

The energy – pressure nexus in the water supply system

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ABSTRACT

Due to the importance of overall sustainable development, efficient energy management should be as significant as water resource management within every water supply system. The pressure reduction, as a measure for loss reduction, not only guarantees less leakage but also minimizes energy consumption. The relationship between energy consumption and pressure in water supply systems has been the subject of many previous studies, mainly based on measurements in real systems. However, a methodology for beforehand assessment of energy savings which occur due to the pressure reduction, has not been proposed yet. The paper proposed a method for the assessment of energy savings in relation to pressure reduction, implemented it on the hypothetical water supply system and verified it on the real system. Results led to the conclusion that the proposed methodology can be considered as a successful tool for better energy and water management. It enables water utility management to estimate energy saving in water supply system in advance, based on the hydraulic model of the system.

Key words | energy-saving, leakage, pressure reduction, water losses, water supply system

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HIGHLIGHTS

- Reduction of water loss leads to a reduction of energy that the system needs to operate.
- Pressure reduction can be used as a very effective measure for energy saving.
- Software simulating water supply systems need to be convenient for delivering data about energy consumption.
- Method for estimation of energy savings in relation to pressure reduction is proposed.
- The energy-saving data will be useful in better energy management of WSS.

INTRODUCTION

Although water is undoubtedly essential for life on Earth, the problem with the scarcity of drinking water has become greater over the years due to climate change, as well as the overexploitation and contamination of ground-water. Water conservation and efficiency are crucial for fighting the global water crisis. The World Economic Forum 2011 announced a forecast for the next two decades,

which predicted an increase of 20 to 50% above the current level of water and energy use (Mosalam & El-Barad 2020). Keeping in mind the principle of the European Water Charter (1998) that ‘everyone has the duty to use water carefully and economically’, topics related to water loss become more actual issues as times go by.

Water loss within a water supply system is a major problem that all water supply companies deal with. More than 32 billion cubic metres of treated water physically leak from urban water supply systems around the world, annually (Kingdom *et al.* 2006). The high level of losses can

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potentially cause various problems, such as water shortages and restrictions that can be a limiting factor for further growth and progress of settlement. But the main issue is that the high level of losses results in extracting, treating and transporting far more water than consumer needs, which additionally leads to higher energy consumption levels.

Water utilities use a high amount of energy to operate water treatment plants, which results in a large percentage of their operating cost being electricity bills (Hasan *et al.* 2020). The energy consumption in water supply systems, along with a high percentage of losses, make managing a water supply company even more challenging. Moreover, water and energy consumption should be considered in policy formulation simultaneously to achieve balanced development of resources (Sun *et al.* 2018).

Besides that, in the age of increasing environmental awareness and environmental protection, the trend in the world is to reduce the consumption of all types of energy; that is, to save it. There is an initiative in the EU regarding establishing a network of positive energy districts, which, in addition to increasing the production of their own energy, will also require minimizing the energy consumed for the balance to be positive. One of the tasks should be the optimisation of water supply systems to fulfil increasing water demand and, at the same time, to manage energy-related environmental issues (Vakilifard *et al.* 2018).

The energy used for water distribution purposes is estimated to be 7% of global energy consumption (Coelho & Andrade-Campos 2014). The energy is required for raising water from one elevation to another, for water distribution, as well as for compensating for losses in the system. Only a portion of energy entering the water supply system is delivered to the consumers (Dziedzic & Karney 2014). Just as the water leaks, energy is dissipated at the leak locations correspondingly (Karney & Filion 2003). Even though leakage is the basic criterion while selecting appropriate methods to control water losses, the total energy consumption in water supply systems should be taken into consideration as well. Objectives focused exclusively on water loss reduction in the distribution system, or only on energy maintenance in them, will not be achieved if the complex connection between energy consumption and water leakage in the system is not considered (Puleo *et al.* 2015). Finding the optimal configuration of the distribution

systems, to minimize the energy consumption, has been the subject of many surveys (Ramos *et al.* 2012; Moreira & Ramos 2013; Bolognesi *et al.* 2014; Mundt & Dodenhoff 2015). Efficient energy management is as important as water resource management.

This paper summarizes the results of extensive research on the relationship between the energy of the system (i.e. the energy required by the water supply system to operate) and the losses in the water supply system. Simulations of losses in the water supply system were done in EPANET software. The research shows how, and to what extent, a reduction of losses in the system affected a decrease in energy that is needed for water distribution. This becomes even more important since there is no energy report for gravity flow systems in EPANET but only for pumping systems (Gómez *et al.* 2016).

