environmental sciences proceedings

MDPI

Proceeding Paper

Innovative Approach for Selection of Pump as Turbine in Water Distribution Network †

Gustavo Marini [1], Marco Maio [1,]*, Francesco Di Menna [1], Francesco Pugliese [2], Francesco De Paola [2] and Nicola Fontana [1]

[1] Department of Engineering, University of Sannio, 82100 Benevento, Italy
[2] Department of Civil, Architectural and Environmental Engineering, University of Napoli "Federico II", 80125 Napoli, Italy
* Correspondence: marco.maio@unisannio.it; Tel.: +39-0824-305516
† Presented at the International Conference EWaS5, Naples, Italy, 12–15 July 2022.

Abstract: While pressure reducing valves (PRVs) have been widely used in water distribution networks (WDNs) to reduce water leakage, research in recent years has focused on the use of turbines instead of PRVs as the means for enabling both pressure reduction and energy production. However, in WDNs daily continuous variability of flow discharge and upstream head make PAT selection a challenging issue. The present paper describes an innovative approach for optimal PAT selection in systems with hydraulic and/or electrical regulation. The methodology was also applied to a district of the Benevento, Italy, WDN, showing the effectiveness of the proposed approach. The findings showed the optimal pumps lie in the vicinity of the maximum of the produced energy. Furthermore, considering weekday pattern instead of long-period pattern gives reliable results only if the PAT system operated with hydraulic regulation.

Keywords: pump as turbine (PAT); water distribution network (WDN); energy recovery; leakage reduction

check for updates

Citation: Marini, G.; Maio, M.; Di Menna, F.; Pugliese, F.; De Paola, F.; Fontana, N. Innovative Approach for Selection of Pump as Turbine in Water Distribution Network. *Environ. Sci. Proc.* **2022**, *21*, 25. https://doi.org/10.3390/environsciproc2022021025

Academic Editors: Vasilis Kanakoudis, Maurizio Giugni and Evangelos Keramaris

Published: 20 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

The devastating effects of climate change caused by fossil fuels are being widely studied across the globe. All the countries are trying to apply solutions that are able to increase the production of electrical energy from renewable sources. In a WDN, where pipe leakage induces considerable energy and water wastage [1], the water lost is strictly connected to the pressure value [2,3]. Indeed, the leakage–pressure relation is often represented by a power law in which the exponent depends on the pipe material [4]. Thus, controlling pressure in order to reduce leakage in WDNs remains an open issue [5–7], which is often addressed by deploying pressure regulation valves (PRVs) for reducing pressure in WDNs [8,9], with various methodologies being proposed in the literature to assess optimal valve location [10]. Additionally, many other studies propose the use of turbines or centrifugal pumps operating in reverse mode to recover the energy otherwise dissipated by the valves [6,11]. Among these, a model proposed by Garcia et al. [12] assesses the optimal solution between a PRV and a PAT based on all the costs involved, effectively showing the higher PAT installation cost to be justified by the energy recovered. Moreover, as compared to conventional turbines, in addition to the lower PAT installation and maintenance costs, pumps are easily available for a wide range of heads and flow rates [13].

One open issue in the use of PATs is the lack of data regarding pump operation in reverse mode since pump manufacturers do not usually provide the pump characteristic curves for reverse mode operation. Consequently, experimental and theoretical models available in the literature may be used [9,14,15], as well as alternative approaches proposed by other authors that focus on CFD models designed to predict PAT performance [16].

As demonstrated by Fontana et al. [17], the flow variability in a WDN makes the selection of PAT a challenging task, strongly influenced by the shape of the flow pattern. To select the optimal PAT in a WDN, several proposed methods seek to maximize energy production. Lima et al. [18] obtained the best efficiency point (BEP) of the PAT using the metaheuristic algorithm in which the objective function maximizes both energy recovery and leakage reduction. Fontana et al. [17] tested four different flow patterns and for each scenario selected the best PAT that maximizes power production. Carravetta et al. [19] proposed the variable operating strategy to select the best PAT by maximizing overall plant efficiency, while other proposed methods select the PAT using the average flow and head drop in the WDN [20,21].

The literature adequately describes the available methodologies, but little information is provided about the real PAT costs and their field application. The total cost is the sum of relevant installation costs, i.e., the machine (PAT and generator), one or more PRVs, civil works and other hydraulic equipment, and maintenance costs. The PAT price is usually assumed as a function of the power at the BEP [19]. Novara et al. [22] proposed a cost model based on 343 pumps and 286 generators in which the cost of the PAT is related to flow and head drop at the BEP. Other authors considered the cost of both PAT and generator as a function of the power at the BEP [23,24]. Notwithstanding the models available in the literature, PAT selection remains very much an open issue due to flow variability in a WDN and a lack of detailed information and analysis about installation and maintenance costs. Moreover, the available methodologies use as input an hourly-based flow pattern; however, such an approach fails to account for flow variability which may occur in non-ordinary conditions.

