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Evaluation of performance and environmental benefits of a full-scale pump as turbine system in Antalya water distribution network

Ayse Muhammetoglu, Cezmi Nursen, I. Ethem Karadirek and Habib Muhammetoglu

ABSTRACT

In recent years, pumps used in turbine mode (pump as turbine, PAT) have started to appear as a viable option to reduce pressure in water distribution networks in addition to energy production at micro scale. In this study, evaluation of performance of a recently installed PAT system in Antalya City, Turkey, is presented for the first operational period of approximately 5 months. This full-scale PAT system was implemented in a parallel pipeline with a pressure reducing valve. The operation of the installed PAT system was continuously monitored online for flow rate, power and pressure. The installed PAT system, being in operation since 26 January 2016, works efficiently in a wide range of inflows (130–300 m^3/h) and the produced energy varies between 0.7 and 8.4 kWh for a reduction of approximately one bar pressure head with an average efficiency of 60%. Based on the initial 5 months of operational data, environmental benefits of green energy production, reduction in physical water losses and carbon dioxide emissions were evaluated. Based on the implementation cost of the PAT system and the revenues from the environmental benefits, payback period of this specific full-scale PAT application was computed as 53 days or 1.8 months.

Key words | energy production, environmental benefits, pressure reduction, pump as turbine (PAT), water distribution network, water losses

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INTRODUCTION

Management of excess water pressure and improving energy efficiency in water supply systems (WSSs) are important issues for operational sustainability. Within the concept of sustainable water management, conservation of water in all sectors has gained importance due to increasing water demand and pressure on water resources. Reduction of water losses in water distribution networks (WDNs) is among the top priorities of water authorities for sustainable management. One of the main factors causing water losses and leakage is pressure, where excess pressure increases the rate of leakage. Consequently, pressure management is the most important and commonly applied action for water losses reduction (Araujo *et al.* 2006; Thornton & Lambert 2006; Karadirek *et al.* 2012; Vicente *et al.* 2016). Excess pressure in WDNs is commonly controlled and reduced to optimum operational levels by the use of pressure reducing valves (PRVs) at selected locations without any power generation. However, both pressure reduction and energy production could be achieved by the use of turbines or pumps as turbines (PATs) using the available excess water pressure. In the literature, mainly two alternative schemes have been proposed for hydropower generation in WDNs: only PAT (Fontana *et al.* 2012), and PAT and PRV together (Carravetta *et al.* 2012; Muhammetoglu *et al.* 2017). PAT

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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 and disadvantages of using PAT systems instead of turbines: (i) turbines provide higher efficiencies than PATs; (ii) turbines are usually more expensive than PATs; (iii) turbines are usually designed specifically for application sites; (iv) PATs are usually maintained easily from the market for different power and flow rate requirements; and (v) spare parts for PATs are easily available. PATs contribute to water saving by reducing water losses and excess pressure in WDNs besides producing energy and reducing carbon dioxide emissions (Fontana *et al.* 2012). In this respect, energy production in WDNs is widely discussed in the literature (Ramos & Borga 1999; Giugni *et al.* 2009; Samora *et al.* 2016a, 2016b). Energy production potential in WDNs is usually at micro scale (<100 kW) and the possibility of using turbines with high capital cost is not a viable choice. Due to their low operational and capital costs, the use of PATs is commonly advised (Ramos *et al.* 2005, 2010; Jain & Patel 2014).

Due to increasing global awareness of the adverse impacts of high energy consumption and carbon dioxide emissions on climate change, all sectors are forced to reduce their energy consumptions and carbon dioxide emissions. Metropolitan cities have priorities to accomplish sustainable WSSs and to take precautions against climate change (Jenerette & Larsen 2006). Consequently, optimization of energy in the water supply sector has gained in interest (Brown *et al.* 2010), and several research studies have been conducted to evaluate technical and economic feasibilities for energy recovery in WSSs, as briefly summarized in Table 1. Some of the presented cases indicate good opportunities for actual implementations with relatively short payback periods and environmental benefits. As an example, PAT systems at pico scale (<4 kW) were recommended as viable options with payback periods of 4 to 22 months by Lopes & Martinez (2006).

Turbines are generally described as having high efficiency values, whereas the efficiency of PAT systems could be raised up to 85%, as indicated by Ramos *et al.* (2010). One of the main issues related to PAT systems is the variations in flow rates where the systems were claimed to be sensitive to medium and high flow rate variations, as discussed by several researchers (Lopes & Martinez 2006; Caxaria *et al.* 2011; Carravetta *et al.* 2012; Fontana *et al.* 2012). Hydropower production performance of PAT and a turbine with five blades were compared by Caxaria *et al.* (2011),

Table 1 | Technical and economic feasibility studies for energy recovery in WSSs

Region/country (site and equipment)	Potential pressure (kPa)	Flow rate (m^3/day)	Potential power (kW)	Reduction in CO_2 emissions (tons CO_2/year)	Payback period (years)	Reference
Kildare/Ireland (7 BPTs)[a]	180–600	714–17,910	2–27	7–128	3–45	McNabola *et al.* (2014)
Dublin/Ireland (3 BPTs)	60–150	26,400–152,760	12–115	57–548	<1–6	
Ireland and United Kingdom (95 different sites)	–	–	17–212	79–268	3–10	Corcoran *et al.* (2013)
New Jersey/USA (micro turbine)			31–43	177–260		Telci (2012)
Aqaba/Jordan (2 BPTs)			400–563	19,0314	0.24–0.37	Khair (2012)
Aqaba/Jordan (7 reservoirs)			4–565		0.24–1.11	
Aqaba/Jordan (9 PRVs)			1–25.5		2.59–13.90	
Scotland/United Kingdom (3 BPTs)	261–558	2,765–7,223	8.2–31.0		4.9–9.1	Rintoul (2012)
Napoli/Italy (PRV and PAT)		29,393	17.5–34.2		2.5–3.0	Giugni *et al.* (2009) and Fontana *et al.* (2012)

[a]BPT, break pressure tanks.

