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Hydropower Potential in Water Distribution Networks: Pressure Control by PATs

Oreste Fecarotta · Costanza Aricò · Armando Carravetta · Riccardo Martino · Helena M. Ramos

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Abstract Pressure control is one of the main techniques to control leakages in Water Distribution Networks (WDNs) and to prevent pipe damage, improving the delivery standards of a water supply systems. Pressure reducing stations (PRSs) equipped by either pressure reducing valves or motor driven regulating valves are commonly used to dissipate excess hydraulic head in WDNs. An integrated new technical solution with economic and system flexibility benefits is presented which replaces PRSs with pumps used as turbines (PATs). Optimal PAT performance is obtained by a Variable Operating Strategy (VOS), recently developed for the design of small hydropower plants on the basis of valve time operation, and net return determined by both energy production and savings through minimizing leakage. The literature values of both leakages costs and energy tariffs are used to develop a buisness plan model and evaluate the economic benefit of small hydropower plants equipped with PATs. The study shows that the hydropower installation produces interesting economic benefits, even in presence of small available power, that could encourage the leakage reduction even if water savings are not economically relevant, with consequent environmental benefits.

O. Fecarotta (✉) · A. Carravetta · R. Martino
Department of Civil, Architechtural and Environmental Engineering, Università di Napoli Federico II, via Claudio, 21, 80125 Napoli, Italy
e-mail: oreste.fecarotta@unina.it

A. Carravetta
e-mail: arcarrav@unina.it

R. Martino
e-mail: rmartino@unina.it

C. Aricò
Department of Civil, Environmental and Aerospace Engineering, Università di Palermo, Viale delle Scienze, 90128 Palermo, Italy
e-mail: costanza.arico@unipa.it

H.M. Ramos
Department of Civil Engineering, Instituto Superior Técnico, Technical University of Lisbon, Avenida Rovisco Pais, 1, 1049-01 Lisboa, Portugal
e-mail: hramos.ist@gmail.com

Keywords Variable operating strategy (VOS) · Water distribution networks · Energy recovery · PATs

Acronyms

BEP	Best Efficiency Point;
HR	Hydraulic Regulation;
NPV	Net Present Value.
PAT	Pump As Turbine;
PRS	Pressure Reducing Stations;
VOS	Variable Operating Strategy;
WDN	Water Distribution Network;

1 Introduction

Water leakages in urban networks are due to several causes, such as pipe breakages or joint failures, and the amount of lost water by leakages is strictly related to the pressure value (Almandoz et al. 2005). Leakage minimization is an important issue in water distribution network (WDN) management (Christodoulou et al. 2013), because it can yields important money savings due to the reduction of water losses (Mutikanga et al. 2013; Gomes et al. 2013). with a consequent improving of delivering standards (Carravetta and Giugni 2009) and performance indicators and protecting roads and buildings from underground cavities (Carravetta et al. 2009).

In existing networks pressure reduction can be achieved by inserting pressure reducing stations (PRSs) equipped by either pressure reducing valves or regulating valves to dissipate excess hydraulic head (Tucciarelli et al. 1999; Walski et al. 2006; Prescott and Ulanicki 2008). The satisfaction of water demand, i.e. a target distribution of pressure in WDN nodes, is the main design constraint of the numerical model proposed in literature for PRSs placement (Van Zyl et al. 2004; Vairavamoorthy and Lumbers 1998; Liberatore and Sechi 2009). Among the others, Araujo et al. (2006) proposed a two steps procedure for the optimal location of valves and their best operational time control. The procedure was applied to Jowitt and Xu (1990) network and the solutions demonstrated that a great saving of water volumes could be obtained by inserting a few PRSs in strategic nodes.

Nevertheless, the head drop in any PRS is a dissipation of energy which should be converted to electric energy (Carravetta et al. 2013b; Filion et al. 2004; Sammartano et al. 2013). Hydropower is considered a proven reliable energy resource (Lin et al. 2013; Li et al. 2013; Fathi-Moghadam et al. 2013) and is proposed herein to recover energy within WDNs. A technical solution, combining both economic benefits and system flexibility for smaller implementations, is the installation of pumps used as turbines (PATs) (Zakkour et al. 2002) within the PRSs.

Currently, to the authors' knowledge, there is no study about an integrated approach aimed to the evaluation of the economical benefit of valves replacement by PATs in water distribution networks. The study is performed with reference to the solutions of Araujo et al. (2006) and the optimal PATs design is obtained by a recently developed procedure, namely VOS (Carravetta et al. 2012; 2013a), on the basis of valve time operations. Then, a buisness plan model for the design of the hydropower plant is presented and the net return determined by both energy production and water savings are compared with hydropower system installation costs. The study is aimed to the evaluation of the hydropower investment in several countries of the world and the values of both leakages costs and green or feed-in energy tariffs of the different have been investigated. The convenience of the investment, even in presence of small installed power and variable hydraulic characteristics is finally demonstrated.

