatively short payback periods and environmental benefits [17, 18]. As an example, the PAT systems at pico scale (<4 kW) were recommended as viable options with payback periods of 4–22 months [19]. Turbines generally have very high efficiency levels, while efficiency of the

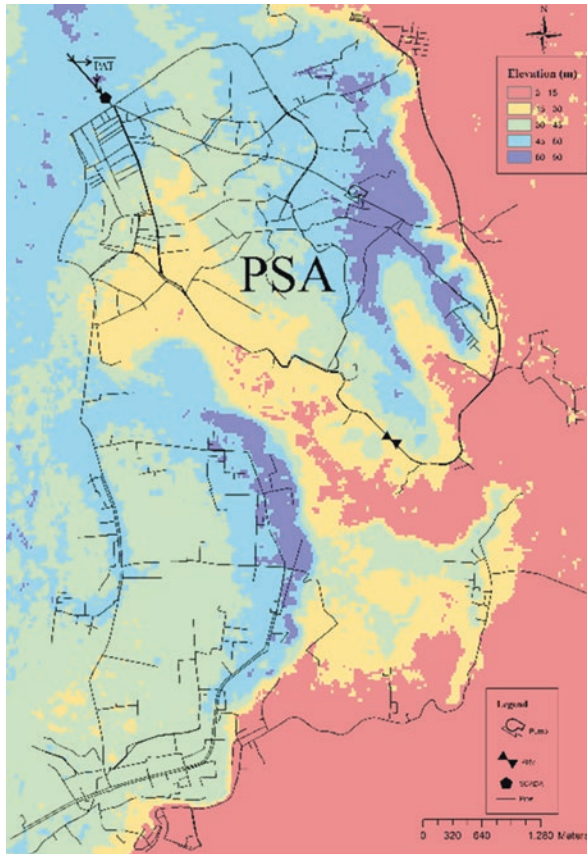
PAT systems could be raised up to 85% [13]. One of the main challenges related to the PAT systems is the variations in the flow rates where the systems are claimed to be sensitive to medium and high flow rate variations as discussed by several researchers [5, 6, 19, 20]. Theoretical, experimental, and numerical investigations are presented for possible applications of micro-hydropower and PAT systems. Moreover, several research studies are focused on the design of the PATs; analysis of cavitation, force, and efficiency; comparison of the conventional turbines with the PATs; and cost analysis for evaluating economic feasibility [14, 21]. To the best of authors' knowledge, there is no published full-scale application of the PAT systems in WDNs for water loss reduction and energy recovery [7]. The following sections present design details, installation scheme, and initial operational results of a full-scale PAT system installed at Antalya City of Turkey. This innovative system was installed on a bypass line and in parallel with a PRV. The performance of the installed PAT system was continuously monitored by online measurement equipment for flow rate, power, and pressure levels at upstream and downstream of the PAT. The PAT system proved to work effectively in a wide range of inflows (130–300 m<sup>3</sup>/h), while the produced energy varied between 0.7 and 8.4 kWh for the reduction of approximately 1 bar pressure head.

## The Case Study

### *Site Selection*

The full-scale PAT system was implemented at a pilot study area (PSA), namely, *Aksu* district WDN of Antalya Metropolitan City, located at the south of Turkey. The PSA was selected by close cooperation with Antalya Water and Wastewater Authority (ASAT) and was evaluated to have excess water pressure and frequent pipe bursts. The WDN data sets such as elevations, coordinates, lengths, diameters, types, and ages of the pipes besides locations of service connections and valves were obtained from ASAT and verified on site. The main components of the PSA with digital elevation model (DEM) are depicted in Fig. 1.

The population of the study area is approximately 25,000 people, while the total length of the WDN is approximately 80 km. A supervisory control and data acquisition (SCADA) station is located at the entrance to the PSA where continuous online measurements of flow rate and pressure are realized and the measured data sets are recorded at the headquarters of ASAT. The existing water pressures at the entrance to the PSA were always in the range of 3–5 bars. The measured flow rates in 2015 demonstrated a wide variation where the minimum, the mean, and the maximum values were 130 m<sup>3</sup>/h, 252 m<sup>3</sup>/h, and 552 m<sup>3</sup>/h, respectively. The occurrence of the maximum flow rate was a very rare condition that lasted shortly due to pipe breaks. Additionally, the minimum flow rate occurred for very short time periods, which was mainly due to some interventions in the WDN for maintenance



**Fig. 1** Main components of the pilot study area (PSA) with digital elevation model [8]

and repair. The topography of the PSA exhibits wide spatial variations, between 3 and 90 m above the mean sea level, and this situation causes high variations in the pressure levels in the WDN. Due to the high variation of topography in the PSA, a booster pump is operated mostly in summer months to supply water to high elevations whereas a PRV is continuously operated to reduce excess water pressure at lower elevations. The excess water pressure level to be reduced by the PAT system was determined approximately as 1 bar as obtained by the results of the hydraulic modeling study carried out for the PSA besides the technical advice of ASAT [7].