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in which the tested turbine was found to be more advantageous than PAT, with a higher hydromechanical efficiency and stability for variations in flow rate. Some recent research studies have focused on novel turbine design (Yang 2012) and PAT design strategies (Fecarotta *et al.* 2011; Agarwal 2012; Carravetta *et al.* 2012, 2013a, 2013b). Carravetta *et al.* (2012) presented a PAT design method based on a variable operating strategy, where a maximum PAT performance curve was defined for constant flow rate and pressure head.

In this study, performance of a full-scale PAT system, installed at Antalya City WDN in Turkey, is presented for hydropower generation, reduction in physical water losses and carbon dioxide emissions. This novel system was installed on a bypass line and in parallel with a PRV. The performance of the installed PAT system is continuously monitored by online measurement equipments for flow rate, power and pressure upstream and downstream of the PAT. Currently, the installed PAT system works efficiently in a wide range of inflows (130–300 m^3/h), and the produced energy varies between 0.7 and 8.4 kWh for a reduction of approximately one bar pressure head. Detailed information about the implementation phase, design and components of the installed PAT system were presented by Muhammetoglu *et al.* (2017). This current study aims to evaluate performance and environmental benefits of this novel application for its initial 5 months of operation and determine its payback period.

METHODS

Case study area

The full-scale PAT system was installed at Aksu district WDN of Antalya Metropolitan City, located in the south of Turkey. This application was realized within a recently completed research project supported by the Scientific and Technological Research Council of Turkey. The decision for the application site of the full-scale PAT system was approved by Antalya Water and Wastewater Authority (ASAT). The application site was evaluated as having excess water pressure and frequent pipe bursts in the WDN, according to the previous years' operational data and experience. The WDN data including elevations, coordinates, lengths, diameters, types, ages of pipes and locations of service connections and valves in the pilot study area (PSA) were obtained from ASAT and verified on site. The geographic information system layout map of the WDN and digital elevation model of the PSA are presented in Figure 1. 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 for evaluation. 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 in which the minimum, mean and maximum values were 130, 252 and 552 m^3/h, respectively. The occurrence of maximum flow rate was a very rare condition that lasted briefly, due to pipe breaks. Additionally, the minimum flow rate occurred for very short time periods, and was mainly due to some interventions in the WDN for maintenance and repair.

The topography of the PSA exhibits wide spatial variations, between 3 and 90 metres above mean sea level, within a few kilometers, and this situation causes high variations in pressure 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 water authority, ASAT, was highly interested in the full-scale application of the PAT system to reduce excess pressure and water losses in the PSA. The excess water pressure level to be reduced by the PAT system was determined approximately as one bar, as obtained by the results of a hydraulic modelling study carried out for the PSA (Muhammetoglu *et al.* 2017), besides the technical advice of ASAT from their long years of operational experience.

Installation and operation of PAT system

Before installation and operation of the full-scale PAT system at the PSA, its initial set-up and test operations were accomplished at the Research and Development Laboratory (R&D Lab) of the manufacturing factory of PAT, established in Istanbul, Turkey. Various flow rates and inlet pressure levels were tested for about 3 months.

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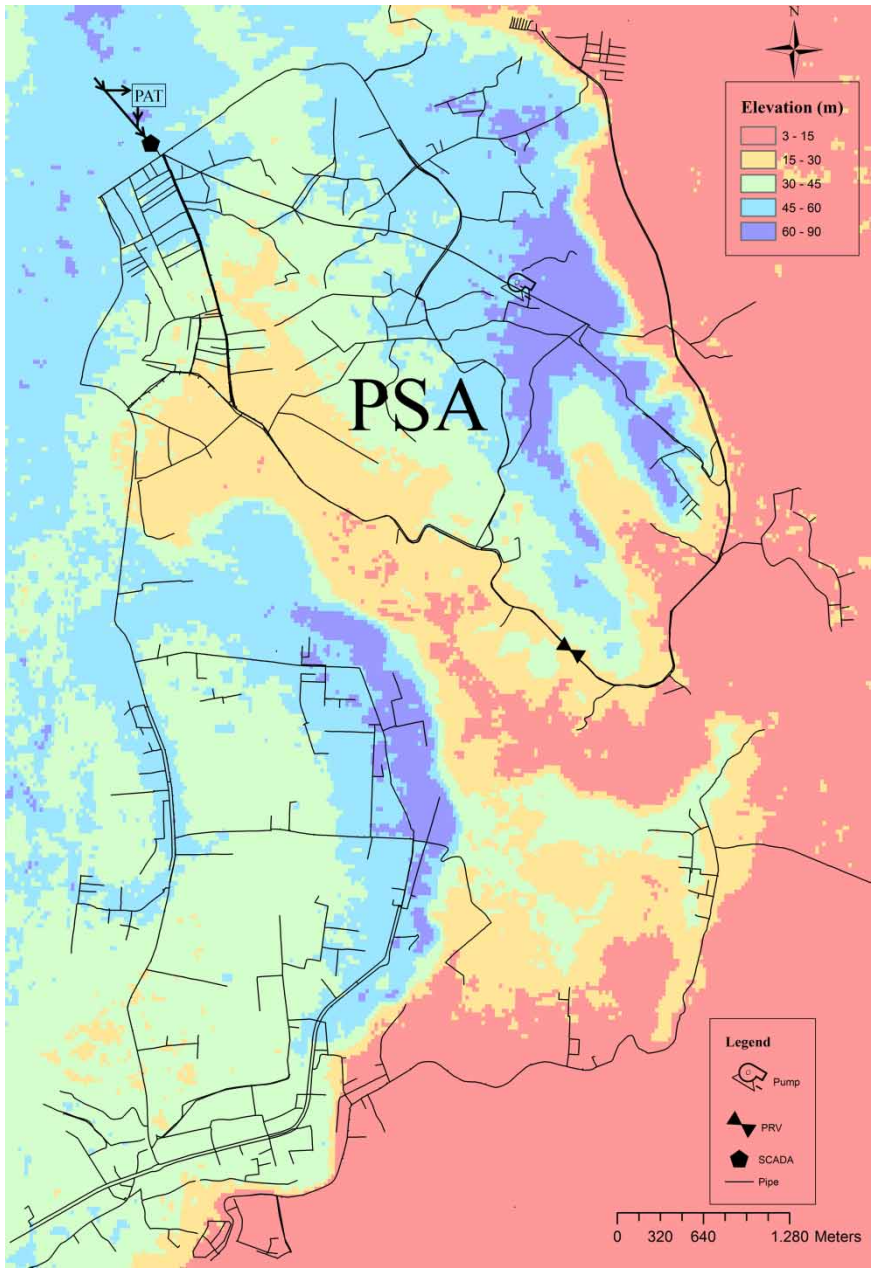