By way of addressing these shortcomings, the paper proposes a methodology for optimally selecting a PAT in a WDN that takes into account both criteria of energy production and economic sustainability. The method is based on actual flow and available head drop and was validated using historical data from a WDN district of Benevento (Italy). Results from three different regulation layout scenarios (electrical, hydraulic, and coupled hydraulic and electrical regulation) tested confirms that the method effectively enables rapid selection of device from a manufacturer list of pumps. A preliminary cost–benefit analysis was also developed, and the net present value (NPV) was computed in order to identify the optimal PAT for all layouts.

2. Methodology

2.1. PAT Layouts

Three different installation layouts, namely LAY1, LAY2, and LAY3, can be used for pressure control using PATs in a WDN (Figure 1).

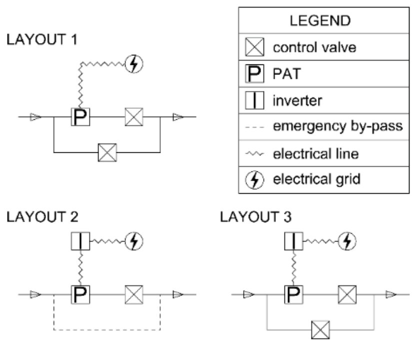


Figure 1. PAT layouts.

The operating conditions vary over time due to demand variability, thus necessitating real time control [25,26]. In all layouts, the PAT is connected to the electrical grid to sell the produced energy.

The hydraulic regulation scenario (LAY1) comprises two lines: a generation line equipped with a PAT and a PRV; and a bypass line with only a PRV installed. Because the PAT works according to its characteristic curve, a PRV is required to obtain the desired pressure at the critical node if the head exploited by the PAT is lower than the available head drop. If the available head drop is lower than the PAT head drop, the bypass line opens and the discharge running the generation line is set to exploit the available head drop [11].

The electric regulation scenario (LAY2) uses a PAT and a PRV installed in the generation line, whereas the bypass is normally closed (ordinary conditions) and opens only for non-ordinary conditions. In this case, pressure is regulated using a frequency converter to vary the impeller rotational speed, which can be calculated following Chapallaz et al. [27]. Different PAT characteristics curves are obtained with the inverter to dissipate the available head drop. In this study, a PRV downstream of the PAT also serves to maximize power production in accordance with the PAT characteristic curve.

The coupled hydraulic and electrical regulation scenario (LAY3) consists of both a generation line and a bypass line, as described in LAY1. However, in this case LAY3 also incorporates the frequency converter as in LAY2 and thus may be considered as a superimposition of LAY2 over LAY1. By managing rotational speed and PRV opening, desired values of flow and head drop may be obtained for any operating condition.

2.2. PAT Operation Model

The PAT operation model is reflected in the curves that relate head drop, power, and efficiency with the discharge. In this work, the equations of Derakhshan and Nourbakhsh [14] as modified by Pugliese et al. [15] were used. For LAY2 and LAY3, the affinity laws for turbomachinery were used to obtain the characteristic curves upon varying the rotational speed from N_1 to N_2. The Sharma [9] relations were used to relate the flow discharge at BEP (Q_{Tb}) and the head drop at BEP (H_{Tb}) in turbine mode to those in pump mode (Q_{Pb} and H_{Pb}).

2.3. PAT Selection

The optimal PAT was selected for all layouts using the proposed method that requires as input the pattern of inflow discharge Q_a and the corresponding available head drop H_a. At each time step, as described by Fontana et al. [7], the produced power for a fixed Q_{Tb} and H_{Tb} was computed by varying the flow running the turbine Q_T for LAY1, the rotational speed N for LAY2, and both Q_T and N for LAY3. By varying Q_{Tb} and H_{Tb}, the method computes the dimensionless-produced energy (e_T) as follows:

$$e_T = \frac{E_T}{E_a \cdot \eta_{Tb}} \tag{1}$$

wherein E_T is the daily produced energy, E_a is the daily available energy, and η_{Tb} is the PAT efficiency at the BEP. Due to the frequency converter, for LAY2 and LAY3 the E_T was multiplied by 0.98, i.e., the inverter efficiency based on ABB documentation [28]. The resulting domain plots the dimensionless-produced energy against the values of Q_{Tb} and H_{Tb}, thereby determining the maximum of e_T which enables the selection of the optimal PAT.

