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Resilience assessment insights based on the energy balance in drinking water networks

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ABSTRACT

The current paper primarily discusses the interconnection between water, energy and resilience, revisits the energy balance, proposes a modified calculation approach and metrics to assess system resilience criteria: energy efficiency and service flexibility. A sensitivity analysis is carried out considering: i) reference elevations, ii) levels of water losses, iii) contribution of shaft energy and pumping groups and iv) impact of water and energy efficiency improvement measures. The modified approach provides a realistic energy balance, while the original approach provides an ideal (no water losses) energy balance. Both approaches provide similar information for surrogate resilience metrics, but offer complementary information for the surplus energy index. Energy in excess per authorised consumption is most suitable to evaluate energy efficiency. Both the ratio between surplus energy and energy in excess and the surplus energy index are complementary in assessing service flexibility. Water and energy efficiency improvements should contribute to energy efficiency, ensuring service flexibility.

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Water-energy-resilience interconnection; energy balance; energy efficiency; service flexibility; water balance; surrogate resilience metrics

Introduction

Water and energy are two critical natural resources necessary for human society that are interdependent, in the so-called water-energy nexus. Drinking water systems rely on energy for water abstraction, treatment, transport and distribution. According to the World Energy Outlook 2018, the International Energy Agency (2018) states that the water sector consumes approximately 1400 TWh of energy per year, with more than half in electricity (counting around 4% of the world's electricity consumption). In Portugal, energy consumption costs can represent 50% of the operating costs of the water supply utilities (ERSAR, and ADENE 2018). As such, being energy efficient is critical for utilities, not only for ensuring a sustainable future, but also for the economic efficiency of utilities.

Resilience-related concerns have been gaining relevance as urban water systems face different types of events that may have a negative effect on the provided service (Çetinkaya et al. 2022; Rokstad, Makropoulos, and Rokstad 2023; Sharma et al. 2022). Resilience is a complex concept defined as the 'ability of a system to anticipate, prepare, respond to and absorb shocks, positively adapt and transform in the face of stresses and challenges' (adapted from ISO/TR 22,370:2020). Therefore, a resilient system should be robust, flexible, reliable, redundant and autonomous.

In managing drinking water systems, including bulk and distribution networks, energy and resilience are two critical concepts in their design and operation and are interconnected in different aspects. Regarding efficiency, more efficient use of water and energy resources may increase the availability of natural or economic resources during scarcity or other disruption events (e.g. extreme weather events). Concerning infrastructure autonomy, backup systems and self-energy production contribute to the system's ability to continue operating in the face of these events. Moreover, although backup pumping equipment may increase initial investment and operational costs in normal conditions, asset redundancy enables a more robust system response to equipment failures or extreme weather events. Lastly, energy-based indices are also used to assess the system's reliability (Liu et al. 2017) during high-demand periods or supply disruptions, as they indicate the system's service flexibility when water demand increases.

In the literature, resilience in water distribution systems has been focused on a system's capacity to provide the service under normal and abnormal demand conditions (Carneiro, Loureiro, and Covas 2023; Cubides-Castro et al. 2021; Liu et al. 2017), mainly assessed by service flexibility metrics. These metrics measure the system's hydraulic capacity to

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ensure the water supply (i.e. the service) under uncertain demand conditions. The first metric to be developed and the most commonly used is the Todini (2000) metric, usually denominated as resilience index (RI), accounting for the surplus energy over the energy in excess. RI has been subjected to several improvement attempts from different authors, introducing coefficients to account for pipe uniformity (Prasad and Park 2004), network topology and nodal importance (Sousa et al. 2022) or to extend the index into multi-source systems (Jayaram and Srinivasan 2008). Nonetheless, the concept of accounting for the surplus energy over the energy in excess is the basis of each suggested metric. These metrics typically have positive values, varying between 0 and 1, and express higher resilience for higher values. However, overdesigned systems with considerable surplus energy, can have high resilience values (Carneiro, Loureiro, and Covas 2023), though these can have problems associated with high pressures (e.g. frequent bursts, high leakage levels).

Attaining the maximum energy efficiency and becoming carbon neutral, concerns inherent to Sustainable Development Goal 7, are, relevant goals of water utilities in the short and medium terms. Knowledge of the system's water balance and energy balance is fundamental for assessing water system operation and identifying the less efficient components. An energy balance accounts for all the energy inputs and outputs during the water transport from the source to the consumer, and is achieved by integrating the energy equation over a given period.

Several studies have been developed for proposing the water and energy balances in different types of water infrastructures, namely drinking water supply systems (Cabrera et al. 2015, 2021; Carriço et al. 2014; Cubides-Castro et al. 2021; Mamade et al. 2017; Mamade et al. 2018), collective irrigation systems (Cunha et al. 2019), urban green spaces (Monteiro, Cristina, and Covas 2021) and wastewater systems (Jorge, Do Céu Almeida, and Covas 2022).

In drinking water systems' energy balances, the supplied energy of a system is divided into minimum hydraulic energy, the sum of the minimum required energy at the consumption nodes, and excess energy, including dissipated energy in the flow and surplus energy (Mamade 2019). Cabrera et al. (2010) considered that the input energy of the system could be divided into natural and shaft input energy, provided by reservoirs and/or pumps, respectively. As outflows, energy is divided into energy supplied to the consumers, outgoing energy through leaks and dissipated energy due to friction losses. Souza, Covas, and Kepler Soares (2011) later quantified the dissipated energy associated with valve head losses, separating the energy delivered to consumers into minimum required and surplus energy. Mamade et al. (2017) added more system components in which energy could be lost (e.g. pumps and turbines). Mamade et al. (2018) proposed two types of assessment of the energy balance: the simplified assessment requiring minimal data and providing a global overview of energy consumption in the system; and the complete assessment requiring a hydraulic model of the network providing a detailed assessment of energy consumption in every component of the balance. Cubides-Castro et al. (2021), from a potentially recoverable energy point-of-view, considered that consumed energy is divided in non-supplied energy, relative to energy dissipated in elements of the network (e.g. pipe friction, inefficiency of pumping systems, leakages), and in useful energy, corresponding to the sum of the minimum required energy and the surplus energy, which could be potentially recovered.

The calculation of energy efficiency metrics assesses the water-energy efficiency. System's energy in excess is one of the main components in the calculation of energy efficiency performance indicators, either being referent to the minimum required energy (Cabrera et al. 2010; Carriço et al. 2014; Mamade et al. 2017), per unit of input water volume or revenue water (Carriço et al. 2014) or authorised consumption (Mamade et al. 2017). Strictly from the energy efficiency point of view, higher surplus energy indicates lower energy efficiency. However, this component has started to be seen as possible to be recovered. Cabrera et al. (2021) considered the topographic energy that could be potentially recovered in pressurised water transport systems. In water distribution systems, Cubides-Castro et al. (2021), refers to the surplus energy as possible to be recovered by installing energy recovery devices at consumption nodes, in valves and in the network.

From a resilience perspective, higher surplus energy demonstrates increased resilience of the system since more unused energy is available to be dissipated in case of demand increase (Carneiro, Loureiro, and Covas 2023). Discussing the interconnections between water-energy and resilience is the main novelty presented herein.

The current paper primarily aims to discuss the interconnection between energy efficiency and resilience and to revisit and reformulate some components of the energy balance proposed by Mamade et al. (2017, 2018). The paper is organized in five sections, including the current one. The second section briefly describes the

water-energy balance, the respective energy efficiency metrics proposed by Mamade et al. (2017) and service flexibility metrics and proposes a modified approach for calculating the energy balance and a new surplus energy performance metric. The third section compares both calculation methods of the energy balance, explores the use of different reference elevations and analyses the effects of real and apparent water losses on the energy balance components. A simple system was used to analyse the impact of varying reference elevations. The same case study was adapted to four situations to comprehend the differences between energy balances approaches for a gravity system and systems with a variable-speed pump and a constant-speed pump. A real case study was used to assess the impact of reducing water losses in energy metrics. A fourth section discusses the interconnection needed between energy efficiency and resilience and the final section presents the main conclusions of this research and highlights foreseen future work.

Energy balance

Balance description

As defined in ISO 50002: (2014), an energy balance accounts for the 'inputs and/or generation of energy supply versus energy outputs based on energy consumption by energy use'. In water supply and distribution systems, the energy balance consists of quantifying all the energy associated with the water flow, that enters and leaves the defined boundaries of the system. From the different developed energy balance approaches (Cabrera et al. 2010; Souza, Covas, and Kepler Soares 2011), the methodology proposed herein is based on the energy balance developed by Mamade et al. (2017, 2018) and Mamade (2019), presented in Table 1. Total system energy (E_{tot}) can be divided into natural input energy (E_N), when added to the system by gravity, and shaft input energy (E_S), when added through water pumping. Output components are the main innovative features, from previous developments, with the separation of energy associated with the authorised consumption from that associated with water losses, as well as the decomposition of the dissipated energy in the different system components (e.g. pipes, valves, pumps and turbines), and the introduction of an additional term related to the recovered energy.

