QUICK ENERGY ASSESSMENT OF IRRIGATION WATER TRANSPORT SYSTEMS

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ABSTRACT

Pressurised water transport systems are highly energy-intensive. Therefore, in the context of resource scarcity and climate change, efficiency is essential. To achieve this, it is necessary to (1) assess the state of the process and (2) evaluate the existing margin for potential improvement. These are the two objectives of this work, which is based on the energy intensity I_e (kW h m^{-3}) of a process that can simultaneously be expressed in units of pressure. Considering water transport, and its incompressible behaviour, there exists a biunivocal relationship between I_e and the sum of energy required to transport water, which can be expressed as equivalent height H (m, energy per unit of mass). From the energy intensity (I_e) and energy requirements (H), the efficiency of a water transport system in operation is evaluated. From installations in the design phase, the range of I_e values that are needed to achieve efficiency can be predicted. The proposed procedure is general, simple and precise, as demonstrated through three case studies.

Nomenclature

Symbols	Meaning of symbols
$a_o(p)$	Constant, depending on working pressure and material cost of the pipe [€ (m m^c)$^{-1}$]
c	Adjustment exponent of material cost evolution
C_1	Energy source context indicator [kW h]
E_I	Supplied (or injected) energy [kW h]
E_N	Natural energy [kW h]
E_p	Shaft (pumping) energy [kW h]
E_{si}	Minimum energy required by the system [kW h]
E_{ti}	Topographic energy [kW h]
f	Friction factor
F_i	Installation factor
f_p	Investment - installation - construction factor
H	Piezometric head [m]
h	Number of operating hours [h year^{-1}]
H_d	Designed height [m]
h_f	Pressure losses [m]
η_{GL}	Global efficiency [%]
H_{PAT}	Energy to be recovered by the PAT [kW h]
I_e	Energy intensity [kW h m^{-3}]
J_{max}	Maximum hydraulic slope [m km^{-1}]
J_{min}	Minimum hydraulic slope [m km^{-1}]
J_o	Optimal hydraulic slope/gradient [m km^{-1}]
J_o^*	Optimal slope of a gravity pipe [m km^{-1}]

L	System length [m]
L_{ei}	Equivalent lengths of the accessories [m]
$\overline{p_e}$	Global average price of energy [€ (kW h)$^{-1}$]
$\overline{p_e}*$	Average selling energy price [€ (kW h)$^{-1}$]
p_i	Pressure at the origin [N m^{-2}]
p_o	Service pressure [N m^{-2}]
Q	Flow [m^3 s^{-1}]
v_j	Water consumption of node j [m^3]
w_f	Friction efficiency
$\bar{z}$	Weighted average of the consumption nodes [m]
z_f	Final node elevation [m]
z_h	Elevation of the highest node [m]
z_i	Initial node elevation [m]
z_l	Elevation of the lowest node [m]
γ	Specific weight of wáter [N m^{-3}]
ΔE	Excess of natural energy [kW h]
η_l	Water efficiency [%]
η_p	Pumping efficiency [%]
θ	Weight of structural losses in the energy balance
λ	Installation cost factor

Abbreviations

PRV	Pressure Reducing Valve
PAT	Pump As Turbine
BEP	Best Efficient Point

1. Introduction

The main benefits of pressurised water transport are its flexibility (because its layout is compatible with the topography), water quality conservation (the pipe itself and its internal pressure maintain the water quality) and higher efficiency. That is why there is a general trend towards the transformation of classic irrigation channels into pressurised networks. Its weak point in pressurised water transport is the energy required which is associated with high costs and greenhouse gas emissions. It is, therefore, crucial to minimise the economic and environmental impacts of pressurised water transport that are responsible for a significant percentage of total energy consumption. In Europe, pumps (including those for industrial use) account for 10% of the electricity demand (Grundfoss, 2014), whilst, in California, water transport represents 6% of the total energy demand (WW, 2013). In Spain, pressurised irrigation is responsible for only 3% of the total consumption (Cabrera et al., 2010a). The European Union's reviews of energy-saving objectives are aimed at least an 20% reduction by 2020 (EC, 2011) and 32.5% by 2030 (EC, 2019). Pressurised water transport should contribute to the achievement of these objectives.

Improving the performance of an operating pressurised water system requires both the identification of the current system state and the subsequent assessment of the margin for improvement that exists with the current level of available technology. In the design phase of new systems, energy efficiency must be a fundamental concern. This work synthesises previous research (Cabrera et al., 2015; Cabrera et al., 2018 and Cabrera et al., 2019) and focuses on their concepts and presents a quick assessment of the energy efficiency of the reported systems. The proposed method is accessible to a wide range of professionals.

2. Fundamentals of quick energy assessment

A simple water transport system consists of movement between two points without any pressure requirements. The levels and distance between the two points determine the energy requirements. If the initial elevation, z_i, is lower than the final one, z_f, the system needs shaft (or pumping) energy. However, if $z_i > z_f$, water can move by gravity, although an additional contribution from pumping energy may be required to overcome friction, h_f, if it exceeds the available energy (i.e. $h_f > z_i - z_f$).

As gravitational energy has no costs, energy analyses have been concentrated on systems with pumping stations. This restrictive selection is nowadays unacceptable because no form of energy should be neglected. If a gravitational energy surplus exists, it can be recovered with turbines or PATs (Pumps as Turbines) reduce energy loss. If that it is not economically feasible, energy can be dissipated with pressure-reducing valves (PRVs). In other words, efficiency analyses could be extended to all systems. This work starts with those systems that arouse the most interest (when pumping is needed) and these are later extended to other cases.

The methodology derived here is based on the equivalence between the units of the energy required to transport 1 m^3 of water, or energy intensity I_e, (kW h m^{-3}), and units of pressure (N m^{-2}). Since water density is constant, each I_e unit corresponds to pressure height on a 1:1 basis. This relationship, with $\gamma = 9810$ N m^{-3} in SI units, is

$$I_e\left(\frac{kWh}{m^3}\right) = 2.725 \cdot 10^{-3} H(m). \quad (1)$$

Therefore, 0.2725 kW h m^{-3} which is equivalent to 100 m of height.