Figure 1 | WDN and digital elevation model of PSA (modified from Muhammetoglu *et al.* 2017).

Consequently, head, power and efficiency curves of the PAT were prepared (Figure 2). Based on the flow rate data sets of the PSA in Antalya, the PAT system was designed to operate between 130 and 330 m^3/h. According to the R&D Lab tests, the PAT system could generate 0.2 kWh energy at 128 m^3/h flow rate and 6.2 m net head, whereas it could generate 9.6 kWh energy at 308 m^3/h flow rate and 17.9 m net head. Consequently, the PAT system was designed and tested to operate at highly varying inflows and pressure levels.

The civil works related to bypass line construction and mechanical work related to the installation of the PAT system and its components were finalized on 26 January 2016 at the PSA. Starting from this date, the full-scale PAT

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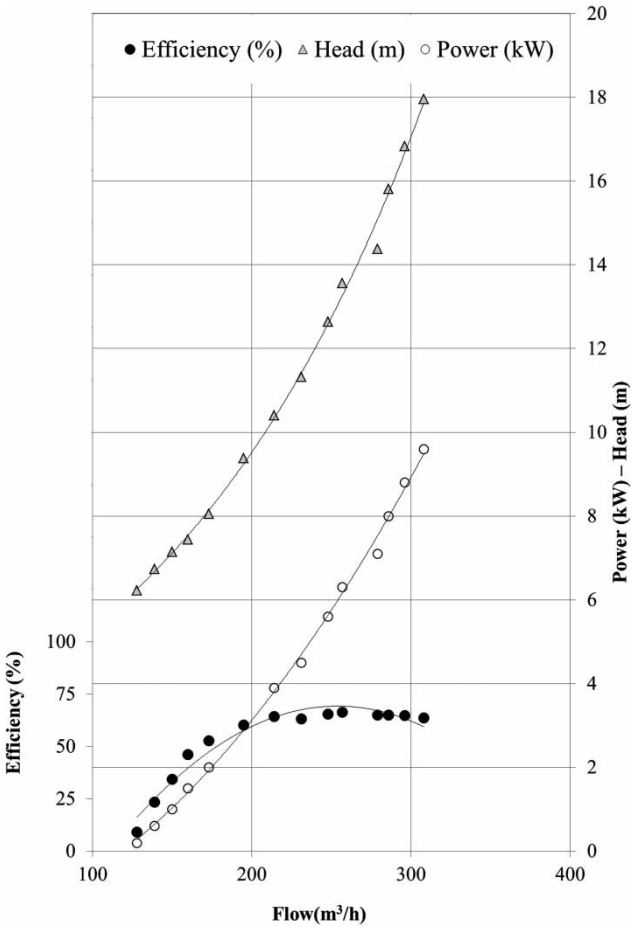

Figure 2 | Head, power and efficiency curves of the PAT system designed for the PSA (Muhammetoglu *et al.* 2017).

system was in operation to provide drinking water for the PSA and to reduce excess pressure and produce energy. The installed PAT system 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 (ELC), a PRV, online measurement equipment (electronic flow meter, pressure transmitters), data loggers, two control panels with display screens and a dummy load to absorb the remaining energy. The cross-sectional view of the bypass line for the installed PAT system and PRV is presented in Figure 3. The synchronous alternator converts the mechanical energy produced by the PAT system 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 overload on the PAT and also distribute the electricity in between the loads. The control panel is connected to an ELC and it continuously monitors the speed, frequency and voltage to maintain high quality power generation. Detailed information about the system components were presented in the study of Muhammetoglu *et al.* (2017).

Hydropower production

Generated power from hydroelectric turbines or PATs can be calculated using Equation (1), where notations are as follows: P, power (watt); Q, flow rate (m^3/s); ρ, density of water (kg/m^3); g, acceleration due to gravity (m/s^2); H, available head (excess pressure) (m); 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 (McNabola *et al.* 2014):

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

Implementation costs and environmental benefits

The implementation cost of the installed full-scale PAT system, with 10 kW capacity, includes electrical and mechanical equipment, construction costs for the underground bypass room and the above-ground protection house, assembling and installation of all electrical and mechanical parts. The costs are presented for the main components, based on the real local prices in Turkey. The mentioned costs were covered through a national scientific research project whereas other construction works (bypass line inlet and outlet connections from the main water distribution pipe, excavation and land-filling, final re-organization of the pilot application area, arrangement of the SCADA station connections, etc.) were realized by the responsible water authority, ASAT.

