# Energy Assessment of Pressurized Water Systems

E. Cabrera, M.ASCE[1]; E. Gómez[2]; E. Cabrera Jr.[3]; J. Soriano[4]; and V. Espert[5]

**Abstract:** This paper presents three new indicators for assessing the energy efficiency of a pressurized water system and the potential energy savings relative to the available technology and economic framework. The first two indicators are the ideal and real efficiencies of the system and reflect the values of the minimum energy required by users—the minimum amount of energy to be supplied to the system (because of its ideal behavior) and the actual energy consumed. The third indicator is the energy performance target, and it is estimated by setting an ambitious but achievable level of energy loss attributable to inefficiencies in the system (e.g., pumping stations, leakage, friction loss). The information provided by these three key performance indicators can make a significant contribution towards increasing system efficiency. The real efficiency indicator shows the actual performance of the system; the energy performance target provides a realistic goal on how the system should be performing; and finally, the ideal efficiency provides the maximum and unachievable level of efficiency (limited by the topographic energy linked to the network topography). The applicability and usefulness of these metrics will be demonstrated with an application in a real case study. **DOI: 10.1061/(ASCE)WR.1943-5452.0000494.** 



## Introduction

A growing population needs more water, more food, and therefore more irrigation. Streamlining these processes is thus essential and especially important in those agricultural countries that are shifting from traditional to pressurized irrigation to save water. However, this transformation process entails a heavy cost: namely, the energy that pressurized water transport systems (PWTS) consume. In California, such consumption accounts for up to 6% of the total energy demand [Water in the West (WW) 2013]. In Europe, energy consumption related to these uses is 109 TWh [Official Journal of the European Union (OJEU) 2012]. Reducing or controlling this consumption is crucial.

However, little attention has been given to a preliminary assessment of the overall energy efficiency of PWTS. Improving pump performance has always been important because of the steady rise in energy costs (Perez-Urrestarazu and Burt 2012; OJEU 2012; Papa et al. 2013). The efficient operation of pressurized systems (Lingireddy and Wood 1998; Ulanicki et al. 2007; Giustolisi et al. 2013; Carriço et al. 2013) is also attracting considerable attention. Calculations of the energy embedded in water leaks (Colombo and Karney 2002; Cabrera et al. 2010) and energy performance indicators are being used to assess aspects of these systems (Pelli and Hitz 2000; Duarte et al. 2009). However, no one has yet proposed metrics that provide a global view of system efficiency and existing improvement margins, which is precisely the main contribution of this paper.

More specifically, three new indicators are presented to achieve this holistic efficiency assessment. The first two indicators are based on an energy balance of the system, using the values of the energy required by users, the minimum amount of energy to be supplied to the system (because of an ideal behavior), and the actual consumed energy. As a result, a real efficiency and an ideal (and unachievable) efficiency are calculated. The third indicator provides an achievable goal linked to a target level of energy loss to account for inefficiencies in the system (e.g., pumping stations, leakage, friction loss). This goal is ambitious but achievable.

The real efficiency indicator provides information on the actual performance of the system, and when used in conjunction with the ideal efficiency indicator it shows the maximum performance gap that could be closed if efficiency was ideally improved. The ideal level of efficiency is limited by the topographic energy (elevation potential energy), and this depends on the topography of the system.

Once a diagnostic is known and providing improvement margins are significant—then a second stage can be considered. This second phase consists in analyzing where energy is lost by means of a system audit (Cabrera et al. 2010). This audit enables determining final uses with enough precision to identify the largest inefficiencies (e.g., leakage, friction, pumps) and the largest potential savings. With the global analysis completed, the focus shifts to those aspects or solutions with the greatest cost-benefit relation (*think globally, act locally*). The second stage is unnecessary if there is little difference between the efficiency target and the diagnostic.

Last, the possibility of recovering part of the *topographic* energy of the system (to be defined later) should be explored. This may be achieved by installing pumps to work as turbines (PATs) (Carravetta et al. 2012), or by dissipating energy with pressure reducing valves (PRVs). The latter practice is more widespread—but both approaches work by reducing the excess pressure in the fluid's energy to decrease water leaks and pipe stress.

This paper presents new assessment concepts with the corresponding metrics. The presented improvement process takes the status quo diagnostic (real efficiency of the present state) as a tool to target specific efficiency gains with current technologies while

[1]Professor, ITA, Universitat Politècnica de València, Apdo, 22012 Valencia, Spain.

[2]Ph.D. Student, ITA, Universitat Politècnica de València, Apdo, 22012 Valencia, Spain.

[3]Associate Professor, ITA, Universitat Politècnica de València, Apdo, 22012 Valencia, Spain.

[4]Assistant Professor, ITA, Universitat Politècnica de València, Apdo, 22012 Valencia, Spain (corresponding author). E-mail: jasool@ita.upv.es

[5]Professor, ITA, Universitat Politècnica de València, Apdo, 22012 Valencia, Spain.

Note. This manuscript was submitted on January 10, 2014; approved on October 3, 2014; published online on November 6, 2014. Discussion period open until April 6, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496/04014095(12)/$25.00.

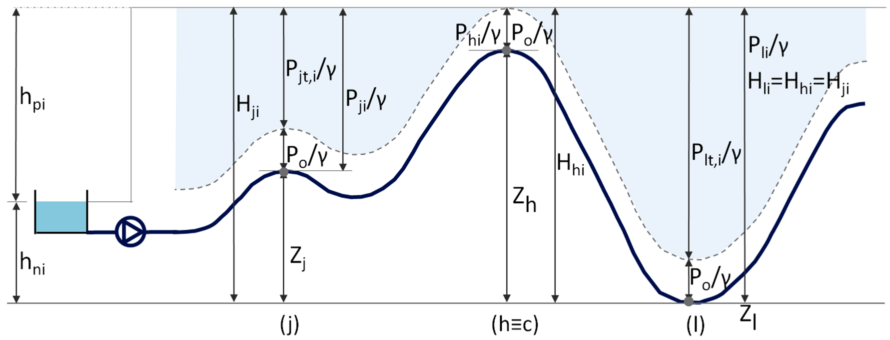


**Fig. 1.** Ideal pressurized water system (partial profile without excess energy)

considering both water and energy costs. This paper simplifies Cabrera's six-step process to three steps (Cabrera et al. 2014).

## Basic Concepts

Fig. 1 represents a partial profile view of a PWTS that shows the most characteristic points of the system: the pumping station; the highest and lowest nodes ($z_h$ and $z_l$); a generic node ($z_j$); and the lowest pressure node, called critical ($z_c$). In an ideal system, $z_h = z_c$. To establish the energy balance that enables defining performances and assessing the overall system energy efficiency, the node with the lowest elevation of the system is chosen as the origin for gravitational energies (Cabrera et al. 2010) and then $z_l = 0$.

### *Ideal System without Excess Pressure*

An ideal system is one where there are no friction head losses or leaks (while the kinetic energy is disregarded, a common practice in network analysis). There is no excess pressure because at the critical point, $p_{ci}$, is equal to the required service pressure, $p_0$. In this case, the critical point pressure is also the required pressure (Fig. 1), and then $p_{ci} = p_{hi} = p_0$. But it must be underlined that in real cases this may not be the case.

The application of the continuity equation to the system shown in Fig. 1 (and for a given steady flow time period) is straightforward. The total injected volume at the pumping station ($V$) is equal (in the absence of water losses) to the sum of the demands of all the consumption nodes ($V = \sum v_j$). The supplied energy in that period is

$$E_{si} = \gamma V H_{hi} = \gamma \sum v_j \left[ (z_j - z_l) + \frac{p_{ji}}{\gamma} \right] = \gamma \sum v_j \left[ (z_j - z_l) + \frac{p_0}{\gamma} + (z_h - z_j) \right] = E_{uo} + E_{ti} \quad (1)$$

where $H_{hi}$ is the piezometric head at the highest node (ideally equal to all nodes). Additionally

$$E_{uo} = \gamma \sum v_j \left[ (z_j - z_l) + \frac{p_0}{\gamma} \right]$$
$$E_{ti} = \gamma \sum v_j (z_h - z_j) = \gamma \sum v_j \frac{p_{jt,i}}{\gamma} \quad (2)$$

being $\gamma$ the specific weight of water, $E_{uo}$ the minimum energy required by the users, and $E_{ti}$ the topographic energy (elevation potential energy) of the system. This latter term depends on the terrain's irregularities, thus its suggested name. In Fig. 1, the shaded area is proportional to $E_{ti}$ (the area between the top horizontal line and the dashed line). In a flat network, $E_{ti}$ would be zero. This energy also represents the amount of energy that, in theory, could be recovered by installing PATs at every consumption node. The energy to be recovered in $\Delta t$ at any demand node by the corresponding PAT is $v_j$ (the volume consumed at node $j$ in the considered time period) times the available topographic pressure, $p_{jt,i}$. In reality, recovering all this energy is impossible. In many systems, this excess (when considered from the user's perspective) energy is dissipated with PRVs (see "Dissipation and Recovery of Energy (with PRV or PATs) in a PWTS").