However, water transport is not just a matter of its movement and elevation. In networks (and sometimes in simple systems as well) a specified service pressure, p_o, must be provided. In urban water networks, this pressure is established by standards (Ghorbanian et al., 2016), whereas, in irrigation, it is set by the requirements of the devices (e.g. sprinklers or drippers). In short, in ideal systems, the energy intensity corresponding to the total energy needed (where p_i is the pressure at the origin) is:

$$I_e\left(\frac{kWh}{m^3}\right) = 2.725 \cdot 10^{-3}\left[\left(z_f - z_l\right) + \left(\frac{p_o}{\gamma} - \frac{p_i}{\gamma}\right)\right]\ (m) \quad (2)$$

In addition to useful energy, there are also inefficiencies (Cabrera et al., 2015) in pumping stations and in pipelines (through leaks and friction). There are metrics (η_p and η_l) corresponding to pumping and water efficiencies. But this is not the case for frictional losses, which, do not allow a similar concept to be established that defines a relationship between useful and required energy. Although frictional losses are inevitable, they must be added to energy needs. Thus, Eq. 3 includes friction, h_f, the sum of all losses in pipes and fittings ($h_f = \sum h_{fi}$). The equivalent height H is therefore

$$I_e\left(\frac{kWh}{m^3}\right) = 2.725 \cdot 10^{-3}\left[\left(z_f - z_l\right) + \left(\frac{p_o}{\gamma} - \frac{p_i}{\gamma}\right) + \left(\sum h_{fi}\right)\right] \quad (3)$$

The final *Ie* formula, refered to the delivered volume and including the inefficiencies and the natural energy $(z_i - z_l)$, is

$$I_e\left(\frac{kWh}{m^3}\right) = \frac{2.725 \cdot 10^{-3}}{\eta_p\, \eta_l}\; H\;(m). \qquad (4)$$

Other inefficiencies (such as the surplus of energy delivered) that are avoidable are not included.

Figure 1 graphically depicts Eq. 4 for different efficiency values ($\prod \eta_i = \eta_p\, \eta_l$), which range from the ideal case ($\prod \eta_i = 1$) to less efficient systems. To qualify the system's behaviour, in the I_e–H plane (Fig. 1), four zones are defined: zone A (excellent), zone B (reasonable), zone C (unsatisfactory) and zone D (unacceptable). The intersection of the horizontal line defined by the real value of I_e with the vertical line given by H (derived from Eq. 3, which includes frictional losses) indicates the global efficiency of the system. These zones are commented on below.

The lower limit adopted for excellent efficiency (zone A in Fig. 1) corresponds to a frequently used point: $I_e = 0.4$ kW h m^{-3}; $H = 100$ m (ERSAR and LNEC, 2013). It corresponds to pumping 100 m of height, with both ends at atmospheric pressure and a short pipe length. Therefore, $h_f \approx 0$, so $H \approx 100$ m. Without leaks, this energy intensity corresponds to an overall pumping efficiency of 68%, which is a moderate value if current requirements are met (EC, 2012). Including leaks, this energy intensity corresponds, to a pumping efficiency of 75% and a water efficiency of 90%. The other zones are separated successively by 10 points in the efficiency product.

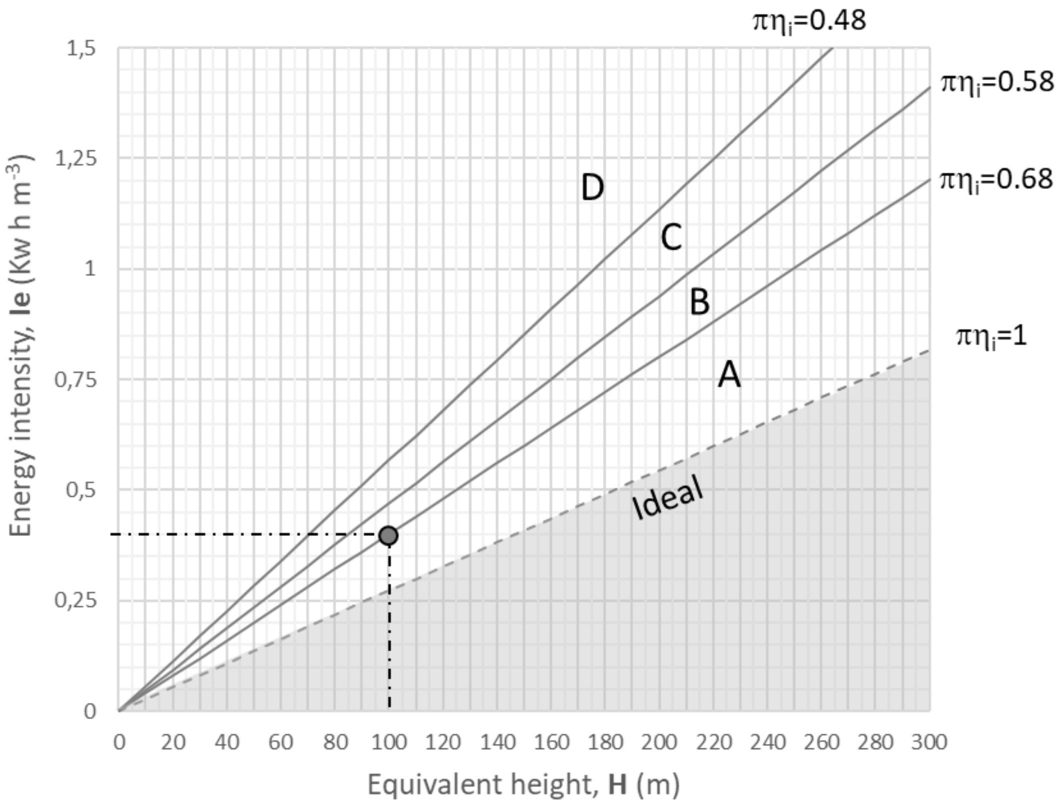

Fig. 1. Assessment of the energy efficiency of a water transport system.