Mamade et al. (2018) proposed a simplified assessment, using a top-down approach, and a complete assessment, using a bottom-up approach. The top-down approach does not require hydraulic simulations and provides an overview of the main components of energy consumption (grey shaded in Table 1): natural and shaft input energy, energy associated with authorised consumption and water losses, minimum energy and pump inefficiencies associated with

Table 1. Energy balance scheme (adapted from Mamade et al. 2017 and 2018).

Natural Input Energy (E_N) / Shaft Input Energy (E_S)	Total system energy (E_{tot})	Energy associated with authorised consumption (E_{AC})	Energy associated with water supplied to consumers (E_{sup})*	Minimum required energy (E_{min})*
				Surplus energy (E_{sur})
			Dissipated energy associated with authorised consumption ($E_{diss,AC}$)	Pipe friction ($E_{diss_f,AC}$)*
				Valve head losses ($E_{diss_v,AC}$)*
				Pumping stations' inefficiency ($E_{diss_p,AC}$)*
				Micro-hydro power plants' inefficiency ($E_{diss_t,AC}$)*
			Recovered energy (E_{rec})	Recovered energy associated with authorised consumption ($E_{rec,AC}$) *
				Recovered energy associated with water losses ($E_{rec,WL}$) *
		Energy associated with water losses (E_{WL})	Dissipated energy associated with water losses at consumption nodes ($E_{diss_n,WL}$)*	
			Dissipated energy associated with water losses ($E_{diss,WL}$)	Pipe friction ($E_{diss_f,WL}$)*
				Valve head losses ($E_{diss_v,WL}$)*
				Pumping stations' inefficiency ($E_{diss_p,WL}$)*
				Micro-hydro power plants' inefficiency ($E_{diss_w,WL}$) *

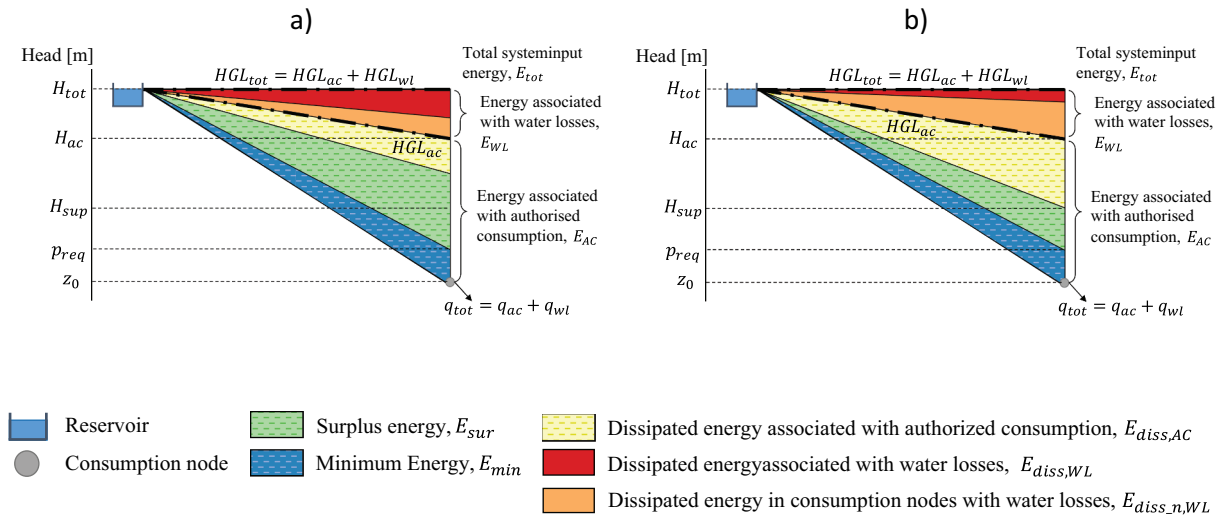


Figure 1. Diagram of gravity water distribution systems with hydraulic grade lines: a) original approach; b) modified approach.

authorised consumption and water losses. This approach assumes that the energy associated with authorised consumption is proportional to the authorised consumption percentage (Lambert and Hirner 2000), see Equation (1). The rate of water losses and authorized consumption relative to system input volume are collected from the water balance.

$$E_{AC} = E_{tot}\frac{\forall_{AC}}{\forall_{inp}} \tag{1}$$

Note that energy terms (E) are expressed in kWh, water flow rates (q) in m^3/s, and elevations and hydraulic heads (H) in m. Terms related to water losses have the subscript WL, while the components related to authorised consumption have the subscript AC.

In the Mamade et al. (2017) approach, referred herein as the original approach, the energy balance components related to authorised consumption are calculated assuming an ideal network, that is without water losses. In this original approach, energy components associated with authorised consumption are calculated with the flow rate and hydraulic head from the hydraulic simulation regarding only authorised consumption. The components E_{sup}, $E_{diss_f,AC}$ and $E_{diss_v,AC}$ are, therefore, calculated using the hydraulic head relative to the authorised consumption simulation, H_{ac}. Consequently, the authorised consumption components represent the energy of the ideal system without water losses.

A modified version of the energy balance is proposed, herein, to provide a better and more realistic energy balance. The calculation sequence is the same as in the original approach. The main difference is on the hydraulic head used to calculate the components related to authorised consumption. In the modified approach, the hydraulic head of the system is used with water losses, H_{tot}, obtained by the network simulation with total water volume (consumption + water losses). This difference leads to different results in surplus and dissipated energy components. This is schematically illustrated in the energy lines of the supply system with a single consumption node at the downstream end, in which both consumption and water losses are located, in Figure 1: while the energy associated with authorised consumption and the energy associated with water losses are the same in both approaches, the respective components are different; the only component that is constant is the minimum required energy.

The modified approach to calculate the energy balance uses the equations presented in Table 2 to calculate the more detailed components, following the same approach as the original energy balance to reach the aggregated components. The description of each variable is presented in the Notation. The subscript *tot* refers to terms resulting from the hydraulic simulation considering the total water volume, while subscript *ac* refers to the simulation considering only the authorized consumption.

In the original approach, the dissipated energy in consumption nodes with water losses can only be calculated by Equation (18). However, with the proposed changes in the modified approach, this component can also be computed as Equation (19).

$$E_{diss_n,WL} = \gamma a \sum_{n=1}^{N_n}\sum_{t=1}^{N_t} q_{wl,n}^{t}\left(H_{tot,n}^{t} - z_0\right)\Delta t \tag{19}$$

A simple case study is used to further discuss and illustrate the differences between Mamade et al.'s (2017)

Table 2. Equations for the calculation of the energy balance using the modified approach.

Supplied energy		**Minimum required energy**		**Surplus energy**	
$E_{sup} = \gamma a \sum_{n=1}^{N_n} \sum_{t=1}^{N_t} q_{ac,n}^t \left(H_{tot,n}^t - z_0 \right) \Delta t$	(2)	$E_{min} = \gamma a \sum_{n=1}^{N_n} \sum_{t=1}^{N_t} q_{ac,n}^t \left(z_n + \frac{p_{req,n}}{\gamma} - z_0 \right) \Delta t$	(3)	$E_{sur} = E_{sup} - E_{min}$	(4)
Dissipated energy due to pipe friction					
$E_{diss_f,AC} = \gamma a \sum_{j=1}^{N_j} \sum_{t=1}^{N_t} q_{ac,j}^t \left(J_{tot,j}^t L_j + \Delta H_{tot,j}^t \right) \Delta t$	(5)	$E_{diss_f,WL} = \gamma a \sum_{j=1}^{N_j} \sum_{t=1}^{N_t} q_{tot,j}^t \left(J_{tot,j}^t L_j + \Delta H_{tot,j}^t \right) \Delta t - E_{diss_f,AC}$			(6)
Dissipated energy in valves					
$E_{diss_v,AC} = \gamma a \sum_{v=1}^{N_v} \sum_{t=1}^{N_t} q_{ac,v}^t \Delta H_{tot,v}^t \Delta t$	(7)	$E_{diss_v,WL} = \gamma a \sum_{v=1}^{N_v} \sum_{t=1}^{N_t} q_{tot,v}^t \Delta H_{tot,v}^t \Delta t - E_{diss_v,AC}$			(8)
Dissipated energy in pumping stations					
$E_p^t = \gamma a \frac{q_{tot,p}^t H_{tot,p}^t}{\eta_p^t} \Delta t$	(9)	$E_{diss_p,AC} = \sum_{p=1}^{N_p} \sum_{t=1}^{N_t} E_p^t \left(1 - \eta_p^t \right) \frac{{}^t_{AC,p}}{{}^t_{tot,p}}$	(10)	$E_{diss_p,WL} = \sum_{p=1}^{N_p} \sum_{t=1}^{N_t} E_p^t \left(1 - \eta_p^t \right) \frac{{}^t_{WL,p}}{{}^t_{tot,p}}$	(11)
Recovered energy					
$E_{rec,w}^t = \gamma a q_{tot,w}^t H_{tot,w}^t \eta_{tot,w}^t \Delta t$	(12)	$E_{rec} = \gamma a \sum_{w=1}^{N_w} \sum_{t=1}^{N_t} q_{tot,w}^t H_{tot,w}^t \eta_{tot,w}^t \Delta t$	(13)	$E_{rec,AC} = \sum_{w=1}^{N_w} \sum_{t=1}^{N_t} E_{rec,w}^t \frac{{}^t_{AC,w}}{{}^t_{tot,w}}$	(14)
Recovered energy		**Dissipated energy in turbines**			
$E_{rec,WL} = E_{rec} - E_{rec,AC}$	(15)	$E_{diss_w,AC} = \sum_{w=1}^{N_w} \sum_{t=1}^{N_t} E_{rec,w}^t \eta_{tot,w}^t \frac{{}^t_{AC,w}}{{}^t_{tot,w}}$	(16)	$E_{diss_w,WL} = \sum_{w=1}^{N_w} \sum_{t=1}^{N_t} E_{rec,w}^t \eta_{tot,w}^t - E_{diss_w,AC}$	(17)
Dissipated energy in consumption nodes with water losses					
$E_{diss_n,WL} = \gamma a \sum_{n=1}^{N_n} \sum_{t=1}^{N_t} q_{tot,n}^t \left(H_{tot,n}^t - z_0 \right) \Delta t - E_{min} - E_{sur}$	(18)				