When the pressure at the critical point is as required (as detailed in Fig. 1), the supplied energy is the same as the minimum required energy or base energy $E_{bi}$. Therefore

$$E_{si} = E_{uo} + E_{ti} = E_{bi} \quad (3)$$

In an ideal frictionless system and for any period of time, the hydraulic grade line (HGL), sum of the natural (or gravitational) head, $h_{ni}$, and the pump head, $h_{pi}$, (or total dynamic head, TDH) is constant and equal to $H_{hi} = H_{ji} = H_{li}$. However, the total supplied energy is proportional to the corresponding demand of each period.

In a real system, friction losses depend on flow and leakage rates. As a result, the supplied head (usually the pump head) must be adjusted to meet the steady demand of each period. This implies that a control system [such as a variable frequency drive (VFD)] must be present at the pumping station. Energy balance calculations are mathematically static and then only valid during brief periods of time ($\Delta t$). Therefore, for longer time periods (h, day, month or year), the total supplied energy must be calculated by integration (Cabrera et al. 2010)—meaning an extended period simulation (Rossman 2000). Alternatively, this energy can be assessed by adding the wire energy (electricity bill) and gravitational energy, the latter being $\gamma h_{ni}(V + \Delta V)$, assuming a constant suction water level ($z_n$).

Finally, it is emphasized that, in this ideal case, the type of supplied energy ($h_{pi}$ or $h_{ni}$) is irrelevant for assessing an energy balance. After all, every single kWh is the same from a physical perspective, regardless of its origin.

### *Ideal System with Excess Pressure*

The only difference between the systems in Figs. 1 and 2 is that in the second case the supplied energy (pressure) is above the minimum necessary value. Fig. 2 shows a pressure value at the critical point higher than the required, $p_o$ ($p_{ei}$ represents excess pressure). To distinguish this case from the previous case, the pressure and head terms are represented with an asterisk.

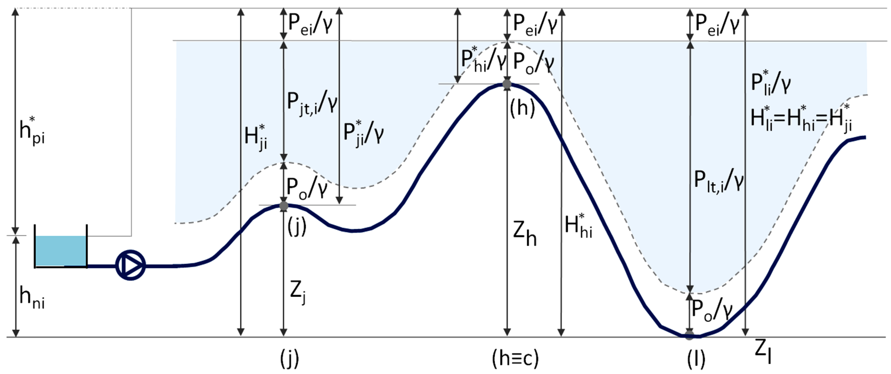


**Fig. 2.** Ideal pressurized water system (partial profile with excess energy)

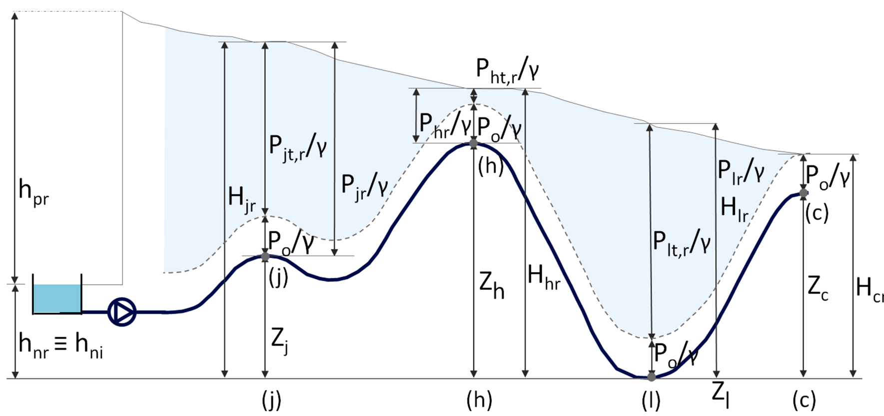


**Fig. 3.** Real pressurized water system (partial profile without excess energy)

The higher pressure ($p^*_{hi} > p_o$) is attributable to excess energy entering the system

$$p_{ei} = p^*_{hi} - p_o, \qquad E_{ei} = \gamma V \frac{p_{ei}}{\gamma} \tag{4}$$

In this case, the system's input energy is

$$E_{si} = E_{uo} + E_{ti} + E_{ei} \quad \text{with } E_{si} > E_{bi} \tag{5}$$

$E_{ti}$ is obviously the same as in the previous case (and proportional to the shaded area), whereas the excess energy, $E_{ei}$, (avoidable most of the time) must be corrected with operational measures.

### Real System

The energy to be supplied, $E_{uo}$, remains constant (Fig. 3). However, the topographic energy of the system, $E_{tr}$, (shaded area) changes because it is linked to the hydraulic head line. Energy losses, which are referred to as global reducible energy, $E_{rg}$, are now different from zero, and include:

- Energized water in leaks ($E_{rl}$). Apparent losses, such as metering inaccuracies, must be included, giving rise to apparent system energy inefficiency;
- Energy dissipated by friction ($E_{rf}$) in pipes, valves, and other elements;
- Energy loss in pumping stations ($E_{rp}$) attributable to several inefficiencies (electrical, friction, pump, and operational losses); and
- Other losses ($E_{ro}$) such as break pressure tanks.

In summary, the real energy supplied to the system is

$$E_{sr} = E_{uo} + E_{tr} + E_{rg} = (E_{uo} + E_{tr}) + (E_{rl} + E_{rf} + E_{rp} + E_{ro}) \tag{6}$$

In a real system, however, the minimum required energy or base energy depends on its hydraulic operation and, therefore, defining a term equivalent to $E_{bi}$ makes no sense. However, $E_{bi}$ will still represent the lower limit of this base energy, which corresponds to the case of a real system in which losses tend to zero. It is also noted that the hydraulic head is no longer a straight line because head losses are not uniform.

Eq. (6) should include the surplus energy if the pressure at the critical point (the point with the lowest pressure in the network) exceeds the required pressure. Then

$$E_{sr} = E_{uo} + E_{tr} + E_{rg} + E_{er} = E_{uo} + E_{tr} + E_{rg} + \gamma(V + \Delta V)\left(\frac{p^*_{cr} - p_0}{\gamma}\right) \tag{7}$$

with $\Delta V$ being the total water losses in the system, and $E_{er}$ the surplus energy (which can be significant because the whole input volume to the system is subject to this excess pressure).

## Energy Efficiency of a Pressurized Water System

From the concepts and the energy balance presented in the previous section, the energy efficiency of PWTS can be stated as the relation between the minimum energy required by users and the actual supplied energy. To introduce these concepts progressively, the ideal case is analyzed first.

### Energy Efficiency of an Ideal System (with and without Energy Recovery)

The minimum required energy (both in real and ideal systems) is $E_{uo}$, whereas the supplied energy in an ideal system is $E_{si}$. If a part of the topographic energy included in $E_{si}$ is recovered, the energy efficiency of the PWTS will improve. Therefore, it seems reasonable to define two different ratios depending on this fact, $\eta_{wi}$ (with) and $\eta_{ai}$ (without recovery).

In an ideal system, all the topographic energy is recovered, and the total useful energy will be the sum of $E_{uo}$ and $E_{ti}$, whereas an ideal performance will be equal to

$$\eta_{wi} = \frac{E_{uo} + E_{ti}}{E_{si}} = 1 - \frac{E_{ei}}{E_{si}} \quad (8)$$

In this case, the only possible inefficiency can be the result of an excessive energy supply [$E_{ei}$, Eq. (4)]. If $E_{ei} = 0$, performance would be one ($\eta_{wi} = 1$), a utopian value obtained from the ideal assumptions made.

