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Energy efficiency optimization in water distribution systems

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Abstract

The evaluation of energy efficiency in water supply systems should account for both actual energy consumed and how efficiently such energy is spent. This work proposes the new concept of Unavoidable Minimum Energy, as the reference for defining an energy efficiency indicator. The aim is to search for possible optimal network configurations that minimize energy consumption and maximize the energy efficiency, acting on the main structural parameters of the system (pipe diameters, leakage rate) and considering the pump efficiency as well. The optimization process is carried out by coupling the heuristic algorithm GHEST with the EPANET solver and applied to a literature synthetic case study.

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Keywords: Indicators; energy efficiency; water supply; leakage; optimization.

1. Introduction

The operation of Water Distribution Systems generally require high amounts of energy, which vary in relation to the characteristics of the served area, but also from design and management choices. The assessment of energy efficiency in water distribution systems is strongly influenced by the nature site-dependent of the water-energy nexus in pressurized networks (Gay et al., 2010; Lenzi et al., 2013). Understanding this link requires a systematic energy analysis to evaluate separately the influence of pumping stations, network and water loss and can allow to highlight inconsistencies in the design and management that are reflected on both the resources, water and energy.

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The definition of a minimum energy value, i.e. a sort of reference baseline, assumed to assess the energy actually consumed by a water distribution system is the key point in the assessment of energy efficiency and may be complex (Lenzi et al., 2013; Pardo et al., 2013).

Pelli & Hitz (2000) propose an energy efficiency indicator referred as to *Quality indicator I2*, defined as the ratio between the energy actually used to lift water during one year and the theoretical minimum energy, taken as energy level of comparison. The minimum energy required is defined as the difference of potential energy of a given quantity of water, between the delivery point and the source, taking into account that the supply should be under pressure.

Abadia et al. (2008) define indicators that compare energy consumed and minimum energy required, pointing out how energy consumption is influenced both by the operation of pumping stations and by the layout of the network.

Boulos & Bros (2010) develop an indicator in order to assess the efficiency of the network: WNEE Water Network Energy Efficiency, which is defined as the ratio between the power required to meet the minimum level of service and the total actual power used. However, the upper term is calculated through the total system demand and the minimum pressure required, regardless of the hydraulic head of the input source.

Cabrera et al. (2010), after defining an approach to evaluate an energy balance of a water distribution system, propose an indicator "Excess of supplied energy I1", defined as the ratio between the real energy entering the system and the minimum useful energy, needed in a flat, frictionless, leak-free network served with the minimum required pressure.

In line with the approaches mentioned above, the indicator WSEE (Water Supply Energy Efficiency) was presented (Lenzi et al., 2013). The added value of this indicator was the ability (possibility) to break down this indicator in three sub-indicators, capable of assessing how the structure of the network, leakage rate and pumping operation may affect the overall energy efficiency of the water distribution system.

The definition of minimum theoretical energy (Pelli & Hitz, 2000) takes into account the difference between the potential energy of the volume delivered to the users (excluding water losses) and the potential energy of the volume supplied to each node, for which elevation, demand and level of service (defined by minimum required pressure) are known. These elements are important, but not sufficient, in fact the minimum theoretical energy does not consider the layout of the network and the structural characteristics, and therefore may be too far from a credible baseline reference. In particular, the length of the network is not considered. The use of the theoretical minimum energy, defined as the difference of potential energy between the delivery point and the source, is both the common aspect and the principal limitation of these indicators.

In this paper, a new concept of energy baseline is introduced to define an energy efficiency indicator that allows to assess the actual use of energy and the energy impacts of possible interventions (leakage reduction, pipe replacement, equipment renewal) as well as the possibility to compare different WDSs. Subsequently, the optimization process, especially whether kept in the region of feasible solutions (Bolognesi et al., 2010; 2013), can drive the understanding of the water-energy relationship and of the interventions, towards the most promising solutions in terms of energy efficiency and energy recovery.