### ***Initial Setup and Test Operations at Lab***

The initial setup and test operations were accomplished at the research and development laboratory (R&D lab) of the manufacturer factory of the PAT (Fig. 2). The PAT system was designed in parallel with a PRV to maintain the continuous and constant reduction of approximately 1 bar water pressure for this specific application. Various



**Fig. 2** The initial setup and test operations at the research and development laboratory

flow rates and inlet pressure levels were tested for about 3 months. Consequently, the head, power, and efficiency curves of the PAT were prepared (Fig. 3). Based on the flow rate data sets of the PSA in Antalya, the PAT system was designed to operate between 130 and 330 m<sup>3</sup>/h. According to the R&D lab tests, the PAT system could generate 0.2 kWh energy at 128 m<sup>3</sup>/h flow rate and 6.2 m net head, while it could generate 9.6 kWh energy at 308 m<sup>3</sup>/h flow rate and 17.9 m net head. The PAT system was designed and tested to operate at highly varying inflows and pressure levels.

### ***Field Installation and Operation of PAT***

The full-scale installation of the PAT system was designed on a separate bypass line of the main pipe where the total flow rate could be directed to the bypass line using the existing control valve on the main pipe (Fig. 4).

Two additional isolation valves were installed at the inlet and the outlet of the bypass line in order to stop operation of the PAT system when needed. The cross-sectional view of the bypass line for the installed PAT system and the PRV is presented in Fig. 5. The pipe diameters are 650 mm for the main pipe and 250 mm for the bypass line. The installed PAT system, shown in Fig. 6, consists of the following equipment: a PAT (10 kW capacity), a synchronous alternator (11 kVA, 750 rpm), a flow modulated actuated valve, an electronic load controller, a PRV, online mea-

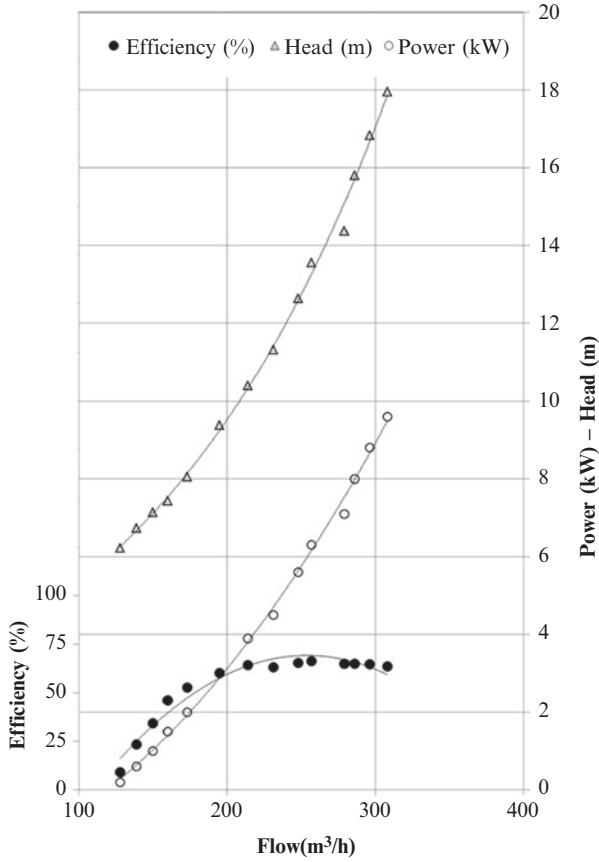


Fig. 3 Head, power, and efficiency curves of the PAT designed for the PSA [7]