In reality, $E_{ti}$ is (partially or totally) lost because energy recovery only makes economic sense in a few occasions. The most common scenario is one where no recovery exists. In this case, the system efficiency, $\eta_{ai}$, is equal to

$$\eta_{ai} = \frac{E_{uo}}{E_{si}} = 1 - \frac{E_{ti}}{E_{si}} - \frac{E_{ei}}{E_{si}} = 1 - \theta_{ti} - \frac{E_{ei}}{E_{si}} \quad (9)$$

If no excess energy is supplied, then $E_{ei} = 0$, $\eta_{ai}$ and $\theta_{ti}$ are complementary with a sum equal to 1. The topographic parameter represents the fraction of the supplied energy that is lost (assuming that no energy is recovered) attributable to the system excess pressure (topographic pressure, $p_{jt,i}$, Fig. 1). If $\theta_{ti}$ approaches its upper limit (a system with an irregular topography), then installing PRVs to reduce pressure levels should be considered to minimize leaks and reduce stress in the pipes. In such cases, however, the possibility of introducing physical changes in the system to reduce $E_{ti}$ (dividing the system into different pressure areas) should have been considered previously. In ideal flat networks, $\theta_{ti}$ is zero, and then $\eta_{wi}$ is irrelevant.

Overall, these performances confirm an obvious truth: when energy losses are zero, supplying the minimum energy ($E_{bi}$) and recovering all the topographic energy ($E_{ti}$) results in a performace value of 1 [Eq. (8)]. Without topographic energy recovery and with $E_{ei} = 0$, the maximum performace is one minus the fraction of topographic energy in the system [Eq. (9)].

### Energy Efficiency of a Real System

Analyzing ideal systems enables establishing maximum values for system performances. Real systems share with ideal systems the numerator of the energy efficiency ($E_{uo}$), whereas the denominator changes to include energy losses. Then Eq. (7) becomes

$$\eta_{ar} = \frac{E_{uo}}{E_{sr}} = 1 - \frac{E_{tr}}{E_{sr}} - \frac{E_{er}}{E_{sr}} - \frac{E_{rg}}{E_{sr}} = 1 - \theta_{tr} - \theta_{er} - \lambda_{rg} \quad (10)$$

where energies and reducible losses are expressed on a per unit basis ($\theta$ for the energies and $\lambda$ for reducible losses). When these losses are broken into different terms, the contribution of each to the system inefficiencies can be clearly seen with the expression

$$\eta_{ar} = 1 - (\theta_{tr} + \theta_{er} + \lambda_{rl} + \lambda_{rf} + \lambda_{rp} + \lambda_{ro}) \quad (11)$$

Analyzing the efficiency of a system should start by calculating $\eta_{ar}$. The numerator ($E_{uo}$) is known, and the denominator ($E_{sr}$) is calculated, as said before, from the energy consumed by the pump (e.g., value from the electricity bill) plus the gravity (natural) supplied energy that is dependent on the characteristics of the system. The global value ($E_{sr}$) is then known, but not its components [second part of Eq. (11)]. Determining their values requires a system audit. The best strategies to improve performance can be selected once the contribution of each term is known.

## Energy Efficiency Target

By comparing the ideal performance ($\eta_{ai}$) with the real performance ($\eta_{ar}$) [Eqs. (9) and (10)], the difference $\eta_{ai} - \eta_{ar}$ provides an initial estimation of the system's improvement gap. Because this diagnostic has to be referred to the optimum value, $\eta_{ai}$, this value must be calculated by making $E_{ei} = 0$ (an unnecessary energy that should always be zero). $\eta_{ar}$ has already been calculated, and $\eta_{ai}$ can be easily determined from Eqs. (1), (2), and (9).

Once the ($\eta_{ai} - \eta_{ar}$) difference is known, the next step is determining the potential improvement gap. Or in other words, how close the second term can get to the first term through improvement measures while maintaining an acceptable cost-benefit ratio. A new reference value ($\eta_{ar,o}$) represents the achievable system efficiency, or target efficiency, that verifies $\eta_{ai} > \eta_{ar,o} > \eta_{ar}$. This value can be estimated from Eq. (10) assuming that $E_{er} = 0$. The numerator is a system invariant, whereas the denominator is given by Eq. (6) (with the recovered energy being zero). Minimizing the energy losses implies reducing as much as possible the four reducible terms ($E_{rl}$, $E_{rf}$, $E_{rp}$ and $E_{ro}$) and understanding which fraction of the topographic energy ($E_{tr}$) can be reduced. Therefore, an efficiency target can be identified for all five terms as $E_{tr,o}$, $E_{rl,o}$, $E_{rf,o}$, $E_{rp,o}$, and $E_{ro,o}$. From all these estimated values, and taking into account Eq. (7), $E_{sr,o}$ will result

$$\begin{aligned} E_{sr,o} &= (E_{uo} + E_{tr,o}) + E_{rg,o} \\ &= (E_{uo} + E_{tr,o}) + (E_{rl,o} + E_{rf,o} + E_{rp,o} + E_{ro,o}) \end{aligned} \quad (12)$$

As more system inefficiencies are removed, $E_{sr,o}$ will approach $E_{si}$ [Eq. (1)].

In Eq. (12), the first term $E_{uo}$ is a system invariant (see "Synthesis of the Assessment"), whereas the real topographic energy ($E_{tr,o}$) depends on the new level of losses and, therefore, on the new pressures calculated for the more efficient scenario

$$E_{tr,o} = \gamma \sum v_j \left( \frac{p_{jt,r}}{\gamma} \right)_o \quad (13)$$

The pressures values in the network can be determined with a mathematical model adjusted for the new level of losses. This will enable the complementary pressures $(p_{jt,r})_o$ to be obtained. $E_{ti}$ can be directly calculated from Eq. (2). Both values are very similar, and so it can be assumed that

$$E_{tr,o} - E_{ti} = \gamma \sum v_j \left\{ \left[ \left( \frac{p_{jt,r}}{\gamma} \right)_o - \frac{p_{ji,r}}{\gamma} \right] \right\} \to 0 \quad (14)$$

This term will have a positive or negative sign depending on the system topography, the position of the critical point, and the working conditions. In a flat network, the difference will always be positive. To provide service pressure to the furthest node (in this case,

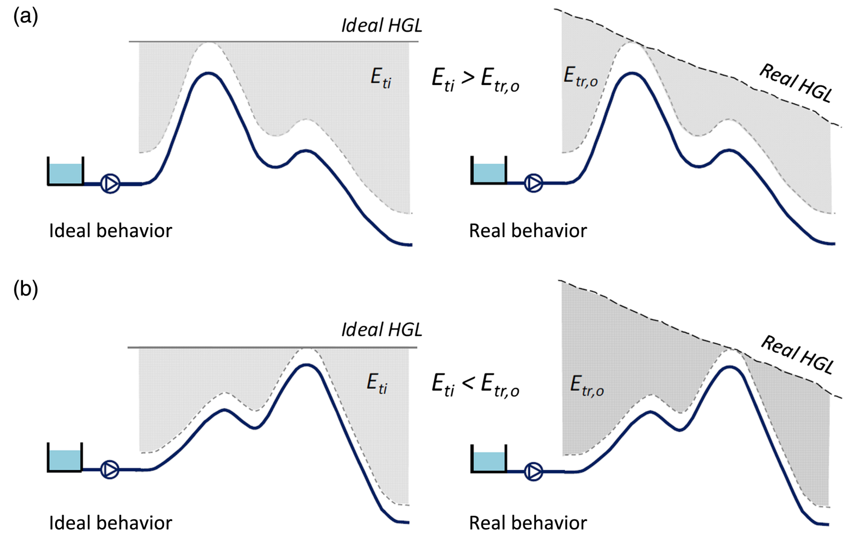


**Fig. 4.** $E_{tr,o}$ and $E_{ti}$ comparison profiles for: (a) system a; (b) system b

the critical node), the head pressure must be greater than the ideal required pressure. In a system with irregular terrain, this value will depend on the topography and the position of the critical point. In Fig. 4, system (a) has a negative difference [Eq. (14)], whereas system (b) is positive. However, these differences will always be small. Therefore, it is reasonable to assume $E_{tr,o} \approx E_{ti}$.

Taking all this into account

$$E_{sr,o} = (E_{uo} + E_{tr,o}) + E_{rg,o} \approx (E_{uo} + E_{ti}) + (E_{rl,o} + E_{rf,o} + E_{rp,o} + E_{ro,o}) \quad (15)$$

And therefore

$$\eta_{ar,o} = \frac{E_{uo}}{E_{sr,o}} = \frac{E_{uo}}{E_{si}}\frac{E_{si}}{E_{sr,o}} = \eta_{ai}\frac{E_{si}}{E_{sr,o}} \quad (16)$$

The target efficiency $\eta_{ar,o}$, depends on the objective level of energy losses. The criteria used to assess these acceptable levels of energy losses follow below.

