From energy balance to energy efficiency indicators including water losses
C. Lenzi, C. Bragalli, A. Bolognesi and S. Artina

ABSTRACT
The collection and distribution of drinking water resources generally require large quantities of energy, that vary according to factors related to the characteristics of the served area, as well as to design and management choices. Energy intensity indicators (energy per unit of volume) are insufficient to assess the weight of different factors that affect the energy consumption and appear not suitable for the comparison of different water supply systems. The key step of this work is to define a methodology for assessing the energy efficiency of water supply systems. In particular, water losses in water distribution systems, generally assessed in relation to the quantity of high quality water dispersed in the environment, are herein considered in relation to their energy content. In addition to the evaluation of energy balance using the approach proposed by Enrique Cabrera et al. in ‘Energy audit of water networks’ (see J. Water Res. Plan. Manage. 136 (6), 669–677) an overall efficiency indicator WSEE (Water Supply Energy Efficiency) is then proposed. Its decomposition finally leads to the definition of further indicators, which may help to assess how the structure of the network, leakage rate and/or pumps affect the energy efficiency of the water system. Such indicators can be used to compare different water supply systems and to identify the impact of individual interventions. The proposed energy analysis was applied to two case studies in Northern Italy.

Key words | energy balance, energy efficiency indicators, water energy nexus, water loss

INTRODUCTION
Water distribution systems are managed and operated with the primary objective of satisfying a certain water demand, according to given hydraulic constraints. Needless to say, such actions require energy; therefore the analysis of the nexus between water and energy and the energy efficiency assessment can help to improve the management as well as to achieve the so-called ‘watergy efficiency’ (Barry 2007). This concept expresses the satisfaction of water demand with the least possible use of water and energy resources.

However, it is necessary to highlight some important differences compared with a normal industrial plant, such as the spatial extent of the network, the localization and characterization of the water resources and of the points of delivery to the users, which differ in elevation, amount of water supplied, pressure level and, furthermore, the presence of water loss. Leaks are directly responsible for water resource depletion, but they also affect the externalities associated with energy consumption (Colombo & Karney 2002; Walski 2004; Artina et al. 2008).

Energy intensity indicators (energy per unit of system input volume or volume delivered to users) are insufficient to assess the weight of different factors that affect the energy consumption. These indicators appear further incomplete as they do not allow a comparison between the energy actually consumed and the minimum energy strictly necessary for the water supply systems operation.

If it is fairly easy to quantify the contribution of pumps to energy efficiency, how much does the network framework impact on the energy balance of a water supply system? Can a minimum energy required be calculated? The study of the relationship between water loss and energy consumption has been addressed (Colombo & Karney 2002, 2004;
Walski 2004; Artina et al. 2008) with respect to different systems in terms of complexity and location of breaks. The numerical simulation, in which leakages are introduced as pressure-dependent, is an important analysis tool, in some cases used to support the measured data (Bragalli et al. 2010). Pelli & Hitz (2000) propose energy efficiency indicators based on the concept of minimum energy, taken as the energy level of comparison. The minimum energy required (see Equation (12)) is defined as the difference of potential energy of a given quantity of water, between the delivery point and the source, taking account of the fact that the supply should be under pressure. Abadia et al. (2008) point out that energy consumption is influenced both by the operation of pumping stations and by the layout of the network. The key step of this work is to define a methodology for assessing the energy efficiency of water supply systems and to understand and quantify the energy impact of water loss by means of a specific energy indicator. In the first part, the energy balance is evaluated using the approach proposed by Cabrera et al. (2010) and Hernández et al. (2010) and applied to two case studies. In the second part, the indicator WSEE (Water Supply Energy Efficiency) is presented. Through its decomposition, three sub-indicators are defined, capable of assessing how the structure of the network (Network Energy Efficiency, NEE), leakage rate (Leakage Energy Efficiency, LEE) and/or pumping operation (Pumping Energy Efficiency, PEE) may affect the overall energy efficiency of the water supply system.