and the proposed modified energy balance algorithm. The modified energy balance is available to run in a computational energy balance tool, developed by Carneiro (2023) and detailed in Appendix A.

Reference elevation

The energy balance calculation requires the definition of the reference elevation (z_0) to compare systems with different elevations. This is an important aspect since this elevation significantly affects the values of the energy balance components and the energy efficiency performance metrics. Several different definitions of reference-elevation can be found in literature in the context of the energy balance, such as the minimum system elevation (Cabrera et al. 2010; Carriço et al. 2014; Mamade et al. 2017, 2018), the minimum consumption node elevation (Walski 2016), or the weighted average consumption node elevation (Mamade 2019). However, to the authors' knowledge, the concern with the selection of the reference elevation has never been mentioned in the context of using surplus energy to assess the service flexibility (Prasad and Park 2004; Sousa et al. 2022; Todini 2000).

The most commonly used definition of reference elevation is the minimum system elevation, which can be either the lowest system demand node elevation or the lowest water source level. Though Mamade et al. (2017) considered the reference elevation equal to the minimum node elevation, Mamade (2019) discussed that this might have consequences on the interpretation of the energy efficiency metrics for the diagnosis of the system and should be chosen to allow a fair comparison between different systems or alternatives. Mamade (2019) suggests using the weighted average consumption node elevation rather than the minimum elevation of the system.

A good definition of the reference elevation is crucial in the energy balance and resilience context, as results can lead to different interpretations of the system's performance. For example, the natural input energy is negative whenever the reference elevation exceeds the water source level. This situation can occur using either the minimum consumption node elevation or the weighted average consumption node elevation. To avoid this situation, the reference elevation should be the minimum elevation of the system.

Proposed surrogate resilience metrics based on the energy balance

As previously introduced, resilience is a complex and comprehensive subject, and its assessment should grasp different resilient characteristics. Concerning energy, a resilient system should efficiently use its resources and ensure service flexibility to supply water during high-demand periods, whilst avoiding the supply with energy in excess, preventing problems associated with high pressures (e.g. frequent bursts, high leakage levels).

The performance metrics aim at assessing the water-energy efficiency. Energy metrics from the literature are based on the concepts of minimum required energy and of energy in excess (E_{exc}). The latter refers to the

Table 3. Metrics to assess energy efficiency and service flexibility.

Resilience criteria	Energy metric obtained from the energy balance	Definition	
System energy efficiency	$E1$ – Energy in excess per unit of input volume (kWh/m^3)	$E1 = \frac{E_{exc}}{\ } = \frac{E_{inp} - E_{min} - E_{rec}}{\ }$	(20)
	$E2$ – Energy in excess per unit of authorised consumption (kWh/m^3)	$E2 = \frac{E_{exc}}{\ ^{tot}} = \frac{E_{inp} - E_{min} - E_{rec}}{\ ^{tot}}$	(21)
	$E3$ – Energy in excess index (-)	$E3 = \frac{E_{exc}}{E_{min}^{AC}} = \frac{E_{inp} - E_{min} - E_{rec}}{E_{min}^{AC}}$	(22)
Service flexibility for increase water demand	$E_{sur,1}$ – Ratio between surplus energy and energy in excess (-)	$E_{sur,1} = \frac{E_{sur}}{E_{exc}} = \frac{E_{sup} - E_{min}}{E_{inp} - E_{min}}$	(23)
	$E_{sur,2}$ – Surplus energy index (-)	$E_{sur,2} = \frac{E_{sur}}{E_{min}} = \frac{E_{sup} - E_{min}}{E_{min}}$	(24)

difference between the total input energy and the minimum required energy. These concepts are calculated through the components of the energy balance.

The five energy metrics that will be used in further analysis are presented in Table 3.

Several energy efficiency metrics have been suggested in the literature (Cabrera et al. 2010; Carriço et al. 2014; Mamade et al. 2017), those proposed by Mamade et al. (2017) being the following three:

- Energy in excess per unit of input volume (kWh/m^3), $E1$, representing the theoretical potential for energy reduction per unit of provided volume ($_{inp}$), Equation (20).
- Energy in excess per unit of authorised consumption (kWh/m^3), $E2$, representing the theoretical potential for energy reduction per unit of authorised consumption ($_{AC}$), Equation (21).
- Energy in excess index (dimensionless), $E3$, or ratio of the total energy in excess, representing the ratio of the theoretical energy in excess that is supplied to the system and the minimum required energy, Equation (22).

Both metrics $E1$ and $E2$ are always positive and should be as low as possible. The main difference is that $E2$ is capable of reflecting the effect of water loss reduction measures on energy efficiency. The third index, $E3$, is always positive, since the hydraulic head provided includes head losses.

Service flexibility accounts for the amount of surplus energy in the system, to comply with the service in a demand increase scenario. Todini (2000) developed a service flexibility index, described by Equation (25), accounting for the energy available at the consumption nodes above the minimum required to supply the consumers. Relating the index formulation with the components of the energy balance, Todini's resilience index can be described as the ratio of surplus energy (E_{sur}), per energy in excess (E_{exc}).

$$RI = \frac{\sum_{n=1}^{N} q_n \left(H_n - H_{req,n}\right)}{\sum_{r=1}^{Nr} q_r H_r + \sum_{b=1}^{Nb} \frac{P_b}{\gamma} - \sum_{n=1}^{N} q_n H_{req,n}} \tag{25}$$

Some improvements have been made to this metric, with the incorporations of diameter uniformity (Prasad and Park 2004) and topology coefficients (Sousa et al. 2022), aiming at making this index more suitable to assess other resilience characteristics along with service flexibility (Carneiro, Loureiro, and Covas 2023). Nonetheless, the base of calculation of service flexibility indices remains the surplus energy over the energy in excess, and the original Todini's index is considered herein as the ratio of surplus energy per energy in excess ($E_{sur,1}$), presented in Equation (23) of Table 3.

A new service flexibility metric, surplus energy index ($E_{sur,2}$), is also proposed and discussed herein. This metric is described by Equation (24) in Table 3 and reflects the surplus energy in the system concerning the minimum required energy.

Sensitivity analyses to surrogate resilience metrics

Case studies

Two case studies were used to apply the energy balance

Case study 1 is a simple system based on the NET1 network (Figure 2(a)), consisting of eight consumption nodes supplied by a constant-level storage tank (water level = 206 m) that needs a constant-speed pump to provide the required pressure at the nodes (minimum consumption node elevation = 210 m). Water losses represent 20% of the input water volume.

Case study 2 is a real Portuguese water distribution network (Figure 2(b)), comprising 96 km of pipes, two water sources and a variable-speed pumping station. Water losses are 14% of the input water volume, with 2/3 of real losses and 1/3 of apparent losses. The elevation of the highest consumption node is 47 m and the elevation of the lowest is 2 m.