Some final remarks apply:

a) The inclusion of head losses and pressure requirements in H (Fig. 1) is key to generalising the scope of Fig. 1. Graphs considering only the net elevation in the abscissa H (Plappally and Lienhard, 2012) are of more limited use.
b) In systems at the design phase, the real value of I_e is not yet known. In this case, using Fig. 1, H can anticipate the range of energy intensities corresponding to different efficiencies. For the friction height, the value $h_f = J_o(L + \sum L_{ei})$ must be adopted, where J_o is the optimal hydraulic slope (Cabrera et al., 2018), and L and L_{ei} are the length of the system and the equivalent lengths of the accessories, respectively.
c) In simple systems, neither the pressure term, nor leakage inefficiencies, are usually involved.
d) The values of the parameter $\prod \eta_i$ are indicators that should reflect the evolution of technological improvements. For example, in submersible pumps, replacing asynchronous motors by synchronous ones improves the efficiency, especially at partial load (Sperlich et al., 2018). In short, in Fig. 1, the values of $\prod \eta_i$ must reflect the saving targets.
e) This assessment is based on the integral energy equation (a power balance) applied to systems limited by control-volumes (White, 1979), a balance that can be extended for any period of time. Therefore, any well-stablished system, no matter its size, can be assessed. Nevertheless, temporal variability of the system's efficiency can be analysed by extending the energy equation during the appropriate time interval, provided that for such period all the energy flows through the system's boundaries are known. In any case, for assessments of average energy, the focus of this paper, current time intervals (i.e. day, month or year) must be adopted.

Finally, and because friction is included as an additional requirement in H, it should be noted that Fig. 1 does not asses the system from the point of view of friction. Therefore, especially for systems in which friction is significant (e.g. where $h_f/H \geq 0.15$), its contribution must be evaluated independently. For this purpose, the friction efficiency, w_f, is of great interest and is defined as

$$w_f = \frac{h_f}{J_o(L+\sum L_{ei})}. \quad (5)$$

A w_f value different from 1 indicates that the diameter is insufficient ($w_f >> 1$) or excessive ($w_f \rightarrow 0$). The need for this complementary analysis increases with the length of the transport L and decreases with height. Obviously, if a facility is being designed, it is reasonable to design it with a diameter that corresponds to the optimal hydraulic slope, J_o, in which case, $w_f = 1$.

3. Different hydraulic grade lines

Regardless of whether the water transport is driven by gravity or pumped, the hydraulic slope J is a key parameter. In our analysis, four J parameters are defined:

- J_{min} which corresponds to the lowest water speed. A minimum value is currently set to maintain quality (time of residence of the water in the system) and avoid sedimentation.
- J_o which corresponds to the optimal slope of a pipe requiring shaft energy. It is generally associated with pumping lines ($z_i < z_f$) but can easily be generalised to gravity pipes ($z_i > z_f$) in which the available slope $(z_i - z_f)/L$ is lower than J_{min}.

- J_o^* which corresponds to the optimal slope of a gravity pipe in which some gravitational energy can be recovered. It is a similar concept to the previous one, but there are some differences. J_o is linked to the purchase price of the energy, whereas J_o^* is linked to the sale price (equations 7 and 8).
- J_{max} which corresponds to the maximum water speed. For the security of the facility (to control the water hammer) and the prevention of erosion, a given value should not be exceeded.

In general, $J_{min} < J_o < J_o^* < J_{max}$ applies, although systems with little use (i.e. low number of hours per year) can increase J_o to a value that is higher than J_{max}. In such a case, J_{max} is adopted. On the other hand, the optimal slopes, J_o and J_o^*, are incompatible (since one applies to pumped systems and the other applies to gravity systems, respectively). Lastly, the boundary values (J_{min} and J_{max}) are subjective and depend on the reference consulted. Two examples follow.

a) According to the American Water Works Association (AWWA), J_{max} depends on the diameter. If it is less than 16 inches (≈ 400 mm), then J_{max} = 7 m km^{-1}. If this diameter is exceeded, then J < 3 m km^{-1} (AWWA, 2012). Other authors (Bouman, 2014) have set the maximum water speed at 3 m s^{-1}; this is a very high value because for a 400 mm pipe (with a friction factor f = 0.015), J ≈17 m km^{-1}. This value is unacceptable outside of exceptional cases (such as with a fire suppression network).
b) The AWWA does not propose a value for J_{min}. It can be set from the minimum speed value of 0.2 m s^{-1} (Bouman, 2014). For a diameter of 400 mm (f = 0.020), J_{min} ≈ 0.1 m km^{-1}, a rather low value.

In short, under normal operating conditions, the interval (0.1 – 7) m km^{-1} can be used as a reference, but singular cases require specific analysis. For instance, in penstocks of large hydroelectric plants, it is common to find speeds of up to 5 m s^{-1} (Stevens and Davis, 1969), a value that is explained by short pipe lengths carrying very large flows.

The optimal slope comes from a well-defined expression that is shown in Eq. 6 (Cabrera et al., 2018). Its major uncertainty lies in the starting data since it is difficult to anticipate the average value of some of the equation's key parameters, such as the price of the energy, for a 50-year period (the pipe's expected lifespan). Its expression is

$$J_o = f_p \left(\frac{\lambda}{e}\right)^{\frac{5}{5+c}} \tag{6}$$

where f_p is dependent on the pipe parameters; c and λ lied on technical performance and cost, respectively, and e is a parameter that synthesises energy costs. Following Cabrera et al. (2018), the same equation can be expressed with additional parameters:

$$J_o = (0.0826 \cdot f)^{\frac{c}{5+c}} Q^{\frac{2c-5}{5+c}} \left[\frac{0.2c.F_i.a_o(p).\eta_p}{\gamma.n.h.\overline{p_e}}\right]^{\frac{5}{5+c}} \tag{7}$$

where f is the friction factor, c and $a_o(p)$ are adjustment factors for pipe cost and diameter variation (very specific to the material), Q is the pipe flow, F_i is the installation factor (it includes all additional costs apart from the cost of the pipe itself: transport, trench, labour, etc.), η_p is the efficiency of the pumping station, γ is the specific water/fluid weight, h is the annual operating hours, and $\overline{p_e}$ is the global average price of energy. Finally, it is important to underline that, because the constant 0.0826 has dimensions, Eq. 7 is not dimensionless (Cabrera et al., 2018) and requires application of SI units.