2.4. Cost Model

In order to select the best pump to use as turbine, an economic analysis was performed applying the net present value (NPV) approach, calculated as follows:

$$\text{NPV} = \sum_{k=1}^{n} \frac{(P - C)}{(1 + r)^n} - I_o \tag{2}$$

where n is the duration of PAT operation, assumed equal to 10 years; P is the annual profit due to the income from sale of the produced energy; C is the annual cost; r is the discount rate for converting cost to present value, assumed equal to 5%; and I_o is the investment cost. The annual profit was computed by multiplying the daily average produced energy by 365 and using the actual efficiency of machine. The selling price of energy was assumed to be 0.159 EUR/kWh, as indicated by the Italian Energy Authority (GSE) [29]. The total investment cost was calculated as the sum of costs of the following:

- PAT and generator ($C_{PAT+gen}$): calculated as $C_{PAT+gen} = 15797.72 \cdot Q_{Tb}\sqrt{H_{Tb}} + 1147.92$ as expressed by Novara et al. [22];
- Civil works: assumed as 30% of $C_{PAT+gen}$ [24];
- PRV: set equal to EUR 2500, i.e., the mean cost of a valve with a nominal diameter of 150 mm [19];
- Frequency converter: computed as $C_{inverter} = 1239.9 + 165.72\ P_{Tb}$, according to Saidur et al. [30].

In LAY1 featuring no electrical regulation, the inverter cost was not provided. The annual cost is due to maintenance and was assumed at 15% of investment cost, as suggested by De Marchis et al. [23] and Fontana et al. [24].

3. Application

In a case study of the proposed methodology applied to a real network, the benefit in replacing a PRV with a PAT in a real WDN district of Benevento, Italy, was assessed using two different field measurement-derived discharge patterns to assess the impact of actual flow and available head drop values on PAT selection.

Benevento is a city in the Campania Region with a population of approximately 60,000 inhabitants. In the Santa Colomba district (Figure 2), a control system comprising PRV, flow meter, and pressure transducers was installed to regulate the pressure in the network [25]. The pipes in the district are made of ductile iron, steel, and high-density polyethylene with the main pipes ranging between 50 and 250 mm in diameter and extending across 8.4 km in length.

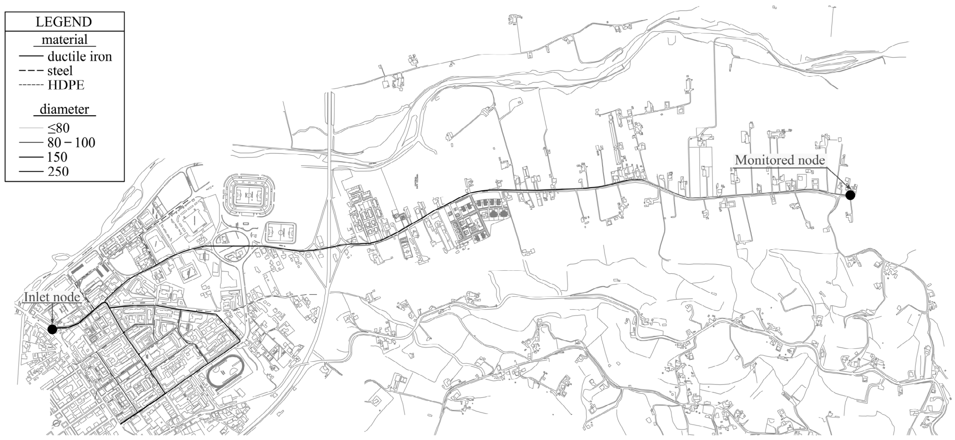
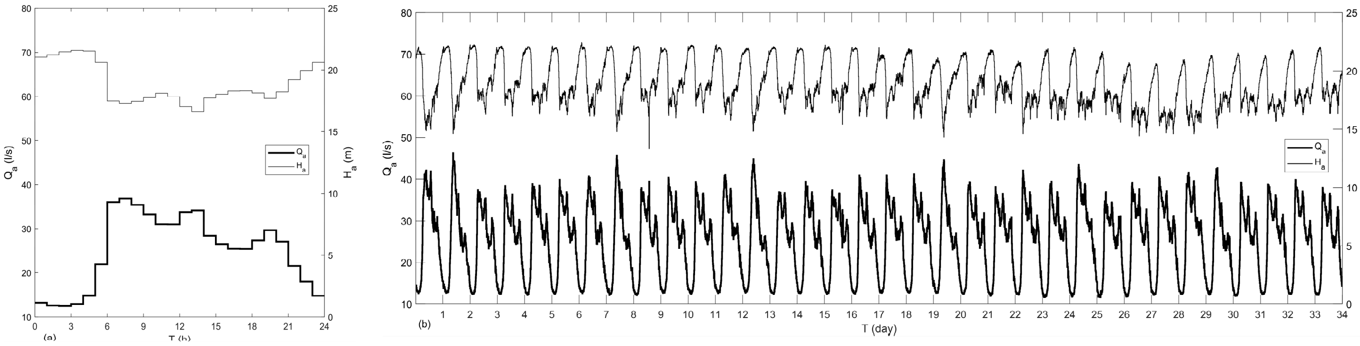