Case study 1 is used to discuss the effect of the reference elevation on the results, to compare the original and the modified energy balances effect to water losses levels and types of pumping groups. Case study 2 aims at analysing the effect of the real and the apparent

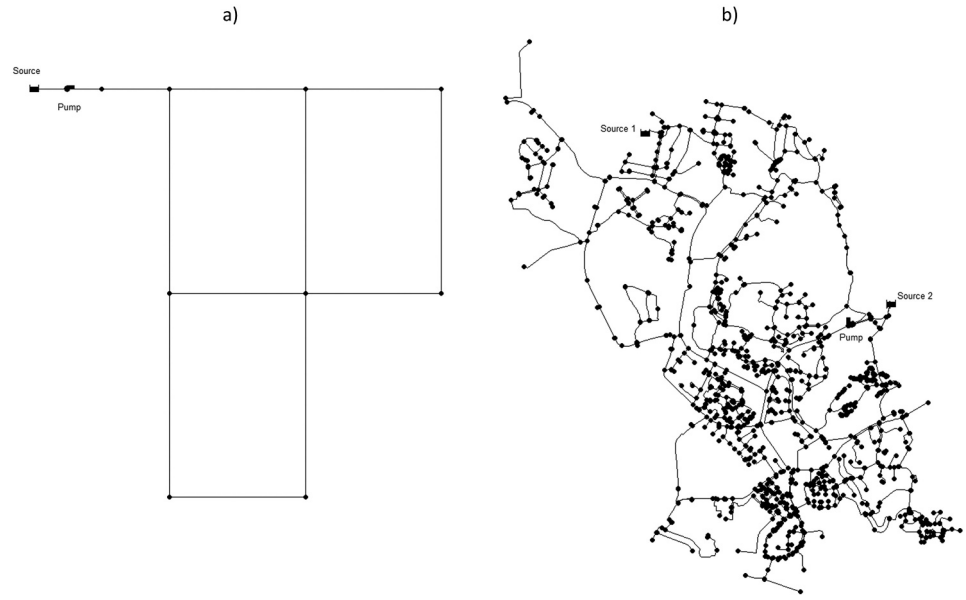


Figure 2. Case studies networks: a) case study 1; b) case study 2.

water losses in energy balance components and on the surrogate resilience metrics proposed. The main energy components of these case studies are summarised in Table 4. Reference elevation is defined as the system's minimum elevation.

Sensitivity analysis to reference elevation

A sensitivity analysis considering case study 1 is carried out to assess the importance of the reference elevation in the energy balance components and in the surrogate resilience metrics. Two reference elevations are considered: the minimum system elevation and the weighted average of consumption nodes elevation. Figure 3 presents the energy balance carried out considering the previous two reference elevations. The results are presented only by using the modified energy balance approach, since the effect of reference elevation is similar in both energy balance approaches.

Reference elevation should be defined as the minimum system elevation. If reference elevation is defined above the minimum system elevation, energy components depending on reference elevation are attenuated due to negative energy in nodes with elevation below the reference. These energy components are: the minimum required energy, Equation (3); the supplied energy to the consumers, Equation (2); and the dissipated energy in consumption nodes due to water losses, Equation (18). In addition, if the water source level is below the reference value, the natural input energy is negative, reducing total input energy (compare E_{tot} in Figure 3(a,b)). The other energy components are independent of the reference elevation, leading to equal dissipated energy due to continuous, local head losses and equipment ($E_{diss,AC}$ and $E_{diss,WL}$). To note that the surplus energy remains the same ($E_{sur} = 237,735 kWh$), independently of the considered reference elevation.

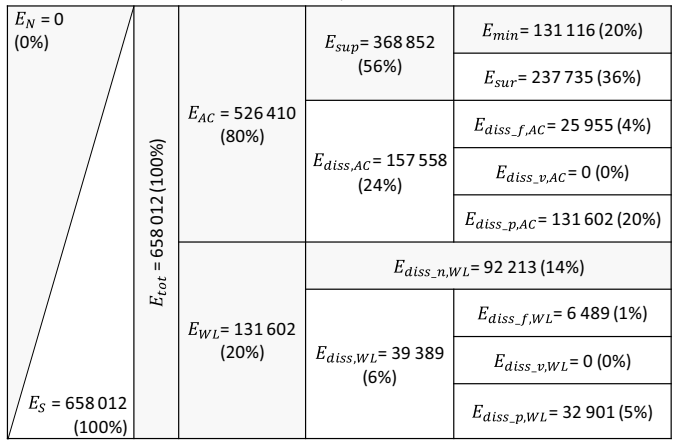
Reference elevation also considerably affects the energy efficiency and service flexibility metrics (Figure 4). Energy metrics $E1$, $E2$ and $E_{sur,1}$ have small variations (1–2%) with these definitions of reference elevation. As opposed to $E3$ and $E_{sur,2}$, which are particularly affected by the definition of the reference elevation (varying 15–37%), due to the direct impact of the reference elevation in the denominator (E_{min}).

Regarding energy efficiency criteria, a higher reference elevation (i.e. weighted average of consumption nodes elevation) decreases slightly the values of $E1$ and $E2$, indicating a more efficient system (Figure 4(a,b)). In opposition, $E3$ increases (Figure 4(c)), implying a less efficient system. Another important aspect is the higher variability in $E3$ to elevations than $E1$ and $E2$.

Table 4. Case studies characteristics.

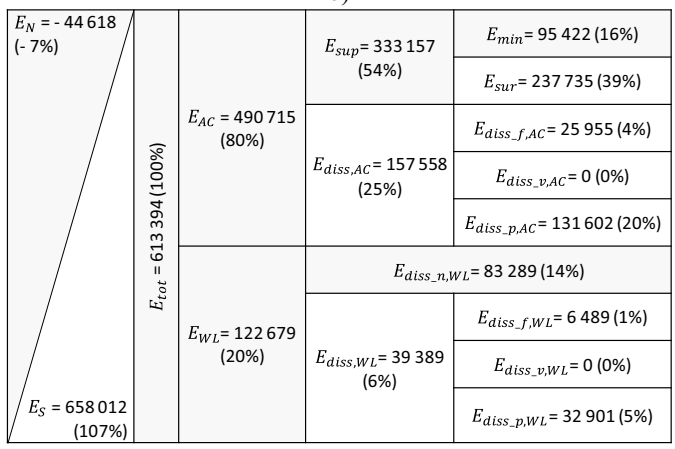
	Case study 1	Case study 2
Reference elevation (z_0) [m]	206	3
E_N [%]	0%	97%
E_S [%]	100%	3%
E_{AC} [%]	80%	86%
E_{WL} [%]	20%	14%
E_{exc}/E_{inp} [-]	0.8	0.5
$(E_{inp} - E_{min} + E_{diss_p,ac})/E_{exc}$ [-]	0.5	0.7

a)



Reference elevation (z_0) = 206 m

b)



Reference elevation (z_0) = 213 m

Figure 3. Energy balance, using the modified approach, for: a) minimum system elevation as the reference elevation, kWh [%]; b) weighted average of consumption nodes elevation as the reference elevation, kWh [%]. Shaded components highlight the differences in the results.

In terms of service flexibility, both metrics ($E_{sur,1}$ and $E_{sur,2}$) have higher results for higher reference elevations. $E_{sur,2}$ appears to be more sensitive to the reference elevation than $E_{sur,1}$ as a consequence of the decrease of the minimum energy due to the higher reference elevation whilst the surplus energy remains the same.

As discussed, the reference elevation definition has a major impact on energy balance results and surrogate resilience metrics. Using the system's minimum elevation as the reference provides a fair measure of energy, while using the weighted average node elevation skews the metrics due to energy attenuation effects. The analysis has demonstrated that the best definition for reference elevation is the minimum value of the system. This assumption avoids negative energy contribution due to consumption nodes and water sources located below the reference elevation.

Sensitivity analysis to water losses levels

The original and the modified energy balances are calculated for different consumption scenarios applied to case study 1 (Figure 2(a)), considering the reference elevation equal to the minimum elevation of the system.