2. Energy Efficiency Indicator for water networks

The growing attention deserved to the so called water-energy nexus is certainly driven by the non negligible amount of energy required for operating water distribution systems. That is, energy-related aspects arise in water network, when one or more electromechanical devices (pumps) are present. Needless to say, the interest towards energy involves environmental, but especially cost issues. This should be clearly remembered, while trying to find the most appropriate way for assessing (or improving) the energy efficiency of a given water system, because on the one hand there is the actual energy consumed, on the other hand there is the way that energy is properly or improperly spent. Finally both aspects always need to be considered in conjunction with the level of service provided.

2.1. Unavoidable Minimum Energy as a new reference for energy efficiency evaluation

When developing an efficiency indicator, the definition of a baseline reference is certainly among the most challenging tasks. As far as water systems are concerned, a robust reference value should account for the level of service required, but also for the structure of the network as well as for the number and the position of the energy demanding devices.

On the basis of the mentioned requirements, a novel definition of the minimum energy required for operating a water distribution network is here proposed. Such definition is given in the most general form, in order to be extendable and applicable to the majority of water networks where one or more pumps are included.

The Unavoidable Minimum Energy required (*UME*) is computed at each device and involves the definition of a reference hydraulic head (H_{ref}).

H_{ref} is the minimum head to be granted at the downstream section of each pump, in order to satisfy the given level of service (namely, a minimum pressure value) throughout the network, during the whole day, considering that no leakages occur. Therefore:

$$UME = \gamma \cdot W \cdot \left(H_{ref} - H_{ups}\right) / 3600000 \tag{1}$$

where *UME* is the unavoidable minimum energy required at the pump (kWh); γ is the specific gravity of water (N/m^3); W is the total volume lifted by the pump (m^3), over the considered period; H_{ref} is the above defined reference head (m) at the downstream section of the pump; H_{ups} is the average hydraulic head at the upstream section of the pump (m).

2.2. Evaluation of EEI in the actual scenario for case study

The ratio between *UME* and the energy actually consumed E_{cons}, gives birth to the Energy Efficiency Indicator (*EEI*):

$$EEI = \frac{UME}{E_{cons}} \tag{2}$$

The H_{ref} calculation has required the following steps: pump closed; downstream end of the pump replaced by a “virtual” reservoir; all the emitters’ coefficient set to zero; pipe leading to the tank closed. The H_{ref} value for the assigned network is found by decreasing iteratively the hydraulic head of the virtual reservoir, until the minimum pressure at nodes is met.

The E_{cons} value is assessed on a daily basis; therefore, in addition to the energy actually consumed by the pump (E_{PC} as defined in Lenzi et al. (2013)), it also accounts for possible excess (or deficit) of water volume stored in the tank ΔE_T at the end of the day. Unlike the $\Delta E_{Compensation}$ defined in Cabrera et al. (2010), where the excess or deficit of water volume in the tank at the end of the day is accounted for as a potential energy, ΔE_T considers the energy actually spent by the pump in order to lift the excess or deficit volume in the tank:

$$E_{cons} = E_{PC} - \Delta E_T = E_{PC} - \frac{\gamma \cdot A \cdot \left(H_{fin} - H_{ini}\right) \cdot H_P}{\eta \cdot 3600000} \tag{3}$$

where E_{PC} is the energy consumed by the pump, considering its electro-mechanical efficiency (kWh); A is the cross sectional area of the tank (m^2); H_{fin} and H_{ini} are the hydraulic heads in the tank (m), respectively at time 0:00 and 24:00; H_P and η are respectively the average pump head and the average efficiency of the pump.

3. Case study

The case study discussed is a modified water distribution network kindly provided by E. Cabrera and M. A. Pardo, has the same layout of the network presented in Cabrera et. al, 2010 (Fig. 1), but different parameters, as indicated in Table 1 and Table 2. Hereinafter, this network will be mentioned as the Original Cabrera network. The pipe roughness is 0.1 mm. The diameter of the compensation tank is 20 m, and its level oscillates between 2.5 m (initial value for the simulation) and 7 m (maximum value). The minimum node pressure is maintained by a pump characteristic curve: $H=93.33-0.003646\cdot Q^2$. The pump starts and stops when the water level reaches the limits in the tank. The characteristics of the emitters follow the EPANET model, the emitter exponent is 1.2. The extended period simulation corresponds to 24 h.