### Reducible Energy Embedded in Leaks, $E_{rl,o}$

This reduction requires recovering the total volume of reasonable leaks ($\Delta V_o$), the sum of the losses ($\Delta v_{jo}$) at each node for a given time period. The energy loss embedded in leaks would then be

$$E_{rl,o} = \gamma \sum \Delta v_{jo} \frac{p_{jr}}{\gamma} = \gamma \sum \Delta v_{jo} \left[\frac{p_o}{\gamma} + \frac{p_{jt,r}}{\gamma}\right] \approx \gamma \Delta V_o \left[\frac{p_o}{\gamma} + \left(z_h - \frac{z_h + z_l}{2}\right)\right] \quad (17)$$

This approximation implies concentrating all the leaks in a median pressure node. Its value can be estimated assuming an ideal behavior of the system ($p_{jt,i}/\gamma = z_h - z_j$, Fig. 1). This approximation is valid for losses of approximately 10–15%, but for higher ratios it could introduce a bias in the calculations. For this paper's purposes, this is not a problem, and the level of losses must be low to set a target. In any case, the exact calculation of the energy embedded in the leaks requires an energy audit (Cabrera et al. 2010), because Eq. (17) does not consider the additional friction losses in pipes attributable to higher circulating flow rates as a result of leakage. Eq. (17) is suitable for the estimation of $E_{rl,o}$ (to calculate later $\eta_{ar,o}$).

### Reducible Energy Attributable to Friction Losses, $E_{rf,o}$

This is the most uncertain estimation, especially in large systems with loops, redundancies, and parallel flows. It requires assigning an average energy loss, related to an average path for the total mobilized volume of water. This path, dependent on the demand and leak distributions, is very variable. Consumptions which are very close to supply points barely have losses. On the other hand, those further away have significant losses. An average path $L_{pm}$ must be estimated between the pumping station and the consumption nodes, and an average unit head loss ($J_m$) (m/km) for all pipes. Again, this is not an easy estimation. $J_m$ is a function of the square value of the flow rate (variable in time with demand and leakage). The preceding factors represent a significant risk of making a biased assessment of this factor.

Additionally, local head losses ($\Delta p_{rf,p}$) must be added owing to the presence of filters, valves, and manifolds. With these assumptions, the following relationship results:

$$E_{rf,o} = \gamma(V + \Delta V_o)\left[(L_{pm})J_m + \frac{\Delta p_{rf,p}}{\gamma}\right] \quad (18)$$

Friction head losses in PRVs will be considered later (see following section).

### Reducible Energy in Pumping Stations, $E_{rp,o}$

Pumping stations are usually responsible for a high percentage of energy losses. However, estimating a reasonable value is not difficult (using the average combined efficiency ($\eta_{po}$) of the variable frequency drive/motor/pump and the corresponding pump head). When the pump's head-flow curve is available, these losses are easy to calculate. Otherwise, they can be estimated using Eq. (19), in which $L_{pc}$ is the distance between the pumping station and the critical point, whereas $z_n$ represents the pump suction level

$$E_{rp,o} = \gamma(V + \Delta V_o)h_{pr}\left(\frac{1}{\eta_{po}} - 1\right)$$
$$= \gamma(V + \Delta V_o)\left[L_{pc}J_m + \frac{\Delta p_{rf,p}}{\gamma} + \frac{p_o}{\gamma} + (z_c - z_n)\right]$$
$$\times\left(\frac{1}{\eta_{po}} - 1\right) \quad (19)$$

### *Other Reducible Energy Losses, $E_{ro,o}$*

Further losses can be found in PWTS. Break pressure tanks (chambers to avoid depressions in high points are required in pipes with an irregular profile) can be responsible for important energy losses that should be avoided—similar to an excess of energy ($E_{er}$) injected in the system. Break pressure tanks (e.g., domestic tanks) are equally inconvenient; in such cases the value of the wasted energy ($E_{ro}$) can be calculated by multiplying the depressurized volume times the network pressure at the delivery node. In the absence of inefficiencies

$$E_{ro,o} = 0 \quad (20)$$

These estimations enable calculating the performance reference value ($\eta_{ar,o}$) [Eqs. (15) and (16)].

## Dissipation and Recovery of Energy (with PRV or PATs) in a PWTS

The topographic pressure line ($p_{jt,i}$ and $p_{jt,r}$) created by land irregularities is an unavoidable factor (Figs. 1 and 3) that leads to higher pressures in the system. However, other pressure surpluses, such as $p_{ei}$ and $p_{er}$, are avoidable in most cases and will not be considered from this point onwards.

Excess pressure in the network may produce a considerable number of leaks (Giustolisi et al. 2008). To reduce these leaks, PRVs are usually installed to limit pressure at consumption nodes to a service value $p_o$. In this case, part of $E_{tr}$ is dissipated at the valves. However, although energy is dissipated at the PRVs, the total energy demanded by the system diminishes because the volume of leaks is smaller—reducing the consumed volume, the flow rate, and the friction losses. In short, $E_{sr}$ decreases because $E_{rl}$ and $E_{rf}$ decrease. Energy dissipated at the PRVs is at the expense of $E_{tr}$ and which, as seen before in Eq. (14) and Fig. 4, can be assumed constant provided the required pressure ($p_o$) is satisfied. For this reason, as Fig. 5 shows, these losses in PRVs do not affect $\eta_{ar,o}$ and only change $\eta_{wr}$.

However, from an energy point of view, it is much better to recover energy installing turbines, or PATs than to dissipate energy with PRVs. An initial approach to identify candidate pipes would be to multiply the average flow at line $k$, $\overline{q_k}$ by the average excess pressure at the end node $j$, $\overline{(p_{jr} - p_o)}$. Pipes verifying $\overline{q_k}\,\overline{(p_{jr} - p_o)} > P_{\min}$ would be selected as potential candidates for a recovery station. The recovered energy (part of the initial topographic energy) is termed $E_{yr}$ (Fig. 5).

The next stage consists in deciding the regulation system (Carravetta et al. 2014) that enables the recovery of the maximum amount of energy without compromising the service pressure ($p_o$) at the consumption nodes downstream of the installation. Only the recoverable amount of energy ($E_{yr}$) can be calculated. However, in practice, just a small part of $E_{tr}$ is recoverable.

The use of turbines instead of PRVs has become more common in recent years (Fontana et al. 2012) and should become an even more feasible option in the future because including energy recovery stations improves the overall energy efficiency of the system. In this case, $\eta_{wr}$ should be used as a performance measure instead of $\eta_{ar}$.

## Improving the Efficiency of a PWTS

Fig. 5 synthesizes the energy efficiency improvement process in a PWTS. This flow chart has two columns or paths that, to some extent, are simultaneously decoupled and complementary.

In one of the paths, the efficiency of the real system ($\eta_{ar}$) is estimated and compared with the target performance value, $\eta_{ar,o}$. At the same time, $\theta_{ti}$ is calculated. If this value is relevant (i.e., $\theta_{ti} > 0.2$), the possibility of reducing it through subdividing the system should be explored. This strategy has been applied to the case study which is a tree-like irrigation network. In fact, one of the major improvements is subdividing the system into three areas with a higher, medium, and lower elevation, which implies reducing the global $\theta_{ti}$.

If the economic analysis does not enable reducing the system's $\theta_{ti}$ (energy savings are insufficient to justify the required investment) and if its value is relevant enough (i.e., $\theta_{ti} > 0.2$) the use of both PRVs and PATs in the system should be studied. A cost-benefit analysis would then indicate which solution is better. If some turbines are finally installed, the system's efficiency will be assessed with $\eta_{wr}$ (which takes into account the recovered energy).

A satisfactory diagnostic requires no further action. If additional efficiencies can be gained, the analysis of possible improvement measures and their implementation is time consuming. In a continuous improvement process, an efficiency improvement cycle may take several months; achieving significant efficiencies will normally take at least one year.

## Synthesis of the Assessment

The evaluation of the system efficiency is based on three indicators: $\eta_{ai}$ [Eq. (9)]; $\eta_{ar}$ [Eq. (10)]; and $\eta_{ar,o}$ [Eq. (16)]. These are defined from four terms: $E_{si}$ [Eq. (1)]; $E_{uo}$ [Eq. (2)]; $E_{sr}$ or sum of the wire (electricity bill)—and gravitational energies supplied to the system and $E_{sr,o}$ [Eq. (15)]. All refer to the control volume (CV) previously selected and integrated over significant periods of time to facilitate the $E_{sr}$ calculation (e.g., a month, quarter, or year). Any CV can be considered as long as the mass and energy flows through the boundary surface (control surface, CS) are known during the specified period of time. This provides the global energy assessment for the system in time and space.