The first scenario refers to case study 1 without water losses, and the energy balances are presented in Figure 5. In this case, the system's hydraulic head (H_{tot}) equals the authorized consumption hydraulic head (H_{ac}) (Figure 1). As such, the energy balances obtained by both approaches give the same results (Figure 5), demonstrating that the results are coherent in the ideal system (i.e. without water losses). The same conclusion would be obtained in a gravity system without water losses. Similarly, the surrogate energy metrics studied herein provide the same results independently of the used energy balance calculation approach. As the total

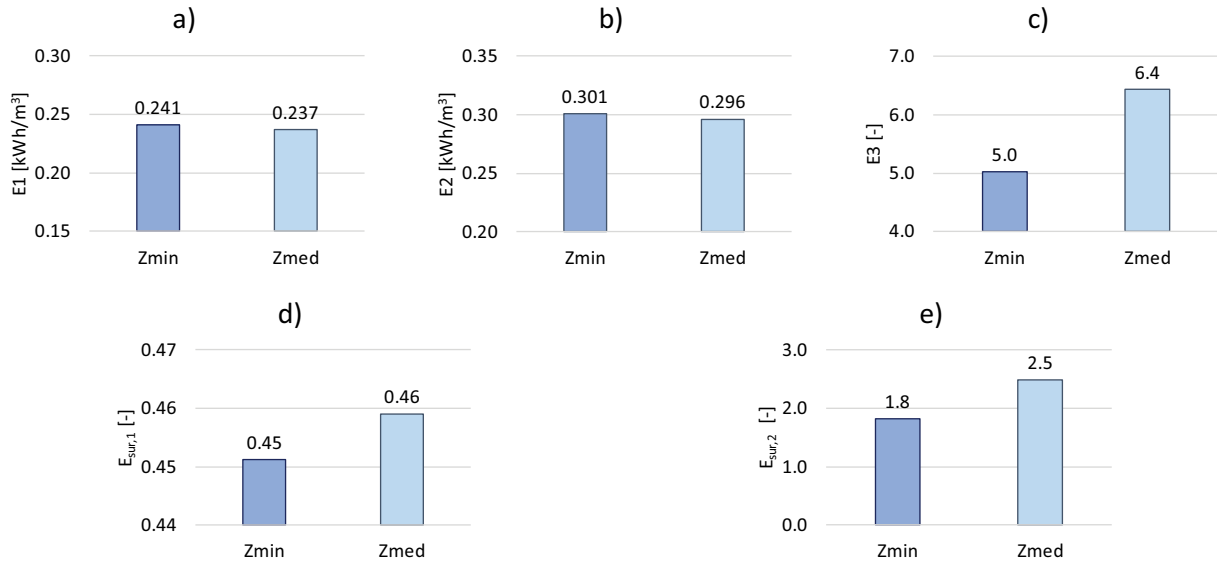


Figure 4. Energy metrics for different reference elevations (minimum system elevation, Zmin, and weighted average of consumption nodes elevation, Zmed): a) $E1$ – energy in excess per unit of input volume (kWh/m^3); b) $E2$ - energy in excess per unit of authorised consumption (kWh/m^3); c) $E3$ – energy in excess index (-); d) $E_{sur,1}$ - ratio between surplus energy and energy in excess (-); e) $E_{sur,2}$ - surplus energy index (-).

a)

E_N = 0 (0%)	E_{tot} = 569 580 (100%)	E_{AC} = 569 580 (100%)	E_{sup}= 410 015 (72%)	E_{min}= 131 116 (23%)
				E_{sur}= 278 899 (49%)
			$E_{diss,AC}$= 159 564 (28%)	$E_{diss_f,AC}$= 17 169 (3%)
				$E_{diss_v,AC}$= 0 (0%)
				$E_{diss_p,AC}$= 142 395 (25%)
		E_{WL}= 0 (0%)	$E_{diss_n,WL}$= 0 (0%)	
			$E_{diss,WL}$= 0 (0%)	$E_{diss_f,WL}$= 0 (0%)
				$E_{diss_v,WL}$= 0 (0%)
E_S = 569 580 (100%)				$E_{diss_p,WL}$= 0 (0%)

Reference elevation (z_0) = 206 m

b)

E_N = 0 (0%)	E_{tot} = 569 580 (100%)	E_{AC} = 569 580 (100%)	E_{sup}= 410 015 (72%)	E_{min}= 131 116 (23%)
				E_{sur}= 278 899 (49%)
			$E_{diss,AC}$= 159 564 (28%)	$E_{diss_f,AC}$= 17 169 (3%)
				$E_{diss_v,AC}$= 0 (0%)
				$E_{diss_p,AC}$= 142 395 (25%)
		E_{WL}= 0 (0%)	$E_{diss_n,WL}$= 0 (0%)	
			$E_{diss,WL}$= 0 (0%)	$E_{diss_f,WL}$= 0 (0%)
				$E_{diss_v,WL}$= 0 (0%)
E_S = 569 580 (100%)				$E_{diss_p,WL}$= 0 (0%)

Reference elevation (z_0) = 206 m

Figure 5. Original and modified energy balances for case study 1, without water losses (scenario 1): a) original energy balance, kWh [%], b) modified energy balance, kWh [%].

input volume is the same as the authorised volume, $E1$ and $E2$ provide the same results.

The second simulation scenario corresponds to a gravity system of case study 1, with 20% of water losses, in which a reservoir replaces an existing pumping station with a total head equal to the downstream pumping station head. Note that the minimum elevation of the system is now the lowest elevated consumption node, changing the reference elevation.

E_{AC} and E_{WL} have the same results in both approaches, being the respective percentages in agreement with those from the water balance. H_{tot} are the same in both methods, despite the differences in the energy components in which E_{AC} and E_{WL} are decomposed. Surplus energy is higher in the original approach (E_{sur} = 271,288 kWh, Figure 6(a)), due to the lower energy dissipation associated with pipe friction ($E_{diss_f,ac}$ = 17,169 kWh, Figure 6(a)), since the flow rate only includes authorised consumption.

In the modified approach, the surplus energy is smaller (E_{sur} = 262,502 kWh, Figure 6(b)), as more energy is dissipated due to pipe friction ($E_{diss_f,ac}$ = 25,956 kWh, Figure 6(b)) from the combined flow rate (authorised consumption plus water losses). The same result is obtained when summing E_{sur} and $E_{diss_f,ac}$ for both approaches (288,457 kWh). The fact is that the E_{sur} decrease in the modified approach is compensated by the increase of $E_{diss_f,ac}$. Similarly, in energy associated with water losses, the difference in dissipated energy in consumption nodes with water losses is compensated by the dissipated energy due to pipe friction (sum of $E_{diss_n,WL}$ and $E_{diss_f,WL}$ equals 99,440 kWh in both approaches). This situation is schematically represented in the diagram of the simplified Figure 1.

The effect of using different energy balance approaches on the surrogate resilience metrics is presented in Figure 7. As the input energy and the minimum required energy remain the same, the used

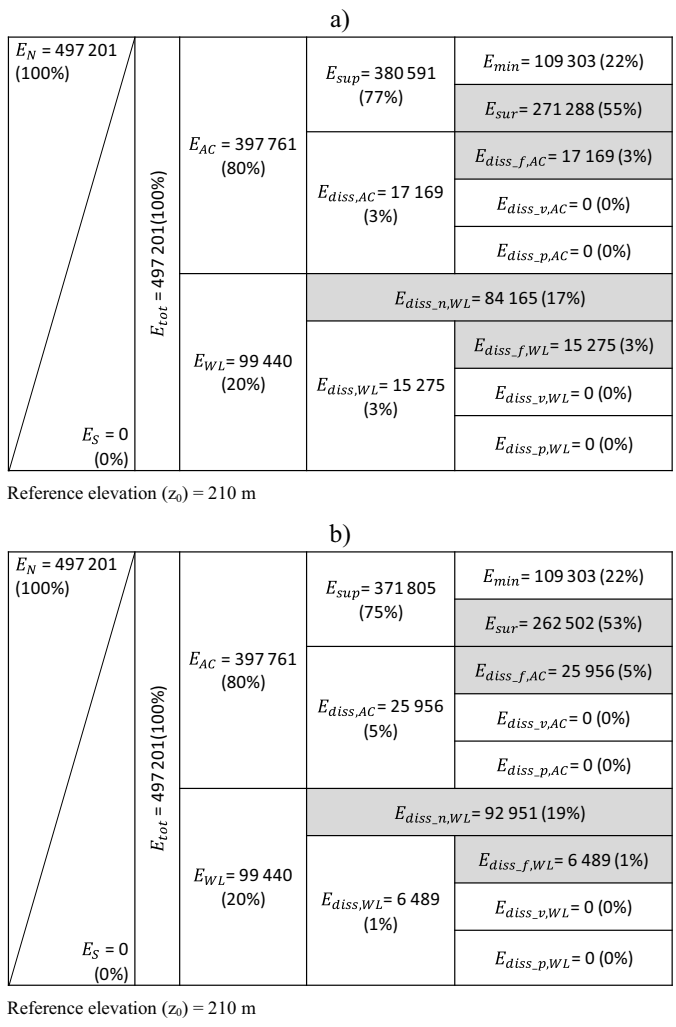


Figure 6. Original and modified energy balances for gravity case study 1, with 20% of water losses (scenario 2): a) original energy balance, kWh [%], b) modified energy balance, kWh [%]. Shaded components highlight the differences in the results.