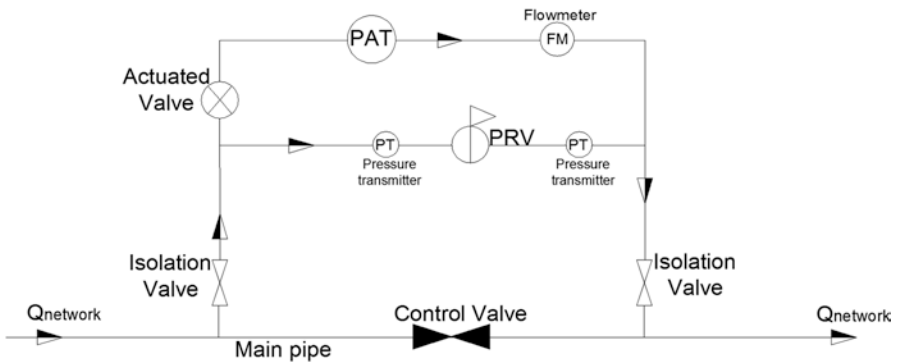


Fig. 4 Installation scheme of bypass line for the PAT and PRV [7]



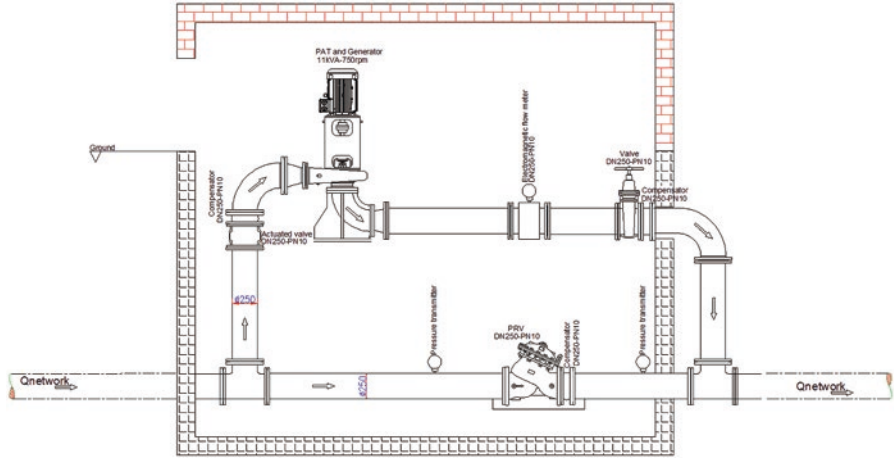


Fig. 5 Cross-sectional view of the bypass line for the installed PAT system and PRV [7]



Fig. 6 Photographs of the installed PAT system [7]

surement equipment (electronic flow meter, pressure transmitters), data loggers, two control panels with display screens, and dummy load to absorb the remaining energy.

The synchronous alternator converts the mechanical energy produced by the PAT into electrical energy. A voltage regulator is installed to maintain a constant voltage from the alternator. The actuated valve is controlled by the control panel, and it receives a signal to close partially when the rotational speed exceeds 750 rpm in the alternator. Conversely, a signal is sent to open the valve more if the inflow is low. Switches mounted on the valve are used to control the valve position. This valve is controlled by the rotational speed of the alternator and the total energy consumed. The panels control the production and consumption of electricity from the PAT system. They prevent the overload on the PAT and also distribute the electricity in between the loads. The control panel is connected to an electronic load controller (ELC), and it continuously monitors the speed, frequency, and voltage to maintain high-quality power generation. Detailed information about the system components were presented elsewhere [7]. The full-scale PAT system was in operation starting from January 26, 2016.

### ***Energy Recovery Analysis***

Generated power from hydroelectric turbines or PATs could be calculated using Eq. 1 where the notations are as follows:  $P$ , power (watt);  $Q$ , flow rate ( $\text{m}^3/\text{s}$ );  $\rho$ , density of water ( $\text{kg}/\text{m}^3$ );  $g$ , acceleration due to gravity ( $\text{m}/\text{s}^2$ );  $H$ , available head (excess pressure) ( $m$ ); and  $e_o$ , total efficiency of power generation system. Total efficiency includes all losses from conversion of kinetic energy into mechanical energy such as turbine/PAT losses, energy conversion, and distribution [22].

$$P = Q \rho g H e_o \quad (1)$$

The performance of the installed PAT system was continuously monitored by the online measurement of the flow rate, power production, and pressure levels at upstream and downstream of PAT. The installed system operated efficiently under the highly varying flow rates and pressure levels, and the automation system of PAT was able to manage with all the operational conditions. The continuous online flow rate and the pressure measurements from the SCADA station, located at the downstream of the PAT system, are presented in Fig. 7 for the period of December 17, 2015, till June 14, 2016 (1 month before the operation of the PAT in addition to about 5 months in operation). Within this period, there were even a few occasions when water was cut for some construction and maintenance works and the installed PAT system was automatically off-line and online without any personal intervention. There were no complaints from the water subscribers in the PSA regarding the reduction of the water pressure. The pressure values, measured continuously at the upstream and downstream of the PAT system, are presented in Fig. 8. Continuously measured hydropower production from the installed PAT system is presented in Fig. 9.