2 Hydropower Potentiality for Pressure Control

The complete rehabilitation of the network, with the replacement of oversized and corrupted branches (Vasan and Simonovic 2010) is very expensive and in most cases can be avoided if an effective control of the head patterns in water distribution networks (Campisano et al. 2012) is performed.

Installing an equivalent small hydropower plant using a PAT as a production device as an alternative to a conventional regulating valve offers new opportunity for pressure control (Carravetta et al. 2012) and can be economically convenient. Another advantage of this technology is in the increase of the flexibility of the network, because its performances can be enhanced in case of pipe failure, by changing the PAT working conditions.

A correct PAT design strategy involves knowledge of flow and head patterns in the installation to allow evaluation of the best performing PAT. Among all the feasible installation schemes (Carravetta et al. 2014a), the hydraulic regulation (HR) mode has been chosen for this study. In such situation the plant is composed of two branches: the first branch is a dissipation/production branch where the PAT and a valve are placed in series, while the second branch is a by pass regulated by another valve (Fig. 1).

Figure 2 shows the system operation: PAT characteristic curve and hypothetical working conditions in a production-dissipation node are reported. Q_i is the demand flow and H_i is the head drop requested for the desired regulation of the network. For a requested head drop, H_i, higher than the head-drop deliverable by the machine, H^T (points above the PAT characteristic curve), the series valve dissipates the excess pressure. Instead, when the discharge, Q_i, is larger (points to the below the PAT characteristic curve), the PAT would produce a head-drop higher than the available head: therefore, the bypass valve is opened to reduce the discharge flowing into the PAT from Q_i to Q_i^T. If a set of characteristic curves is available (Carravetta et al. 2014b), the design PAT is the one which yields the best plant efficiency, which is defined as follows:

$$\eta_p = \frac{\sum_{i=1}^{n} H_i^T \; Q_i^T \; \eta_i^T \; \Delta t_i}{\sum_{i=1}^{n} H_i \, Q_i \, \Delta t_i} \quad \text{with} \quad Q_i^T \le Q_i \quad \text{and} \quad H_i^T \le H_i \tag{1}$$

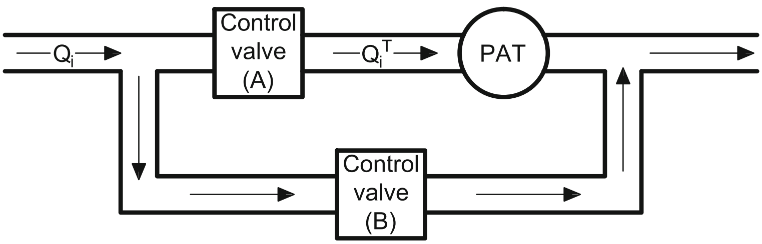

Fig. 1 Installation scheme of a PAT with hydraulic regulation, as proposed by Carravetta et al. (2012)

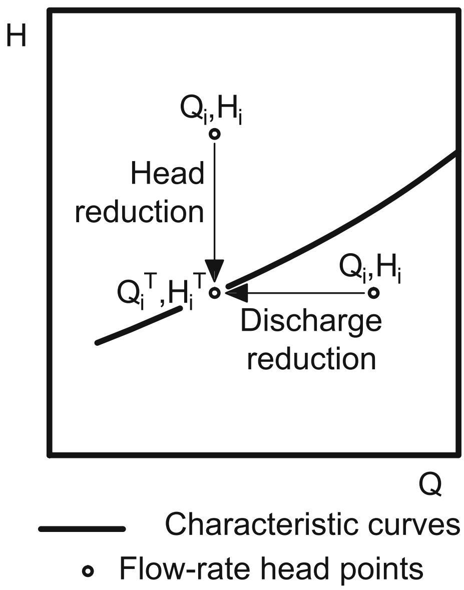

Fig. 2 PAT operating conditions in hydraulic regulation mode, as proposed by Carravetta et al. (2012)

being Δt_i the duration of the i-th time interval with constant hydraulic characteristics (Q_i, H_i) and (Q_i^T, H_i^T) the hydraulic characteristics delivered by the machine with η_i^T mechanical efficiency.

The plant efficiency, η_p, is a synthetic value which describe the amount of available hydraulic energy that can converted into electric energy.

It is important to stress that the plant efficiency is different from the best mechanical efficiency: the latter is relative to the best working performances of the machine in a specific hydraulic condition, while the former corresponds to the whole response of the machine to a given variable flow-head pattern.