These aspects are fundamental to identify the factors that must have an influence on the energy efficiency of the whole system; also, these indicators (NEE, LEE and PEE) can be used to compare different water supply systems and to identify the impact of individual interventions, in particular the reduction of leakages and the improvement of the water supply infrastructure. The proposed energy analysis was applied to two case studies in Northern Italy: Ganaceto and Marzaglia District Meter Areas (DMAs).

**ENERGY BALANCE OF WATER DISTRIBUTION NETWORK**

The energy balance, shown for both case studies, is based on the approach proposed by Cabrera et al. (2010), computed within a certain control volume (boundary), but which does not include pumps’ efficiency. The hydraulic power delivered by pumps is seen as an external contribution that must be separately evaluated. This approach is based on the use of a calibrated water distribution model to solve the hydraulic state on an extended period simulation. The hydraulic heads are referred to the lowest node within the control volume, which is assumed as the \( z = 0 \) reference.

**Energy components evaluation**

Following the notation of Cabrera et al. (2010), the energy components, related to a time interval \( t_p \) with respect to which the energy balance is carried out, are summarized in Table 1 and shown in Figure 1: \( E_N(t_p) \) energy supplied by the \( n_N \) external sources (1); \( E_P(t_p) \) energy supplied to the water by the \( n_P \) pumping stations (2) (also called ‘Shaft

<table>
<thead>
<tr>
<th>Definition</th>
<th>Notation</th>
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<tbody>
<tr>
<td>Natural energy (supplied by external sources)</td>
<td>( E_N(t_p) )</td>
</tr>
<tr>
<td>Water energy (supplied to water by pumps)</td>
<td>( E_P(t_p) )</td>
</tr>
<tr>
<td>Useful energy delivered to users</td>
<td>( E_U(t_p) )</td>
</tr>
<tr>
<td>Friction energy losses</td>
<td>( E_F(t_p) )</td>
</tr>
<tr>
<td>Leakage energy losses</td>
<td>( E_L(t_p) )</td>
</tr>
<tr>
<td>Compensation energy (associated with internal system tanks)</td>
<td>( \Delta E_C(t_p) )</td>
</tr>
</tbody>
</table>

**Figure 1| Control volume of the water distribution network with the energy components.**
energy' in Cabrera et al. (2010)); \( E_U(t_p) \) energy delivered at the \( n \) demand nodes (3); \( E_L(t_p) \) energy that leaves the water systems (4); \( E_d(t_p) \) energy dissipated due to friction in \( n_L \) links (5); \( \Delta E_C(t_p) \) variation of potential energy stored in tanks of constant section for a given period of time (6), where \( \gamma \) is the specific weight of water. Equations from (1) to (6) are shown in Table 2, where at time \( t_k \): \( Q_{N,i}(t_k) \) is the flow rate supplied by the external sources \( i \); \( H_{N,i}(t_k) \) is the piezometric head by the external sources \( i \); \( \Delta t \) is the interval time such that \( t_p = p \cdot \Delta t \); \( Q_{P,i}(t_k) \) is flow rate pumped by station \( i \); \( H_P(t_k) \) is the pump head by station \( i \); \( q_{ui}(t_k) \) and \( q_{oi}(t_k) \) are, respectively, the supplied and leakage flow rate delivered in node \( i \); \( H_i(t_k) \) is the piezometric head in node \( i \); \( q_{ui}(t_k) \) and \( q_{oi}(t_k) \) are, respectively, the supplied and leakage flow rate circulating in line \( j \); \( \Delta h_i(t_k) \) is the friction loss in line \( j \); \( A_i \) is the section of tank \( i \); \( z_i(t_p) \) and \( z_1(t_p) \) are the level of tank \( i \) at the initial and final time, respectively.