A gravitational pipe (as used for the penstock of a hydroelectric plant) is similar to a pumping line; therefore, the differences between J_o and J_o^* are minimal. In J_o, the energy term is quantified by the cost of the energy to be paid to the energy provider, $\overline{p_e}$; conversely, in J_o^*, the energy term is affected by the average selling energy price, $\overline{p_e^*}$. The second difference lies in η_p, the efficiency of the hydraulic machine (pump or turbine). In J_o, it appears in the numerator (the hydraulic energy is the output), while, in J_o^*, it is in the denominator (the hydraulic energy is an input). Thus, J_o^* is determined by

$$J_o^* = (0.0826 \cdot f)^{\frac{c}{5+c}}\, Q^{\frac{2c-5}{5+c}} \left[\frac{0.2c.F_i.a_o(p)}{\gamma.n.h.\overline{p_e^*}.\eta_t}\right]^{\frac{5}{5+c}}. \quad (8)$$

4. Quick assessment of the energy efficiency of simple systems

As mentioned before, in the current context of climate change, it is necessary to generalise the energy analysis to all simple systems and not limit it to pumping systems. The possibility of recovering excess energy is arousing growing interest (Fecarotta et al., 2015). From this view, simple systems can be classified (Fig. 2) into five groups on the basis of energy.

1. Impulsion pipes (conventional pumping) must overcome elevation ($z_f - z_i \geq 0$) and friction. Shaft (pumping) energy, E_p, must be supplied.
2. Gravitational pipes ($z_f - z_i < 0$) have insufficient natural energy available because $(z_i - z_f)/L < J_{min}$. Therefore, additional shaft energy must be introduced.
3. Classic adduction means that the available natural energy can move the water at a reasonable speed.
4. Adduction with excess natural energy, ΔE, which energy cost analysis advises against recovering, means that the excess energy ($\Delta E = (z_i - z_f) - J_{max} L$) is dissipated with a PRV.
5. Adduction with excess, recoverable natural energy is a case similar to the previous one. However, the cost/benefit analysis is now positive.

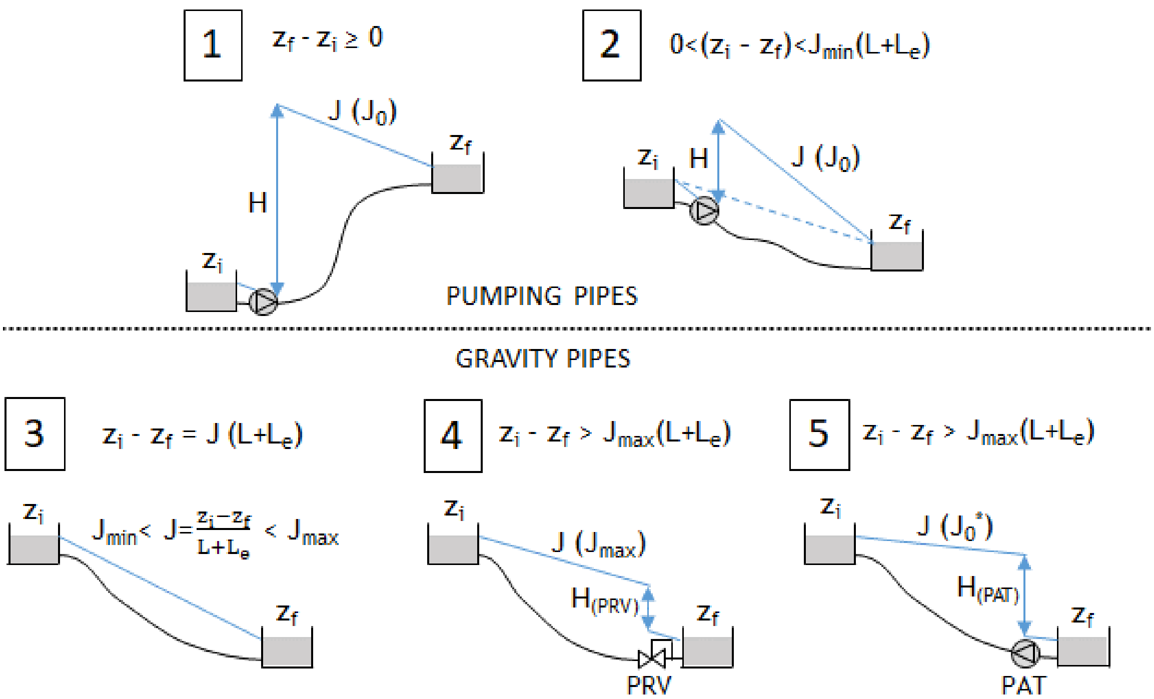

Fig. 2. Pressurised water transport in simple systems (different energy configurations).

Long-distance water transport systems include some (or all) of these five cases because the pipelines must be adapted to the topography of the terrain. Even if the slope of the terrain decreases monotonically (as in case 3), an open channel is a feasible solution. In any case, global energy analysis of the whole system must be performed in stages. Each section constitutes a volume of control to be analysed. Then, from the energy efficiency of each section and proper weighting, the final overall value is obtained. Notable examples of these transports are the California Aqueduct (CDWR, 2011), which is 700 km long with a 370 $m^3 s^{-1}$ capacity; Israel's National Water Carrier (Cohen, 2008), which is 130 km long with a 20 $m^3 s^{-1}$ capacity; and the Tajo Segura transfer system in Spain (Melgarejo and Montaño, 2009), which is 290 km long with a 33 $m^3 s^{-1}$ capacity.