3 Case Study

3.1 System Characteristics.

Araujo et al. (2006) compared the effect of different number of control valves on the reduction of leaks in the water distribution networks of Jowitt and Xu (1990) reproduced in Fig. 3. The network presents 34 branches and 22 internal nodes and 3 tanks. The daily average demand of the network equals to 121.5 l/s, corresponding to a population ranged between 26000 and 70000 inhabitants (in) and a daily water consumption ranging between 150 $l/(in \cdot day)$ and 400 $l/(in \cdot day)$). The localization of valves in each scenario, as computed by the optimization model, and corresponding level of leaks are reported in Table 1, together with the diameter D of the installation pipe. Results obtained with a different optimization technique by Liberatore and Sechi (2009) on the same network led to only slightly different results. It is evident that leakage will be significantly reduced by just adding of a couple of valves, and that the optimized results are obtained with the installation of six valves. This network has been used as case study by many researchers (Campisano et al. 2009; Vairavamoorthy and Lumbers 1998).

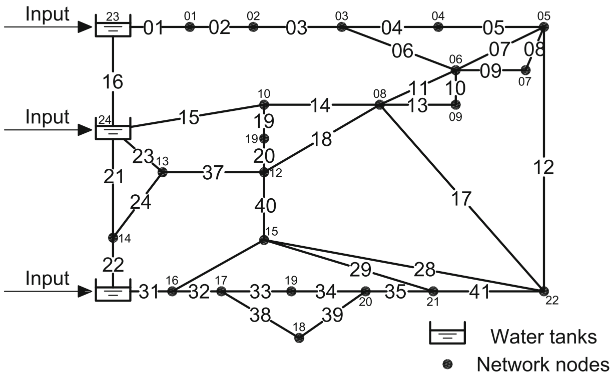

Fig. 3 Sketch diagram of Jowitt and Xu (1990) water distribution network used as case study, with the numbering of branches and nodes

Araujo et al. (2006) furnished, as a part of their solution, the optimal operational dynamic control of each valve, and this data has been used in this case study. A hydro-power plant in HR mode is configured to reproduce the operational dynamic control of valves. The economic benefit of the substitution of a number of valves with hydro-power plants has been investigated and is presented in the succeeding sections.

3.2 Hydro-power Design

According to the operational dynamic control of throttle control valves proposed by Araujo et al. (2006), the software EPANET version 2.0 (http://www.epa.gov/nrmrl/wswrd/dw/epanet.html) has been applied to obtain the flow rate and head drop daily patterns of the valves of each scenario. EPANET is a computer software that solves the flow continuity and head loss equations by the gradient method by Todini and Pilati (1988), given the discharge flowing in or out of each node. Head-losses in the pressurized pipes are modeled by the Darcy-Weisbach formula, while valves are treated as pipes where the resistance depends on the opening. In Fig. 4 the hourly average discharge and the available head values are plotted for each PRS in each scenario. In the scenarios III-V, the valves installed

Table 1 Leak reduction for the different simulated scenarios (Araujo et al. 2006)

Scenario				Installation pipe				Average leaks $[l/s]$	Average leak reduction
0	–	–	–	–	–	–	–	27.3	–
I	–	–	–	–	37	–	–	23.5	13.92 %
II	01	–	–	–	37	–	–	22.8	16.48 %
III	–	–	–	–	37	40	41	23.3	14.65 %
IV	01	–	28	31	37	–	–	22.2	18.68 %
V	01	–	–	31	37	40	41	22.6	17.21 %
VI	01	15	28	31	37	40	–	22.1	19.04 %
D $[mm]$	500	300	250	400	500	250	150		

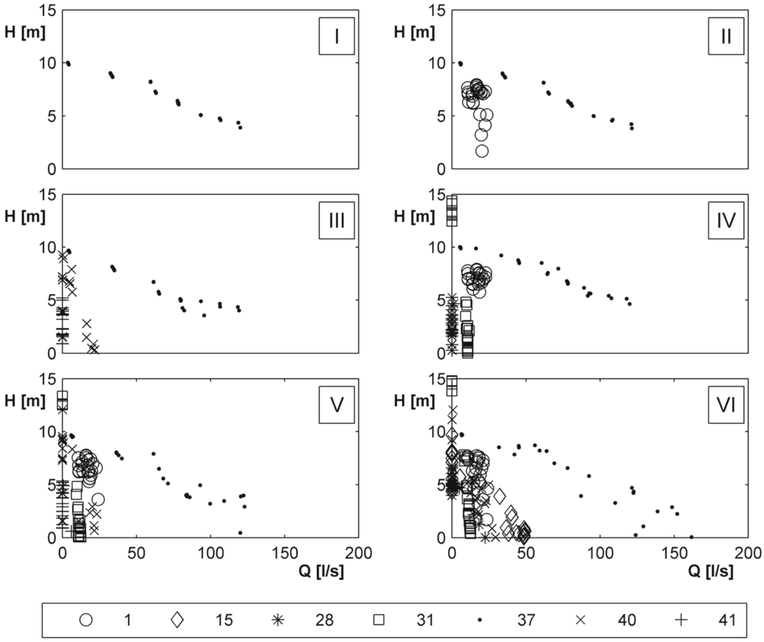

Fig. 4 Available discharge and head in each PRS for scenarios I-VI

on pipes 41, 28 and 41 respectively are are completely closed. Thus, gate valves can be used instead. All PRSs deals with a discharge less than 50 l/s except the one installed on pipe 37.