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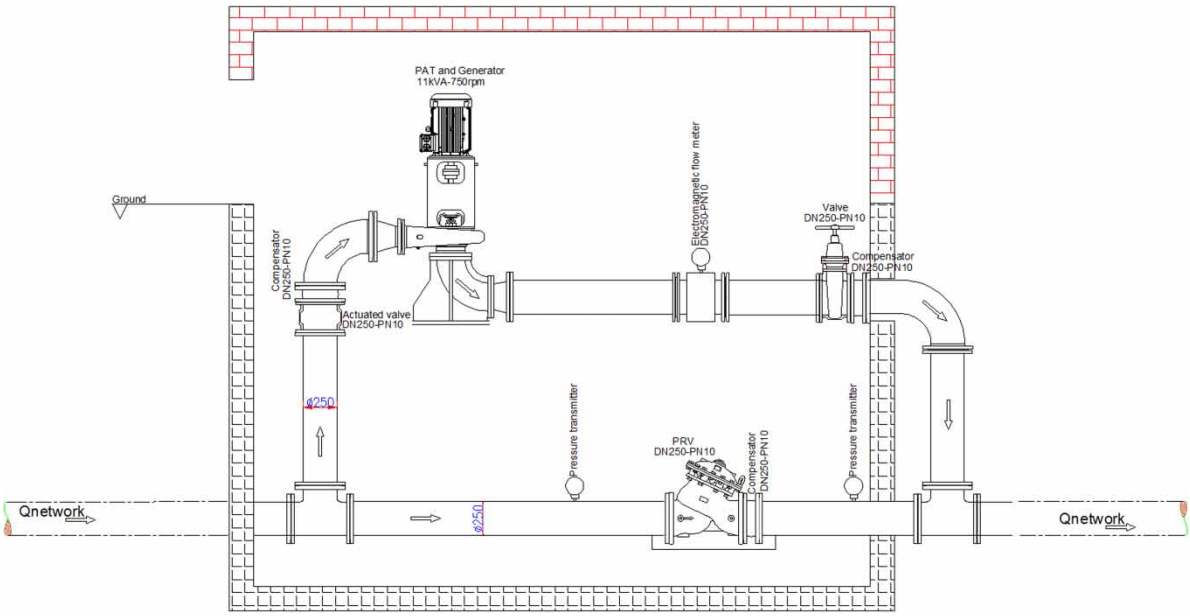

Figure 3 | Cross-sectional view of bypass line for the installed PAT system and the components (Muhammetoglu *et al.* 2017).

Environmental benefits of the installed PAT system were evaluated in four major groups: (i) green energy production by the installed PAT system by reducing excess pressure; (ii) reduction in carbon dioxide (CO_2) emissions due to green energy production; (iii) water saving in the WDN due to reduced pressure and physical water losses; and (iv) energy saving and carbon dioxide emission reductions from transmission and distribution of saved water. The revenues of the environmental benefits were estimated/computed based on the local and national economic values as listed below:

- The electricity tariff for municipal use in Turkey was taken as 0.1269 euro/kWh including all taxes.
- The reference value of CO_2 emission for energy production in Turkey was estimated at 0.53426 kg CO_2/kWh as an average value (Can 2007).
- The energy consumption for transmission and distribution of drinking water in Antalya City WSS was estimated at 0.67 kWh/m^3 due to yearly water and energy budgets of the responsible water authority, ASAT.
- The environmental benefit of water saving was considered to be equivalent to the cost of water, according to the 'full recovery cost' principle of the European Water Framework Directive. In this respect, the average water tariff of 0.50 euro/m^3, applied by ASAT for water subscribers in Antalya City, was considered in this study.

The payback period was calculated by dividing the total implementation cost by the total amount of revenues for each operational day.

RESULTS AND DISCUSSION

Evaluation of the full-scale PAT system operation

The performance of the installed PAT system was continuously monitored by online measurement equipment for flow rate, power and pressure upstream and downstream of the PAT by the start of its operation on 26 January 2016 until the time of writing, and the measured data sets were recorded by data loggers. 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. The installed system operated efficiently under highly varying flow rates and pressure levels and the automation system of PAT was able to handle all the operational

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variations of a real WDN. The continuous online flow rate and pressure measurements from the SCADA station, located at the downstream of the PAT system, are presented in Figure 4 for the period of 17 December 2015 to 14 June 2016 (1 month before the operation of PAT in addition to about 5 months in operation) to evaluate the performance of the installed PAT system.

With the operation of the full-scale PAT system, the pressure in the WDN was reduced by approximately one bar, satisfying the operational limit and requirement of the water authority ASAT. There were no complaints from the water subscribers in the PSA regarding the reduction of water pressure. The pressure values, measured continuously at the upstream and downstream of the PAT system, are presented in Figure 5 for an approximate period of 1 month, which demonstrates the operational stability of the PAT system. With the reduction of pressure, a significant reduction was observed in the measured flow rates as well. Before operation of the PAT system, the average flow rate was calculated as 293 m^3/h for an approximate period of 1 month (between 17 December 2015 and 25 January 2016). However, the average flow rate reduced to 190 m^3/h during the first operational period of approximately five months (between 26 January 2016 and 14 June 2016), which was taken as the 'evaluation period' in this study. The observed reduction in the flow rates was due to pressure reduction in the WDN, which was highly effective in reducing physical water losses.

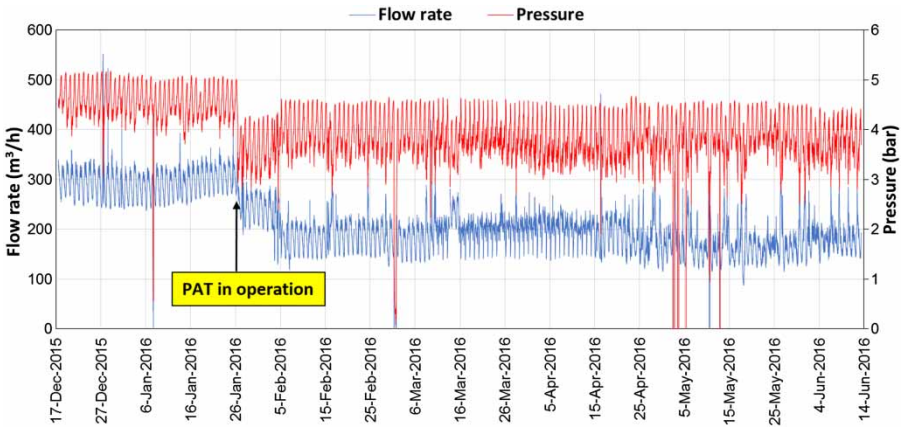

Figure 4 | Online flow rate and pressure measurements at SCADA station before and after the operation of the PAT system.

