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POTENTIAL REDUCTION OF LEAKAGE VOLUME BY COMBINING DYNAMIC PRESSURE MANAGEMENT AND ENERGY RECOVERY IN VALENCIA

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Abstract

The main objective of a drinking water distribution network is to supply all consumption points with the quantity of water demanded under sufficient pressure and quality conditions. Currently, pressure regulation in water supply networks consists of managing pressure of district metered areas (DMAs) to ensure a sufficient supply to users, being traditionally carried out by reducing excessive pressures, and therefore diminishing water losses. The most basic form of regulation is to maintain a constant pressure at the inlet of the DMAs by means of a pressure reducing valve (PRV). Another turn on the screw in regulation is dynamic sectorization, modifying the set points of the PRVs according to the time of the day to reduce pressure during off-peak hours. This modification of the set point in the PRV involves the movement of a mechanism, requiring a constant energy source.

This work proposes the incorporation of an energy recovery system in the distribution network by installing small water turbines at the inlet of the DMA in order to obtain the necessary energy to feed the dynamic regulation equipment, coming the energy required from the network itself. The case study proposed is the water distribution system of the city of Valencia, where a DMA will be selected for the analysis of the dynamic sectorization. To do that, in the first place it is required to analyse the potential energy recovery in the inlets of the DMAs taking into count average values of pressure upstream and downstream and the minimum night flow. This parameter is one of the criteria selections for the pilot DMA. A hydraulic model will be calibrated for the subsequent analysis of the pressure regulation enabling to evaluate the alternatives of dynamic pressure management: by time control, flow control and critical point control. The results from this pilot DMA will include quantifying economically both water savings and the cost of installation of the small water turbines, with the purpose of bringing the city closer to an example of climate-neutral supply.

Keywords
Water Supply Networks, Pressure Dynamic Management, Pressure Reducing Valve, Energy Recovery, Circular Energy, Climate-neutral Water Supply Network.

1 INTRODUCTION

Increasing energy efficiency is a cutting edge topic in any economic activity. The excessive use of energy cause, among others, increasing greenhouse gases (GHG) emissions and energetic dependencies. GHG emissions are related with climate change and global warming. Energetic dependencies generate geopolitical instabilities. As an example, the price of energy is dramatically increasing in the 21st century, as can be seen in Figure 1. The average price of energy in Spain is in 2022 seven times the price it had in 2000, and it is still raising. Same behaviour has been observed in the rest of Europe.