Based on these discharge-head patterns, VOS procedure has been applied, selecting the best commercial pump utilizing among the centrifugal and semi-axial pumps produced by Caprari (an Italian manufacturer). PAT available characteristic curves were obtained either experimentally or by numerical techniques (Carravetta et al. 2011). The turbomachinery affinity law (Carravetta et al. 2014b) has been used in order to calculate the characteristic curve of each machine for different values of rotating velocity. The feasible rotating velocity is considered in the range between 750 and 3200 rpm, since the machines can be coupled with 8, 6, 4 and 2 poles motors, and a speed drive can be used to modify the rotating speed from the synchronizing value. Thus, for each production/dissipation node, the optimal PAT for the installation of a hydropower station has been calculated as the machine which maximizes (1). The available discharge and head values of Fig. 4 have been used as input data.

In Table 2 the seven optimal machines (here identified as a, b, c, d, e, f, g) are indicated as well as their installation pipe, their BEP power (P_{BEP}) and their operating speed. In the $8-th$ column of Table 2, the values of the objective function of the optimization procedure, namely η_p, are showed. The maximum power ($P_{\max}$) and the daily produced energy (E_{pr}) of each PRS are presented as additional information.

In three cases (pipe 41 of the scenario III, pipe 28 of the scenario IV and pipe 41 of the scenario V) VOS procedure did not indicate any PAT able to produce energy, since at those nodes the flow is zero and a simple closed gate valve is suitable. In few cases the plant efficiency is above 40 % while in other few cases only about one tenth of the available energy can be converted.

Table 2 Characteristics of each hydropower plant (SSS - Semi axial Single Stage; SMS - Semi axial Multi Stage; CSS - Centrifugal Single Stage)

Scenario	Installation pipe	Machine and type	P_{BEP} $[W]$	$P_{\max}$ $[W]$	E_{pr} $[kWh/day]$	η_p $[-]$	Speed $[rpm]$
I	37	a/SSS	4743	3218	37.67	0.423	750
II	1	b/CSS	352	597	9.53	0.374	750
	37	a/SSS	4743	3194	37.80	0.415	750
III	37	c/SSS	2265	2465	30.99	0.402	750
	40	d/SMS	219	288	1.03	0.354	800
	41	–	–	–	–	–	–
IV	1	b/CSS	352	596	11.09	0.396	750
	28	–	–	–	–	–	–
	31	b/CSS	352	188	0.33	0.109	750
	37	a/SSS	4743	3598	45.85	0.453	750
V	1	b/CSS	352	582	9.68	0.388	750
	31	b/CSS	352	181	0.27	0.102	750
	37	e/SSS	2112	2341	25.03	0.351	750
	40	d/SMS	180	304	0.32	0.117	750
	41	–	–	–	–	–	–
VI	1	f/CSS	491	705	8.30	0.355	850
	15	f/CSS	409	412	0.41	0.074	800
	28	d/SMS	180	124	0.23	0.233	750
	31	d/SMS	180	279	1.36	0.211	750
	37	g/SSS	2249	2941	24.83	0.308	750
	40	f/CSS	337	526	3.46	0.379	750

Only in one case (pipe 15 of scenario VI) the rotational speed is 800 rpm, which equals the velocity of an asynchronous generator with 8 poles, while in the other cases a mechanical speed drive is needed. All these results give important information about the benefit from the substitution of a valve in a water distribution network, but do not indicate which is the best design solution. To this aim, an intensive economic analysis has been performed in order to find the optimal scenario.

4 Economic and Financial Feasibility

4.1 Best Design Solution

The convenience of a micro-hydro power plant in a water distribution network, where a PAT substitutes a valve in order to convert the head dissipation to energy production, has been proved by Carravetta et al. (2013a).

In this paper, several design solutions have been proposed: the leakage reduction can be achieved with a different number of PRSs, from 1 to 6, and each of them can be equipped with either a regulating valve or a hydropower system. The best design solution can be identified as the scenario which maximizes the Net Present Value (NPV), which can be defined as follows:

$$NPV = \Sigma_{i=1}^{n} \left[\frac{R_i}{(1+r)^i} \right] - I + V_r \quad (2)$$

where R_i are the net cash flow during the i-th years, n is the considered number of years, I is the start investment, r the discount rate and V_r is the residual value of the plant after the considered base period.