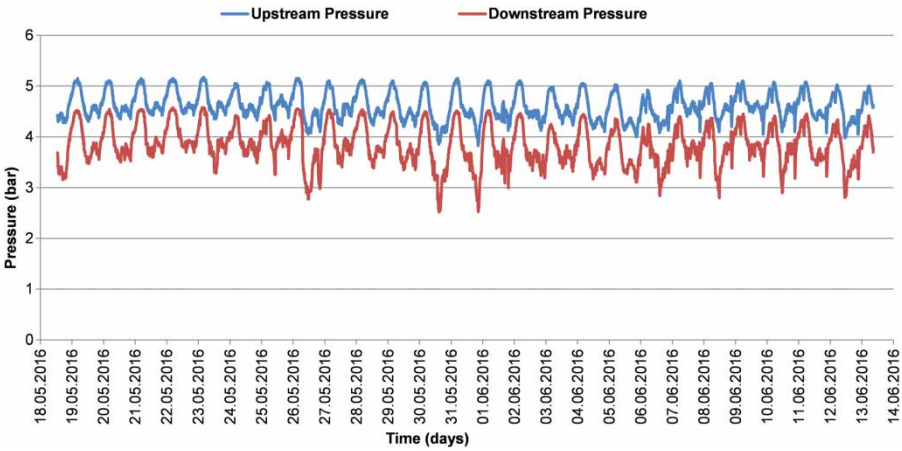

Figure 5 | Pressure values measured at upstream and downstream of the PAT system.

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In order to estimate the reduction of physical water losses in the PSA due to operation of the PAT system, water consumption in the PSA was assumed to be similar for the years 2015 and 2016 during the evaluation period. 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, are presented in Figure 6 for the years 2015 and 2016 for the period between 1 January to 14 June. This figure clearly shows the significant reduction of flow rates, i.e., reduction in the physical water losses in the PSA, which is about 59 m^3/h for the evaluation period.

The flow rate passing through the PAT system was continuously measured by the electromagnetic flow meter installed at the downstream of the PAT unit, and the measured flow rate values for the evaluation period are presented in Figure 7. Within this period, the average and maximum flow rates that passed through the installed PAT system were 169 m^3/h and 289 m^3/h, respectively. The frequencies were 90.89% and 4.83% for flow rate values between 130 and 210 m^3/h and above 210 m^3/h, respectively. Additionally, the hydropower production from the installed PAT system is presented in Figure 8 for the evaluation period. Within this period, the average and maximum values of hydropower production were

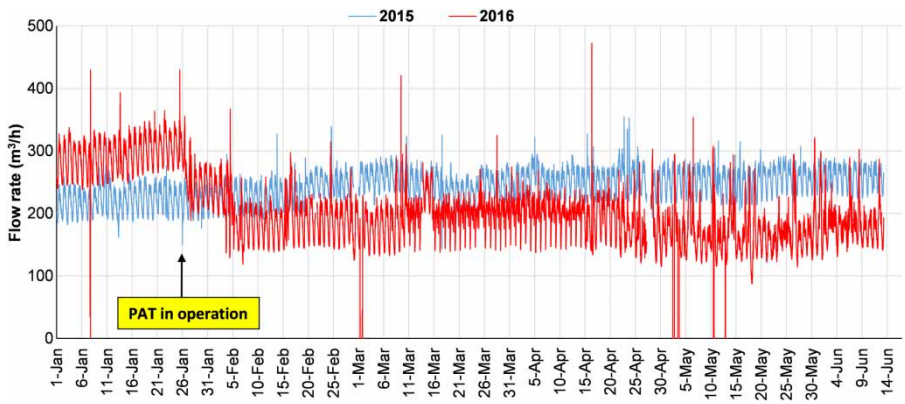

Figure 6 | Comparison of flow rate values measured in the years 2015 and 2016 at SCADA station, located at the downstream of the PAT system.

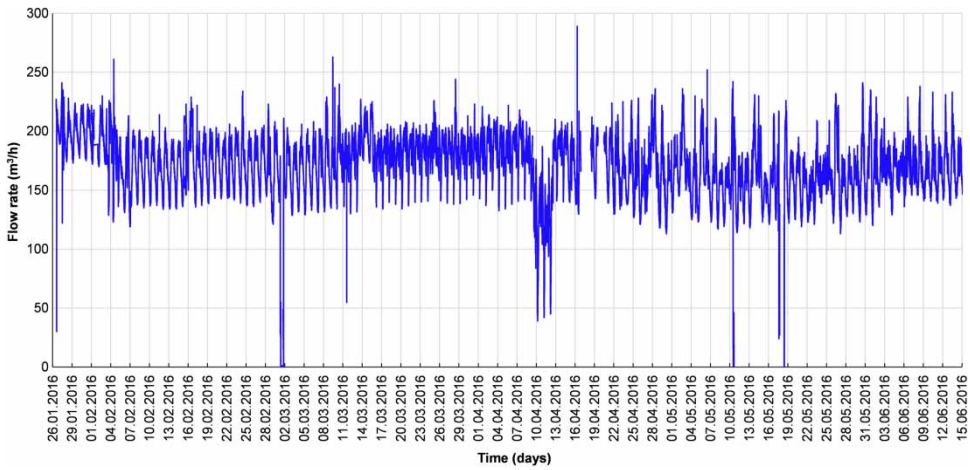

Figure 7 | Continuously measured flow rate that passed through the installed PAT system.