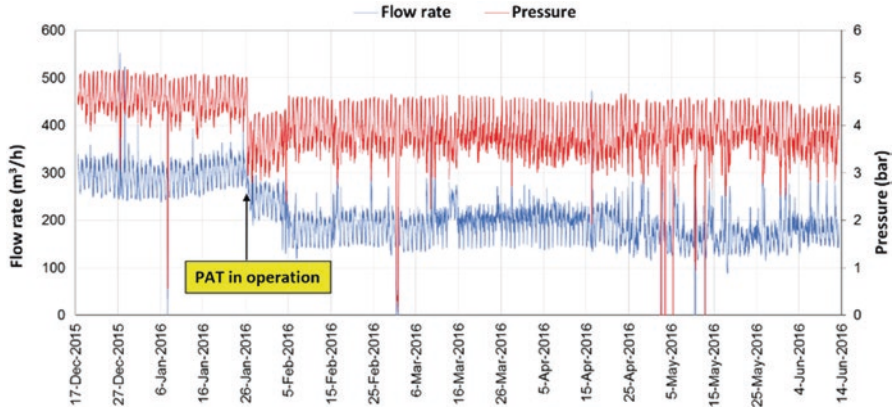


Fig. 7 Flow rate and pressure values at the PSA before and after the operation of PAT [8]

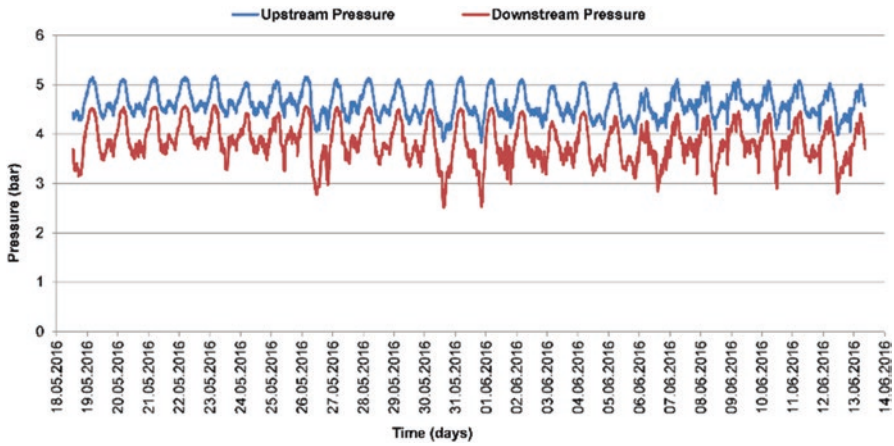


Fig. 8 Pressure values measured at upstream and downstream of PAT system [8]

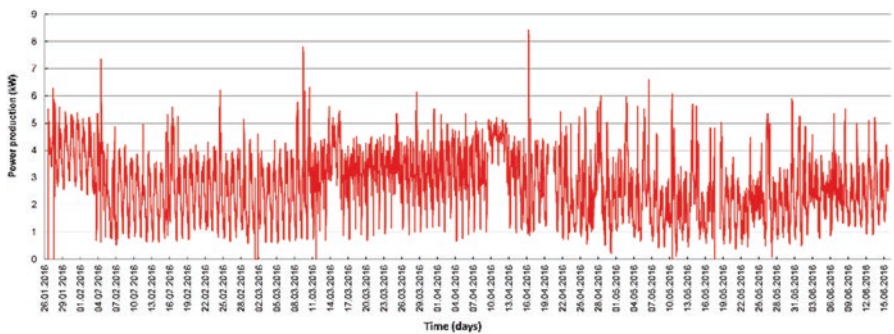


Fig. 9 Continuously measured hydropower production from the installed PAT system [8]