By applying the above definitions (1), (2) and (3) to the Original Cabrera network, and considering 22.92 m as the minimum pressure value required at each node, during the whole day, the following values are obtained:

- UME = 208.4 kWh/day
- E_{cons} = 1073.2 kWh/day
- EEI = 0.194

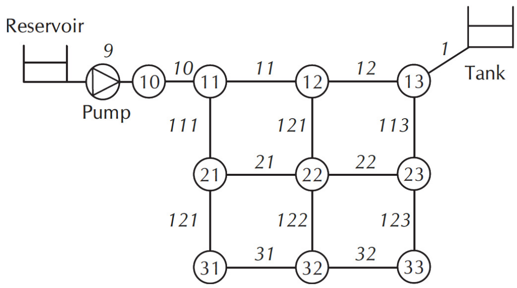


Fig. 1. General layout of the network (Cabrera et al, 2010)

Table 1. Line and Node data of Cabrera's network.

Line	Length (km)	Original Diameter (mm)	Optimized(D) Diameter (mm)	Node	Base demand (l/s)	Elevation (m)	Emitter coefficient ($m^{3-\alpha}/s$)
10	2	300	400	Node 10	0	5.8	0.003992878
11	2	250	400	Node 11	5	5.8	0.015971513
12	2	250	400	Node 12	5	4	0.015971513
21	2	100	60	Node 13	3	2	0.015971513
22	2	100	250	Node 21	4	3	0.019964391
31	2	100	60	Node 22	8.5	2	0.023957269
111	4	150	150	Node 23	4	0	0.019964391
112	4	150	150	Node 31	2	1	0.011978634
113	4	150	125	Node 32	5	0	0.015971513
121	4	150	100	Node 33	2	0	0.011978634
122	4	150	250	Reservoir	-	25	
123	4	150	80	Tank	-	52	
32	2	100	100				
1	2	300	400				

Table 2. Hourly coefficients of water demand modulation.

Time	1	2	3	4	5	6	7	8	9	10	11	12
Coefficient	0.6	0.5	0.45	0.45	0.5	0.6	0.7	1.1	1.3	1.2	1.1	1
Time	13	14	15	16	17	18	19	20	21	22	23	24
Coefficient	1.1	1.45	1.5	1.3	1.2	1.1	1.1	1.25	1.3	1.4	1	0.8

4. Optimization Analysis

In order to test both the descriptive capabilities of EEI and its potential role as a guide for network optimization, a number of simulations have been performed on the Cabrera case study. The simulations are all based on the Cabrera network scheme and aim at investigating the relationship between E_{cons} and *EEI* for all the possible networks belonging to that scheme. In particular, the final target is to determine the configurations representing the possible optimal scenarios in terms of watergy efficiency, i.e.: the lowest possible energy-demanding networks and, among the low energy networks, those showing the highest energy-efficiency.

In this optimization exercise, some of the network features are allowed to vary, while others are kept fixed:

- reservoir head is left unchanged,
- tank elevation and initial level are left unchanged,
- pump ON/OFF rule is left unchanged,
- base demand values and nodes elevation are left unchanged,
- pump performance curve and efficiency curve are left unchanged,
- emitter coefficients are kept fixed during the optimization process, but varied at a later stage,
- pipe diameters are allowed to vary, according to the following diameters set (mm): [60, 80, 100, 125, 150, 200, 250, 300, 350, 400].

Given the highly combinatorial nature of the problem as well as the strong non-linearity, the use of heuristic algorithms is required. The algorithm chosen is the population based GHEST (Bolognesi et al., 2010) coupled with the EPANET2 hydraulic solver.

GHEST is namely a single-objective algorithm, however it has already proved to be capable of dealing with multi-objective problems, through the generation of the so called pseudo-fronts (Bolognesi et al., 2013).

The problem is defined as the maximization of the Energy Efficiency Indicator (EEI) (2) subject to a set of constraints: i) the hydraulic equations of mass and energy conservation (for each node and pipe in the network, respectively); ii) the pressure in each node has to be higher than a minimum pressure; iii) the diameters have to be chosen among a set of discrete sizes.