Methods and tools for water supply systems optimisation, in the sense that water and energy savings are sustainably achieved, has been the subject of much research. According to this, one of the crucial components of water and energy management is pressure control. Authors of the article (Wu *et al.* 2020) perceived that pressure control implies keeping high pressure to ensure the required water supply for consumers and, at the same time, reducing both leakage and the risk of pipes bursting. Pressure management is asserted to be an effective technique for leakage reduction (Nazif *et al.* 2010). The leakage reduction may lead to the achievement of significant savings in power consumption (Ociepa *et al.* 2019). Since the worldwide water loss is estimated to be 30%, it means that the very same portion of the energy is lost (Feldman 2009). According to the case study, high annual electricity costs can be reduced up to 22% if demand management strategies are applied (Hasan *et al.* 2020).

Several case studies were carried out, measuring water and energy consumption before and after pressure reduction, and the authors reported significant savings in water and energy. In their case study, Xu *et al.* (2014) found that 5.6 m reduction in inlet pressure resulted in water-saving of 62,633 m³/year per km of pipe, as well as associated savings of 1.1 × 10⁶ MJ of energy. Zhao *et al.* (2018) demonstrated an actual 14,773 m³ water (reduction of 11.9%) and 15,955 kWh energy saving per year, after the implementation of a branch pipe pressure-reducing

valves (PRV) retrofitting measure. Monsef *et al.* (2018) in their study proposed measures to achieve uniform distribution of the pressure and reduction of the excessive pressure during the whole day, reducing the water leakage and energy consumption accordingly. The results of their case study showed that the network background leakage and energy consumption have been reduced by 41.72% and 28.4% respectively.

The results of all of these studies promote pressure management as an excellent tool for leakage reduction and associated energy benefits. They revealed numeric values of how much pressure reduction impacts energy saving, based on measurable data in real systems. Although the relationship between energy consumption and pressure in water supply systems has been the subject of many studies, a methodology for advance assessment of energy savings (which occur due to the reduction of the pressure in the system) has not been proposed yet.

This paper proposes a methodology that will enable water utility management to estimate energy saving in water supply system in advance, based on the hydraulic model of the system realised in the EPANET software. The method for calculation of the total required energy in the water supply system, based on knowledge of basic data about it: system configuration, water consumption and the amount of water loss in the system, is presented. Furthermore, the aim is to show the change in the energy of the system that occurs as a result of changes in the leakage rate, and consequentially, the possibility of energy saving in order to improve energy and water management.

METHOD

Theoretical background

The total energy entered in water supply systems can be classified into potential energy and kinetic energy. Potential energy is that which is introduced into the system through reservoirs and tanks. Kinetic energy is introduced into the system through pumps.

Characteristically, in a water supply system, energy integrates the two key parameters of the system: pressure and

flow. It was calculated using Equation (1) by Dziedzic & Karney (2014):

$$E = \int_0^t P dt = \int_0^t (\gamma H Q) dt \quad (1)$$

where:

P – is power (W),

γ – is the specific weight of water (N/m³),

t – is time (s),

H – is head (m) and

Q – is flow (m³/s).

According to the Law of conservation of energy, the quantity of energy that enters the system is equal to the one that leaves, so the total supplied energy ($E_{supplied}$) is converted into:

- energy dissipated in pipes, pumps and valves due to friction and inefficiency ($E_{dissipated}$),
- energy lost due to leakage of pressurized water (E_{lost}) and
- energy delivered in the form of pressure ($E_{delivered}$),

as given in Equations (2)–(5), by Dziedzic & Karney (2014):

$$\Sigma E_{supplied} = \Sigma E_{dissipated} + \Sigma E_{lost} + \Sigma E_{delivered} \quad (2)$$

Energy dissipated is calculated according to the equation:

$$E_{dissipated} = \gamma H_{loss} Q t \quad (3)$$

where:

H_{loss} – head loss (m), which includes minor and friction losses (m).

Energy lost is calculated by means of the equation:

$$E_{lost} = \gamma \Delta H Q_{leak} t \quad (4)$$

where:

ΔH – is the difference in head between the inside and outside of the pipe (m),

Q_{leak} – is the leak flow (m³/s).

Energy delivered is calculated according to the equation:

$$E_{delivered} = \gamma H_{node} Q_{delivered} t \quad (5)$$

where:

H_{node} – is the head delivered at the node (m),
 $Q_{delivered}$ – is the flow delivered at the node (m³/s).

As can be seen from Equations (3) and (4), minimizing losses in the system directly causes the reduction of energy dissipated and energy lost. From Equation (5) it can be concluded that the lowering of the pressure in the system (and thus the reduction of the head delivered at the node) results in a decrease of the energy delivered. The main advantage and reason for the implementation of pressure management strategy is leak reduction (Garmendia et al. 2019), but as seen, pressure reduction will impact on decreasing the total supplied energy in the system. Therefore, pressure reduction has been selected in the process of analysis of the link between energy in the system and leakage in it.