The cash flow, which determines the NPV, depends both on the cost of the equipment, which results in the I value, and on both the water costs and the electricity selling prices which together produce the cash inflow during the life of the plant. In this study, 10 years are considered as base period for the assessment of NPV, since it can be considered a reasonable time period for the evaluation of an energetic investment of a water company. Thus, both the residual value and the maintenance costs can be neglected with a satisfying approximation. Obviously, both the water costs and the energy prices depend on the country. Thus, a literature review has been performed in order to assess the different tariffs and their influence on the design solutions.

4.2 Water Tariffs and Water Costs

Assessment of the cost of water is fundamental in the evaluation of economic savings produced by leakages reduction. Even if the water tariff is a widely accessible information, it is not useful in the evaluation of savings, because it comprises a lot of different issues, like taxes, company profits and the cost of leakage itself. The parameter which allows the calculation of the money savings is the water unit cost, which can be considered as the sum of water resourcing, treatment, pumping and distribution. Such value is very difficult to obtain by water companies, but in 2005 Water Services Regulation Authority, which is the body responsible for economic regulation of the privatized water and sewerage industry in England and Wales, investigated the water delivery costs of several water companies which serve different cities of the world (OFWAT 2005). In such report, the water cost is available only for the UK and the USA, while for several other countries it can be assessed as 60 % of the cost of operations (which is the sum of water costs and buisness activities). The results of that research are summarized in Table 3, together with the water cost in southern Italy, which is the average of several values obtained by the Authors from different Southern Italian water companies.

4.3 Energy Production Tariffs

The energy selling price can be variable in time according to the market, therefore a precise business prevision can be very difficult. Nevertheless, in several countries there are interesting subsidies (namely feed-in tariffs) for the production and the sale of renewable energies, which results in long term contracts (i.e. 15 or 20 years) for the generation of energy. Unfortunately, such tariffs are widely established for solar energy (Reiche and Bechberger 2004), while only few countries guarantee special tariffs for hydropower.

The current situation in some countries is reported in Table 3.

4.4 Installation Costs

The evaluation of the installation costs has been performed, using the market values of PATs, valves, PAT hydraulic circuit, speed drive and piping, which are reported in Table 4.

Table 3 Cost of operations (COP), buisness activities (BA) and water costs (WC), together with energy tariff, for different countries

Country	Region	COP [€/m^3]	BA [€/m^3]	WC [€/m^3]	Energy tariff
UK	England and Wales	0.436	0.160	0.276	21.650 p/kWh
	Scotland	0.479	0.174	0.305	
DK	Six cities group	0.348	-	0.208	0.08045 €/kWh
FI					0.0835 €/kWh
NW					-
SE					0.0805 €/kWh
NL	South Holland	0.870	-	0.208	0.071-0.122 €/kWh
	Amsterdam	0.957	-	0.519	
	North Holland	1.030	-	0.571	
	Gelderland, Overijssel and Friesland	0.725	-	0.433	
	Limburg (Maastricht)	0.725	-	0.433	
	Mid-Netherlands (Utrecht)	0.638	-	0.381	
	North Brabant	0.566	-	0.338	
AUS	Brisbane, QLD	0.276	-	0.164	-
	Melbourne, VIC	0.348	-	0.208	0.0800 AUS$kWh
	Gold Coast, QLD	0.334	-	0.199	-
	Adelaide, SA	0.290	-	0.173	-
	Melbourne, VIC	0.348	-	0.208	0.0800 AUS$kWh
	Sydney, Illawarra and Blue Mountains, NSW	0.421	-	0.251	-
	Perth, WA	0.261	-	0.156	-
	Melbourne, VIC	0.334	-	0.199	0.0800 AUS$kWh
US	East LA and South San Francisco	0.493	0.131	0.363	0.08923 US$/kWh
	Northern New Jersey	0.334	0.131	0.189	-
	Chicago, Peoria and Alton	0.494	0.218	0.276	-
	Indiana	0.320	0.189	0.131	0.120 US$/kWh
	New Jersey	0.595	0.247	0.348	-
	Pennsylvania	0.667	0.348	0.319	-
	Philadelphia	0.493	0.232	0.261	-
	San Jose	0.493	0.087	0.406	0.08923 US$/kWh
	Sacramento, Santa Barbara, LA	0.421	0.145	0.276	0.08923 US$/kWh
IT	Southern Italy	-	-	0.300	0.220 €/kWh

Six cities group includes Copenhagen, Helsinki, Oslo, Stockholm, Gothenburg and Malmo