The weakest point of this analysis, the target energy estimation, $E_{sr,o}$ (and therefore, $\eta_{ar,o}$) has little relevance to the whole process because the value ($\eta_{ar,o} - \eta_{ar}$) is only used to trigger the next step (the analysis phase with the corresponding audits, Fig. 5). From an engineering point of view, some subjective estimations and simplifications required to determine $E_{sr,o}$ (see "Energy Efficiency Target") have little influence on the results of the analysis. The key factor in the analysis is the order of magnitude of the term ($\eta_{ar,o} - \eta_{ar}$), a value that, in absolute terms, is not especially sensitive to the formulated hypotheses. In any case, these estimated terms can be precisely determined from the energy audit (Cabrera et al. 2010), and this value can therefore be determined during the second phase.

This global assessment is based on average values and cannot reflect any temporal evolution of the system losses nor the influence of their location. This must be taken into account, particularly if during the considered period the pumps are working under variable flow conditions. In such cases, maintaining high pump

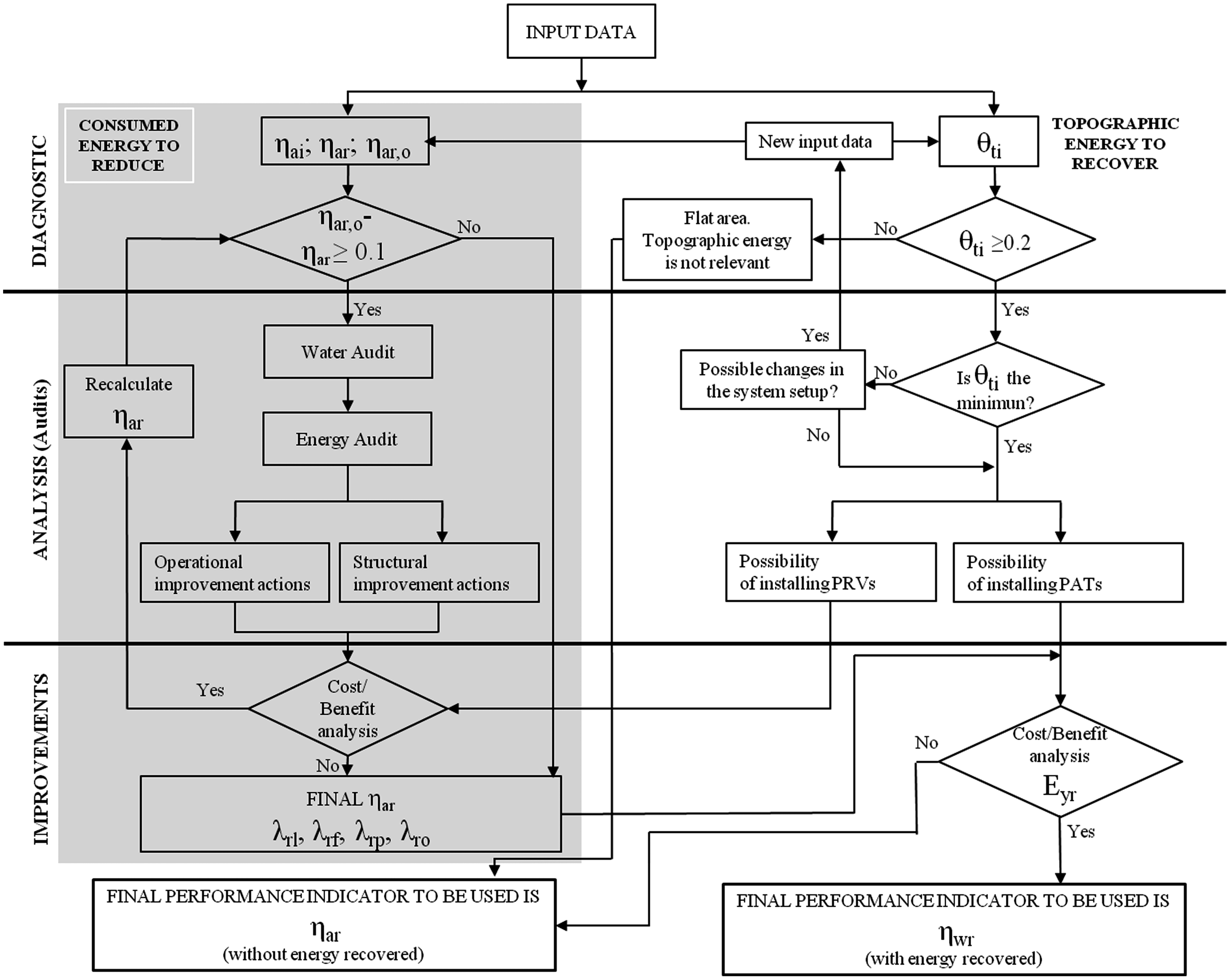


**Fig. 5.** Flowchart to improve the efficiency in PWST

efficiencies at all times becomes a difficult task; an issue that, because of its relevance, has been on the research agenda for many years (Ormsbee et al. 1989; Walski 1993; Ulanicki et al. 2007; Papa et al. 2013; Kurek and Ostfeld 2014).

In the assessment hereby proposed, the target value for the required energy in pumping stations is estimated by setting an ambitious although realistic average efficiency target. The presented case study corresponds to an on-farm irrigation schedule with a constant pumping flow rate.

In summary, the proposed assessment provides a global indication of the system efficiency, but with no information on where and how energy is lost. Structural inefficiencies (owing to inappropriate designs), and those resulting from operational decisions are all included in $\eta_{ar}$.

This simple assessment (which can be carried out with a simple spreadsheet) will identify the presence (or absence) of an energy problem in a system. To make the assessment:

- A system-wide CV must be defined. The same approach could be used to analyze subsystems (through alternative CVs). In such cases, these subsystems or district energy areas (DEAs) can play (in energy terms) a similar role to DMA (district metering areas).
- Water and energy flows coming into the CV must be known.
- Water delivered to users and leaving the CV must be known.
- The elevation of system nodes must be known and pressure ($p_o$) defined. In practice this pressure standard should not only be defined but also actually met.
- If no minimum pressure standard is defined, $p_o$ should be the minimum pressure at the critical node.
- The zero value for node elevation will be assigned to the lowest node ($zl = 0$). Potential energy terms will be referred to this lowest node.
- Wire energy consumption for the system must be known.

From this data, $\eta_{ai}$ and $\eta_{ar}$ can be calculated, whereas $\eta_{ar,o}$, will be set as the target reference. Using these hypotheses to set this target comes at the cost of some uncertainty. However, although this target may not be considered a fixed reference, it provides a goal that is close enough to the real goal and helps generate change and efficiency. A similar example can be found in water loss, where the infrastructure leakage index (ILI) (Lambert et al. 1999) provides a far from accurate target, and yet it has changed the international scene by helping to promote the reduction of leakage around the world. In this particular case, the target is the result of a conscious decision at the desired level of service—promoting a more active