Hypothetical water supply system description

Water supply systems are complex systems, and therefore, very challenging to manage. System models design, simulations of various scenarios of the water supply system, and then adequate analysis of the simulation results, can be of great help for making the right decisions in the management of the system. For that purpose, a hypothetical water supply system was designed and the impact of pressure reduction on the decrease of the total energy in the system was analyzed. This offers some insight into the possibility of energy savings along with water loss reduction. The energy savings can be calculated for each scenario of water loss reduction.

The hypothetical water supply system used for simulation represents well enough the real system, taking into account the parameters of real systems, first of all – leakage, as well as the change in demand during a day. At the same time, the theoretical system is comprehensible, in a way that the method for energy estimation can be displayed on it. It is modelled by the EPANET

software, in which the leakage model is made using a software function, so-called ‘Emitters’. This option physically introduces a fictional pipe between a node and a fictional reservoir. The head at the fictional reservoir is actually the elevation of the node. The loss flow is calculated as flow through the fictitious pipe.

In the EPANET software, the total leakage is calculated as the sum of leakage of all the nodes, according to Equation (6):

$$Q_{leak} = \sum_{i=1}^n Q_{leak,i} = \sum_{i=1}^n C_i \cdot P_i^{N_i} \quad (6)$$

where:

Q_{leak} – is the leak flow (m³/s),
 n – is the number of nodes in a model,
 C_i – is the ‘Emitter’ coefficient,
 P – is the pressure at the node (m),
 N_i – is the exponent.

The values of C_i and N_i are not constant for a given system but depend on the pressures at which they are being estimated (Van Zyl & Cassa 2014).

The system consists of 45 nodes and 62 pipes of equal length and 200 m long. A systems schematic, with marked diameters of pipes (in millimetres), is shown in Figure 1. The elevations of nodes in the system are given in Table 1. The water in the system is delivered by tank and its elevation is 100 m. The water losses within the system are modelled by the software function ‘Emitters’. This means that the consumption in each node is increased due to the existence of leaks. The ‘Emitter’ coefficient value of 0.225 is adopted for each node so that participation of leak flow (obtained from Equation (6)) in the total demand flow is 58%.

Pressure reduction as a measure for water loss management

The analysis of the mutual relationship between water loss reduction and pressure reduction has been the subject of much research. The leakage reduction is calculated as a function of pressure reduction, according to the generally

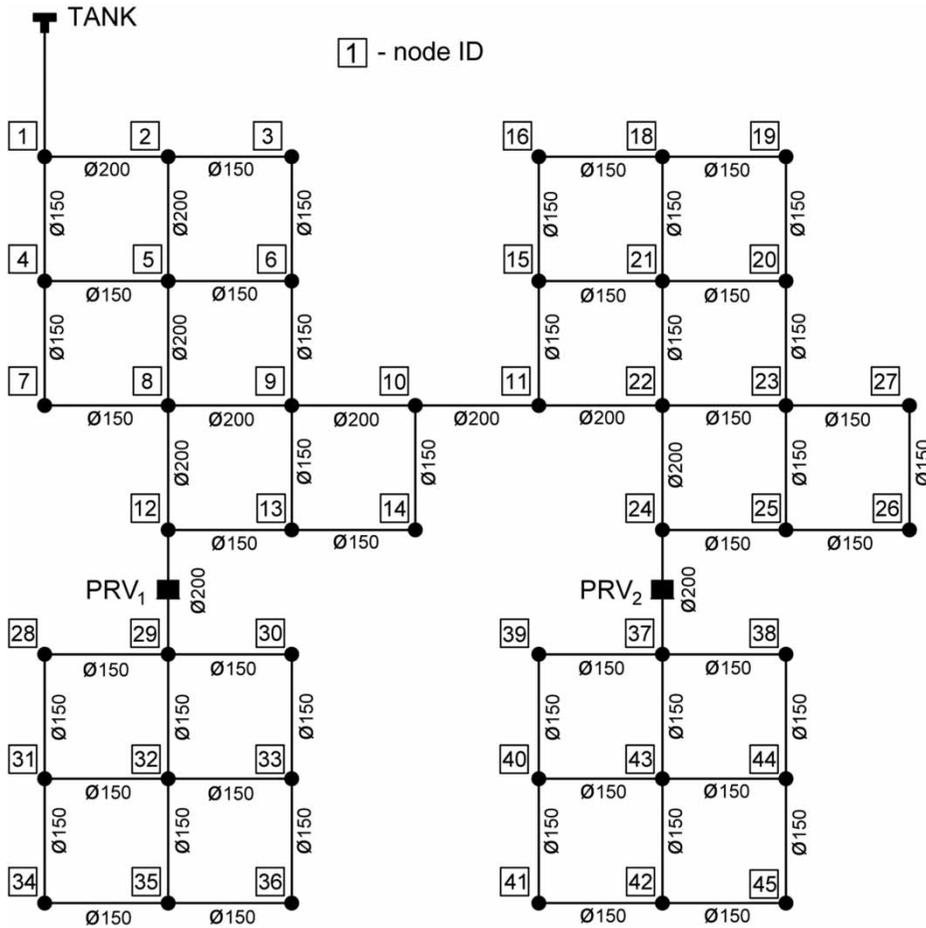


Figure 1 | Schematic of the hypothetical system with positions of PRVs.