Using meta-heuristic algorithms, the hydraulic equations are solved by an external hydraulic simulator, which, in the case of GHEST, is EPANET2, while the constraint on the diameter is implicitly satisfied by the algorithm.

The fitness function to minimize *OF* is defined by (4) and solutions are considered feasible if they comply with constraints on the minimum pressure (5). A further penalty OF_E (6) is introduced in order to concentrate the search space and the optimized solutions close to a specific consumed energy value E_0. Pseudo fronts are obtained by running multiple simulations, each having a different E_0 value.

$$OF = \begin{cases} 0 & if\, HD > 0 \\ \dfrac{UME}{E_{cons}} - OF_E & otherwise \end{cases} \quad (4)$$

$$HD = max\ \left(p_{i,min} - p_i\right) \qquad i \in N \quad (5)$$

$$OF_E = \frac{(E_{cons} - E_0)}{E_0} \tag{6}$$

where p_i is the head at node i; $p_{i,min}$ is the minimum pressure required (set at 22.92 m for all nodes); N is the number of nodes; HD is the maximum pressure constraint violation; OF_E is the penalty introduced in order to keep the search space close to the consumed energy value E_0.

5. Results

Ten runs have been carried out, assuming ten different E_0 values; each run consisted in 2500 EPANET calls (Population = 50; number of iterations = 50). A first set of simulations was run on the original network, varying the pipes' diameter only and leaving all other parameters unchanged. The results of such set are shown in Fig. 2, where each cross represents a feasible network and the black line is the non dominated front for all solutions. The small circles and red line (Fig. 2) represent instead all the feasible solutions and their non dominated front, when the emitter coefficients are all set to zero.

Fig. 2 could be interpreted as follows: starting from the original network (grey circle), there are two possible ways that network could be energetically improved, by moving up (increase of the efficiency) or moving left (reduction of the energy consumed). By moving up and left would lead to a combined improvement of both factors, which in other words means that the upper-left-most solution may be assumed as the optimal one in terms of energy consumption and efficiency. The solution located in the left-most point of the non dominated front (yellow circle) is then defined as "Optimized(D)", since the optimization procedure is based on the diameter variation only. The relationship between EEI, E_{cons} and the Leakage Rate has been then investigated for both the Original network and the Optimized(D) network (Fig. 3).

Besides the optimization process, an additional energetic improvement to the original network has been tried and proposed, by simply changing the operating point of the pump [l/s; m] from [80; 70] to [40; 70], resulting in a new performance curve: Head = 93.33 - 0.01458*(Flow)^2.