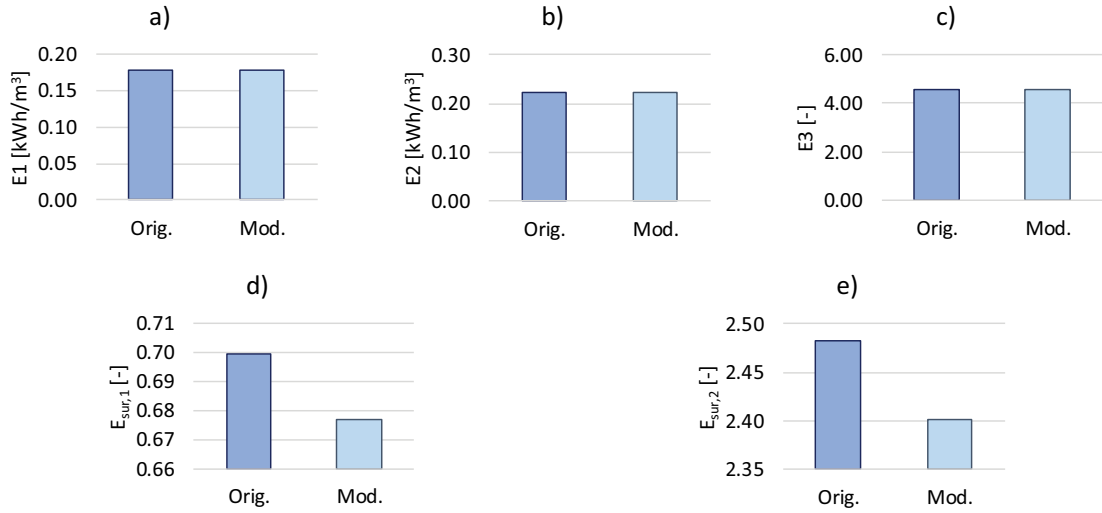


Figure 7. Scenario 2 surrogate resilience metrics for both approaches (original and modified): a) $E1$ – energy in excess per unit of input volume (kWh/m^3); b) $E2$ – energy in excess per unit of authorised consumption (kWh/m^3); c) $E3$ – energy in excess index (-); d) $E_{sur,1}$ – ratio between surplus energy and energy in excess (-); e) $E_{sur,2}$ – surplus energy index (-).

approach does not affect energy efficiency metrics (Figure 7(a,b,c)). However, in terms of service flexibility, the use of different approaches alter the metrics results (Figure 7(d,e)). This is because the surplus energy component is higher in the original than in the modified approach. As the original approach uses H_{ac} to calculate the components associated with authorised consumption, in the particular case $E_{sur,2}$, the metric calculation infers the theoretical service flexibility in the optimal case of no water losses.

Sensitivity analysis to shaft energy contribution and types of pumping groups

Scenarios 3 and 4 correspond to Case study 1 with 20% of water losses and different types of pumps. Scenario 3 comprises a variable-speed pump, while scenario 4 is a constant-speed pump. The pumps' efficiency is assumed to be the same (75%). The energy balances for both approaches are presented in Figures 8 and 9, respectively.

The original energy balance approach distributes E_{AC} through its subcomponents in an ideal (no water losses) situation, particularly adjusting E_{sur} and $E_{diss_f,ac}$, by considering the H_{ac}. Consequently, the water losses components, $E_{diss_n,WL}$ and $E_{diss_f,WL}$, are also adjusted to maintain the H_{tot}.

In scenario 3, the variable-speed pump provides the same downstream pressure with the authorised consumption and the total system input flow rate. As a result, the energy diagrams are similar to the gravity system (Figure 1). Similar to scenario 2 (Figure 6), E_{AC} and E_{WL} have the same results but differ in their components (Figure 8).

The major differences between approaches are observed in scenario 4. In the original energy balance, the energy associated with water losses (E_{WL}) corresponds only to 15% of the input energy and the energy associated with authorised consumption (E_{AC}) is 85% (Figure 9a), disagreeing with the ratio given by the water balance. Also, all components of the energy balance associated with authorised consumption are calculated using H_{ac}, with the exception of the dissipated energy in pumps ($E_{diss_p,ac}$). As in Equation (10), $E_{diss_p,ac}$ is calculated as the ratio of authorised consumption volume of the total inefficiency of the pumping energy (E_p), which in turn is obtained using H_{tot}, see Equation (9).

For constant-speed pumps (scenario 4), H_{tot} is different to H_{ac}, since different flow rates result in different downstream pressures (i.e. authorised consumption has higher downstream pressure whilst the total flow rate has lower downstream pressure). This difference leads to a change in the hydraulic head of the dissipated energy associated with authorised consumption ($E_{diss_p,ac}$) which changes the ratio of energy associated with authorised consumption (E_{AC}). Lipiwattanakarn et al. (2021) reached the conclusion that the ratio of energy associated with water losses to the total system energy is slightly higher than the water losses ratio. However, the authors also rely on the same assumption made by Mamade et al. (2017, 2018). This problem is not present in the modified approach, since it uses the H_{tot}

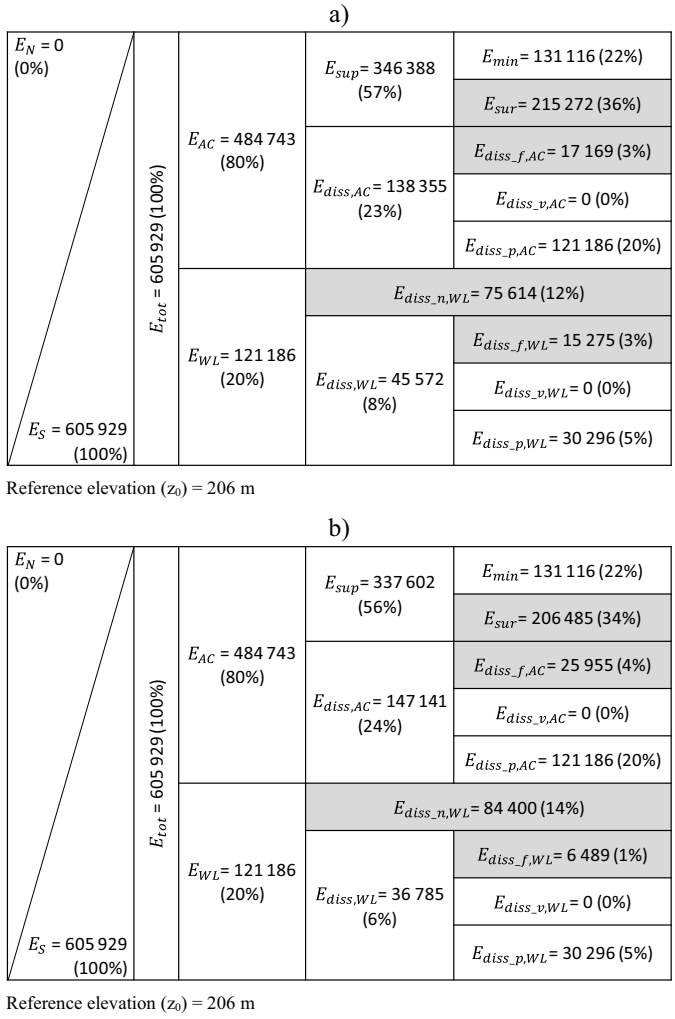


Figure 8. Original and modified energy balances for case study 1, with 20% of water losses and variable-speed pump (scenario 3): a) original energy balance, kWh [%], b) modified energy balance, kWh [%]. Shaded components highlight the differences in the results.

to calculate the components of the energy balance associated with authorised consumption. As such, only the modified approach must be used in systems containing constant-speed pumps.

The effect of using different energy balance approaches on surrogate resilience metrics is similar to that presented in the previous section. For scenarios 3 and 4, the used energy balance approach does not affect the energy efficiency metrics ($E1$, $E2$ and $E3$), though it has a high impact on the service flexibility metrics ($E_{sur,1}$ and $E_{sur,2}$).

Sensitivity analysis of the water loss reduction on energy efficiency and service flexibility

Reduction of water losses is an important management policy to improve water-use and energy efficiency. Water losses can be real (e.g. physical) or apparent (e.g. meter reading errors, data handling errors, unauthorized consumption). Actions to reduce water losses can focus on repairing leakage, reducing pressures, or minimizing erroneous readings and data processing issues.

Three water loss scenarios are considered for case study 2 (Table 5): the *status quo*; the 50% reduction of real water losses; and the 50% reduction of apparent water losses. Real and apparent losses are modelled as distinct demand categories, in EPANET. The reduction of these losses is achieved by modifying the demand pattern associated with each category. The effect of these scenarios on the energy balance, when using the modified approach, is presented in Figure 10.