accepted equation (Lambert 2001):

$$\frac{Q_1}{Q_0} = \left(\frac{P_1}{P_0} \right)^N \quad (7)$$

where:

- P_0 – is initial pressure (m),
- Q_0 – is initial leak flow (m^3/s),
- P_1 – is corrected pressure (m),
- Q_1 – is corrected leak flow (m^3/s),
- N – is the exponent.

The majority of mathematical models have accepted Equation (7) as the base for leakage modelling, adopting different values of the exponent N . The exponent N depends on the orifice type and the flexibility of pipe material. In the

above equations, the exponent N can range from close to 0.50 to as much as 2.50, depending upon the dominant type of leaks, as well as the combination of leak types (Lambert 2001). In our simulation, a value of 0.5 is used, since other researchers' laboratory testing on particular leaks in pipes showed that for round holes the leakage exponent is close to 0.5 irrespective of the pipe material or hole size (Van Zyl & Malde 2017), or even orifice shape (De Paola & Giugni 2012).

The pressures in the nodes of the hypothetical water supply system, before pressure reduction, are shown in Table 1.

High-pressure rates (more than 60 m) were obtained in nodes 28 to 45. Because of that, pressure reduction is selected as a measure for the decrease in leakage. Pressure reduction is accomplished by introducing PRVs on the

Table 1 | Pressure rates at the nodes before and after pressure reduction

Node ID	Elevation (m)	Pressure rates before reduction (m)	Pressure rates after reduction (m)	Node ID	Elevation (m)	Pressure rates before reduction (m)	Pressure rates after reduction (m)
1	42	59.69	60.18	24	38	52.75	55.62
2	40	58.74	59.87	25	39	51.79	54.63
3	38	59.66	61.02	26	36	54.79	57.62
4	37	60.89	62.22	27	37	53.82	56.64
5	38	59.23	60.72	28	18	76.37	29.83
6	38	58.84	60.40	29	15	79.53	32.90
7	33	63.67	65.29	30	16	78.37	31.83
8	35	60.70	62.58	31	19	75.31	28.80
9	38	57.04	59.04	32	20	74.31	27.80
10	37	56.76	58.99	33	19	75.31	28.80
11	29	62.96	65.53	34	18	76.28	29.79
12	38	56.94	59.08	35	19	75.28	28.79
13	38	56.76	58.86	36	19	75.28	28.79
14	37	57.17	59.34	37	21	69.37	31.90
15	39	52.23	54.94	38	20	70.22	32.81
16	39	52.10	54.82	39	20	70.23	32.82
18	37	54.04	56.78	40	19	71.17	33.78
19	37	53.98	56.74	41	18	72.14	34.77
20	36	54.97	57.73	42	19	71.14	33.77
21	35	56.06	58.81	43	19	71.17	33.79
22	39	52.11	54.86	44	18	72.17	34.78
23	36	54.90	57.69	45	20	70.14	32.77

EPANET system model. Positions of the PRVs are on the pipes which bring water into the zones with high-pressure rates. The proposed positions of PRV are shown in Figure 1.

Consequently, the pressure was decreased; that is, the pressure rates were reduced up to 60% in some parts of the system (Table 1).

Estimation of the total energy in the system before and after pressure reduction

Energy is supplied to the system through the tank. Afterwards, it is distributed within the network in different forms: energy dissipated, energy lost and energy delivered. Based on the equations specified previously, as well as on the results obtained by the system simulation in the EPANET software, the values of these energy forms in the

two scenarios, before and after pressure reduction, were obtained.

The values for $E_{delivered}$ and $E_{dissipated}$ are obtained based on the output results from the EPANET software, using Equations (3) and (5). Estimation of the E_{lost} is based on Equation (4). Also, a new equation is proposed, by which the relationship between E_{lost} before and after pressure reduction is given.

Energy lost depends on leak flow and pressure of the flow. Leak flow for each of the nodes in the system was calculated based on the difference between demand in every node of the system with modelled leakage (by introducing the ‘Emitter’ coefficient for each node) and demand in every node of the system without leakage simulation. All demand data for nodes (in both scenarios) were obtained from the EPANET model. By processing the results from the model, obtaining data flow for each node is possible in

both scenarios, i.e. flow with included leakage and flow without it. For each node, the difference of flow with included leakage and the flow without it presents the leakage flow for the node.