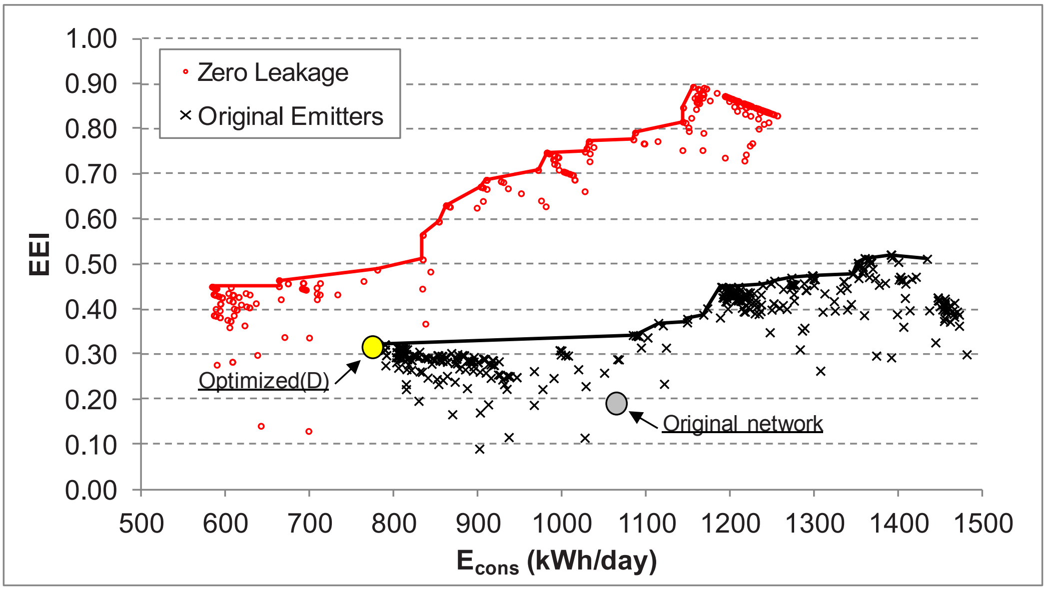
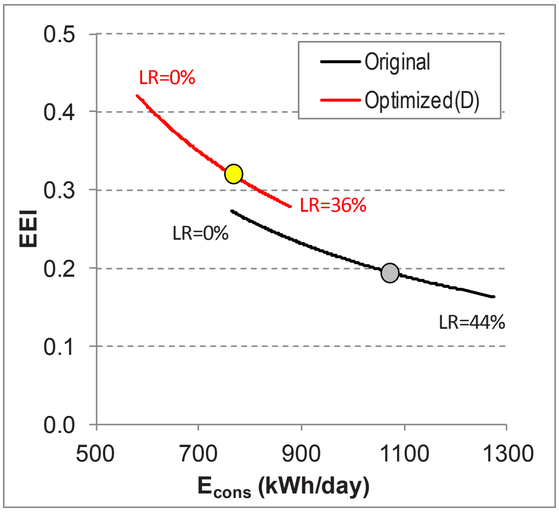
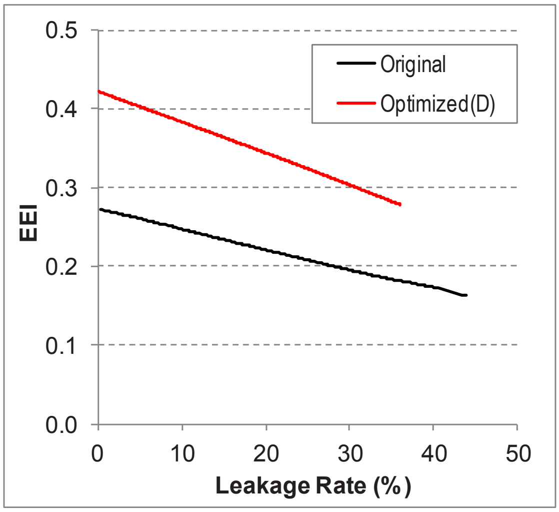


Fig. 2. Feasible networks resulting from the optimization process and related non-dominated pseudo front



(a)



(b)

Fig. 3. Energy consumed and EEI values for the Original and the Optimized(D) networks, as a function of the leakage rate.

The pump efficiency curve has been changed accordingly, transforming each point having coordinates [Flow; η] into [Flow/2; η]. The network resulting from this pump modification, leaving all parameters and diameters as in the Original network, is defined as Optimized(P40), while Optimized(D_P40) represents the application of the new pump to the Optimized(D) network.

The relationship between E_{cons} and Leakage Rate for all four networks is shown in Fig. 4, while Fig. 5 and 6 describe with more detail the energetic performances of network Optimized(P40) and Optimized(D_P40), compared to the Original one.