Figure 2. Santa Colomba District of the Benevento network.

A PLC was installed at the inlet node to control the PRV and record flow discharge at the inlet and pressure at the critical node, upstream and downstream of the PRV. The pressure downstream of the PRV was set so as to maintain the pressure at the critical node at 1.6 bar, with available head drop H_a being calculated as the difference between the pressure upstream and downstream of the valve. The data were recorded at 30 s intervals over the period 11 February 2017 to 8 April 2017. However, from 2 March 2017 to 15 March 2017 the pressure at the critical node was fixed at 1.8 bar; consequently, the study disregarded the data for this interval, as well as for any days with sensor failure, thus resulting in 34 non-consecutive days of recorded data (24 weekdays and 10 weekends).

In assessing the benefit of replacing the existing PRV with a PAT, the two different flow and head drop patterns considered were: (i) the hourly average weekday pattern (Figure 3a), calculated as the hourly average values over 24 weekdays; and (ii) the long-period pattern (Figure 3b), obtained based on the 10 min average values recorded over 34 non-consecutive days. The daily available energy was 109.02 kWh/day and 109.15 kWh/day, respectively, for hourly average weekday pattern and long-period pattern.



(**a**) (**b**)

Figure 3. Hourly weekday pattern (**a**) and long-period pattern (**b**).

For all layouts, the domain of e_T was obtained for both patterns, by varying Q_{Tb} between 5 l/s and 70 l/s, and H_{Tb} between 5 m and 40 m, thereby deriving a total of six different configurations.

4. Results

The recoverable energy domains for all layouts and for both patterns obtained for the case study were plotted in Figure 4. The results showed that the maximum energy producible for LAY1 occurs for a single pair of Q_{Tb}-H_{Tb} values. The hourly average weekday pattern (Figure 4a) showed the maximum dimensionless-produced energy (e_T = 0.72) for Q_{Tb} = 27.40 l/s and H_{Tb} = 17.95 m. Similarly, for the long-period pattern (Figure 4b) the maximum e_T of 0.70 was obtained for a PAT with Q_{Tb} = 28.50 l/s and H_{Tb} = 18.45 m.

The domain for LAY2 showed a large zone with e_T = 0, for which regulation is unfeasible, thus confirming electric regulation to have the lowest flexibility [19]. Because of the inverter, the maximum energy was achieved for several values of Q_{Tb} and H_{Tb} with the highest produced energy occurring at the boundary of the zone with e_T = 0. The domains computed for both weekday (Figure 4c) and long-period patterns (Figure 4d), show the maximum dimensionless energy equal to e_T = 0.67 and e_T = 0.43, respectively. As a result of greater variability in the long-period pattern and lower flexibility of electrical regulation, the dimensionless-produced energy values differ significantly for the two patterns.

For LAY3, which couples both hydraulic and electrical regulation, the maximum dimensionless energy was e_T = 0.73 and e_T = 0.71 for weekday (Figure 4e) and long-period patterns (Figure 4f), respectively. For LAY3 as for LAY2, due to the inverter, the maximum energy can be achieved for several Q_{Tb} and H_{Tb} values.

The results for LAY1 and LAY3 returned similar maximum e_T values for both patterns, which, given the greater flexibility of hydraulic and coupled hydraulic and electrical regulation, indicates that for these scenarios, the hourly average weekday pattern of the case study can effectively be used to select the best PAT. For LAY2, the lower flexibility of the system resulted in significantly different domains for the two patterns: the long-period pattern (Figure 4d) showed a greater unfeasible zone and a smaller dimensionless-produced energy value as compared to the average weekday pattern (Figure 4c).