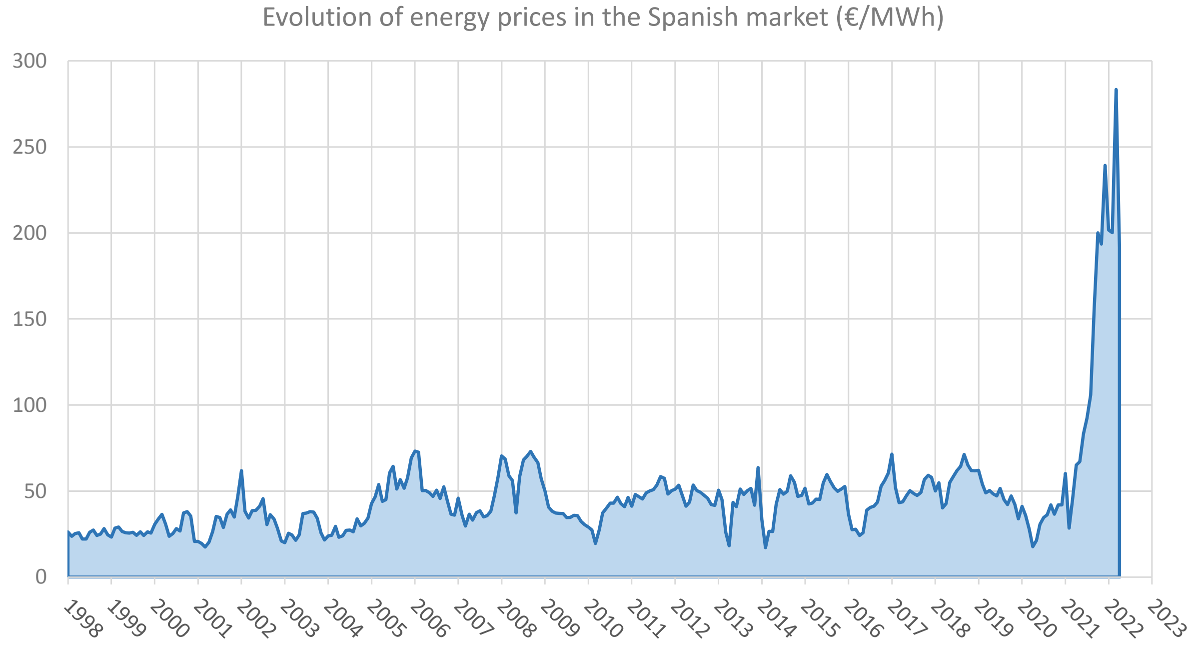


Figure 1. Evolution of the energy prices in Spain. (Source: OMIE, Spanish NEMO Nominated Electricity Market Operator)

The water industry (distribution, sewage and treatment) is one of the main energy consumers in the world. It has been proved that around 7% of energy consumption is directly related with the different water industry activities. Up to 40% of this energy is spent in the transportation and distribution of water. Therefore, energy is highly related with water. Water and energy are two limited resources used in the same utility that has been very important throughout the history but hardly considered jointly [1]. However, some authors are starting studying the water-energy nexus (WEN) [2]. Zaragoza et al. [3] created the concept Watergy to describe the mutual relation between water and energy in the water industry.

Colombo and Karney [4] described two different interactions between water and energy involving leakage. On the one hand, leakage implies additional water volume to be introduced in the water network. This waste of water supposes a loss of revenue for the industry but also may compromise water quality issues. On the other hand, the larger the flow rate, the larger the head losses in the network. It leads to additional power in pumping stations, increasing the energy consumption. Therefore, leakage reduction has an additional outcome consisting in the reduction of consumed energy.

The relation between leakage flow and pressure was defined by Germanopoulos and Jowitt [5]. As a result of this relation, Jowitt and Xu [6] started to optimize the pressure in a network in order to reduce leakage, also known as pressure management. These authors concluded that using pressure reducing valves (PRV) might significantly reduce leakage volumes. Besides, modifying the setting of the valves along the day leads to a larger reduction of leakages but has also some drawbacks. First, changes in the setting may affect operation of pumps in the network. Second, someone (meaning labour costs) or something (energy costs associated to the actuator of the valve) must change the setting. From an energy point of view, this action may be taken as a waste of energy: energy is first provided by pumps or elevated tanks and then dissipated in a valve. In an energy-scarcity scenario, this can be understood as illogical. That is why use of small turbines (pump as turbines –PAT–, miniturbines and picoturbines) are starting being used in water distribution networks (WDN). In other words, the energy we need to dissipate can be converted in electricity. That is way Iglesias-Castelló et al. [1] defines Potential Recoverable Energy (PRE).

Use of small hydropower plants presents some difficulties for their implementation in WDN. First, it is difficult to find information about small turbines. Besides, operation of turbines in installations as WDN, with a highly varied conditions, is difficult to control [7]. To solve this issue, Nautiyal et al. [8] propose a setup with two valves: one in series and another in parallel. Nowadays, the use of small turbines in WDN is widely extended in networks with high differences of pressure.

To sum up, pressure management has demonstrated its efficiency to reduce water losses. Pressure management requires the use of PRV, that is, needs to dissipate excess of pressure. Small turbines may convert this excess of pressure into energy. The variation of the settings of the valves with time requires a small amount of energy. The main objective of this work consists of studying the viability of using small turbines to generate the energy needed by actuators to modify the setting of the valves. The method used will consist into three steps: a) selecting suitable turbines based on the available head drops and flow rates, b) selecting suitable district metering areas (DMA) with PRE enough to feed the actuators, and c) using a calibrated model to determine the improvement of both water and energy consumptions and evaluate the validity of the system.