Figure 3 qualifies each case from an energy perspective. The process begins with the calculation of hydraulic slopes. The order of magnitude of the extremes (J_{min} and J_{max}), although subjective, is well defined, while J_o and J_o^* must be calculated appropriately. For operational pumping pipes (left column, cases 1 and 2), if the system is working, the adopted hydraulic slope is the real one, J. H is determined from J, and the efficiency is obtained. During the design phase of pipelines, the goal is to set the intervals of I_e that correspond to each efficiency level. These ranges are established by means of J_o and H_d (the d subscripts refer to the design phase).

The qualification of gravitational adductions (cases 3, 4, and 5) is, to some extent, subjective. Natural energy therefore has no cost and minimising costs is futile. However, I_e, the basic indicator of the analysis and linked to the energy to be paid, does not exist. It only makes sense in adductions with PATs, which is a case of economic balance in the conventional context. In case 3, in which J lies between the extreme slopes, there is no alternative and, therefore, the global efficiency (η_{GL}) is equal to 1. In cases 4 and 5, the measure of efficiency is linked to the difference between the real H and the designed one, H_d.

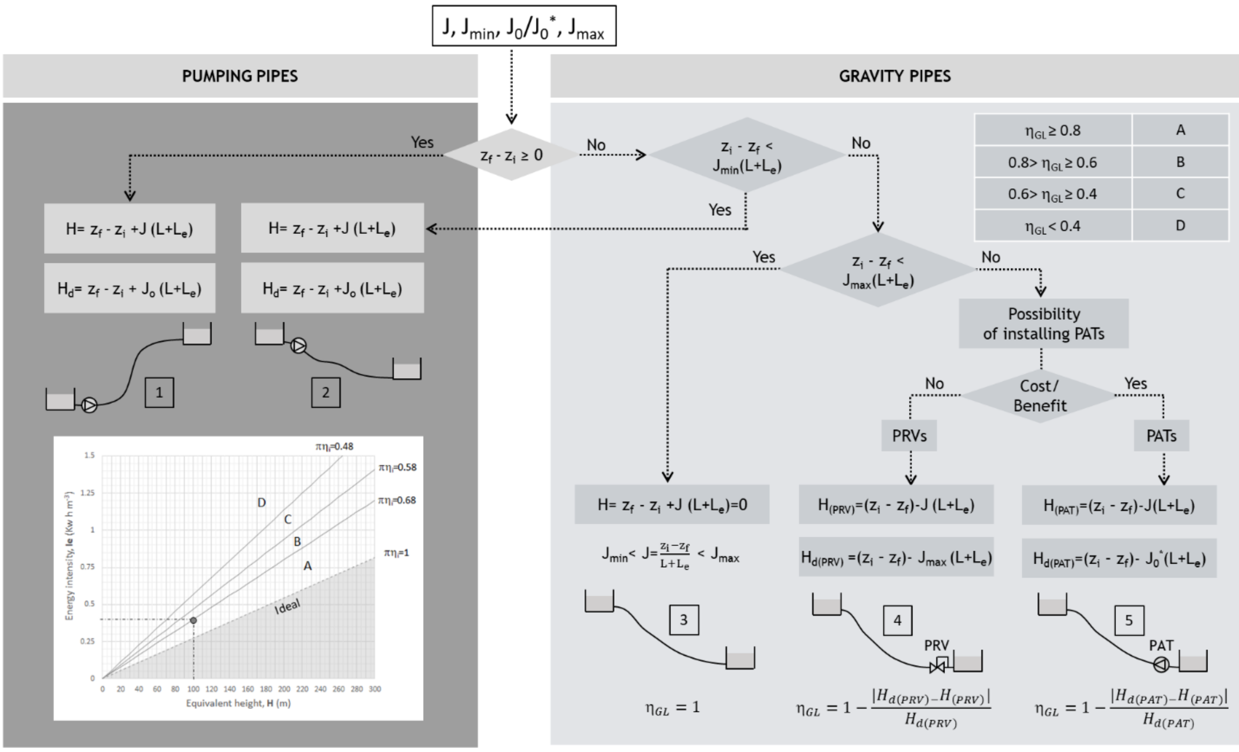

Fig. 3. Energy efficiency of pressurised water transport in simple pipelines.

5. Quick assessment of the energy inefficiencies in networks: operational and structural losses

The assessment of the energy efficiency of complex systems resembles that of simple systems, although there are important differences. The first and most relevant one is the existence of topographic energy, which is a consequence of different consumption at different heights (in simple systems, there is just one delivery point). The design of any network aims to meet the requirements of the most unfavourable node, while the volume of the other nodes is delivered with excess pressure (the higher the node, the lower the pressure). The sum of all these excesses is topographic energy, E_{ti} (Cabrera et al., 2015). This energy is not an energy loss linked to the system's operation, although, in practice, it implies that more energy is supplied than is strictly necessary. Therefore, it is advisable to associate that energy with another type of inefficiency, that is structural loss (Cabrera et al., 2019). The second difference is the potential presence of several energy sources. In a network, it is common to supply water from two (or more) pumping stations or reservoirs.

Once the system is defined (with its surface and volume of control), the integral energy equation can be applied (Cabrera et al., 2010b). For this reason, in complex systems, it is common to divide the supplied (or injected) energy (E_I) into natural (E_N) and pumping energy (E_p): $E_I = E_N + E_p$. The weight of each form is represented by the parameter $C_1 = E_N/(E_N + E_p) = E_N/E_I$. In simple systems, the energy injected, E_I, only has both components in scenario 2.

There remains a third major difference between simple and complex systems. It is possible to define the optimal hydraulic slope, J_o, in both types (Cabrera et al., 2018). Nevertheless, this is not the case for the slope J_o^*, which is typical of simple gravitational systems. The explanation is clear: while J_o is based on the evaluation of the friction in all pipes, it is unrealistic to assess the energy in any line in which it could be recovered with PATs, and this is the basis of J_o^*. So, it is a challenge to typify complex networks the way that simple systems are characterised in Fig. 3. There are additional minor differences, such as the habitual existence of leaks in complex systems (in simple systems, they are usually negligible) or the current requirement to supply pressure of service p_o in networks.