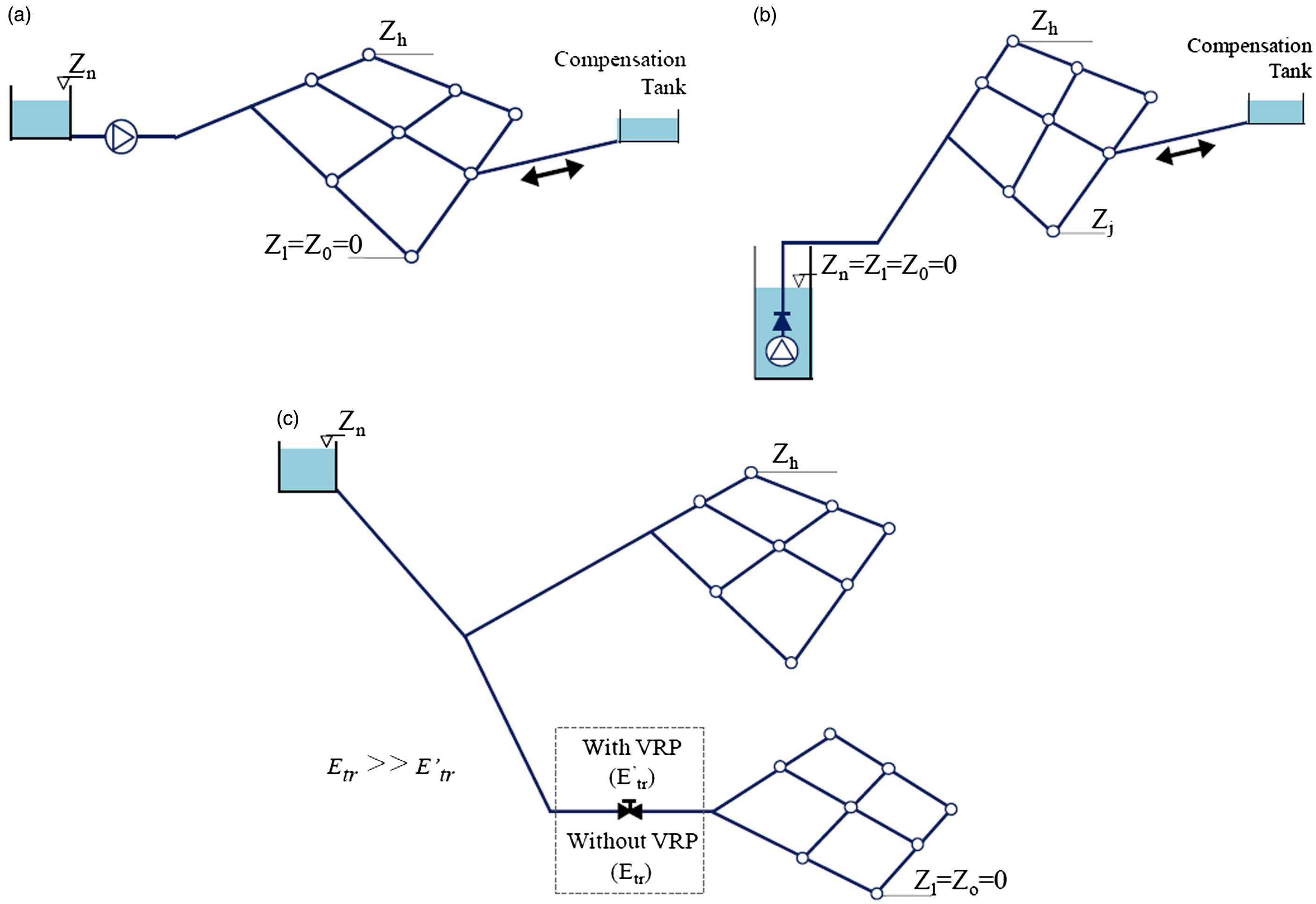


**Fig. 6.** Network layouts with three energy sources: (a) case a—natural and wire energy are supplied to the system; (b) case b—only wire energy is supplied to the system; (c) case c—only natural energy is supplied to the system

participation in target setting—whereas ILI coefficients have a set value that cannot be changed.

The diversity of situations to be found in practice is enormous. Fig. 6 depicts three typical network layouts with different energy inputs. In case (a), similar to the example that follows, wire and natural energy are supplied to the system. The compensation tank acts as a water and energy flywheel (Cabrera et al. 2010). In case (b), only wire energy is supplied to the system because the lowest node is situated at the water table level (at the borehole). In case (c), the potential is the only source of energy. In this latter system, the installation of a PRV will introduce friction losses in the system, but has no influence on the efficiency of the system because the losses generated by the PRV are at the expense of topographic energy (Fig. 5, right side).

## Case Study

This case study corresponds to a real pressurized irrigation network (Cap de Terme) that has been operational since 2006. The need for the study arose in 2008 when energy for agricultural use lost all subsidies, and the electricity bills paid by farmers significantly increased in just two years. Most of the ideas in this paper were inspired from this study in a bottom up process. Although the actual study has already been concluded (see the different stages in Fig. 5), the analysis that follows only contains the diagnostic stage, which is the subject of this paper. The results that follow have been confirmed in practice.

Fig. 7 depicts a real system with more than 400 consumption nodes and 55 km of pipes.

The assessment presented here was prepared with data from 2011:

- Irrigation ≡ 125.51 equivalent days per year, a value that depends on yearly rainfall. It works in the same way as an intermittent urban supply.

**Fig. 7.** Cap de Terme irrigation network

- $V = 18{,}580\ \mathrm{m^3/day}$ (delivered to users).
- $V + \Delta V = 19{,}164\ \mathrm{m^3/day}$ (supplied) with $\Delta V = 584\ \mathrm{m^3/day}$. New network with few leaks.
- Required pressure by drip emitters ($p_o$) = 20 m.
- Consumed energy: natural 664 kWh/day, wire energy 5,833 kWh/day, total 6,497 kWh/day.
- Elevations: $z_h = 35.53$ m; $z_l = 14.39$ m. Natural water level at suction tank $z_n = 25$ m.

Because of the node demands and elevations ($v_j, z_j$), the energy requirements for the ideal system are:

$$E_{si} = \gamma \sum v_j \left[(z_h - z_l) + \frac{p_0}{\gamma}\right] = \gamma V \left[\frac{p_o}{\gamma} + (z_h - z_l)\right] = 2{,}082.94\ \mathrm{kWh/day}$$

$$E_{uo} = \gamma \frac{p_o}{\gamma} V + \gamma \sum v_j (z_j - z_l) = 1{,}494.23\ \mathrm{kWh/day}$$

$$E_{ti} = \gamma \sum v_j \frac{p_{jt,i}}{\gamma} = \gamma \sum v_j (z_h - z_j) = 588.71\ \mathrm{kWh/day}$$

The theoretical value of the achievable performance is

$$\eta_{ai} = \frac{E_{uo}}{E_{si}} = \frac{1{,}494.23}{2{,}082.94} = 0.72$$

The percentage of the topographic energy is, logically, the complementary value

$$\theta_{ti} = \frac{E_{ti}}{E_{si}} = \frac{588.71}{2{,}082.94} = 0.28$$

The real value of $\eta_{ar}$ is determined from registered energy consumptions. Therefore

$$\eta_{ar} = \frac{E_{uo}}{E_{sr}} = \frac{1{,}494.23}{6{,}497} = 0.23$$

The comparison of both values indicates that the improvement margin is important

$$\frac{\eta_{ai}}{\eta_{ar}} = \frac{0.72}{0.23} = 3.13$$

If the demands and elevation nodes are not available, the values $E_{uo}$ and $E_{ti}$ can be estimated from the average elevation. If demand is homogenously distributed, the results are fairly precise. Fig. 8 represents the simplified system for the estimation of $E_{uo}$ and $E_{ti}$.

The simplified expressions for $E_{uo}$ and $E_{ti}$ are

$$E_{uo} \approx \gamma \frac{p_o}{\gamma} V + \gamma V (z_m - z_l) = \gamma V \left[\frac{p_o}{\gamma} + (z_m - z_l)\right] = 1{,}547.44\ \mathrm{kWh/day}$$

$$E_{ti} = \gamma \sum v_j (z_h - z_j) \approx \gamma V (z_h - z_m) = 534.62\ \mathrm{kWh/day}$$

These are very reasonable values and, as shown below, they have minimal effect on the final estimation. However, it should be highlighted that if the demand is irregularly distributed (i.e., concentrated in the lowest nodes), major errors will result from this simplification. In any case, the necessary values are often available, and these simplifications are not needed.

If the simplified values had been used (Fig. 8), the results would have been $\eta_{ai} = 0.74$, $\theta_{ti} = 0.26$, $\eta_{ar} = 0.24$ and $\eta_{ai}/\eta_{ar} = 3.08$ (all of these values being quite accurate estimations). However, it should be pointed out that the node synthesizing the global behavior of the network must be chosen carefully. In this case, because all the data were available, the weighted average (node elevation × consumed volume) was known.

For ideal and real energy intensities ($I_{ei}$ and $I_{er}$, respectively), the relation remains the same

$$I_{ei} = \frac{E_{si}}{V} = \frac{2{,}082.94}{18{,}580} = 0.11\ \mathrm{kWh/m^3}$$

$$I_{er} = \frac{E_{sr}}{V} = \frac{6{,}497}{18{,}580} = 0.35\ \mathrm{kWh/m^3}$$

If, as usual, energy intensities are only referred to wire energy (ignoring the supplied natural energy) the performance indicator, logically, improves. In this case

$$I'_{er} = \frac{E_{sr,p}}{V} = \frac{5{,}833}{18{,}580} = 0.31\ \mathrm{kWh/m^3}$$

However this analysis fails to accurately reproduce reality. If all the energy was natural, this value would be zero, an unacceptable result from a physical point of view, although system efficiencies are less relevant in practice. In such a case, it would only make sense to perform an analysis aimed at recovering part of the topographic energy.