**Global energy balance**

The energy balance within the control volume, on a period time \( t_p \), is given by Equation (7):

\[
E_{\text{Input}}(t_p) = E_N(t_p) + E_P(t_p) \\
= E_U(t_p) + E_L(t_p) + E_F(t_p) + \Delta E_C(t_p) \\
= E_{\text{Output}}(t_p) + E_{\text{Dissipated}}(t_p) + \Delta E_{\text{Compensation}}(t_p)
\]

(7)

**Table 2** | Evaluation of energy components (Cabrera et al. 2010)

<table>
<thead>
<tr>
<th>Energy components</th>
<th>Expression</th>
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<tbody>
<tr>
<td>( E_N(t_p) )</td>
<td>( \gamma \cdot \sum_{i=1}^{n} \left[ \sum_{k=1}^{t_0} Q_{N,i}(t_k) \cdot H_{N,i}(t_k) \right] \cdot \Delta t )</td>
</tr>
<tr>
<td>( E_P(t_p) )</td>
<td>( \gamma \cdot \sum_{i=1}^{n} \left[ \sum_{k=1}^{t_0} Q_{P,i}(t_k) \cdot H_P(t_k) \right] \cdot \Delta t )</td>
</tr>
<tr>
<td>( E_U(t_p) )</td>
<td>( \gamma \cdot \sum_{i=1}^{n} \left[ \sum_{k=1}^{t_0} q_{ui}(t_k) \cdot H_i(t_k) \right] \cdot \Delta t )</td>
</tr>
<tr>
<td>( E_L(t_p) )</td>
<td>( \gamma \cdot \sum_{i=1}^{n} \left[ \sum_{k=1}^{t_0} q_{oi}(t_k) \cdot H_i(t_k) \right] \cdot \Delta t )</td>
</tr>
<tr>
<td>( E_F(t_p) )</td>
<td>( \gamma \cdot \sum_{i=1}^{n} \left[ \sum_{k=1}^{t_0} [q_{ui}(t_k) + q_{oi}(t_k)] \cdot \Delta h_i(t_k) \right] \cdot \Delta t )</td>
</tr>
<tr>
<td>( \Delta E_{\text{Compensation}}(t_p) )</td>
<td>( \gamma \cdot \sum_{j=1}^{n_C} \left[ A_i \cdot \frac{z^2_i(t_p) - z^2_i(t_1)}{2} \right] \cdot \Delta t )</td>
</tr>
</tbody>
</table>

where \( E_{\text{Input}}(t_p) \) is the total energy supplied to the water; \( E_{\text{Output}}(t_p) \) and \( E_{\text{Dissipated}}(t_p) \) are defined in (8) and (9), respectively:

\[
E_{\text{Output}}(t_p) = E_U(t_p) + E_L(t_p)
\]

(8)

\[
E_{\text{Dissipated}}(t_p) = E_F(t_p)
\]

(9)

**ENERGY BALANCE APPLIED TO CASE STUDIES**

The above-mentioned balance is applied to two different case studies. The first (Ganaceto DMA) does not have a pumping station within its domain border, but it shows a significant leakage rate; while the second (Marzaglia DMA) exhibits a very low leakage rate and is supplied only by a pumping station.

**Ganaceto DMA**

Ganaceto DMA is part of the water distribution network of Modena (Italy), has an area of 23.92 km² and is bounded by Secchia river, which forms a natural border. The network, with an extension of 35.37 km and 540 connections, serves a population of 2,925 inhabitants and is mainly realized in asbestos cement and polyethylene. The elevation of the area appears to be rather flat, with an average height of 32.86 m, a minimum of 27.54 m and a maximum of 41 m, at the input of the district. Ganaceto DMA is supplied by a single input, with a pressure always above 20 m. The DMA was monitored using simultaneous measures of flow and pressure at inlet. Two additional pressure gauges within the district allowed the calibration of the model simulation in EPANET 2.0. The system input volume is 447.30 $\times 10^6$ m³/year and the average pressure is equal to 33.5 m. The amount of Real Losses is determined by the Water Balance (Alegre et al. 2006) and the value of inefficiency of use of water resources indicator WR1 (100 × RL/system input volume) is equal to 42.1%; also, Intra-structure Leakage Index IILI = Current Annual Real Losses/Unavoidable Annual Real Losses (Alegre et al. 2006) is equal to 11.9. The distribution of leakage at nodes of the model is obtained by means of an automatic allocation that reflects the state of the infrastructure and
minimizes an objective function in which the deviation between measured and simulated values is considered (Liserra et al. 2007). The value assumed for the emitter exponent in EPANET 2.0 was $n = 0.8$.