Acronyms: UK-United Kingdom, DK-Denmark, FI-Finland, NW-Norway, SE-Sweden, NL-Holland, AUS-Australia, US-United States, IT-Italy, QLD-Queensland, VIC-Victoria, SA-Southern Australia, NSW-New South Wales, WA-Western Australia

References for Energy tariffs are: (Fouquet 2012), http://www.fitariff.co.uk, http://www.dpi.vic.gov.au, http://www.nipsco.com, http://www.cpuc.ca.gov

Table 4 Market values of hydromechanical devices (ϕ is the diameter of the valve in mm)

Device		Price [€]	Device		Price [€]
PATs	a	6800	Valves	ϕ 50	7200
	b	1700		ϕ 80	7700
	c	6500		ϕ 100	8500
	d	3100		ϕ 125	9400
	e	6500		ϕ 150	10000
	f	1200		ϕ 200	13000
	g	6500		ϕ 250	16300
Speed drive		300		ϕ 300	22400
Piping		2000		ϕ 400	30700
Grid connection		500		ϕ 500	42000

The cost of a PRS without a PAT along a pipe equals the cost of the control valve (C^{vlv}), whose diameter depends on the maximum flow along the pipe and the maximum allowed velocity in the valve. The total cost of the hydro power plant (C^{hp}) is the sum of the machine cost, piping (2000 €have been considered as average total cost of piping) and speed drive, together with the cost of two control valves (series and parallel) whose diameter are chosen depending on the flow pattern. The reported costs of the valves refers to regulating hydro-valves with SCADA system and remote control. For the hydropower plant, the additional cost of grid connection has been evaluated as 500 €, which includes the administrative allowances, the physical connection and the control, measurement and safety devices. The costs of the gate valves of scenario III, IV and V have been neglected. The installation costs of each PRS, either with a single control valve or a PAT, are reported in Table 5.

4.5 Discount Rate

The discount rate can be considered as the the opportunity cost of capital, i.e. the rate of return that could be earned on an investment in the financial markets with similar risk. In the case where the company is financed with only equity, and both the costs of water and the energy tariffs can be considered not variable, the risk of the investment is very low, and the discount rate can be computed as the discount rate of governments bond. Table 6 shows the last 10 years averaged values of bonds for the considered countries.

4.6 Results

With the collected information about the costs and the tariffs, (2) can be specialized in:

$$NPV = B^e + B^w - C^{hp} - C^{vlv} \tag{3}$$

where:

$$B^e = \Sigma_{i=1}^{n} \left[\frac{t_i^P}{(1+r)^i} \right] \tag{4}$$

$$B^w = \Sigma_{i=1}^{n} \left[\frac{C_i^w}{(1+r)^i} \right] \tag{5}$$

Table 5 Total installation costs of pressure reducing station with either valves or hydropower plants (ϕ is the diameter of the valve in mm)

Scenario	Installation pipe	Valve	C^{vlv} [€]	Machine	Valve A	Valve B	Speed drive	C^{hp} [€]
I	37	ϕ 250	16300	a	ϕ 200	ϕ 200	yes	35600
II	1	ϕ 100	8500	b	ϕ 80	ϕ 100	yes	20700
	37	ϕ 250	16300	a	ϕ 200	ϕ 200	yes	35600
III	37	ϕ 250	16300	c	ϕ 200	ϕ 200	yes	35300
	40	ϕ 100	8500	d	ϕ 50	ϕ 100	no	21300
	41	–	–	–	–	–	–	–
IV	1	ϕ 100	8500	b	ϕ 80	ϕ 80	yes	19900
	28	–	–	–	–	–	–	–
	31	ϕ 80	7700	b	ϕ 80	ϕ 80	yes	19900
	37	ϕ 250	16300	a	ϕ 200	ϕ 200	yes	35600
V	1	ϕ 100	8500	b	ϕ 80	ϕ 100	yes	20700
	31	ϕ 80	7700	b	ϕ 80	ϕ 80	yes	19900
	37	ϕ 250	16300	e	ϕ 200	ϕ 200	yes	35300
	40	ϕ 100	8500	d	ϕ 50	ϕ 100	yes	21600
VI	11	–	–	–	–	–	–	–
	1	ϕ 100	8500	f	ϕ 100	ϕ 100	yes	21000
	15	ϕ 150	10000	f	ϕ 100	ϕ 150	no	22200
	28	ϕ 100	8500	d	ϕ 50	ϕ 100	yes	21600
	31	ϕ 80	7700	d	ϕ 50	ϕ 80	yes	20800
	37	ϕ 300	22400	g	ϕ 200	ϕ 200	yes	35300
	40	ϕ 125	9400	f	ϕ 100	ϕ 125	yes	21900

t_i^P is the year income of produced energy, C_i^w the year savings of costs of water, C^{hp} is the cost for the installation of the hydropower stations and C^{vlv} the cost of the valves. Thus, B^e and B^w are the capitalized benefit of produced energy and saved water.