2 METHODOLOGY

2.1 Installation description

Regulating turbines is a complicated task, especially in a WDN where the flow demands are variable throughout the day. As mentioned above, the setup proposed by Nautiyal et al. is an installation with a PRV in series and a control valve in parallel. These two valves control the behaviour of the turbine to maintain the design operating point. On one side, when the flow rate is larger than the operating point the turbine, following its characteristics curve, will generate a head loss greater than expected. However, control valve is opened and this excess of discharge is taken to the by-pass. On the other side, when the flow rate is less than operating point, the head loss that will produce the turbine is less than expected. In that case, PVR reduces pressure head until it reaches an operating point within turbine characteristic curve.

In the installation proposed in this work there is a main PRV and its setting will be the only one to be modified according to the pressure necessities of the WDN. On that basis, the proposed setup consists of a small turbine and PRV in parallel to the main PRV. In this case, the PRV in parallel has a protection purpose in the event of a turbine failure. Therefore, this setup can only admit design flow rate or higher. When the flow rate is larger than the operating point, the excess flow is by-passed to the main PRV.

Demand flow fluctuates throughout the day in an urban WDN. Normally there are two valleys of consumption, one in mid-afternoon and other in the early morning hours, in this last the consumption is minimum. The measured flow during these hours is known as Minimum Night Flow (MNF) and it is characterised by low user consumption and high level of leakage.

Considering the setup proposed, for the optimum operation of the installation the design flow rate shall be the MNF for the WDN. In this way, during the early morning hours all flow will only pass through the turbine and the main PRV will stay closed.

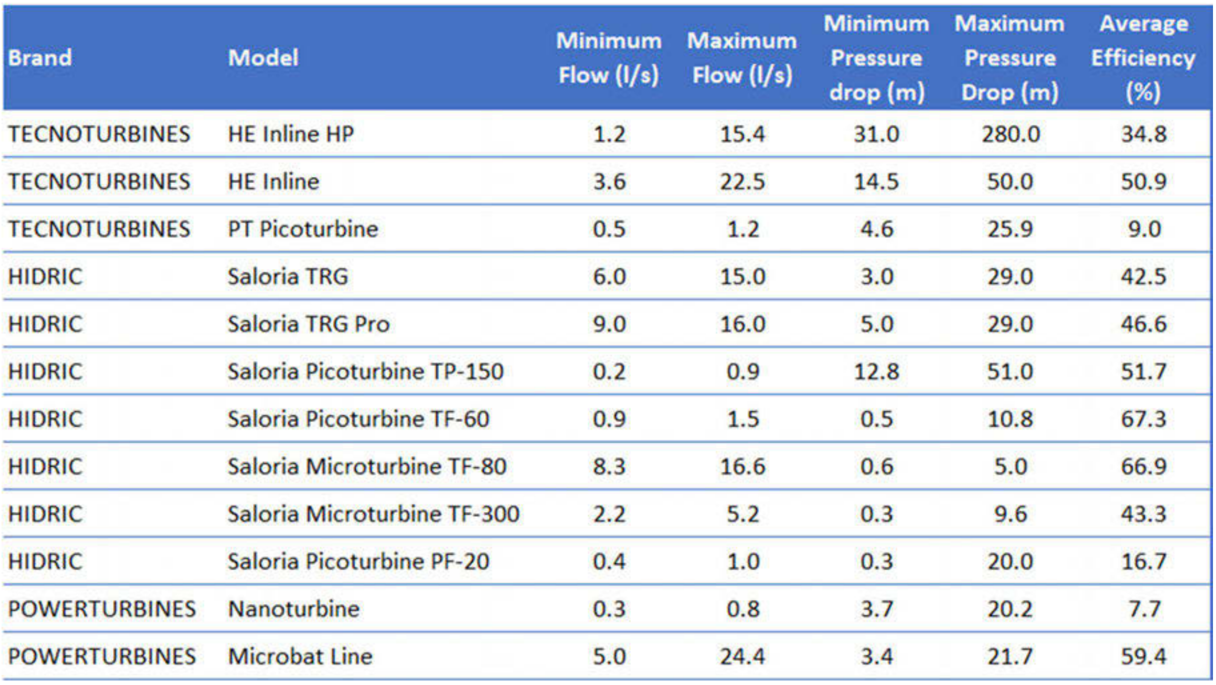
Other variable of the turbine design operating point to be determined is pressure drop. Pressure drop at the same time depends on two variables: pressure at the inlet point of the WDN and the pressure delivered to the WDN. Therefore, it will be defined at a later stage.