The 50% reduction of real water losses (scenario 2) proportionally decreases the total input energy as well as the dissipated energy, maintaining the energy associated with authorized consumption (E_{AC}) and the minimum required energy (E_{min}) the same as for the *status quo*, scenario 1 (Figure 10(a,b)). Accordingly, the surplus energy (E_{sur}) is slightly higher and the energy dissipated due to

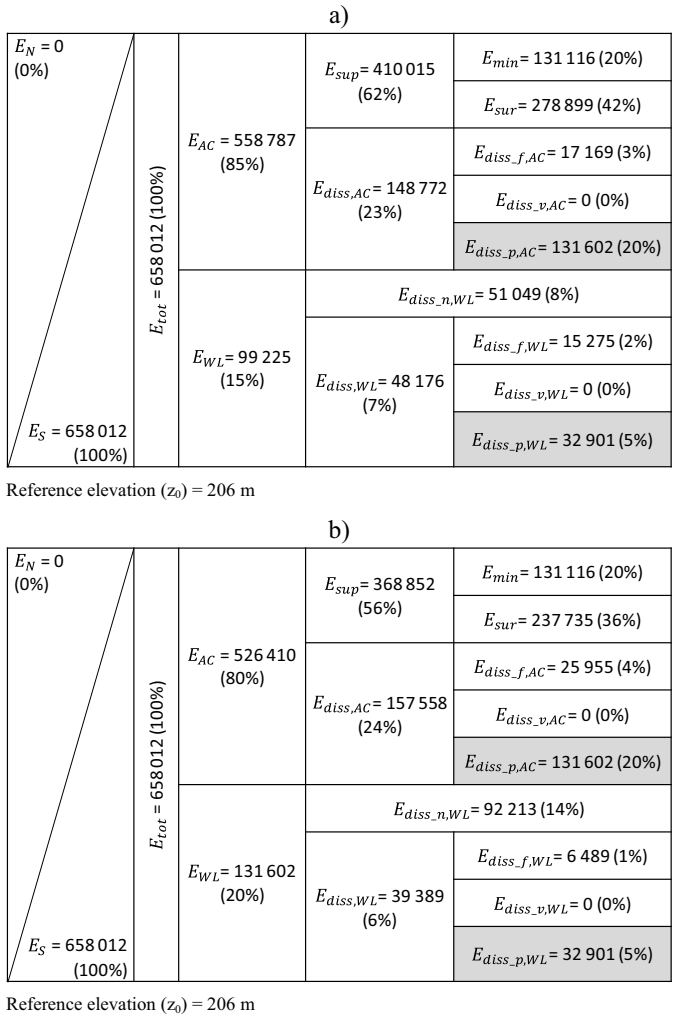


Figure 9. Original and modified energy balances for case study 1, with 20% of water losses and constant-speed pump (scenario 4): a) original energy balance, kWh [%], b) modified energy balance, kWh [%]. Shaded components highlight the differences in the results.

Table 5. Input water, authorised consumption and water losses description for each water loss scenario.

Scenario	Scenario 1 *Status quo*	Scenario 2 50% reduction of real water losses	Scenario 3 50% reduction of apparent water losses
Input water, m^3	7,317,038	6,971,905	7,317,038
Authorised consumption, m^3	6,281,641	6,281,641	6,454,207
Total water loss, m^3 **(%)**	1,035,396 (14.2%)	690,263 (9.9%)	862,830 (11.8%)
Real loss, m^3 **(%)**	690,264 (9.4%)	345,132 (5.0%)	690,264 (9.4%)
Apparent loss, m^3 **(%)**	345,132 (4.7%)	345,132 (5.0%)	172,566 (2.4%)

pipe friction ($E_{diss_f,AC}$) is lower, compensating each other. As expected, the water loss energy component (E_{WL}) is lower.

In the reduction of 50% apparent water losses, scenario 3 transfers the apparent water losses to authorized consumption (Figure 10(a,c)). As such, the total input energy remains the same but is redistributed from the water losses related components to the authorized consumption components. The energy associated with authorized consumption (E_{AC}) increases, such as the minimum required energy (E_{min}) and the surplus energy (E_{sur}).

The effect on energy efficiency and service flexibility metrics for both energy balance calculation approaches are observed in Figure 11.

*E*1, *E*2 and *E*3 provide the same results regarding the calculation approach used and are similarly affected by the reduction in water losses. Since *E*2 is more sensitive to water loss reduction (i.e. real water loss reduction reduces

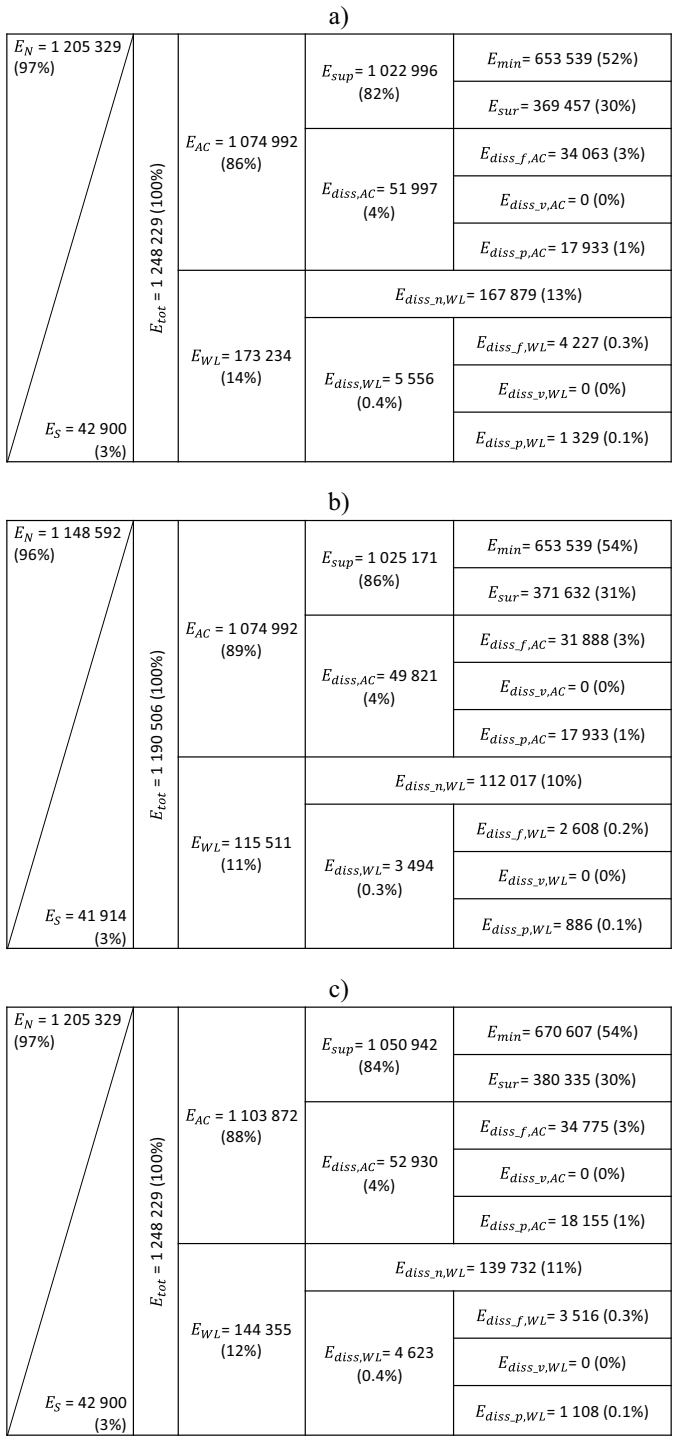


Figure 10. Effect of the reduction of real and apparent water losses in the energy balance: a) *status quo* (scenario 1); b) 50% reduction of real water losses (scenario 2); c) 50% reduction of apparent water losses (scenario 3).

*E*2 by 10% and *E*1 only by 5%), its results are presented in Figure 11(a), demonstrating the energy efficiency improvement with the reduction in water losses.

Regarding service flexibility for an increase in water demand, the ratio between surplus energy and energy in excess ($E_{sur,1}$) demonstrates there is an improvement with the reduction of water losses (Figure 11(b)). Although $E_{sur,1}$ results are different in both approaches, resulting from the surplus energy difference, the same conclusions can be drawn.