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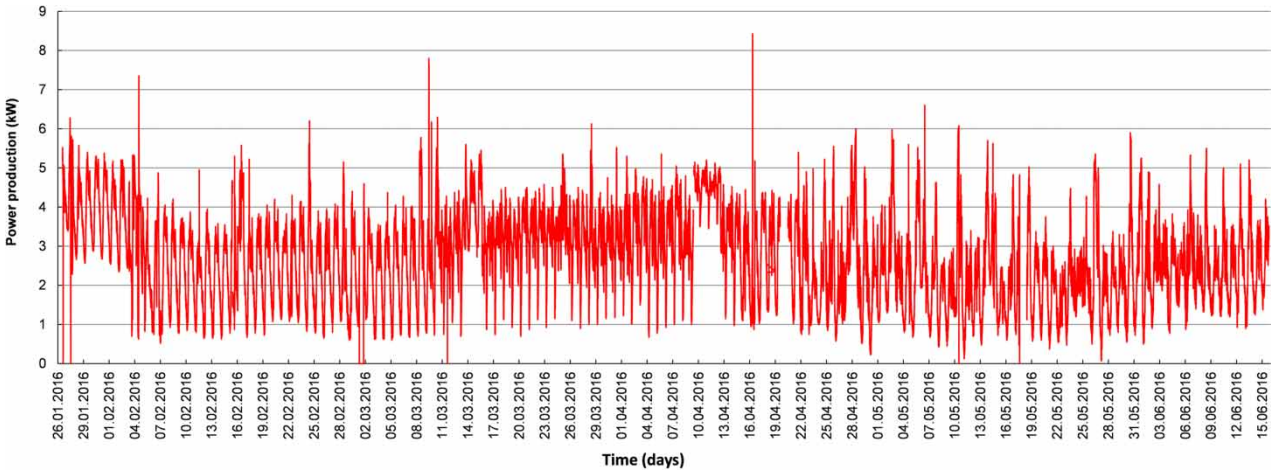

Figure 8 | Continuously measured hydropower production from the installed PAT system.

2.7 kW and 8.4 kW, respectively. The frequencies were 92% and 58% for 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 25 May and 2 June 2016) are presented in Figure 9 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%. Efficiency levels below 40% or above 80% were less frequent. In this specific application, the efficiency of the PAT system increases with the increase in the flow rate, as the level of pressure reduction was approximately one bar. The installed PAT system was designed to operate for flow rate values between 130 and 330 m^3/h, and when the flow rate was less than 130 m^3/h, the efficiency of the PAT system was very low (<10%). In general, power and efficiency values obtained from the full-scale application of the PAT system were consistent with the characteristic curve of PAT. The marginal differences were due to some minor variations in piping, fittings and accuracy of measurements. The mean flow velocity in the bypass pipe, where the PAT system was installed, was less than 1 m/s. Consequently, minor hydraulic losses due to piping (bends, fittings, etc.) were neglected. The installed full-scale PAT system was observed to work efficiently and without any failure for highly varying operational

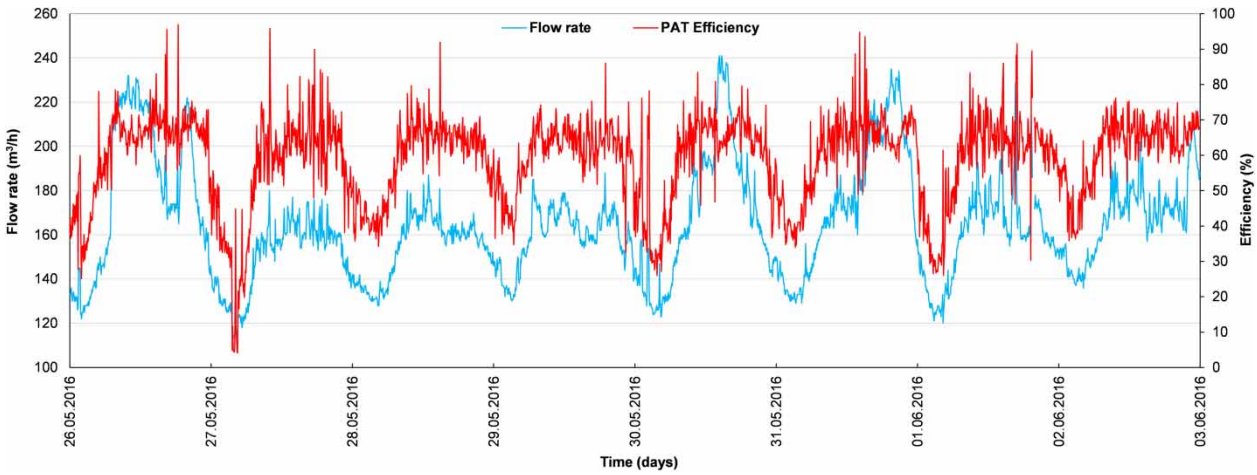

Figure 9 | Efficiency of the installed PAT system and its variation with flow rate.

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conditions, with respect to flow rate, pressure and even interruptions due to maintenance and repair of the WDN.

Implementation costs

The implementation cost of the installed full-scale PAT system with 10 kW capacity is presented in Table 2 for the main components, based on the real local prices in Turkey. Total cost of the installed PAT system, as covered by the research project, was approximately 38,210 euros (€). Other know-how costs related to the research and development, initial design, set-up and supervision of the installed PAT system were not accounted here. Additional construction works (bypass line inlet/outlet connections from the main water distribution pipe, excavation/landfilling, final re-organization of the pilot application area, arrangement of the SCADA station connections, etc.) were realized by ASAT, and they were not accounted here either. The implementation cost depends significantly on the overall system capacity and the local case-specific conditions. All the presented costs are valid for the installed PAT system with 10 kW capacity and the system specific flow rate and pressure variations for the applied WDN.