In fact, small turbine must generate the energy to manipulate the main PRV for that MNF and pressure drop. It is necessary 18 W in case to use a PRV controller or 50W in case to use a motorised pilot, based on the information from brand catalogues.

2.2 Selection of turbines

A wide variety of turbines for different flow and pressure drop ranges are available on the market. In this research it is analysed the turbine catalogue from different brands which are focus on recovering energy from WDN. Based on the information extracted from the operating range curves of twelve turbine models, where the recovered power in terms of flow and pressure drop are displayed, it has been possible to calculate the theoretical recovered power and hence, average efficiency for each model.

Table 1. Flow and pressure drop ranges and average efficiency for turbine models from different brands (Source: commercial catalogues of Tecnoturbines, Hidric and Powerturbines, available at the Internet).



Brand	Model	Minimum Flow (l/s)	Maximum Flow (l/s)	Minimum Pressure drop (m)	Maximum Pressure Drop (m)	Average Efficiency (%)
TECNOTURBINES	HE Inline HP	1.2	15.4	31.0	280.0	34.8
TECNOTURBINES	HE Inline	3.6	22.5	14.5	50.0	50.9
TECNOTURBINES	PT Picoturbine	0.5	1.2	4.6	25.9	9.0
HIDRIC	Saloria TRG	6.0	15.0	3.0	29.0	42.5
HIDRIC	Saloria TRG Pro	9.0	16.0	5.0	29.0	46.6
HIDRIC	Saloria Picoturbine TP-150	0.2	0.9	12.8	51.0	51.7
HIDRIC	Saloria Picoturbine TF-60	0.9	1.5	0.5	10.8	67.3
HIDRIC	Saloria Microturbine TF-80	8.3	16.6	0.6	5.0	66.9
HIDRIC	Saloria Microturbine TF-300	2.2	5.2	0.3	9.6	43.3
HIDRIC	Saloria Picoturbine PF-20	0.4	1.0	0.3	20.0	16.7
POWERTURBINES	Nanoturbine	0.3	0.8	3.7	20.2	7.7
POWERTURBINES	Microbat Line	5.0	24.4	3.4	21.7	59.4

This information is used to identify the minimum flow rate (0.2 l/s) and minimum head loss (0.3 m) for install any of these 12 turbines. A representative value of efficiency is also estimated as first quartile of average efficiency ($\eta_{Q1} = 20\%$).

2.3 Selection of DMA based on Potential Recoverable Energy (PRE)

Potential recoverable energy (PRE) is excess energy, over the minimum required, supplied in the nodes of WDN. A portion of the PRE could be recovered inside the WDN itself by installing energy recovery devices (PAT, turbines), in certain points of the network in order to reduces the excess energy supplied to all network node [1].

Valencia city WDN is formed of more than 50 DMAs of which 32 have installed at least one PRV and have available data related with it. With the available data is possible to obtain the variables that affect the turbine operation.

For a first estimation of pressure drop, it can be calculated as the difference between average upstream pressure and average downstream pressure of the PRV. In addition, there is a target MNF for each DMA set by water utility. For the DMAs with two or more inlets, it is assumed that MNF distribution among the inlets is the same as the average flow distribution during all day. In this way, it is calculated a MNF per inlet.

In energy recovery using turbines, the portion of the PRE that could be recovered is limited by turbine efficiency. Therefore, the useful power out is calculated as shows in equation (1).

$$P(W) = \gamma \cdot \Delta p \cdot Q \cdot \eta \tag{1}$$

Where P is useful recovered power in watts, γ is the specific weight of water in newton per cubic metres, Δp is the pressure drop in metres column water, $Q$is the flow rate in cubic metres per second and η is the efficiency dimensionless.