Leak flow of the entire system is obtained as the sum of leakage flows of all the nodes in the system (Equation (8)):

$$Q_{leak} = \sum_{i=1}^n Q_{i,leak} = \sum_{i=1}^n (Q_{i,demand+leak} - Q_{i,demand}) \quad (8)$$

where:

Q_{leak} – is the leak flow (m^3/s),

$Q_{demand+leak}$ – is demand and leak flow (m^3/s),

Q_{demand} – is demand flow (m^3/s),

n – is the number of nodes in the model.

After the pressure is reduced, the leak flow (Q_{leak}) is decreased. Consequently, energy lost is reduced as well, by Equation (4).

According to Equation (4), energy lost is proportional to the difference in the head between the inside and outside of the pipe, ΔH , which is actually the pressure of the flow (Karney & Filion 2003). Taking this into account, altogether with Equations (4) and (7), the new Equation (9) is proposed, by which the relationship between energy lost before and after pressure reduction is presented as follows:

$$\frac{E_{lost1}}{E_{lost0}} = \frac{\gamma P_1 Q_1 t}{\gamma P_0 Q_0 t} = \frac{P_1}{P_0} \left(\frac{P_1}{P_0}\right)^N = \left(\frac{P_1}{P_0}\right)^{N+1} \quad (9)$$

where:

E_{lost1} – is the energy lost after pressure reduction (kWh),

E_{lost0} – is the energy lost before pressure reduction (kWh),

P_0 – is initial pressure (m),

Q_0 – is initial leak flow (m^3/s),

P_1 – is reduced pressure (m),

Q_1 – is corrected leak flow (m^3/s).

Estimation of the E_{lost} is based on the EPANET data for leak flow and pressure of the flow.

RESULTS AND DISCUSSION

Method application to the hypothetical water supply system

The examination of energy reduction in the system encompassed analysis of the following forms of energy: energy dissipated in pipes (due to friction and inefficiency), energy lost due to leakage and energy delivered in the form of pressure. The reduction of each form of energy in the system is registered as a result of the pressure drop, by different equations.

Energy lost is obtained according to the new described methodology, which is based on determining the leak flow of each node and the pressure in it. Also, a new Equation (9) that shows how the pressure change affects E_{lost} is defined.

In Figure 2, the diagram presents the changes of energy lost during the day in the two scenarios: before and after pressure reduction. Decreasing the energy lost daily, calculated in the scenario after pressure reduction, amounts to 32.4% of the daily energy lost value.

Energy dissipated is determined based on the head losses for each pipe in the system calculated in EPANET. It depends on pipe roughness, pipe diameter and flow velocity. Pressure reduction leads to flow reduction through the pipes, as well as to the decrease in energy dissipated. The energy dissipation changes over the day, in the two scenarios before and after pressure reduction, as illustrated in the diagram (Figure 2).

Energy delivered depends on water demand and pressure of the flow. Pressure reduction leads to a decrease of leakage in a node ($Q_{i,leak}$) which then leads to a decrease of total consumption in the node ($Q_{i,leak+demand}$). Then, the leak flow in the entire system decreases, according to Equation (8), and the energy delivered reduces as well. In Figure 2, the diagram illustrates the changes of energy delivered during the day in the two scenarios, before and after pressure reduction.

In the case of the hypothetical water supply system, after the drop in the pressure, the highest reduction rate is registered within the energy lost component. This can be explained through high levels of losses and high pressure, which are dominant in the system before pressure reduction.