Despite these differences, calculating the energy efficiency of a network is similar to that of a simple system. However, in this new case, the starting point is the minimum energy E_{si} required by the system for a period of time T. This energy can be expressed (Cabrera et al., 2015) by

$$E_{si} = \gamma V \left[(z_h - z_l) + \frac{p_o}{\gamma} \right] \tag{9}$$

where γ is the specific weight of the water (N m^{-3}), V is the volume supplied (m^3) to the system in period T, z_h and z_l are the elevation (m) of the extreme (highest and lowest) nodes and p_o is the pressure of service (N m^{-2}). To this minimum energy, the energy required to overcome friction must be added. This term is more diffuse in water-looped networks than in simple systems because the water path is not a priori defined. To overcome this problem, the friction energy is maximised, adopting the energy lost between the source and the critical node for the whole system. In a real network, this value can be measured or, alternatively, estimated by multiplying the distance between the two points (L) by a reasonable hydraulic grade line slope; for instance, J = 0.0015 m/m. In a real case, if J is ultimately higher than the estimated value, H will be smaller. Consequently, the energetic requirements of the system will be smaller, too.

In short, assuming that the suction pressure is zero, the equivalent final height *H*, with the real h_f measured (the abscissa of Fig. 1), is determined by

$$H = (z_h - z_l) + \frac{p_o}{\gamma} + h_f. \tag{10}$$

A quicker but less accurate estimation (without measurements) is obtained from

$$H = (z_h - z_l) + \frac{p_o}{\gamma} + 0.0015 \cdot L\,. \tag{11}$$

In Fig. 1, the purpose of the intersection between the horizontal given by I_e and the vertical defined by *H* (equation 10 or 11) is to qualify the behaviour of the system in terms of energy and, at the same time, determine the margin for improvement. The relevance of the friction, h_f/H, which is typically moderate in networks, indicates whether the estimation's error is more or less significant.

Finally, if the height of the source, z_s, is intermediate between extremes ($z_l < z_s < z_h$), natural energy must be included in the balance. The natural energy is

$$E_N = \gamma V(z_i - z_l). \tag{12}$$

The natural energy plus the shaft energy amounts to the total energy injected, E_I. The result obtained from Figure 1 illustrates the overall energy assessment of the network and includes both operational and structural losses. This is because the energy requirements were calculated according to the needs of the most unfavourable node.

In order to assess the contribution of structural losses to the inefficiency, it is necessary to calculate the weight of the topographic energy, E_{ti}, relative to the total energy requirements. In a network without friction (Cabrera et al., 2015), topographic energy is equal to

$$E_{ti} = \gamma \sum v_j \left[\left(z_h - z_j \right) \right] \approx \gamma V (z_h - \bar{z}) \tag{13}$$

where v_j is the water consumption of node *j*, z_j is its height and $\bar{z}$ is the weighted average of the consumption nodes. In Eq. 13, E_{ti} can be roughly estimated from the extreme nodes' average elevation. This approach is reliable for uniform spatial demand distribution. However, if most of the consumption transpires in the upper part of the network, the average value overestimates E_{ti}; in the opposite case, E_{ti} is underestimated. As previously mentioned, the topographic energy is the total excess of the energy delivered, and it is independent of the type of energy (natural or pumped). The relation between E_{ti} and the ideal total energy delivered is the parameter θ, the weight of structural losses in the energy balance. That is,

$$\theta = \frac{\sum v_j [(z_h - z_j)]}{V\left[(z_h - z_l) + \frac{p_o}{\gamma}\right]}\,. \tag{14}$$

The value of θ enables the decoupling of the total energy losses and, therefore, the identification of the most effective improvement strategies. Better management reduces the operational losses, while structural losses can only be diminished with a layout modification (Cabrera et al., 2019).

6. Examples

Three examples are presented to clarify the concepts previously explained. Two of them are in operation (Examples 1 and 3). Example 2 is in the design phase: specifically, it describes a working facility that is being renovated. The objective in each example is to assess their energy efficiency behaviour.

6.1. Example 1. Pumping line

Water is pumped from a well to a tank (Fig. 4). The use is residential (25%) and agricultural (75%); therefore, the number of hours of operation per year is variable. In 2018, the total energy consumption was 646672 kW h, and 415317 m^3 was pumped (I_e = 1.56 kW h m^{-3}).