For the selection of which DMA would be most convenient to install turbines were considered the following criteria:

a) The turbine must be installed in line, that is, it must be a reaction turbine. This criterion excludes Pelton turbines.

b) Hydraulic criteria: MNF per inlet must be achieved and a minimum pressure drop for install a turbine.

c) Useful recovered power must be enough to move the actuator of the PRV. A PRV needs at least 18 W in the case the PRV uses a controller or 50 W in the case of a motorised pilot.

d) Number of inlets to the DMA. Due to the complexity of controlling a DMA with more than one entry, DMA with few entries are preferred.

2.4 Preparation of the calibrated models

Hydraulic models utilised in this work are built using QGISRed plugin, which is a free professional software to build and analyse WDN models from a shapefile database. The initial hydraulic model consists of junctions with base demand that is real information of water consumption at each service connection. The demand pattern is assumed same as input flow rate pattern. Furthermore, reservoirs in the inlets of the DMAs represents the PRV upstream pressure with total head of 1 and a head pattern that includes elevation and pressure head and PRV with setting same as average of PRV downstream pressure.

To obtain the calibrated model, it is followed the calibration methodology for pressure-dependent demand and consumption introduced by Martinez-Solano [9]. One relevant hypothesis is that non-revenue water volume consists of leakage in the WDN and therefore it is considered pressure dependent. The objective of this methodology is to calculate emitter coefficient for each junction, based on a general emitter coefficient for the entire WDN, and adjust consumption pattern coefficients for the base demand in an iterative process.

On one hand, daily balance of injected flow and revenue flow results in the estimated average leakage rate ($\overline{Q_L}$).

$$\overline{Q_L} = \overline{Q_S} - \sum_{i=1}^{N_D} \overline{Q_{BD,i}} \tag{2}$$

Where $\overline{Q_S}$ is average water supplied, $\overline{Q_{BD,i}}$ is base demand of node i within the total of all consumption nodes in the network N_D.

On the other hand, it is admitted that all junctions have the same emitter coefficient and same pressure temporal variation to calculate average leakage flow in equation (3). To calculate average pressure for the entire network, it is considered as initial hypothesis that base demand follow same pattern as injected flow rate.

$$\overline{Q_L} = \sum_{i=1}^{N_D} c_{E,i} \cdot \sqrt{\overline{p_i}} \tag{3}$$

Where $c_{E,i}$ is emitter coefficient for node i and $\overline{p_\iota}$ is average pressure in node i. In this work, it is assumed that emitter coefficient is same for all nodes in the network ($c_{E,i} = c_E$). Consequently, if equation (2) and (3) are equated, general emitter coefficient c_E is calculated as in equation (4).

$$c_E = \frac{\overline{Q_S} - \sum_{i=1}^{N_D} \overline{Q_{BD,\iota}}}{\sum_{i=1}^{N_D} \sqrt{\overline{p_\iota}}} \qquad (4)$$

Average leakage rate calculate in equation (2) must coincide with the result in (3). If not, general emitter coefficient is corrected iteratively until the average pressure in junction in two successive iterations is differs less than a certain value.

Adjustment of the consumption pattern coefficients is the next step in the process. The coefficients are calculated following equation (4).

$$m_d(t) = \frac{Q_S(t) - c_E \sum_{i=1}^{N_D} \sqrt{p_i(t)}}{\sum_{i=1}^{N_D} Q_{BD,i}} \qquad (4)$$

Where $m_d(t)$ is the consumption coefficient at time t, $Q_S(t)$ is water supplied at time t and $p_i(t)$ is pressure in node i at time t. For this work, leakage rate is calculated with pressure temporal variation of a representative junction of the network.

The alteration of the consumption pattern involves changes in network pressure, thus iteration continuous until the error between observed and simulated input flow rate is less than a certain value (in this work this value was assumed to be <1%).

In DMA with more than one inlet is essential that the model represents exactly the flow rate that passes in every entrance. For that, when the iteration process is concluded, valve settings are modified. At this point is worth mentioning the modification with a lower setting in PRV implies that passes less flow rate in this entrance. However, this flow is compensated by the other inlets. It happens the opposite with a higher setting in PRV.