Environmental benefits and the revenues

In this study, all the environmental benefits and their revenues were evaluated for the period between 1 February and 13 June 2016, which covered 133 days of full operation (Table 3). The environmental benefits and their revenues were considered in five major groups: (i) energy production by the installed PAT system; (ii) reduction of CO_2 emissions due to energy production; (iii) water saving due to reduction in physical water losses; (iv) energy saving from transmission and distribution of water that previously accounted for physical losses; and (v) additional reduction of CO_2 emissions due to energy saving. Energy production from the installed PAT system was 8,599 kWh for the operational period of 133 days and the revenue for this produced energy was computed as €1,091. The reduction of CO_2 emissions due to this amount of energy production was estimated at 4,594 kg. The estimated volume of water savings (reduction in physical water losses) due to pressure reduction by the installed PAT system was approximately estimated at 188,600 m^3 with a revenue of €94,300 based on the local full recovery cost of water. The additional environmental benefits of water saving were the additional energy saving of 126,362 kWh and 67,510 kg of CO_2 emission reduction. Total revenue for 133 days of operation of the installed PAT system was approximately €95,391 (approximately €717/day). Based on the total implementation cost and the total amount of revenues for each day of operation,

Table 2 | Implementation cost of the installed full-scale PAT system (covered by the research project)

Items	Cost (€)
Construction costs (underground bypass room and above-ground protection house)	8,450
Mechanical installation of PAT system	5,050
Cost of PAT system (including generator, ELC panel, hydraulic unit, display panel, 3 dataloggers, 2 pressure sensors)	15,680
Other mechanical equipment (including PRV, valves, electromagnetic flowmeter, all pipe fittings)	9,030
Total cost	38,210

Table 3 | Environmental benefits and revenues of the installed PAT system

Main groups	Environmental benefit	Revenue (€)
Energy production by the installed PAT system	8,599 kWh	1,091
Reduction of CO_2 emissions due to energy production of 8,599 kWh	4,594 kg CO_2 reduction	–
Water saving due to pressure reduction by the installed PAT system	188,600 m^3	94,300
Energy saving from transmission and distribution of water (due to water saving of 188,600 m^3)	126,362 kWh	[a]
Reduction of CO_2 emissions from energy saving of 126,362 kWh	67,510 kg CO_2 reduction	–
Total revenues from environmental benefits for 133 days of operation	95,391 €	
Revenues from environmental benefits for each day of operation	717 €/day	
Payback period (days)	53	

[a]The revenue for energy saving from transmission and distribution of saved water (126,362 kWh) was already accounted in the water saving revenue.

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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 revenue obtained from water saving, and it clearly demonstrated that pressure reduction using a PAT system was very effective and feasible to reduce physical water losses and recover energy.

In addition to the mentioned environmental benefits, the number and frequency of pipe bursts and failures were reduced in the PSA according to the information received from the technical staff of the water authority. In this respect, operation of the full-scale PAT system has contributed to improving the operational performance of the WDN. The installed PAT system is still in operation and there is ongoing research to monitor and evaluate its performance and environmental benefits.

CONCLUSION

The advantages, disadvantages, operational difficulties, technical and economic feasibility studies of theoretical PAT systems in WDNs have been widely discussed in the literature. In this study, performance of a full-scale PAT system in Antalya City WDN in Turkey was presented for hydropower generation, reduction in physical water losses and carbon dioxide emissions. The performance of the installed PAT system was continuously monitored by online measurement equipment for flow rate, power and pressure. The installed PAT system, being in operation since 26 January 2016, works efficiently in a wide range of inflows (130–300 m^3/h) and the produced energy varies between 0.7 and 8.4 kWh for a reduction of approximately one bar pressure head with an average efficiency of 60%. Based on the initial 5 months of operational data, environmental benefits of green energy production, reduction in physical water losses and carbon dioxide emissions were evaluated. Based on the implementation cost of the PAT system and the revenues from the environmental benefits, the payback period of this specific full-scale PAT application was computed at 1.8 months. Environmental benefits and operational advantages of the PAT system can be listed as follows: (i) reduction of excess pressure and physical water losses in WDNs; (ii) energy recovery from excess pressure; (iii) reduction of CO_2 emissions; (iv) improving energy efficiency for sustainable management of WSSs; (v) reduction of number and frequency of pipe failures and bursts by reducing pressure; (vi) reducing time, money and effort spent for maintenance and repair of pipes; (vii) improving water supply services by reducing the frequency of interventions; (viii) improving satisfaction of water subscribers; and (ix) delaying the need for new water supply projects by reducing water losses in WDNs. However, there are still some challenges related to operation of a full-scale PAT system as well: (i) the efficiency of the PAT system reduces considerably with reduced flow rate; (ii) the design of the PAT system could be modified to operate with high efficiencies; and (iii) electricity produced from the PAT system needs to be consumed immediately on-site for operational control. Regarding the full-scale PAT system application in Antalya, there is an ongoing study to investigate possible options to use the produced electricity for public services on site.

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REFERENCES

Agarwal, T. 2012 Review of pump as turbine (PAT) for micro-hydropower. *International Journal of Emerging Technology and Advanced Engineering* **2** (11), 163–169.

Araujo, L. S., Ramos, H. & Coelho, S. T. 2006 Pressure control for leakage minimisation in water distribution systems management. *Water Resources Management* **20**, 133–149.