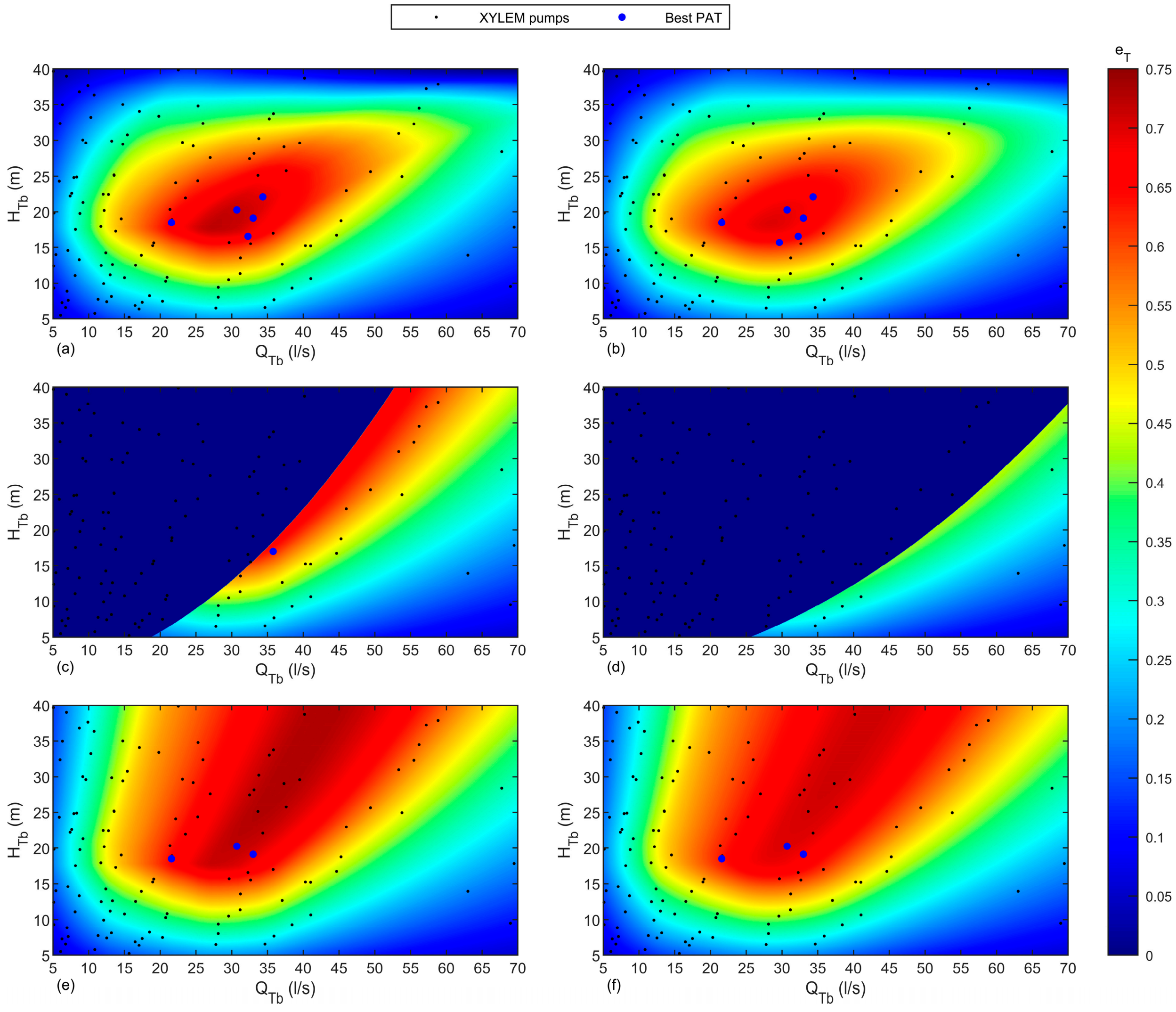


Figure 4. Domain and best pumps obtained for LAY1 (hourly weekday pattern (**a**) and long-period pattern (**b**)); LAY2 (hourly weekday pattern (**c**) and long-period pattern (**d**)); and LAY3 (hourly weekday pattern (**e**) and long-period pattern (**f**)).

Such dimensionless domains can be used to identify the optimal PAT to be selected from a manufacturer's list, since the best solution is to be found from the pumps with Q_{Tb} and H_{Tb} close to the maximum produced energy zone.

To validate the proposed methodology, the NPV was computed for pumps belonging to the Xylem products catalogue [31]. Using the Sharma relations [9], the BEP in turbine mode was calculated for all 316 single-stage Xylem pumps of e-NSC series. In Figure 4, the black points represent all the PATs of the catalogue and the blue points are the pumps with the best NPVs. For the sake of simplicity, for each scenario only pumps with NPV greater than 85% of the maximum NPV were plotted. Because of the existing PRV, the economic analysis incorporates in the costs only one PRV for LAY1 and LAY3, and no PRV for LAY2.