The previous parameters deliver a good measure of the system's potential for improvement. However, $\eta_{ar}$ provides an even closer examination. It cannot be assumed that performance can improve from its actual value (0.23) to the ideal value (0.72), as the latter does not include losses. To determine a good, but realistic performance, a reasonable loss levels must be established:

- Water losses: Their real value is, in this case, very good at ($584/19{,}164 = 0.03$), thus no estimation is required. The current value is used, and the water loss embedded energy:

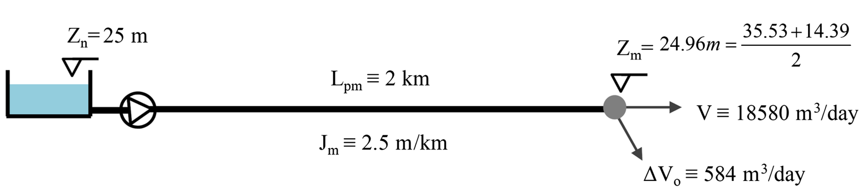


**Fig. 8.** Cap de Terme equivalent irrigation network

$$E_{rl,o} = \gamma \sum \Delta v_{jo} \frac{p_{jr}}{\gamma} = \gamma \sum \Delta v_{jo} \left[ \frac{p_o}{\gamma} + \frac{p_{jt,r}}{\gamma} \right]$$
$$\approx \gamma \Delta V_o \left[ \frac{p_o}{\gamma} + \left( z_h - \frac{z_h + z_l}{2} \right) \right]$$
$$= \frac{9{,}810 \cdot 584}{3{,}600{,}000} \left[ 20 + \left( 35.53 - \frac{35.53 + 14.39}{2} \right) \right]$$
$$= 48.61 \text{ kWh/day}$$

- Friction losses: The assumed average path, $L_{pm}$, can be again estimated with a weighted average (being a tree network, the length covered by all the consumed volumes is known). In this case its value is 2 km, with a unit head loss of 2.5 m/km and 4 m of local losses at the pumping station (where water is filtered). Then:

$$E_{rf,o} = \gamma(V + \Delta V_o) \left[ L_{pm} J_m + \frac{\Delta p_{rf,p}}{\gamma} \right]$$
$$= \frac{9{,}810 \cdot 19{,}164}{3{,}600{,}000} [2 \cdot 2.5 + 4] = 443.88 \text{ kWh/day}$$

- Pumping losses: A (very good) global performance of 0.82 for the pumping station (variable frequency drive—motor pump) is selected. Taking into account that the critical point is the furthest point ($L_{pc} = 2L_{pm}$) shaft losses are

$$E_{rp,o} = \gamma(V + \Delta V_o) \left[ L_{pc} J_m + \frac{\Delta p_{rf,p}}{\gamma} + \frac{p_o}{\gamma} + (z_c - z_p) \right] \left( \frac{1}{\eta_{po}} - 1 \right)$$
$$= \frac{9{,}810 \cdot 19{,}164}{3{,}600{,}000} [(4 \cdot 2.5) + 4 + 20 + (35.53 - 25)] \left( \frac{1}{0.82} - 1 \right)$$
$$= 510.46 \text{ kWh/day}$$

- Other losses: $E_{ro,o} = 0$ (none in this network)

In consequence, $E_{sr,o}$ results

$$E_{sr,o} = (E_{uo} + E_{tr,o}) + E_{rg,o}$$
$$\approx (E_{uo} + E_{ti}) + (E_{rl,o} + E_{rf,o} + E_{rp,o} + E_{ro,o})$$

$$E_{sr,o} \approx (1{,}494.23 + 588.71) + (48.61 + 443.88 + 510.46)$$
$$= 3{,}085.89 \text{ kWh/day}$$

And the target performance would be

$$\eta_{ar,o} = \frac{E_{uo}}{E_{sr,o}} = \frac{1{,}494.23}{3{,}085.89} = 0.48$$

which is halfway between the real and ideal values (0.23 and 0.72). The conclusion is that there is an important improvement margin (0.48 over 0.23) and efficiency can be doubled. Furthermore, the hypothesis considered to calculate $\eta_{ar,o}$ does not affect the final decision: proceeding with an in-depth analysis (a precise estimation, with an audit, will result in a final value of $0.48 \pm 0.05$). Therefore, the authors are in a position to state that the diagnostic is correct, and that expectations have been met (Cabrera et al. 2014).

Actions carried out include the elimination of the initial energy surplus; one of the five operating pumps is deemed redundant because the required pressure can be achieved with only four pumps, whereas the existing frequency drive motors are set to match the required pressure (20 m). Irrigation schedules have also been modified to guarantee that pumps operate at a constant flow rate. Additionally, the system has been decoupled in three zones: high, medium, and low irrigation areas. Being a tree-like network fed by four pumps working in parallel, the required cost is assumable. The result has been to decrease the global $\overline{\theta_{ti}}$ (must be weighted with the value of each subnetwork) thus increasing its complementary value, $\eta_{ai}$. The new value, 0.22, is a significant upgrade with regard to the initial value (0.28).

## Conclusion

Improving hydraulic and energy efficiency in PWTS (regardless of urban or irrigation water use) is an issue that is gaining in importance—but there are no simple solutions. Before attempting to find a solution, the implementation of a range of operational (no investment required, e.g., removing supplied excess energy) and structural measures (e.g., dividing the system to reduce $\theta_{ti}$ or installing PATs) is required. Prior to any analysis, a system diagnostic with the proposed metrics is necessary to estimate with sufficient precision the real improvement margins.

This paper presents an assessment methodology that requires some hypotheses that cannot be rigorously formulated at the initial stage of the process; and as a consequence, the final $\eta_{ar,o}$ value cannot be precisely determined. However, for the purposes of the diagnostic (based on the order of magnitude of the difference $\eta_{ar,o} - \eta_{ar}$) this lack of accuracy has no special relevance on the outcome of the analysis. Furthermore, because this value can be precisely calculated from an energy audit, an in-depth analysis of further case studies will help to refine this subjective hypothesis in the near future.

If the improvement margin ($\eta_{ar,o} - \eta_{ar}$) is deemed relevant, it should trigger the subsequent stages in the process (not described in this paper); the first being a water and energy audit to discover which parts of the system have the greatest improvement margins and which present the best cost-benefit opportunities. Furthermore, in systems with an irregular terrain in which topographic energy is significant, the recovery of this energy should be explored—and if found to be inviable, then the overpressures should be neutralized with PRVs.

## Acknowledgments

The authors acknowledge the very valuable contributions made by the reviewers of this paper, because their comments and suggestions have helped to significantly improve the contents. Additionally, we thank the staff of Aguas de Valencia for providing helpful advice and real case studies used to tune the software tool developed based on this paper. And last but not least, the research leading to these results received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement number 265122. The translation of this paper was funded by the Universitat Politècnica de València, Spain.

## Notation

*The following symbols are used in this paper:*

$E_{bi}$ = base energy or minimum required energy for the ideal system ($E_{bi} = E_{uo} + E_{ti}$);

$E_{ei}$; $E_{er}$ = supplied excess energy for the ideal and real systems;