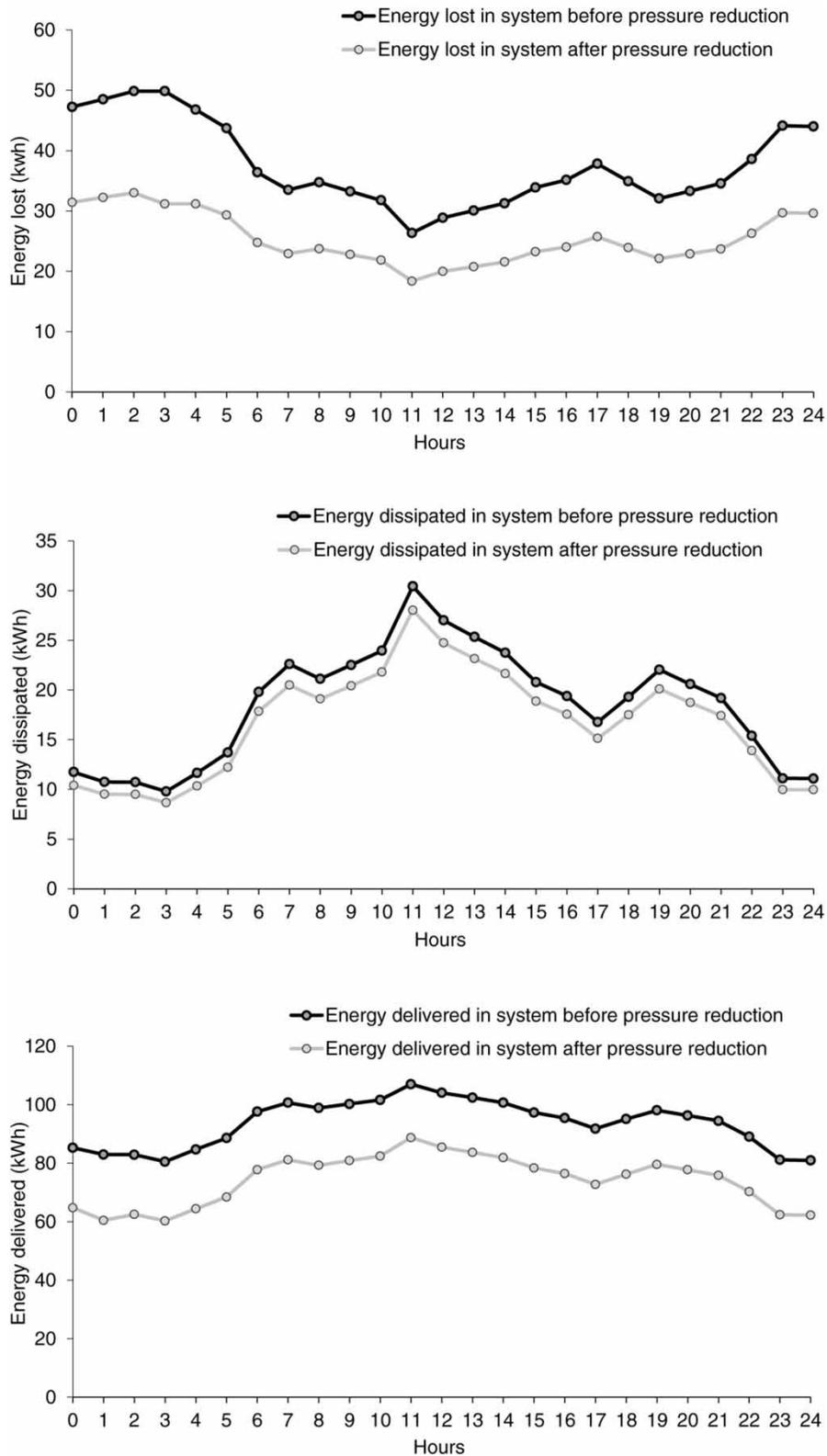


Figure 2 | The energy change during the day (before and after pressure reduction in the system).

Moreover, the reductions in energy delivered and energy dissipated are not negligible. To provide an outline of the total energy reduction in the system, at the expense of pressure reductions in it, the overview of the total energy change during the day in the two scenarios is presented in Figure 3. Based on the analysis of the hypothetical water supply system, pressure reduction results in an energy decrease of 22% per day, while water-saving amounts to 9%.

Varying positions and characteristics of PRVs in the system would result in a different percentage reduction in system energy. To save energy, the optimal position of the PRV in the system is the one that results in the greatest energy saving. Location of the PRV must be chosen taking into account water availability constraints at each node and minimal required pressure.

Experimental verification of a method

This verification aims to apply the method on a real water supply system and to compare results with measured data.

The method is applied to the part of the distribution network of Podgorica city (Montenegro). Five well pumps lift water from the underground and discharge it directly into the distribution system. Pipes are made of polyethylene and their diameters range from 90 to 200 mm. The total length of pipes amounts approximately 35 km. The number of connections is approximate 9760. There is a high level of water loss within the network (55%). The

system is modelled in EPANET and its schematic is shown in Figure 4.

Pressure data are obtained from the measure station (within the pump station) database, as well as energy consumption data. For further analysis, hourly pressure data were chosen, during two characteristic days: Day 1 – when the pressure rate was higher; Day 2 – when the pressure rate was lower (Figure 5).

Measured energy consumption for the same days, hourly, is shown in Figure 6. Besides, calculated energy consumptions for the higher and lower pressure rate, based on the proposed method, are given in the diagram as well. Based on the analysis of the real system, pressure reduction results in an energy decrease of 16% per day.

Comparing measured with calculated energy consumption, the variance is noticed and it amounts up to 7%. This may be a consequence of the inputs for the real system modelling:

- chosen value of the leakage exponent N_I ;
- chosen value of the ‘Emitter’ coefficient C_i ;
- exact leakage positions may be unknown, although in EPANET leakage is assigned to each node, proportionally to the node demand;
- although a real demand could vary due to the pressure, in the model demand is assumed to remain unchanged.