2.5 Setpoint curve

Once the model is calibrated, it is built the setpoint curves in order to know the specific head pressure that is needed to deliver a flow rate considering the pressure in the critical node of the network, as accurately as possible. The critical node is the node with the lowest pressure and can change depending on demand variation. In a network each inlet or source of supply has a setpoint curve.

The process followed to calculate the setpoint curves is explained by Leon Celi et al [10]. Specifically, the explanation for the cases with pressure dependent consumptions both only one water source and more than one water source supply. Besides, in the case of more than one water source the flow rates to be supplied are fixed considering the data from the calibrated model.

According to the Urban Planning Regulations of the General Urban Development Plan of Valencia, the minimum pressure in the service connection must not be less than 25 m. Being conservative, the minimal pressure established as required is 27m if it is takes into account possible losses in the service connections.

The setpoint curve obtained can be approximated by the following equation (5) as a function of flow demand Q_d.

$$H^{(c)} = H_0 + R_c \cdot Q_d^n \qquad (5)$$

Where H_0 is the minimum head pressure for zero flow demand, R_c and n are parameters for a power regression.

This way, the head pressure required for any flow demand in the network is easily calculated.

3 CASE STUDY

3.1 Description of the network

The network under study is Benimaclet sector which includes the area of the old Benimaclet neighbourhood in Valencia city. This network has 1,047 service connections and 10,708 clients. These clients are mainly domestic (88.1%), besides industrial (10.8%) and municipal and fire hydrants (1.1%).

The Benimaclet network has two water inlets. First one is located in the central west area and water through a 250mm pipe in Vicente Zaragoza St. The second one is in the southeast area and water through a 200mm diameter pipe in Catalunya Ave. In each inlet there is a PRV of 200mm of diameter. In addition, pressure gauges are installed both upstream and downstream of each PRV, and a water meter is installed in each of the inlet pipes.

In the same way as other areas of Valencia City, topography is practically flat with no major slopes. The difference between the highest and lowest elevation in DMA is only 6 metres. The lowest elevation in east area and the highest in west area, where is located the critical point of the DMA. The network has 23.1 km of pipelines of which 57.6% was installed before 2001, 34.4% between 2002 and 2003, and the remaining percentage from 2004.

The hydraulic model is composed of 2 reservoirs, 2 valves, 3342 pipelines 3202 nodes of which 822 are consumption nodes.

Figure 2. Hydraulic model of Benimaclet sector in Epanet [Source:]

3.2 Initial operation and pressure management

Calibrated model has revenue water in each service connection for the maximum consumption day of March 2020 with a demand multiplier to adjust average base demand for a week of August 2020, when was possible to take pressure data from 3 points inside the DMA.

Until November 2021, PRVs were fully open thus water arrived at the inlets with a pressure around 41 m was not reduced and average pressure inside network was around 40. Under these conditions, for calibrated model for a week of August 2020, average water supplied was 29.27 l/s and average revenue water was 18.52 l/s. Therefore, non-revenue water (NRW) was 10.75 l/s, which represents 36.7% of water supplied.

Considering this, from November 2021 the DMA has a pressure modulation based on fixed pressure output where PRV setting are 34 and 35 m in Vicente Zaragoza St. and Catalunya Ave., respectively. Consequently, average pressure inside the network is around 35.3 m and average pressure at the critical point is 31.2 m. Besides, this implies a reduction of 1.6% in NRW compared to the previous situation.

DMA water consumption has the common daily variations for urban networks. For instance, there is a great valley between 2 a.m. and 6 a.m. with very low the consumption compared to daytime. In factor, the average flow rate for this period is 17.13 l/s and the target MNF sets is 14.1 l/s.

3.3 Dynamic pressure management

In this work it is proposed a time-based dynamic pressure management which allows higher downstream pressure to be set for daytime and lower pressure at night when consumption decreases. For the calibrated model input flow is lower in the period between 2 a.m. and 6 a.m., when the consumption is around 55-60% of average input flow.

It is used the setpoint curves of the DMA for determining the valves setting (Figure 3). On one hand, setpoint curve for PRV in Catalunya Ave. indicates that for the range of input flow, the minimum pressure needed barely fluctuated and it is around 32 m. Thus, PRV will remain with a modulation based on fixed pressure output. On the other hand, PRV in Vicent Zaragoza St. will have a setting of 29.8 m in the night period and 30.7 m for the daytime period.