Firstly, the NPVs of the different solution proposed by Araujo et al. (2006), using only valves for pressure control, have been calculated for the different countries, as reference condition. In this case, in Eq. 3, B^e and C^{hp} equal to zero. The results of NPV calculation are plotted in Fig. 5. The best NPVs correspond to the installation of four valves.

The installation of one or more PATs to replace of valves can modify the optimal solution, because B^e and C^{hp} of Eq. 3 should be taken into account in the calculation of NPVs. The modification of NPV depends on which and how many PRSs are conidered for the PAT installation. Among all the combinations of PATs and valves, the solution that

Table 6 10-years averaged values of Government bonds rate

Country	IT	UK	DK	SE	FI	NL	AU	US
Bond rate	0.0542	0.0194	0.0154	0.0168	0.0197	0.0215	0.0342	0.0188

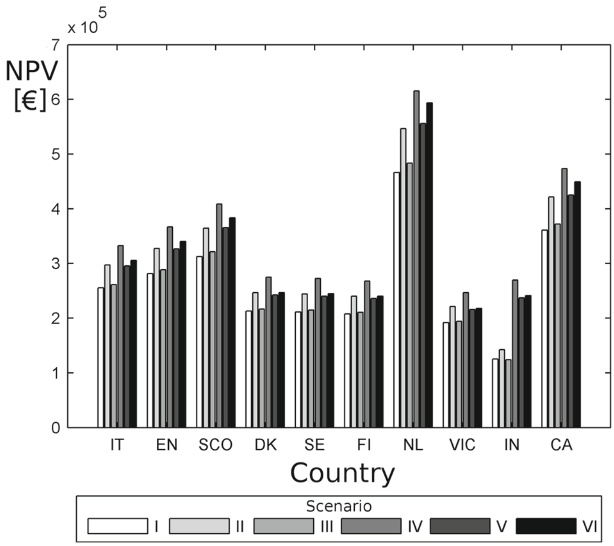

Fig. 5 Calculated NPVs for the installation of valves aimed to water savings

maximizes the NPV has been found as the installation of three PATs (at pipes 1, 31 and 37) in scenario IV (for all countries). Moreover, for each scenario, the increase of NPV (Δ_{NPV}) due to the presence of PATs is shown in Fig. 6. The plot of Fig. 6 shows that the increase of NPV is considerable if compared with the small maximum (always less than 4 kW) and daily average (always less than 2 kW) power and the large variability of the flow.

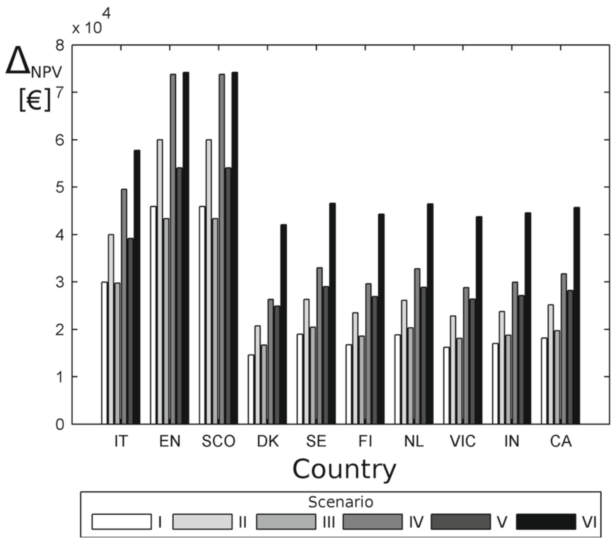

Fig. 6 Increase of NPV (Δ_{NPV}) due to the valve substitution by PATs

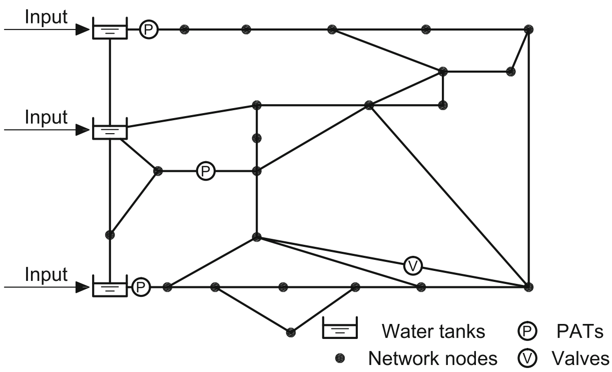

Fig. 7 Optimal solution for all countries

In Fig. 7 the location of PATs and valves in the optimal solution is plotted.

The values of Table 3 are concerning specific companies and are considered herein as average values for each country. The real water supply conditions for the water companies can be different and two more scenarios are described below:

- free access to water resource
- scarcity of water during dry months.