For LAY1, the weekday pattern shows the maximum NPV (EUR 11,822.62) being attained for the pump e-NSC 65-125/55 with Q_{Tb} = 30.71 l/s and H_{Tb} = 20.25 m, moreover with similar results being obtained for the long period pattern (the best NPV was EUR 11,043.93). As expected, all the pumps with NPV greater than 85% of the NPV of the best pump were lying in the vicinity of the maximum produced energy.

Table 1 presents the characteristics of the best pumps for all layouts and both patterns. For LAY2, the weekday pattern shows the commercial PAT with the best NPV (EUR 9896.62) to be e-NSC 80-200/50 (Q_{Tb} = 35.79 l/s and H_{Tb} = 17.00 m), having a daily produced energy of 56.28 kWh, with the NPV of all other pumps of the catalogue being less than 85% of the NPV of the best pump. For the long-period pattern, none of the 316 pumps of the catalogue returned an NPV > 0, thus implying that PAT implementation offered no economic advantage.

Table 1. Direct and reverse mode characteristics of best pumps in economic terms for both patterns and for all layouts.

Layout	Pattern	Pump ID	Q_{Pb} (l/s)	H_{Pb} (m)	η_{Pb} (-)	Q_{Tb} (1/s)	H_{Tb} (m)	*NPV* (EUR)	E_T (kWh/day)
LAY1	Weekday	e-NSC 65-125/55	25.61	15.43	0.80	30.71	20.25	11,822.62	62.05
	long-period	e-NSC 65-200/40	18.05	14.17	0.80	21.57	18.52	11,043.93	55.53
LAY2	Weekday	e-NSC 80-200/55	30.68	13.5	0.82	35.79	17.00	9896.61	56.28
	long-period	\	\	\	\	\	\	\	\
LAY3	Weekday	e-NSC 65-125/55	25.61	15.43	0.80	30.71	20.25	7592.04	62.48
	long-period	e-NSC 65-200/40	18.05	14.17	0.80	21.57	18.52	7051.24	55.08

Finally, for coupled hydraulic and electrical regulation, the maximum NPV was assessed for the pumps e-NSC 65-125/55 (EUR 7592.04) for weekday pattern, and e-NSC 65-200/40 (EUR 7051.24) for the long-period pattern respectively. Also in this case, the best pumps from the catalogue lie in the vicinity of the maximum of the dimensionless energy domain.

By comparing the results obtained for all layouts, the maximum NPVs were obtained for LAY1, with values of EUR 11,822.62 and EUR 11,043.93 for weekday and long-period patterns, respectively. LAY3 showed similar results in terms of produced energy and optimal PAT, but the low variability in flow and available head drop makes the inverter installation more expensive (LAY3 yielded a lower NPV than LAY1). Model e-NSC 65-125/55 proved to be the optimal PAT for LAY1 and LAY3 for weekday pattern, with model e-NSC 65-200/40, however, being the best solution for both layouts for long-period pattern. The results obtained for LAY2 showed that for the long-period pattern, electrical regulation makes the use of XYLEM catalogue pumps economically unfeasible (NPV < 0); for weekday pattern; however, the best pump yielded a lower NPV for LAY2 than for LAY1.

Anyway, for all scenarios the best pumps in economic terms lie in the vicinity of the maximum of the dimensionless-produced energy, which can therefore be used effectively for a fast preliminary assessment of the optimal PAT in a real case.

5. Conclusions

The study proposes a new methodology to select the best PAT for optimally enabling both pressure regulation and energy production in a WDN. For assigned flow and available head patterns, the dimensionless-produced energy can be calculated by varying values of Q_{Tb} and H_{Tb}, thus providing the basis for an economic analysis used to identify the optimal PAT.

The method was validated with data from a district of the Benevento WDN, in which a PRV was installed for optimal pressure regulation. With a view to replacing the pre-existing PRV with an energy production system, the study was designed to identify the optimal PAT from a manufacturer list of 316 pumps. Two different patterns of flow and available head were considered: the first pattern calculated as the hourly average values during weekdays; the second, long-period pattern obtained considering 10 min average data for all monitored days.

LAY1 and LAY3 results were similar for both weekday pattern and long-period pattern, although the maximum NPVs were assessed for LAY1. In contrast, the lack of hydraulic regulation for LAY2 resulted in a large zone with $e_T = 0$, for which regulation is unfeasible, thus confirming electric regulation to have the lowest flexibility. Moreover, this low flexibility is also directly responsible for LAY2 domains showing very significant differences in respect of weekday pattern vs long-period pattern.