With the reduction of the pressure, a significant reduction was observed in the measured flow rates as well. Before the operation of the PAT system, the average flow rate was calculated as  $293 \text{ m}^3/\text{h}$  for an approximate period of 1 month (between December 17, 2015, and January 25, 2016). However, the average flow rate reduced to  $190 \text{ m}^3/\text{h}$  during the first operational period of approximately 5 months (between January 26, 2016, and June 14, 2016). The observed reduction in the flow rates was due to the pressure reduction in the WDN which was highly effective to reduce physical water losses. In order to estimate the reduction of the physical water losses in the PSA due to the operation of the PAT system, water consumption in the PSA was assumed to be similar for the years 2015 and 2016. Consequently, the difference between the flow rates was taken as the reduction in the physical water losses, i.e., water saving. The flow rate values, continuously measured online at the SCADA station for the years 2015 and 2016 for the period between January 1 and June 14, were compared. During this period, reduction in the physical water losses in the PSA was estimated at about  $59 \text{ m}^3/\text{h}$ . Within the same period, the average and maximum flow rates that passed through the installed PAT system were  $169 \text{ m}^3/\text{h}$  and  $289 \text{ m}^3/\text{h}$ , respectively. The frequencies were 90.89% and 4.83% for flow rate values between  $130 \text{ m}^3/\text{h}$  and  $210 \text{ m}^3/\text{h}$  and above  $210 \text{ m}^3/\text{h}$ , respectively. Within this period, the average and the maximum values of the hydropower production were 2.7 kW and 8.4 kW, respectively. The frequencies were 92% and 58% for the hydropower production values between 1-5 kW and 2-4 kW, respectively. Furthermore, the efficiency of the installed PAT system was evaluated, and the computed efficiency values for a period of 1 week (between May 25 and June 2, 2016) are presented in Fig. 10 as an example.

The efficiency of the PAT system demonstrated a high variation and the average efficiency was determined as 60%. The frequency was 77.14% for efficiency values between 50 and 80%. The efficiency levels below 40% or above 80% were less frequent. The installed PAT system was designed to operate for flow rate values between 130 to  $330 \text{ m}^3/\text{h}$  and when the flow rate was less than  $130 \text{ m}^3/\text{h}$ , the efficiency of the PAT system was very low (<10%). In general, the power and efficiency values obtained from the full-scale application of the PAT system were consistent

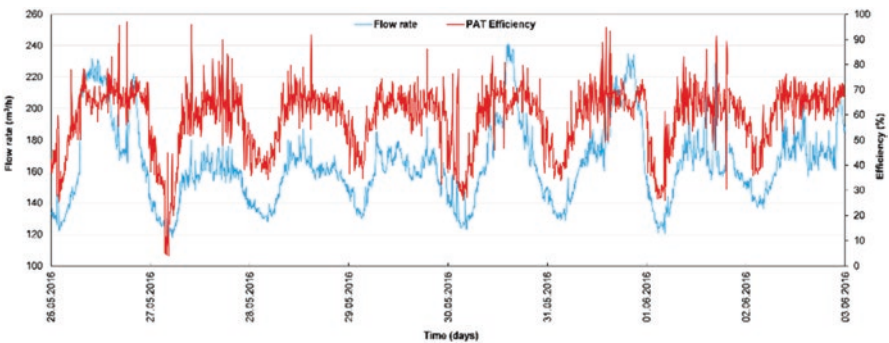


Fig. 10 Efficiency of the installed PAT system and its variation with flow rate [8]

with the characteristic curve of the PAT. The installed full-scale PAT system was observed to work efficiently and without any failure for highly varying operational conditions, with respect to flow rate, pressure, and even interruptions due to the maintenance and repair of the WDN.