It is assumed that such variations can be reduced to a minimum by the model calibration so the proposed

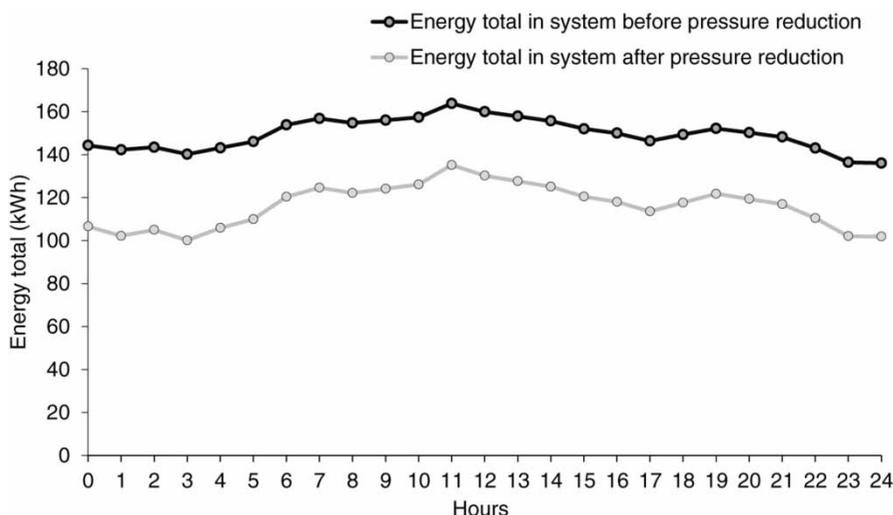


Figure 3 | The total energy change during the day (before and after pressure reduction in the system).

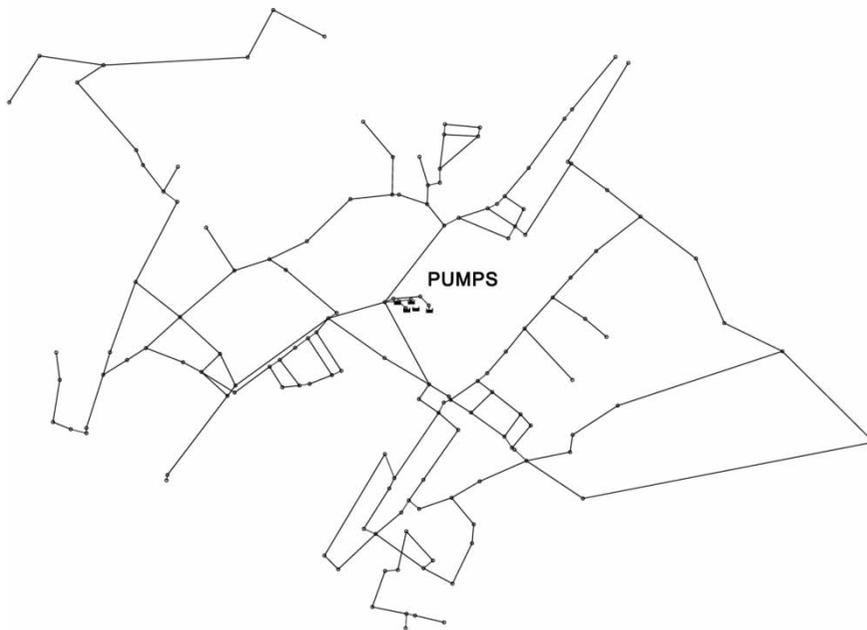


Figure 4 | The schematic of the system.

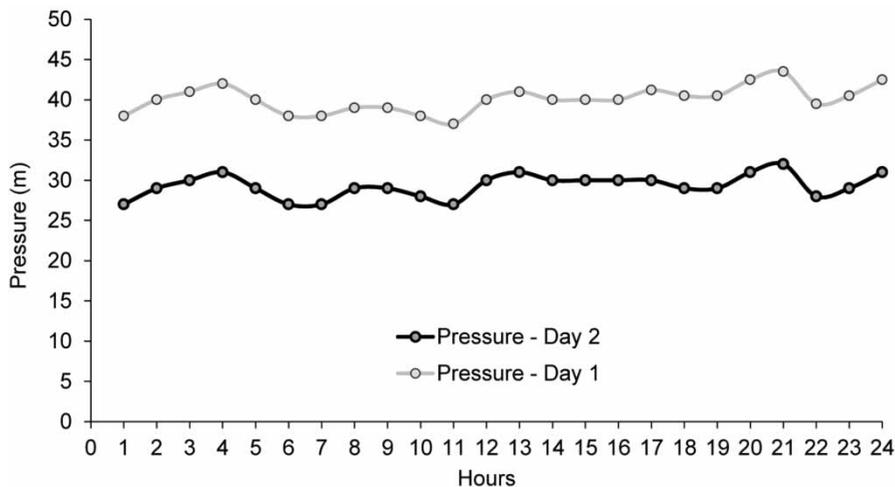


Figure 5 | The pressure change during Day 1 and Day 2.

method could be considered as accurate enough to predict energy-saving, due to pressure reduction.