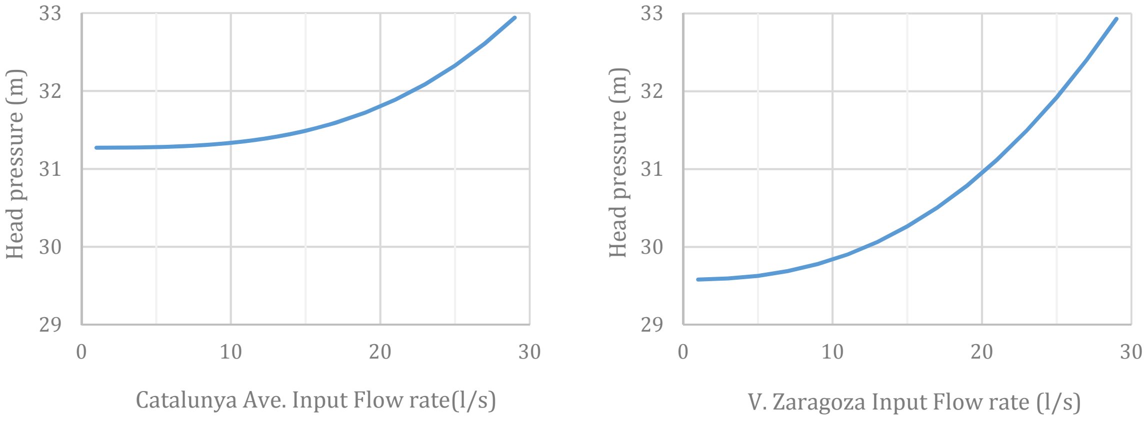


Figure 3. Setpoint curves for both sources water supply in Benimaclet network.

The proposed operation will allow pass 9.18 l/s through Vicente Zaragoza St. and 18.85 l/s trough Catalunya Ave. Besides, it will suppose a reduction of 2.8% in NRW.

In fact, as it is showed in Figure 4, it could be an improvement in volumetric efficiency as minimum required pressure in the network is lower (Figure 4). The volumetric efficiency of a network is the relation between revenue water and the total supplied volume during a period of time. In the calibrated model, volumetric efficiency is 63.3% with 33m of minimum pressure in the critical point. If the minimum pressure required is lowered to 20m, volumetric efficiency improves by 5.6%.

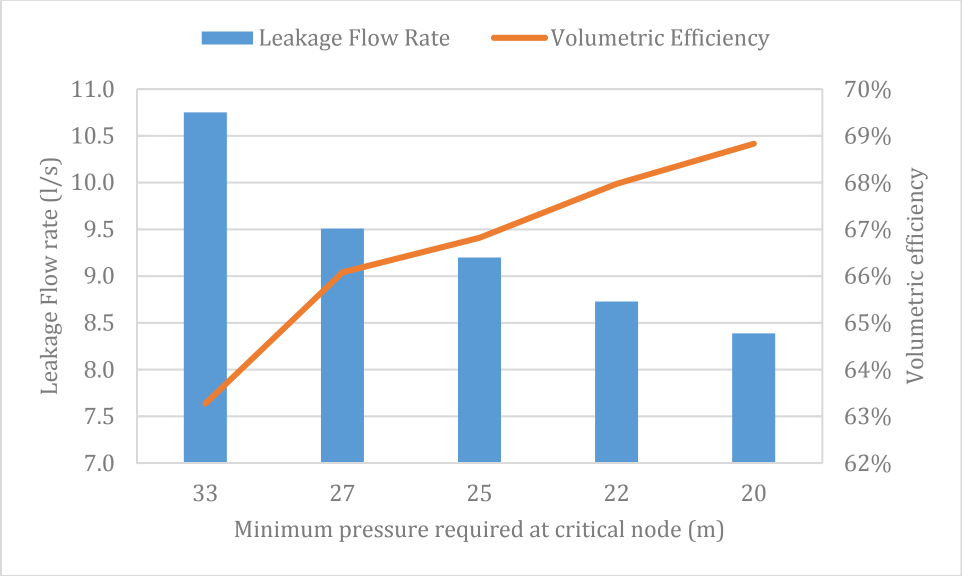


Figure 4. Relation between leakage flow rate and volumetric efficency in Benimaclet network.