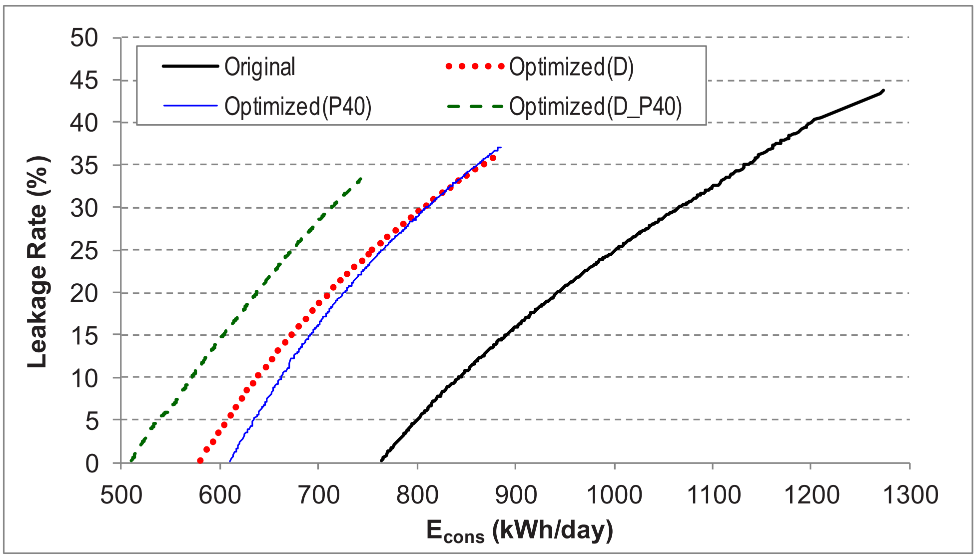


Fig. 4. Energy consumed as a function of Leakage Rate for all three Optimized networks and the Original one.

The Leakage Rate presented in Fig. 3, 4, 5 and 6 is defined as follows:

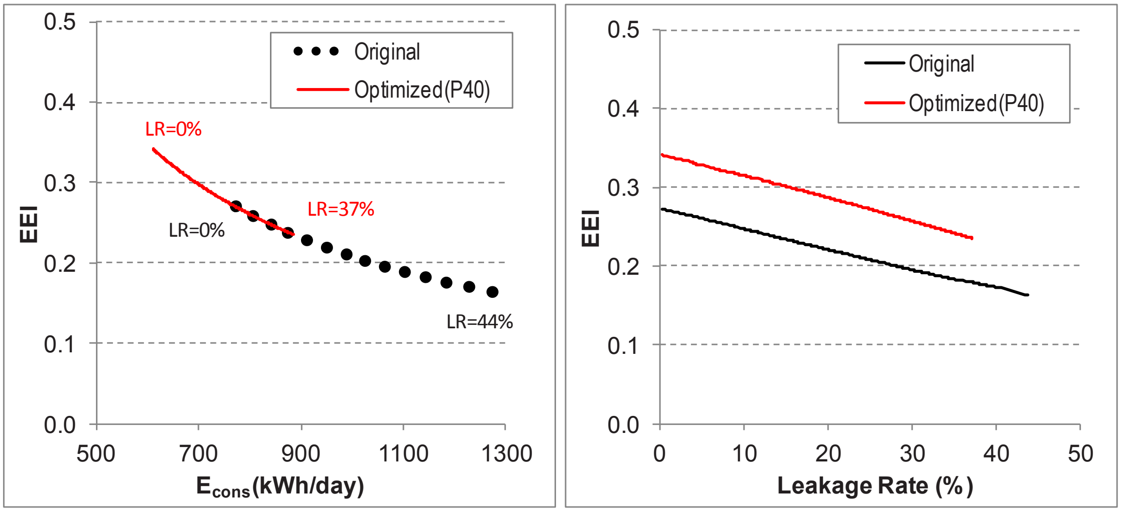
$$Leakage\,Rate(\%) = \frac{\left(\sum_{t=0}^{t=24} \sum_{i=1}^{N} D_i(t) \cdot \Delta t - 86400 \cdot \sum_{i=1}^{N} BD_i \right)}{\sum_{t=0}^{t=24} \sum_{i=1}^{N} D_i(t) \cdot \Delta t} \tag{6}$$

where $D_i(t)$ is the actual demand (including leakage) at the i-th node (l/s); BD_i is the base demand at the i-th node (l/s).

Fig. 3(a) shows the effects of leakages on the energy consumed and the energy efficiency for two different networks, leading to the straightforward conclusion that leakage reduction saves energy and improves energy efficiency. Fig. 3(a) also helps explaining the role and the meaning of EEI: the Original and the Optimized(D) network may consume the same amount of energy, but with two different EEI values. The Optimized(D) has higher energy efficiency, because it grants the same level of service, with equal amount of energy, although affected by a significantly higher leakage rate.