The practical application of the method and future research directions

The proposed method gives water companies a possibility to estimate beforehand the energy saving caused by the pressure reduction. In that way, the management can test in advance various scenarios of pressure reduction (pressure

reduction in different zones, different PRV locations, various reduction rates etc.) and obtain a different amount of energy savings for each one. Afterwards, the best strategy for water and energy savings can be made. Such analysis could be used for the preliminary identification of the most affected zones in terms of energy inefficiency.

Besides, when it comes to pressure management, it is known that dividing the system into areas (Pressure Management Areas – PMAs) enables more efficient pressure control and makes system monitoring easier. The proposed

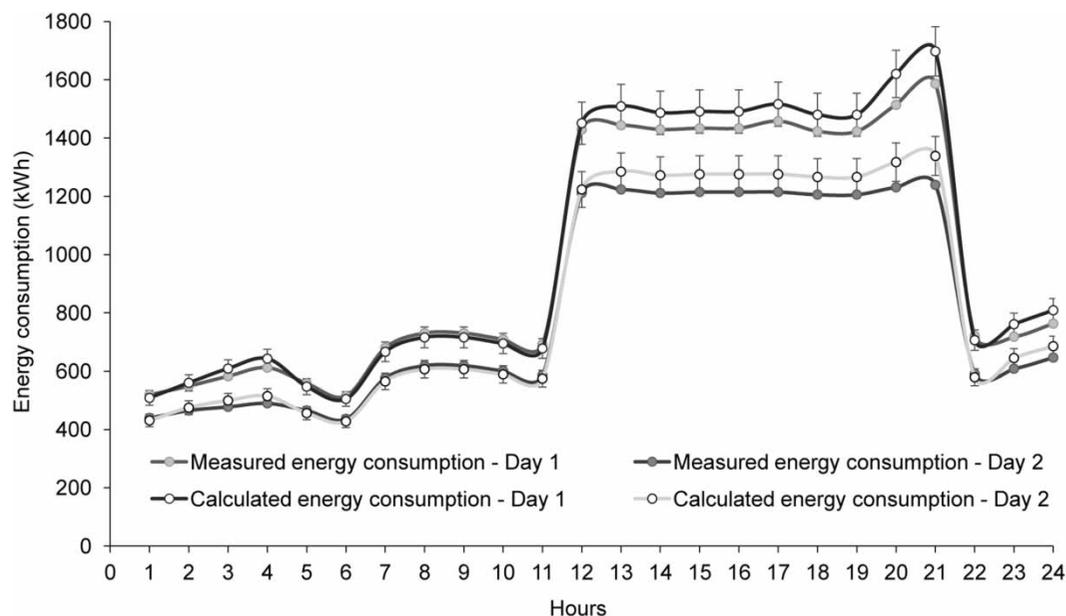


Figure 6 | The comparison of measured and calculated energy consumption.

method for obtaining energy-saving data could be useful for creating additional criteria for the establishment of these areas. In that way, sectorisation of the distribution network into smaller sub-networks would result not only in loss management but also in energy management. Further research can be directed on the assessment of weight coefficients in multicriteria analysis, which will be assigned to those additional criteria.

Finally, the application of the proposed methodology in software used for modelling of the water supply systems can be beneficial, since in software such as EPANET there is no energy report for gravity flow systems but only for pumping systems. Equations proposed in this paper could be a base for software improvement. In that regard, for the hydraulic model of the system, energy consumption data would be available (energy lost, energy dissipated and energy delivered). This implies that energy-saving data could be easily obtained for each variation of system parameters (pressure, demand, leakage, etc.).

CONCLUSIONS

In this paper, the methodology for the assessment of energy-saving due to pressure reduction was proposed and applied to the hypothetical water supply system. The methodology

was based on the hydraulic model of the system. The selected positions of the PRVs resulted in a decrease in pressure of up to 60% in certain parts of the system. This scenario caused an energy saving of 22%. Besides, verification of the method on the real system proved that the proposed method could be considered as precise enough to predict energy saving that occurs due to pressure reduction. The energy-saving data, obtained from the model of the system, could be useful for making a strategy of reducing loss in water supply systems which will finally result in better energy and water management.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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