As regards energy recovery, the PRE in the Vicente Zaragoza inlet is calculated as in equation (1) without considering the turbine efficiency yet. The average pressure drop is 10.1m taking in count upstream pressure is 40.61 m and average downstream pressure is 30.5m. As mentioned above, it is expected that MNF distribution among the inlets is the same as the average flow distribution during all day. Therefore, MNF for Vicente Zaragoza inlet is 6.5 l/s and, as result, the PRE is 643W, enough to operate the actuator of the PRV.

3.4 Economic assessment

With the proposed operation there is a reduction in the average annual input volume of 39,201 m^3. Considering fee for typical consumption set by local government in 2020 and currently in force (0.5584 €/m^3), it would stop losing an amount of 21,890€ per year.

Furthermore, water price in the water treatment plant inlet is 0.1712 €/m^3 to which must be added the Hydrographic Confederation tax (regulatory agency for the basin supplying the city) of 0.0206 €/m^3. Thus, leakage reduction will result in saving of 7,518 €/m^3 on the cost of bringing the water to the water treatment plant.

In this work only the unit price of the turbine has been taken into account in the economic assessment. From HIDRIC catalogue information, where is displayed the price list of its turbines, it has been related maximum recoverable power of each turbine model and its unit price. The equation (6) is the result of applying a regression analysis by the method of least squares.

$$C = 1148 + 0.06 \cdot PRE^{1.54} \tag{6}$$

Where C is the turbine unit price in euros and PRE is potential recovered energy inlet in watts. The PRE in the Vicente Zaragoza inlet is 643 W, thus the unit price of the turbine could be estimated as 1,147 €.

However, installation of a turbine implies an initial investment that includes the building of the extension or the new chamber, all necessary connections for the incorporate the turbine into the network, PRV controller, the turbine itself and all staff necessary to generate energy.

4 CONCLUSIONS

Energy efficiency is a crucial factor considering currently energy situation. As water industry is one of the main consumers of energy, relation water-energy has started to be studied in the last few years. Related to this matter is leakage in WDN which its reduction directly involves a reduction in consumed energy. The leakage volume is diminished using PRVs, which need energy to be controlled. This energy come from the network itself by using small turbines. In this way the energy that initially will be dissipated can be converted into electricity.

The setup of installation determines the operation of turbines. In this work the proposed installation has a turbine with a PRV in series and a main PRV in parallel. It is expected that the turbine works with a flow rate equal to MNF if the WDN has only one inlet or the MNF in that entrance if there are more than one. In this way, turbine will operate not only during daytime but also during night-time.

The study of different turbine models lets define minimum flow and drop pressure for turbine performance. This, joined to other criteria, allows the selections of network to be built and studied. The hydraulic model for this works represents non-revenue water as pressure-dependent demands by using emitter coefficients. The dynamic pressure management considered is based on the minimum pressure required at critical node of the network. By means of the setpoint curve is possible to know the PRV setting for specific input flow and, consequently, is possible proposed a PVR control based on time periods.

The network under study in this work is Benimaclet that has a volumetric efficiency of 63.3% and consists of two inlets with a fixed pressure output. The dynamic pressure management proposed is to keep one of the inlets with a fixed pressure output and other inlet with a pressure modulation based on time. This modulation involves a fixed a lower pressure output between 2 a.m. and 6 a.m. than daytime.

In conclusion, implementing dynamic pressure management in the Benimaclet DMA could lead to a reduction in the leakage rate. Consequently, it results in savings in water cost at the inlet of drinking water treatment plant and in lost revenue due to leakages. In fact, only with the savings in the cost paid at the entrance to the drinking water treatment plant, the price of the turbine could be amortised over a period of one year. These outcomes are reached by setting the minimum required pressure at 27 m. Undoubtedly, these savings can be greater if minimum required pressure lowered to 25 m as local regulations mandates.

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