### ***Cost-Benefit Analysis***

The implementation cost of the PAT system, with 10 kW capacity, includes electrical and mechanical equipment, construction costs for the underground bypass room and the aboveground protection house, and assembly and installation of all electrical and mechanical parts. The costs were presented in Table 1 for the main components, based on the real local prices in Turkey. Environmental benefits of the PAT system were evaluated in four major groups: (1) green energy production by the PAT system by reducing the excess pressure, (2) reduction in carbon dioxide (CO<sub>2</sub>) emissions due to the green energy production, (3) water saving in the WDN due to the reduced pressure and the physical water losses, and (4) energy saving and CO<sub>2</sub> emission reductions from the transmission and distribution of the saved water. The reference value of CO<sub>2</sub> emission for energy production in Turkey was estimated at 0.53426 kg CO<sub>2</sub>/kWh as an average value [23]. The revenues of the direct economic benefits were estimated/computed based on the local and national economic values. The electricity tariff for municipal use in Turkey was taken as 0.1269 Euro/kWh including all taxes. The energy consumption for transmission and distribution of the drinking water in Antalya City WSS was estimated at 0.67 kWh/m<sup>3</sup>. The average water tariff of 0.50 Euro/m<sup>3</sup>, applied by ASAT for the water subscribers in Antalya City, was considered. The payback period was calculated by dividing the total implementation cost by the total amount of revenues, as presented in Table 2. All the direct economic benefits and their revenues were evaluated for the period between February 1 and June 13, 2016, which covered 133 days of operation. The total revenue for this period was approximately 95,391 € or 717 €/day, and the payback period was computed as 53 days or 1.8 months. The considerably short payback period in this specific application was mainly due to the high revenues obtained from the water savings.

**Table 1** Implementation cost of the installed full-scale PAT system [8]

Items	Cost (€)
Construction costs	8,450
Mechanical installation of PAT system	5,050
Cost of PAT system (generator, ELC panel, hydraulic unit, display panel, three data loggers, two pressure sensors)	15,680
Other mechanical equipment (PRV, valves, electromagnetic flow meter, all pipe fittings)	9,030
Total cost	38,210

**Table 2** Environmental benefits and revenues of the installed PAT system [8]

Main groups	Environmental benefit	Revenue (€)
Energy production by the installed PAT system	8,599 kWh	1,091
Reduction of CO <sub>2</sub> emissions due to energy production of 8599 kWh	4,594 kg CO <sub>2</sub> reduction	–
Water saving due to pressure reduction by the installed PAT system	188,600 m <sup>3</sup>	94,300
Energy saving from transmission and distribution of water (due to water saving of 188,600 m <sup>3</sup> )	126,362 kWh	<sup>a</sup>
Reduction of CO <sub>2</sub> emissions from energy saving of 126,362 kWh	67,510 kg CO <sub>2</sub> reduction	–
Total revenues of environmental benefits for 133 days of operation	95,391 €	
Revenues from environmental benefits for each day of operation	717 €/day	
Payback period (days)	53	

<sup>a</sup>The revenue for energy saving from transmission and distribution of saved water (126,362 kWh) was already accounted in the water saving revenue

The installed PAT system proved to be efficient in reducing water pressure and leakage and producing energy. However, there are still some challenges related to the operation of the full-scale PAT system: (1) the efficiency of the PAT system reduces considerably with the reduced flow rate, (2) the optimum design of the PAT system depends on the levels of the flow rates and the pressure levels, and (3) Produced electricity from the PAT system needs to be consumed immediately on-site for operational control.

## Conclusion

One of the challenging operational problems of WDNs is water loss which is mainly due to excess water pressure. Consequently, different types of PRVs are commonly installed at WDNs for pressure management to reduce excess pressure and water losses. However, PAT is an alternative system that improves efficiency of WDNs by reducing pressure and water losses besides producing energy at the same time. Theoretical PAT systems are widely discussed in the literature for their advantages, disadvantages, operational difficulties, and technical and economic feasibility compared with PRVs. In this study, implementation and operational performance of a full-scale PAT system in Antalya City WDN in Turkey were presented. To the best of authors' knowledge, there is no full-scale application of PAT systems in WDNs for water loss reduction and energy recovery [7]. The performance of the installed PAT system was continuously monitored by online measurement equipment for flow rate, power, and pressure levels. The PAT system, being in operation since January 2016, works efficiently in a wide range of inflows (130–300 m<sup>3</sup>/h), while

the produced energy varies between 0.7 and 8.4 kWh for a reduction of approximately 1 bar pressure head with an average efficiency of 60% and a payback period of 1.8 months. Implementation of PAT system leads to many further environmental benefits and operational advantages such as reducing CO<sub>2</sub> emissions and improvement of energy efficiency for sustainable management of WDNs; reducing number and frequency of pipe failures and bursts; reducing time, money, and efforts spent for maintenance and repair of pipes; improving water supply services by reducing the frequency of interventions; improving satisfaction of water subscribers; and also delaying the need for new water supply projects. However, there is a need for further studies to improve efficiency of PAT systems at fluctuating flow rates and to design PAT systems with a frequency regulator for operating at variable rotational speeds.

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