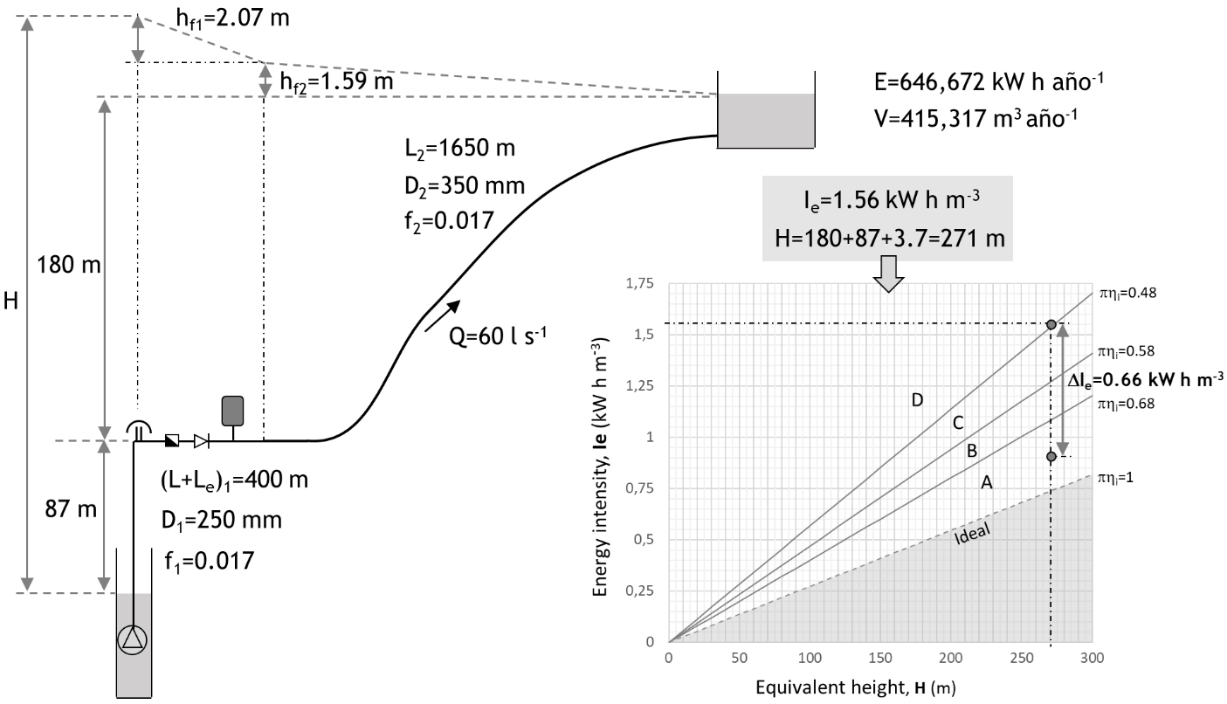

Fig. 4. Simple pipeline in Castellon (Spain) with its energy assessment.

The equivalent height H (270.66 m) is equal to the water elevation (267 m) plus friction losses h_f (3.66 m). The defined lines meet at a point located in the unsatisfactory–unacceptable zones (zones C-D in Fig. 4), and there is considerable room for improvement before reaching a status of excellent (0.66 kW h m^{-3}, greater than 40%). This justifies a thorough review of the system's operation. In the absence of leaks, the conclusion is obvious: all operational inefficiencies are located at the pumping station, with a global efficiency of 49% (Fig. 4). However, seasonal variations in the well water table level can contribute to this degree of poor performance.

Figure 1 does not assess the contribution of friction. That is, it does not answer the question of whether 3.66 m of friction is (or is not) a reasonable value. To this end, the first step is to calculate J_o (equation 7). The basic data of a cast iron pipe are c = 1.4; $a_o(p)$ = 635.575 € $(\text{m}\cdot\text{m}^{1.4})^{-1}$; n = 50 years; F_i = 1.5; $\overline{p_e}$ = 0.14 € kW h^{-1}; h = 4000 h $year^{-1}$ and η_p = 75%, which is a more reasonable pump efficiency than the current value (49%). These data should represent the pipe's 50-year average lifespan. From these values, J_o = 2,213 m km^{-1}, and the optimal head loss is 4.56 m (L_T = 2.05 km), which is almost equal to the actual value (3.66 m). In short, w_f = 3.66/4.56 = 0.80, while the weight of friction is low (h_f/H = 3.66/270.66 = 0.014), and it should be less without the contribution of local losses (e.g. foot valves, filters, elbows, etc.). Therefore, system's friction is reasonable.

6.2. Example 2. Gravity line

This example corresponds to an operational gravity pipe in Cusco, Peru (Fig. 5). The old pipeline requires renewal and, at the same time, the potential recovery of excess gravitational energy (actually dissipated by a PRV located at the entrance to the Picchu Alto tank) is economically feasible. For the new cast iron pipe, data from Example 1 are assumed to apply. The specific data are F_i =1.5; $\overline{p_e^*}$ = 0.08 € (kW h)$^{-1}$, h = 8760 h year^{-1} and PAT efficiency = 72%. From these data, J_o^* (equation 8) is 2,743 m km^{-1}, which corresponds to a 502 mm diameter pipe (rounded to 500 mm). The energy to be recovered by the PAT (H_{PAT}) should be 83.1 m. A positive cost/benefit analysis would justify its installation. As seen in Figure 5, the energy efficiency of the design would be the unit.

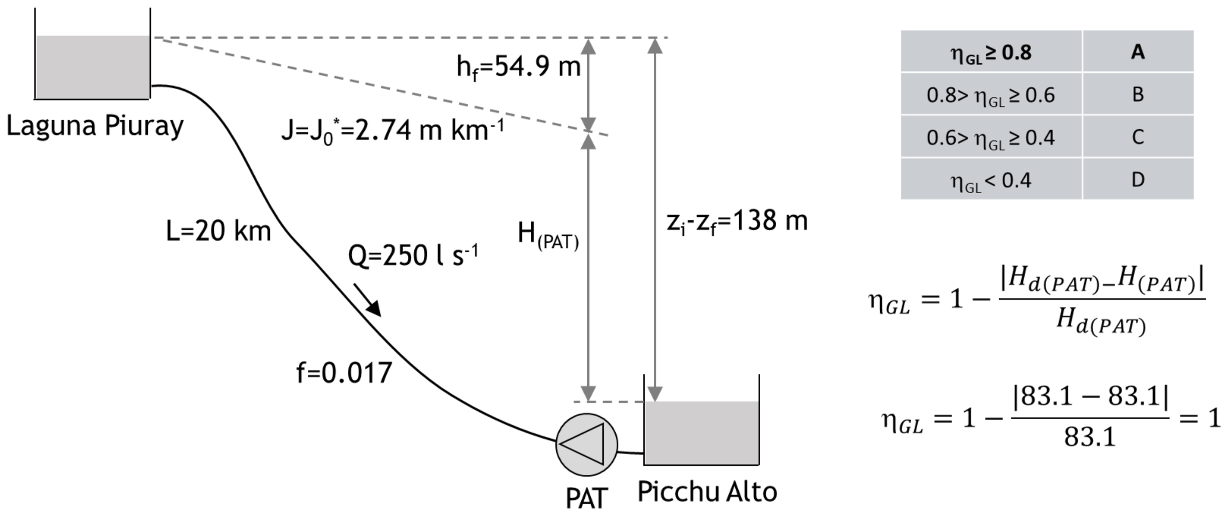

Figure 5. Gravity pipeline in Cusco (Peru).