As a consequence, PAT selection can be effectively based on the hourly weekday pattern in the case of hydraulic, and coupled hydraulic and electrical, regulation. However, the low flexibility of electric regulation could lead to significant differences when using the hourly average pattern rather than instantaneous values.

For the analyzed case study, the NPV assessment identified hydraulic regulation as being the best solution in economic terms. Indeed, because of low variability in flow and available head, coupled electrical and hydraulic regulation is unable to compensate the greater cost of the inverter. Finally, for all analyzed patterns and layouts, the pumps with the best NPV lie in the vicinity of the maximum produced energy, which can therefore be used for a fast preliminary assessment of the optimal PAT in a real case.

Author Contributions: Conceptualization, G.M. and N.F.; methodology, G.M. and N.F.; software, M.M. and F.D.M.; validation, F.P. and F.D.P.; investigation, G.M.; resources, N.F.; data curation, M.M. and F.D.M.; writing—original draft preparation, M.M.; writing—review and editing, G.M.; visualization, F.D.M.; supervision, N.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Farley, M.; Trow, S. *Losses in Water Distribution Networks*; IWA Publishing: London, UK, 2003; ISBN 1900222116.
2. Xu, Q.; Chen, Q.; Ma, J.; Blanckaert, K.; Wan, Z. Water Saving and Energy Reduction through Pressure Management in Urban Water Distribution Networks. *Water Resour. Manag.* **2014**, *28*, 3715–3726. [CrossRef]
3. Nazif, S.; Karamouz, M.; Tabesh, M.; Moridi, A. Pressure Management Model for Urban Water Distribution Networks. *Water Resour. Manag.* **2010**, *24*, 437–458. [CrossRef]
4. de Paola, F.; Giugni, M. Leakages and Pressure Relation: An Experimental Research. *Drink. Water Eng. Sci.* **2012**, *5*, 59–65. [CrossRef]
5. Fontana, N.; Giugni, M.; Glielmo, L.; Marini, G.; Zollo, R. Operation of a Prototype for Real Time Control of Pressure and Hydropower Generation in Water Distribution Networks. *Water Resour. Manag.* **2019**, *33*, 697–712. [CrossRef]
6. Fontana, N.; Eng, C.; Asce, M.; Giugni, M.; Glielmo, L.; Marini, G. Real Time Control of a Prototype for Pressure Regulation and Energy Production in Water Distribution Networks. *J. Water Resour. Plan. Manag.* **2016**, *142*, 04016015. [CrossRef]
7. Fontana, N.; Marini, G. A Methodology to Assess Optimal Operation of a Prototype for Pressure Regulation and Hydropower Generation. *J. Water Resour. Plan. Manag.* **2021**, *147*, 04021088. [CrossRef]
8. Fontana, N.; Giugni, M.; Glielmo, L.; Marini, G.; Zollo, R. Use of Hydraulically Operated PRVs for Pressure Regulation and Power Generation in Water Distribution Networks. *J. Water Resour. Plan. Manag.* **2020**, *146*, 04020047. [CrossRef]
9. Sharma, K. *Small Hydroelectric Project-Use of Centrifugal Pumps as Turbines*; Kirloskar Electric Co.: Bangalore, India, 1985.
10. Fernández García, I.; Mc Nabola, A. Maximizing Hydropower Generation in Gravity Water Distribution Networks: Determining the Optimal Location and Number of Pumps as Turbines. *J. Water Resour. Plan. Manag.* **2020**, *146*, 04019066. [CrossRef]
11. Carravetta, A.; del Giudice, G.; Fecarotta, O.; Ramos, H.M. Energy Production in Water Distribution Networks: A PAT Design Strategy. *Water Resour. Manag.* **2012**, *26*, 3947–3959. [CrossRef]
12. García, I.F.; Novara, D.; Nabola, A.M. A Model for Selecting the Most Cost-Effective Pressure Control Device for More Sustainable Water Supply Networks. *Water* **2019**, *11*, 1297. [CrossRef]
13. Williams, A.A. *WREX 1996 Pumps as Turbines for Low Cost Micro I-Iydro Power*; Nottingham Trent University: Nottingham, UK, 1996.
14. Derakhshan, S.; Nourbakhsh, A. Experimental Study of Characteristic Curves of Centrifugal Pumps Working as Turbines in Different Specific Speeds. *Exp. Therm. Fluid Sci.* **2008**, *32*, 800–807. [CrossRef]
15. Pugliese, F.; de Paola, F.; Fontana, N.; Giugni, M.; Marini, G. Experimental Characterization of Two Pumps As Turbines for Hydropower Generation. *Renew. Energy* **2016**, *99*, 180–187. [CrossRef]
16. Nautiyal, H.; Varun; Kumar, A. Reverse Running Pumps Analytical, Experimental and Computational Study: A Review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2059–2067. [CrossRef]
17. Fontana, N.; Asce, M.; Marini, G.; Creaco, E. Comparison of PAT Installation Layouts for Energy Recovery from Water Distribution Networks. *J. Water Resour. Plan. Manag.* **2021**, *147*, 04021083. [CrossRef]