Brown, L. E., Mitchell, G., Holden, J., Folkard, A., Wright, N., Beharry-Borg, N., Berry, G., Brierley, B., Chapman, P., Clarke, S. J., Cotton, L., Dobson, M., Dollar, E., Fletcher, M., Foster, J., Hanlon, A., Hildon, S., Hiley, P., Hillis, P., Hoseason, J., Johnston, K., Kay, P., McDonald, A., Parrott, A., Powell, A., Slack, R. J., Sleigh, A., Spray, C., Tapley, K., Underhill, R. & Woulds, C. 2010 Priority water research

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questions as determined by UK practitioners and policy makers. *Science of the Total Environment* **409** (2), 256–266.

Can, O. 2007 *Carbon Management and Voluntary Carbon Market*. http://www.rec.org.tr/dyn_files/32/351-Oguz-Can-ISTAC.pdf (accessed 10 December 2015).

Carravetta, A., Del Giudice, G., Fecarotta, O. & Ramos, H. M. 2012 Energy production in water distribution networks: a PAT design strategy. *Water Resources Management* **26**, 3947–3959.

Carravetta, A., Del Giudice, G., Fecarotta, O. & Ramos, H. 2013a PAT design in water distribution network by system effectiveness. *Water* **5** (3), 1211–1225.

Carravetta, A., Del Giudice, G., Fecarotta, O. & Ramos, H. 2013b PAT design strategy for energy recovery in water distribution networks by electrical regulation. *Energies* **6** (1), 411–424.

Caxaria, G. A., Sousa, D. M. & Ramos, H. M. 2011 Small scale hydropower: generator analysis and optimization for water supply systems. In: *Proceedings of World Renewable Energy Congress*, Linköping, Sweden.

Corcoran, L., Coughlan, P. & McNabola, A. 2013 Energy recovery potential using micro hydropower in water supply networks in the UK and Ireland. *Water Science and Technology: Water Supply* **13** (2), 552–560.

Fecarotta, O., Carravetta, A. & Ramos, H. M. 2011 CFD and comparisons for a pump as turbine: mesh reliability and performance concerns. *International Journal of Energy and Environment* **2** (1), 39–48.

Fontana, N., Giugni, M. & Portolano, D. 2012 Losses reduction and energy production in water-distribution networks. *Journal of Water Resources Planning and Management* **138** (3), 237–244.

Giugni, M., Fontana, N. & Portolano, D. 2009 Energy savings policy in water distribution networks. In: *Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ'09)*, Valencia, Spain.

Jain, S. V. & Patel, R. N. 2014 Investigations on pump running in turbine mode: a review of the state-of-the-art. *Renewable and Sustainable Energy Reviews* **30**, 841–868.

Jenerette, G. D. & Larsen, L. 2006 A global perspective on changing sustainable urban water supplies. *Global and Planetary Change* **50** (3–4), 202–211.

Karadirek, I. E., Kara, S., Yılmaz, G., Muhammetoglu, A. & Muhammetoglu, H. 2012 Implementation of hydraulic modelling for water-loss reduction through pressure management. *Water Resources Management* **26**, 2555–2568.

Khair, A. 2012 *Integration of Hydro Turbines in Water Supply Systems for Energy Recovery in Jordan; Case Study Aqaba Water Supply System*. MSc Thesis, Faculty of Graduate Studies, University of Jordan, 122 pages.

Lopes, R. E. & Martinez, C. B. 2006 Use of pumps as turbines for systems with water discharge. In: *Proceedings of VISEREA – Seminário Iberoamericano sobre Sistemas de Abastecimento Urbano de Água*, João Pessoa, Brazil.

McNabola, A., Coughlan, P., Corcoran, L., Power, C., Williams, A. P., Harris, I., Gallagher, J. & Styles, D. 2014 Energy recovery in the water industry using micro-hydropower: an opportunity to improve sustainability. *Water Policy* **16**, 168–183.

Muhammetoglu, A., Karadirek, I. E., Ozen, O. & Muhammetoglu, H. 2017 Full-scale PAT application for energy production and pressure reduction in a water distribution network. *Journal of Water Resources Planning and Management* (in press) **143** (8).

Ramos, H. & Borga, A. 1999 Pumps as turbines: an unconventional solution to energy production. *Urban Water* **1** (3), 261–263.

Ramos, H., Covas, D., Araujo, L. & Mello, M. 2005 Available energy assessment in water supply systems. In: *Proceedings of XXXI International Association for Hydro-Environment Engineering and Research Congress*, Seoul, Korea, 11–16 September 2005.

Ramos, H. M., Vieria, F. & Covas, D. I. C. 2010 Energy efficiency in a water supply system: energy consumption and CO_2 emission. *Water Science and Engineering* **3** (3), 331–340.

Rintoul, M. 2012 *Modelling Water Distribution Networks to Determine Potential Energy Recovery Using ESP-r*. MSc Thesis, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Scotland, 51 pages.

Samora, I., Manso, P., Franca, M. J., Schleiss, A. J. & Ramos, H. M. 2016a Energy recovery using micro-hydropower technology in water supply systems: the case study of the city of Fribourg. *Water* **8** (344).

Samora, I., Manso, P., Franca, M. J., Schleiss, A. J. & Ramos, H. M. 2016b Opportunity and economic feasibility of ınline microhydropower units in water supply networks. *Journal of Water Resources Planning and Management* **142** (11).

Telci, I. T. 2012 *Optimal Water Quality Management in Surface Water Systems and Energy Recovery in Water Distribution Networks*. PhD Thesis, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, 68 pages.

Thornton, J. & Lambert, A. 2006 Managing pressures to reduce new break. *Water21* **8** (6), 24–26.

Vicente, D. J., Garrote, L., Sanchez, R. & Santilla, D. 2016 Pressure management in water distribution systems: current status, proposals, and future trends. *Journal of Water Resources Planning and Management* **142** (2).

Yang, M. 2012 *Electricity From Water Mains*. *Technology Frontier*, Nov 2012, The Hong Kong Polytechnic University, https://www.polyu.edu.hk/ife/corp/cntimgs/techfrontier/Printing_DM_ENG_Nov12.pdf (accessed 10 March 2017).

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