6.3. Example 3. Irrigation network

In 2011, the irrigation network shown in Figure 6 displayed poor energy-related behaviour. Operational data for an average day in that year were an injected flow of 19164 m^3 d^{-1}, supplied flow of 18580 m^3 d^{-1} (leaks = 584 m^3 d^{-1}, a good performance for a 5-year-old network), pressure service of 20 m and consumed shaft energy of 5833 kW h d^{-1}. The physical data are z_h = 35.53 m, z_l = 14.39 m and the suction pressure, z_s, 25.00 m. The length from the source to the most unfavourable node is 3 km (the total network length is slightly over 50 km).

From these data, H ≈ (35.53 - 14.39) + 20 + 0.0015. 3000 = 45.64 m. The energy intensity, I_e, (considering the natural energy of 554 kW h) is

$$I_e = \frac{5833+554}{18580} = 0.34\ kWh\ m^{-3}.$$

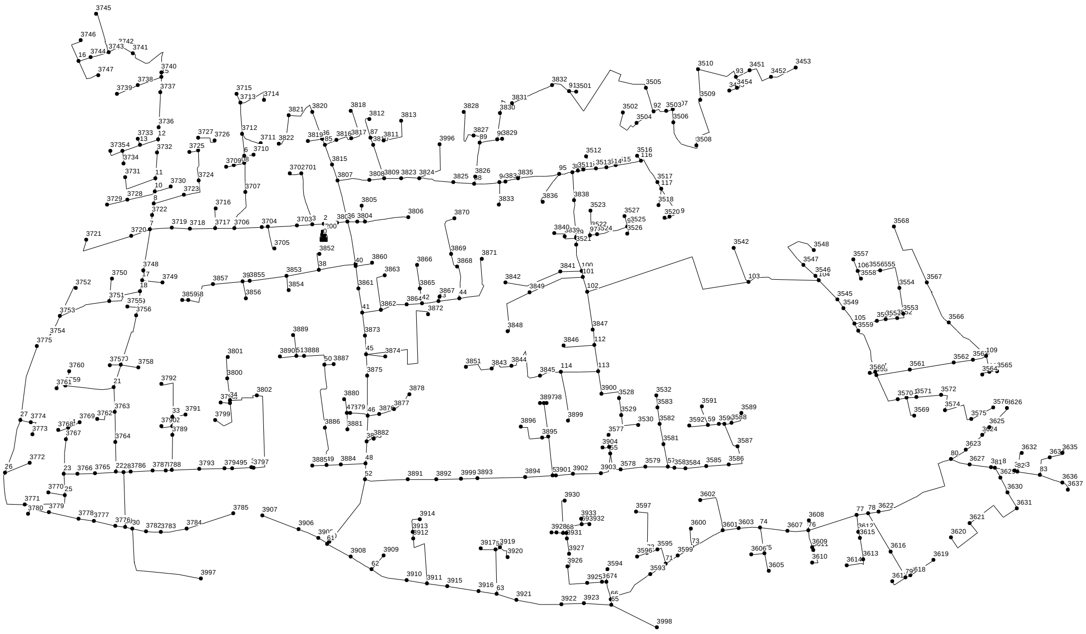

Figure 6. Irrigation network in Vila-Real (Spain).

This point (45.64; 0.34) falls into the D (unacceptable) area (Fig. 1), given that this energy evaluation of the network occurred before any improvement. In order to assess the weight of the structural losses, the topographic energy was estimated by Eq. 13. The result is

$$E_{ti} \approx \gamma \cdot V(z_h - \bar{z}) = 9810.\ 19164.\ \left(35{,}54 - \frac{35{,}54+14{,}39}{2}\right) = 1{,}99.\ 10^{9}\ \text{J d}^{-1} = 552.78\ \text{kW h d}^{-1}.$$

In this case, the correct topographic energy (588.71 kW h d^{-1}), evaluated using the non-simplified Eq. 13, is slightly higher than the approximated value (552.78 kW h d^{-1}), a small difference due to the relatively homogeneous spatial distribution of the demand.

If the inefficiencies are only due to operational losses, I_e is recalculated without considering the topographic energy; the result is I_e = 0.31 kW h m^{-3}. This value intersects with H = 45.64 m in Figure 1 and again results in an unacceptable assessment (D zone). This figure shows that the network efficiency should only be classified as excellent if I_e < 0.17 kW h m^{-3}. After some operational and structural improvements, the present energy intensity is 0.16 kW h m^{-3}. As the focus of this paper is on the average values only a brief description of the three main implemented actions (one operational and two structural) are provided:

a) This system operated with two turns of two hours each with rigid patterns for irrigation and very different flows (up to 50% of difference). With that variability, the system could hardly operate constantly at best efficient point (BEP). The irrigation was re-scheduled (constant flow, no matter the turn) and with these new load conditions, one of the five pumps was stopped, and the remaining operating pumps worked steadily at their BEP.
b) Local losses at the pumping and filtering station were very high (10 m). With a more rational piping layout and new efficient filters, this loss was dramatically reduced (3 m).
c) The pumps, working in parallel, supplied water to the highest and lowest nodes. To reduce the topographic energy, the network was divided into three independent sectors and the pumps were conveniently decoupled. Although the partition, strongly conditioned by the existing network, was not the optimum, the requested energy by the four pumps was significantly reduced.

7. Conclusion

A methodology designed to perform quick energy assessments for irrigation water transport systems is presented. Among these systems, those that require pumping energy are of special interest because of their economic implications. The proposed procedure is based on the fact that the energy intensity units (kW h m^{-3}) are effectively pressure units as well (N m^{-2}). Therefore, a direct and biunivocal relationship between I_e and the equivalent height H (sum of the energies required per unit of weight) can be established. From the real transport needs (I_e) and the minimum energy needs (H), the inefficiencies (in kW h m^{-3}) can be estimated. This analysis requires use of concepts that are generally ignored, such as natural energy or topographic energy.

From the physics of pressurised water transport systems, with the inefficiencies duly classified (as operational losses, pumps and leaks, and friction) and quantified, the global efficiency can be assessed. The proposed labels (Fig. 1) are, to some extent, subjective and can be reformulated from the energy efficiency goals set by the regulators and the current state of the technology.

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