18. Lima, G.M.; Luvizotto, E.; Brentan, B.M. Selection and Location of Pumps as Turbines Substituting Pressure Reducing Valves. *Renew. Energy* **2017**, *109*, 392–405. [CrossRef]
19. Carravetta, A.; del Giudice, G.; Fecarotta, O.; Ramos, H.M. PAT Design Strategy for Energy Recovery in Water Distribution Networks by Electrical Regulation. *Energies* **2013**, *6*, 411–424. [CrossRef]
20. Alberizzi, J.C.; Renzi, M.; Nigro, A.; Rossi, M. Study of a Pump-as-Turbine (PaT) Speed Control for a Water Distribution Network (WDN) in South-Tyrol Subjected to High Variable Water Flow Rates. *Energy Procedia* **2018**, *148*, 226–233. [CrossRef]
21. Stefanizzi, M.; Capurso, T.; Balacco, G.; Binetti, M.; Torresi, M.; Camporeale, S.M. Pump as Turbine for Throttling Energy Recovery in Water Distribution Networks. In *Proceedings of the AIP Conference Proceedings*; American Institute of Physics Inc.: College Park, MD, USA, 2019; Volume 2191.
22. Novara, D.; Carravetta, A.; McNabola, A.; Ramos, H.M. Cost Model for Pumps as Turbines in Run-of-River and In-Pipe Microhydropower Applications. *J. Water Resour. Plan. Manag.* **2019**, *145*, 04019012. [CrossRef]
23. de Marchis, M.; Fontanazz, C.M.; Freni, G.; Messineo, A.; Milici, B.; Napoli, E.; Notaro, V.; Puleo, V.; Scopa, A. Energy Recovery in Water Distribution Networks. Implementation of Pumps as Turbine in a Dynamic Numerical Model. In *Proceedings of the Procedia Engineering*; Elsevier Ltd.: Amsterdam, The Netherlands, 2014; Volume 70, pp. 439–448.
24. Fontana, N.; Giugni, M.; Portolano, D. Losses Reduction and Energy Production in Water-Distribution Networks. *ASCE* **2012**, *138*, 237–244. [CrossRef]
25. Fontana, N.; Giugni, M.; Glielmo, L.; Marini, G.; Zollo, R. Real-Time Control of Pressure for Leakage Reduction in Water Distribution Network: Field Experiments. *J. Water Resour. Plan. Manag.* **2018**, *144*, 04017096. [CrossRef]
26. Fontana, N.; Giugni, M.; Glielmo, L.; Marini, G.; Zollo, R. Hydraulic and Electric Regulation of a Prototype for Real-Time Control of Pressure and Hydropower Generation in a Water Distribution Network. *J. Water Resour. Plan. Manag.* **2018**, *144*, 04018072. [CrossRef]
27. Chapallaz, J.-M.; Eichenberger, P.; Fischer, G. *Manual on Pumps Used as Turbines*; Deutsche Gesellschaft fuer Technische Zusammenarbeit GmbH (GTZ): Eschborn, Germany, 1992.
28. ABB (Asea Brown Boveri). *ABB Industrial Drives Technical Catalogue*; ABB: Zurich, Switzerland, 2007.
29. DM 04.07.2019 Incentivazione Dell'energia Elettrica Prodotta Dagli Impianti Eolici on Shore, Solari Fotovoltaici, Idroelettrici e a Gas Residuati Dei Processi Di Depurazione. Italy. Available online: https://www.gazzettaufficiale.it/eli/id/2019/08/09/19A05099/sg (accessed on 12 May 2022).
30. Saidur, R.; Mekhilef, S.; Ali, M.B.; Safari, A.; Mohammed, H.A. Applications of Variable Speed Drive (VSD) in Electrical Motors Energy Savings. *Renew. Sustain. Energy Rev.* **2012**, *16*, 543–550. [CrossRef]
31. Xylem. *2019 E-NSC Series Catalogue, Cod. 191002950*; Xylem Water Solutions Italia S.R.L.: Lainate, Italy, 2019.