$E_{si}$; $E_{sr}$ = total supplied energy for the ideal and real systems, respectively;
$E_{sr,o}$ = target energy to be supplied to the system;
$E_{ti}$; $E_{tr}$ = topographic energy required by the ideal and real system, respectively;
$E_{tr,o}$ = topographic energy of the system working with the target conditions;
$E_{uo}$ = minimum required energy by users (constant, no matter the system be real or ideal);
$E_{rf}$; $E_{rf,o}$ = reducible friction energy (corresponding to real or target conditions);
$E_{rg}$; $E_{rg,o}$ = reducible global energy (corresponding to real or target conditions);
$E_{rl}$; $E_{rl,o}$ = reducible energy embedded in leaks (corresponding to real or target conditions);
$E_{ro}$; $E_{ro,o}$ = other reducible energy (corresponding to real or target conditions);
$E_{rp}$; $E_{rp,o}$ = reducible energy in pumping stations (corresponding to real or target conditions);
$E_{yr}$ = recovered energy (from the topographic energy);
$H_{cr}$; $H_{hr}$ = piezometric head in the real system at the critical and highest node;
$H_{jr}$; $H_{lr}$ = piezometric head in the real system at the generic and lowest node;
$H_{hi}$; $H^*_{hi}$ = piezometric head at the highest node (ideal system without and with pressure excess);
$H_{ji}$; $H^*_{ji}$ = piezometric head at the generic node (ideal system without and with pressure excess);
$H_{li}$; $H^*_{li}$ = piezometric head at the lowest node (ideal system without and with pressure excess);
$h_{pi}$; $h^*_{pi}$ = head pump in the ideal system (without and with excess pressure);
$h_{pr}$ = head pump in the real system;
$h_{ni}$; $h_{nr}$ = natural supplied head in ideal and real systems respectively (usually $h_{ni} = h_{nr}$);
$I_{ei}$; $I_{er}$ = ideal and real energy intensity, considering all supplied energy (natural and wire);
$I'_{er}$ = real energy intensity using only wire energy;
$J_m$ = average pipe head loss (m/km);
$L_{pc}$ = distance between the pumping station and the critical point;
$L_{pm}$ = average distance between the pumping station and the consumption nodes;
$P_{\min}$ = fixed power value to select candidate pipes for placing PATs stations;
$p_{ci}$; $p^*_{ci}$ = pressure at the critical node (ideal system without and with excess pressure);
$p_{cr}$; $p^*_{cr}$ = pressure at the critical node (real system without and with excess pressure);
$p_{ei}$; $p_{er}$ = excess pressure of the system (ideal and real case);
$p_{hi}$; $p^*_{hi}$ = pressure at the highest node (ideal system without and with excess pressure);
$p_{hr}$; $p_{jr}$; $p_{lr}$ = pressure in the real system at the highest, generic and lowest node, respectively;
$p_{ht,r}$ = topographic real pressure at highest node ($p_{ht,r} = 0$ if critical node = highest node);
$p_{ji}$; $p^*_{ji}$ = pressure at the generic node (ideal system without and with excess pressure);
$p_{jt,i}$; $p_{jt,r}$ = topographic pressure at generic node (ideal and real systems);
$p_{li}$; $p^*_{li}$ = pressure at the lowest node (ideal system without and with excess pressure);
$p_{lt,i}$; $p_{lt,r}$ = topographic pressure at lowest node (ideal and real systems);
$p_o$ = required pressure (established by standards);
$\overline{q_k}$ = average flow in pipe $k$;
$V$ = total volume demanded by the system;
$v_j$ = volume demand at node $j$;
$z_c$; $z_h$; $z_j$; $z_l$ = critical ($c$), highest ($h$), generic ($j$) and lowest node ($l$) elevation, respectively;
$z_m$ = average of the extreme nodes elevation;
$z_n$ = reservoir or tank water natural level elevation (= pump suction level);
$\gamma$ = water specific weight (N/m$^3$);
$\Delta t$ = time period;
$\Delta p_{rf,p}$ = local losses in the water pumping station;
$\Delta v_j$; $\Delta v_{jo}$ = leaked volume and target leaked volume at a node $j$ of the system;
$\Delta V$; $\Delta V_o$ = total leaked volume and total target leaked volume of the system;
$\eta_{ai}$; $\eta_{ar}$ = ideal and real performance of the system without recovery;
$\eta_{ar,o}$ = target energy efficiency performance of the system without recovery;
$\eta_{po}$ = target energy efficiency performance for the whole pumping group;
$\eta_{wi}$; $\eta_{wr}$ = ideal and real performance of the system with energy recovery;
$\theta_{ei}$; $\theta_{er}$ = percentage excess energy; ideal case $= E_{ei}/E_{si}$, real case $= E_{er}/E_{sr}$;
$\theta_{ti}$; $\theta_{tr}$ = percentage of total topographic energy; ideal case $= E_{ti}/E_{si}$, real case $= E_{tr}/E_{sr}$;
$\lambda_{rf}$ = percentage of reducible friction energy related to the supplied energy ($E_{rf}/E_{sr}$);
$\lambda_{rg}$ = percentage of reducible global energy related to the supplied energy ($E_{rg}/E_{sr}$);
$\lambda_{rl}$ = percentage of reducible energy embedded leaks related to the injected energy ($E_{rl}/E_{sr}$);
$\lambda_{ro}$ = percentage of other energy losses related to the supplied energy ($E_{ro}/E_{sr}$); and
$\lambda_{rp}$ = percentage of reducible energy in pumping related to the supplied energy ($E_{rp}/E_{sr}$).

## Subscripts

$a$ = achievable;
$b$ = base or minimum;
$c$ = critical;
$e$ = excess (normally, except for the indicator energy intensity, $I_{er}$);
$f$ = friction;
$g$ = global;
$h$ = highest;
$i$ = ideal;
$j$, $k$ = generic (node, pipe);
$l$ = lowest (if placed first); Leaks (if placed second);
$m$ = medium;
$n$ = natural;
$o$ = usually indicates Target; occasionally indicates *other* in reducible losses;
$p$ = pump;
$r$ = reducible (if placed first); real (if placed second);
$s$ = supplied;
$t$ = topographic;
$u$ = user;
$w$ = with recovery; and
$y$ = yield.

### Superscripts

* = indicates excess of pressure (more than the required value $p_o$); and

′ = indicates that the energy intensity indicator, $I'_{er}$ only includes wire energy.

## References


Cabrera, E., Cabrera, E., Jr., Cobacho, R., and Soriano, J. (2014). "Towards an energy labeling of pressurized water systems." *Procedia Eng.*, 70, 209–217.

Cabrera, E., Pardo, M. A., Cobacho, R., and Cabrera, E., Jr. (2010). "Energy audit of water networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000077, 669–677.

Carravetta, A., Fecarotta, O., Del Giudice, G., and Ramos, H. M. (2012). "Energy production in water distribution networks: A PAT design strategy." *J. Water Resour. Plann. Manage.*, 26(13), 3947–3959.

Carravetta, A., Fecarotta, O., Sinagra, M., and Tucciarelli, T. (2014). "Cost-benefit analysis for hydropower production in water distribution networks by a pump as turbine." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000384, 04014002.

Carriço, N., Covas, D., Alegre, H., and Almeida, M. (2013). "How to assess the effectiveness of energy management processes in water supply systems." *Proc., Int. Conf. on Asset Management for Enhancing Energy Efficiency in Water and Wastewater Systems*, IWA. Marbella, Spain.

Colombo, A., and Karney, B. (2002). "Energy and costs of leaky pipes: Toward comprehensive picture." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2002)128:6(441), 441–450.

Duarte, P., Covas, D. I. C., and Alegre, H. (2009). "PI for assessing effectiveness of energy management processes in water supply systems." *Int. Conf. PI09: Benchmarking water services—The way forward*, IWA, Amsterdam, Netherlands.

Fontana, N., Giugni, M., and Portolano, D. (2012). "Losses reduction and energy production in water-distribution networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000179, 237 –244.

Giustolisi, O., Laucelli, D., and Berardi, L. (2013). "Operational optimization: Water losses versus energy costs." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000681, 410–423.

Giustolisi, O., Savic, D., and Kapelan, Z. (2008). "Pressure-driven demand and leakage simulation for water distribution networks." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2008)134:5(626), 626–635.

Kurek, W., and Ostfeld, A. (2014). "Multiobjective water distribution systems control of pumping cost, water quality, and storage-reliability constraints." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000309, 184–193.

Lambert, A., Brown, T. G., Takizawa, M., and Weimer, D. (1999). "A review of performance indicators for real losses from water supply systems." *J. Water SRT: Aqua*, 48, 227–237.

Lingireddy, S., and Wood, D. (1998). "Improved operation of water distribution systems using variable-speed pumps." *J. Energy Eng.*, 10.1061/(ASCE)0733-9402(1998)124:3(90), 90–103.

Official Journal of the European Union (OJEU). (2012). "Directive 2009/125/EC of the European parliament and of the council with regard to ecodesign requirements for water pumps." European Commission, Brussels, Belgium.

Ormsbee, L. E., Walski, T. M., Chase, D. V., and Sharp, W. W. (1989). "Methodology for improving pump operation efficiency." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(1989)115:2(148), 148–164.

Papa, F., Radulj, D., Karney, B., and Robertson, M. (2013). "Pump energy efficiency field testing & benchmarking in Canada." *Proc., Int. Conf. on Asset Management for Enhancing Energy Efficiency in Water and Wastewater Systems*, IWA. Marbella, Spain.

Pelli, T., and Hitz, H. U. (2000). "Energy indicators and savings in water supply." *AWWA J.*, 92(6), 55–62.

Perez-Urrestarazu, L., and Burt, C. M. (2012). "Characterization of pumps for irrigation in central California: Potential energy savings." *J. Irrig. Drain. Eng.*, 10.1061/(ASCE)IR.1943-4774.0000463, 815–822.

Rossman, L. A. (2000). "EPANET 2: User's manual." U.S. Environmental Protection Agency, Cincinnati.

Ulanicki, B., Kahler, J., and See, H. (2007). "Dynamic optimization approach for solving an optimal scheduling problem in water distribution systems." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2007)133:1(23), 23–32.

Walski, T. M. (1993). "Tips for saving energy in pumping operations." *J. Am. Water Works Assoc.*, 85(7), 49–53.

Water in the West (WW). (2013). "Water and energy nexus: A literature review." Stanford Univ., Standford, CA.