4.6.1 Free Access to Water Resource

In some cases, water companies have free access to water resources. That is, for example, the case of several mountain towns, where there is a large availability of pure water and the cost of leakage can be neglected in the financial balance. In such cases, for the calculation of NPV, the cost of water C_i^w becomes negligible but the scheduled reduction of pressure in the network could be equally pursued in order to improve water delivering standards, prevent pipe damages or preserve the ground from subsidence and caving-in due to water losses. In such cases the importance of the installation of hydropower devices is relevant, because the produced energy constitutes the only cash inflow and consequently the only chance to amortize the investment. In Fig. 8, the NPVs for the considered cases where the water resources was free or unconstrained are plotted. Figure 8 shows that only few solutions are economically convenient, and only in those regions where the energy tariff is reasonably high.

4.6.2 Scarcity of Water During Dry Months

Another typical situation for water companies is the large availability of the water resource during the wet months, while the cost of water substantially increases during summer and dry months (i.e. more consumption, pumping from wells or basins, additional treatments). In such case the NPV of the pressure reducing investment can be calculated taking into account the water cost savings gathered during the wet months. Figure 9 shows that even with only one month of water scarcity annually, the investment in the reduction of pressure becomes economically viable in all considered countries.

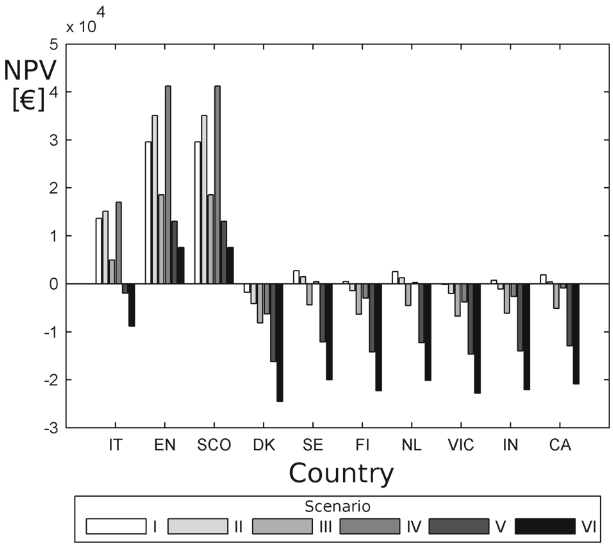

Fig. 8 Best NPVs when the access to water resource is free

5 Conclusions

The reduction of water leakage can be achieved by means of an effective control of the head patterns in water distribution networks. An equivalent performance in terms of regulation between PRSs and small hydropower system using a pump as turbine (PAT) as energy production device offers a new opportunity for pressure control. Indeed, a hydropower plant with a hydraulic regulated PAT can be configured to reproduce the operational dynamic

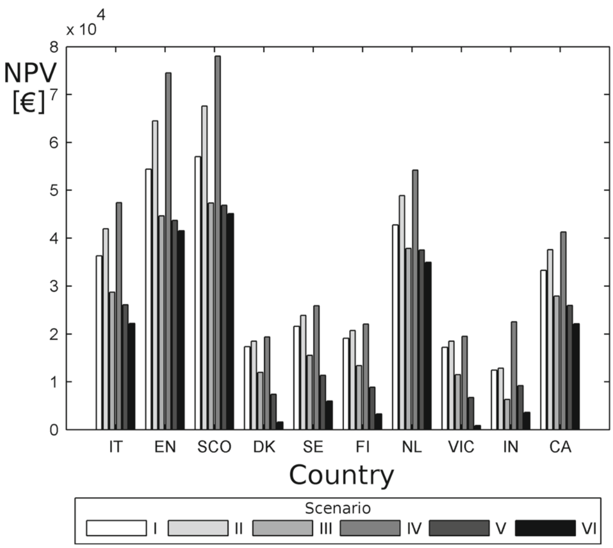

Fig. 9 Best NPVs with 1 month of water scarcity per year

control of valves. In this study, the economical convenience of the replacement of a certain number of valves with a hydropower plant was investigated in terms of water savings and produced energy, with reference to a literature network. The reduction of leakage of the analyzed network can be performed with several proposed design solution. Six scenarios, with a different number of pressure reducing stations (PRS) each, have been analyzed. Each PRS can be equipped with either a valve or a PAT plant. The 10-years net present value (NPV) of each design solution has been investigated, considering both the savings of water and the selling price of produced energy for different countries. The savings of water mostly influence the NPV, while the installation of hydropower plants produces a considerable increase of benefits even in presence of small installed power a variable hydraulic characteristics.

Thus, the minimization of leakage could be economically convenient even in the areas where the water is abundant and its cost is very low, with consequent environmental benefits.

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