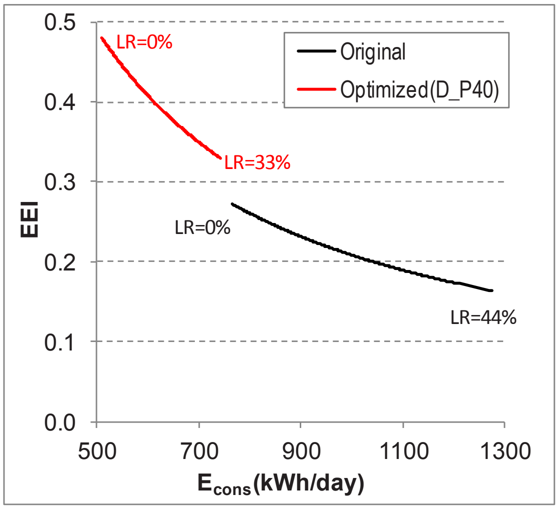
Unlike Fig. 3(a) and 6(a), the Original and Optimized curves presented in Fig. 5(a) appear aligned. This happens because the network structure is left unchanged and because UME is not affected by the solely change of the pump. However, interesting considerations may be drawn, as the simple substitution of a pump, allows the same identical network to reach energy savings and efficiency levels, which could have never been reached through an active leakage control campaign. Similar outcomes derive from Fig. 4, where the almost coincident curves belonging to Optimized(D) and Optimized(P40) solutions reveal that the replacement of a number of pipes has the same energy impact of a simple pump substitution.

Finally, nearly linear relationships between Leakage Rate and EEI are presented in Fig. 3(b), 5(b) and 6(b).

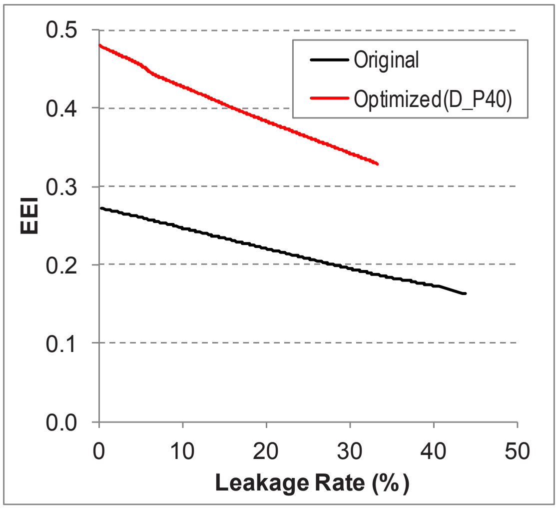


(a) (b)

Fig. 5. Energy consumed and EEI values for the Original and the Optimized(P40) networks, as a function of the leakage rate.



(a)



(b)

Fig. 6. Energy consumed and EEI values for the Original and the Optimized(D_P40) networks, as a function of the leakage rate.

6. Conclusions

In this paper, the new concept of Unavoidable Minimum Energy, as a reference for the energy efficiency evaluation, has been proposed. Unlike the minimum theoretical energy, UME considers the layout and length of the network as well as pipes' size and nodes' elevation, and therefore constitutes a more realistic baseline.

Energy Efficiency Indicator, defined as the ratio between UME and the energy actually consumed, has been used as one of the objective functions within a multi-objective optimization problem: minimization of the actual energy consumed and improvement of the way that energy is properly or improperly spent, introduced as the maximization of EEI. Finally both aspects have been considered in conjunction with the level of service provided. The optimized results are strictly feasible and the search space has been locally concentrated in the regions of interest through the generation of pseudo-fronts by GHEST.

The methodology has been tested on a water distribution network kindly provided by E. Cabrera and M. A. Pardo, having the same layout of the network presented in Cabrera et. al. (2010). The outcomes allows for the assessment of the water-energy relationship, according to possible different interventions, towards the most promising solutions in terms of energy efficiency and energy recovery.

The relationship between EEI, E_{cons} and the Leakage Rate has been then investigated for the original network and the optimized networks, achieved by varying diameter, pump, or both. Trends obtained show non-trivial relationships, confirming the complexity of the water-energy nexus. In particular, the optimization process has allowed to determine the configurations representing the optimal scenarios in terms of watergy efficiency, i.e.: the lowest possible energy-demanding networks and, among the low energy networks, those showing the highest energy-efficiency.

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