**Energy balance**

The energy balance was determined both in relation to the real WDN and to zero-leakage scenario. The node having minimum elevation has been set as the reference for the hydraulic heads. The extended period simulation was conducted over 24 h, with a time step of 3 min. The energy balances related to both scenarios are shown in Figure 2. In this case the energy at the inlet point to the district $E_{\text{Input}}$ can be seen as the amount of potential energy $E_N$ naturally possessed by the water, without the contribution of pumping $E_P$.

**Marzaglia DMA**

Marzaglia DMA is part of the water distribution network of Modena (Italy). The length of the network is about 5 km, consisting predominantly of polyethylene pipes and asbestos cement. There are 113 connections, serving a population of 1,247 inhabitants. The pressure in the district is guaranteed by the presence of two variable speed pumps in parallel controlled to maintain a downstream pressure of 39 m. The level of real losses is low, with WR1 = 9%. The energy balance was determined for the actual water distribution network and for an ideal condition of absence of leakage.

**Energy balance**

The energy balance was determined according to the same assumptions of the previous case study. The results related to both scenarios are shown for Marzaglia DMA in Figure 3.
The role of pump efficiency

The energy balance proposed by Cabrera et al. (2010) does not consider the energy consumed by pumps. This approach does not allow the pump efficiency to be considered, which implies an effective energy consumption much greater than $E_p$. The energy actually absorbed by $n_p$ pumping stations inside the control volume, or rather the required electrical energy, is called $E_{PC}(t_p)$ and defined by (10):

$$E_{PC}(t_p) = \sum_{i=1}^{n_p} E_{PC_i}(t_p) \quad (10)$$

Figure 4 (left) shows the variation of energy $E_{PC}$ and $E_p$ as a function of the water loss level. The water loss level is defined as $\Delta V_\% = (V - V_0)/V_0 \times 100$ in which $V$ is the actual volume supplied and $V_0$ is the volume due to customers’ use only.

Figure 4 (right) shows the energy saving terms $\Delta E_p(t_p)$ and $\Delta E_{PC}(t_p)$ as a function of the water loss level. Both terms represent the difference between the real and the zero-leakage conditions: $\Delta E_p(t_p) = E_p(t_p) - E_{P0}(t_p)$; $\Delta E_{PC}(t_p) = E_{PC}(t_p) - E_{PC0}(t_p)$.

For example, a reduction of $\Delta V_\%$ from 40 to 10 implies a real energy saving of about 5 kWh, if $\Delta E_{PC}(t_p)$ is considered, while just about 3.5 kWh if $\Delta E_p(t_p)$ is used, which is 30% less.

Assuming a constant energy cost during the day equal to 0.22€/kWh, the above $E_{PC}$ approach leads to a potential saving of 401.50 € on a yearly basis.

ENERGY EFFICIENCY INDICATORS

The energy actually consumed by the pumps $E_{PC}(t_p)$ can be evaluated, comparing it to a minimum energy required value. With reference to an observation period $t_p$, an indicator of energy efficiency of the water supply system WSEE is proposed (11), defined by the ratio between the minimum energy $E_{min}(t_p)$ (12) and the energy $E_{PC}(t_p)$ actually consumed by the pumps:

$$WSEE = \frac{E_{min}(t_p)}{E_{PC}(t_p)} \quad (11)$$

WSEE is clearly dependent on $E_{min}$. The definition of a minimum energy value, i.e. a sort of baseline reference, assumed to assess the energy actually consumed by a water distribution system, or a portion of it, may be complex. The minimum energy required $E_{min}$ (as suggested by Pelli & Hitz (2000)) is set equal to the difference between the minimum potential energy of water supplied to users $E_{U, min}(t_p)$ and $E_{N,0}$ which is the potential energy input to the system (1) in absence of water loss:

$$E_{min}(t_p) = E_{U, min}(t_p) - E_{N,0}(t_p) \quad (12)$$

where:

$$E_{U, min}(t_p) = y \sum_{i=1}^{n} \left[ \sum_{t_{i-1}}^{t_{i}} q_{ai}(t_k) \cdot H_{min,i}(t_k) \right] \cdot \Delta t \quad (13)$$

$H_{min,i}$ is the sum of the ground elevation and a minimum required pressure at the $i$-th node.
WSEE allows a comprehensive assessment of energy efficiency, but does not show the weight with which pumps and network contribute in a specific water distribution system.

WSEE is then decomposed into three factors (14) that correspond to three indicators to analyze the impact of the structural aspects NEE (15), of the leakage LEE (16) and of the pumping operation PEE (17), on the energy efficiency of a water supply system:

\[
\text{WSEE} = \frac{E_{\text{min}}(t_p)}{E_{P0}(t_p)} \times \frac{E_{P}(t_p)}{E_{PC}(t_p)}
\]

(14)

\[
\text{NEE} = \frac{E_{\text{min}}(t_p)}{E_{P0}(t_p)}
\]

(15)

\[
\text{LEE} = \frac{E_{P0}(t_p)}{E_{P}(t_p)}
\]

(16)

\[
\text{PEE} = \frac{E_{P}(t_p)}{E_{PC}(t_p)}
\]

(17)

The terms \(E_P\) and \(E_{P0}\) are calculated with (2). While \(E_P\) is evaluated in relation to the real network with leakages, \(E_{P0}\) is considered in condition of zero water loss and its calculation requires a modeling approach (Artina et al. 2008).

**Energy efficiency indicators applied to case study**

The energy efficiency indicators WSEE (13), NEE (15), LEE (16) and PEE (17) have been calculated for the Marzaglia DMA for \(t_p = 24\) h. The energy actually consumed by the pumps of Marzaglia DMA is \(E = 27.55\) kWh/day while the theoretical minimum energy \(E_{\text{min}}\) (12) (assuming a minimum required pressure of 20 m) is equal to 9 kWh. Table 3 shows the energy efficiency indicators referred to the actual condition of leakage (WR1 = 9%).

The pumping efficiency PEE (17), usually referred to as ‘wire-to-water efficiency’, clearly appears as the main contribution in lowering the value of WSEE, while both the indicators related to the leakage LEE (16) and to the structure of the network NEE (15) assume rather high values. Figure 5 shows the variation of the energy efficiency indicators as a function of the water loss level. This result has been obtained with extended period simulation for \(t_p = 24\) h, using EPANET 2.0.

Figure 5 shows that, as the leakage rate increases, the overall energy efficiency WSEE decreases due to the
Contribution of LEE. In contrast, in this specific case, the indicator PEE increases, due to the fact that the pumps will move toward operating points characterized by higher efficiency.

CONCLUSIONS

A methodology for evaluating energy efficiency in water distribution systems has been presented. The water-energy nexus in pressurized systems has been confirmed to be highly site-dependent, thus requiring a systematic energy analysis to evaluate separately the influence of pumping, network and water loss. The knowledge of the proportions among the single energy components involved in the considered water supply system may help to highlight problems potentially not evident in an overall view. Such an approach may therefore contribute to identify inconsistencies in design and operation affecting both water and energy resources. The WSEE indicator is independent from the head reference assumed and thus allows the comparison of different water distribution systems. From its decomposition three different indicators were finally defined, in order to assess the way the structure of the network (NEE), water loss (LEE) and the operation of pumping (PEE), contribute to the global energy efficiency of the water system. The application of this methodology to two case studies has shown how this analysis may represent the evaluation basis in support of the choice of appropriate strategies.

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REFERENCES


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