As for the surplus energy index ($E_{sur,2}$) (Figure 11(c)), the original approach does not change the result with a reduced water loss. This is a consequence of the calculation process: by accounting for HGL_{ac}, the metric

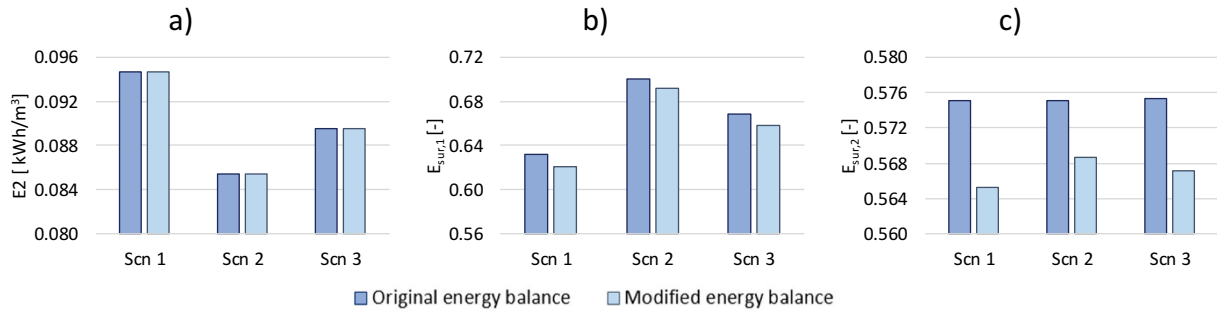


Figure 11. Impact of the reduction of real and apparent water losses in energy efficiency metrics: a) $E2$ – energy in excess per unit of authorised consumption (kWh/m^3); b) $E_{sur,1}$ – ratio between surplus energy and energy in excess (-); c) $E_{sur,2}$ – surplus energy index (-).

reflects the maximum theoretical ratio between surplus energy and the minimum required energy. With the modified approach, the metric reflects the real ratio between surplus energy and the minimum required energy. By reducing water losses, $E_{sur,2}$ calculated with the modified approach increases and approximates to the maximum theoretical $E_{sur,2}$ provided by the original approach.

Discussion

Water, energy and resilience interconnection is a fundamental subject to be addressed. A resilient system should be robust, flexible, efficient, reliable, redundant and autonomous. Energy is implied in the resilience of drinking water systems (Liu et al. 2017), since a resilient system should be energy efficient and at the same time have service flexibility to continue to water demand increase events. Energy in excess is a common factor between energy efficiency and service flexibility. To recall that energy in excess is disaggregated in surplus energy and dissipated energy, due to water losses, continuous and singular head losses and equipment inefficiencies.

From an energy efficiency point of view, the system should have minimal water losses, equipment inefficiencies and dissipated energy, and recover most of the surplus energy. From the energy efficiency metrics (Table 3), $E1$ and $E2$ provide similar information, with $E2$ being more sensitive to assess the impact of leakage control measures, in agreement with Mamade (2019). $E3$ is considerably more susceptible to topologies differences. Therefore, $E2$ is suggested herein to assess energy efficiency. Another benefit of $E2$ is the possibility to disaggregate it into the different aspects that compose energy in excess (Appendix B), allowing a more detailed diagnosis of the system's inefficiencies.

From a service flexibility perspective, systems with higher surplus energy are more resilient to water demand increase (Carneiro, Loureiro, and Covas 2023). However, overdesigned systems with high surplus energy are likely to have problems associated with high pressures (e.g. frequent bursts, high leakage levels), decreasing infrastructure integrity and therefore the system's robustness. The ratio between surplus energy and energy in excess ($E_{sur,1}$) provides the amount of excess energy available as surplus energy. Higher values indicate higher resilience, demonstrating that the majority of the energy in excess should be in the form of surplus energy, highlighting the importance of a system with lower water losses and dissipated energy. However, it does not assess the amount of surplus energy in the system, whether high or low. The surplus energy index ($E_{sur,2}$), provides an assessment of how much surplus energy exists in the system relative to the minimum required energy, reflecting the amount of energy available in a demand increase scenario. Due to the complementary metrics, both are suggested to assess the service flexibility. $E_{sur,1}$ is more suitable to compare different systems while $E_{sur,2}$ is more suitable to compare improvement measures of the same system due to its susceptibility to higher topology differences.

Reference values are relevant to comprehend whether the obtained metrics represent a good, average or poor performance. In the comparison of systems, a gravity system is typically more energy efficient than a system that requires water abstraction. Under the Portuguese project Avaler+ 'Assessment of energy efficiency and sustainability in urban water systems' (Loureiro et al. 2020), reference values for $E2$ have been proposed based on the metric variation of 13 different Portuguese drinking water and wastewater systems (Pisoeiro et al. 2020). For $E_{sur,1}$ and $E_{sur,2}$, there are no reference values in the literature, being suggested herein. Table 6 presents the reference values indicated for the performance assessment of the surrogate resilience metrics.

Table 6. Suggestion of reference values for surrogate resilience metrics.

		Good performance	Average performance	Poor performance
E_2	Abstraction, transport and distribution	]0;0.40]	]0.40;1.00]	]1.00; +∞]
	Transport and distribution	]0;0.15]	]0.15;0.30]	]0.30; +∞]
$E_{sur,1}$	Abstraction, transport and distribution	[1;0.60]	]0.60;0.30]	]0.30; 0]
	Transport and distribution	[1;0.75]	]0.75;0.50]	]0.50; 0]
$E_{sur,2}$		]0;0.75]	]0.75;1.00]	]1.00; +∞]

Concerning $E_{sur,1}$, higher results indicate lower dissipated energy in the system, and thus more surplus energy available in case of a demand increase. However, dissipated energy is natural to the systems, particularly due to pipe friction, valve headlosses and pumping inefficiencies. In transport and distribution systems, it is suggested that between having a system with no dissipated energy ($E_{sur,1} = 1$) and dissipated energy equal to a quarter of the total input energy ($E_{sur,1} = 0.75$) the performance is good. If over half the input energy is dissipated ($E_{sur,1} = 0.50$), then the system has poor performance. Once again, a more tolerant threshold should be assumed in systems requiring abstraction since the pumping station will always be associated with dissipated energy. In abstraction, transport and distribution, the lower limit of good performance is 0.6, and the poor performance upper limit is 0.3.

$E_{sur,2}$ is the difference between the supplied energy at the node and the minimum required energy, being indifferent to pump inefficiencies. As such, a single set of reference values is suggested. If $E_{sur,2}$ is equal to 0, the supplied energy equals the minimum required energy and there is no additional energy available to be used in case of a demand increase. If $E_{sur,2} = 1$the supplied energy is equal to double of the minimum required energy, indicating that the system may be overdesigned. A threshold of 0.75 of the minimum energy is proposed to alert the approximation of high surplus energy. As discussed previously, the original approach of the energy balance returns a surplus component in an ideal (no water losses) system. As such, $E_{sur,2}$ calculated with the original approach components provides the maximum theoretical ratio between surplus energy and minimum energy the system may reach in the ideal case of zero water losses. Promoting improvement measures to reduce water losses will approximate the calculated values of $E_{sur,2}$ with the modified and the original approaches.

Note that the original approach of the energy balance returns a surplus component in an ideal (no water losses) system. As such, $E_{sur,2}$ calculated with the original approach components provides the maximum theoretical ratio between surplus energy and minimum energy the system may reach, in the ideal case of zero water losses. Promoting improvement measures to reduce water losses will bring closer $E_{sur,2}$ calculated with the modified approach, to $E_{sur,2}$ calculated with the original approach.

Conclusions

In summary, it was recognised that energy is fundamental in the resilience assessment of drinking water systems, particularly regarding the system's energy efficiency and service flexibility to increase water demands. The energy balance calculation allows the computation of energy components fundamental for calculating energy efficiency and service flexibility metrics. $E2$ is suggested as the metric most suitable to assess energy efficiency, and both $E_{sur,1}$ and $E_{sur,2}$ are complementary in assessing service flexibility.

The energy balance calculation approach offers different information. The modified energy balance provides a more realistic energy balance, by using the real hydraulic head of the system with water losses. The original energy balance provides energy components associated with authorised consumption in an ideal (no water losses) system. Consequently, systems with constant-speed pumps fail to agree on the energy associated with authorised consumption and water losses with the respective percentages from the water balance.

The modified energy balance concerns the complete assessment developed by Mamade et al. (2018), which requires water utilities to have a numerical model of their systems to implement it effectively. If the model is unavailable, it is recommended that utilities apply the simplified assessment, as in Mamade et al. (2018).

Reference values for the metrics were proposed, but the application of the metrics to other case studies, along with a detailed analysis, may provide better adjustments in the threshold values. The impact of energy recovery in the energy balance and surrogate energy metrics is also a step to be made in the future. Another aspect to be considered in the future is the implementation of turbines, that can be numerically simulated by control valves and the respective recovery energy incorporated in the developed tool.

Notations

α	Conversion factor from Ws to kWh (1/(1000x3600))
^{tot}	Volume of input water
$\Delta H^{t}_{tot,j}$	Singular head losses (m/m)

Δt	Time step (s)
AC	Authorised consumption (or value referent to authorised consumption model)
E_{AC}	Energy associated with authorised consumption (kWh)
$E_{diss_f,AC}$	Dissipated energy due to pipe friction associated with authorised consumption (kWh)
$E_{diss_n,WL}$	Dissipated energy associated with water losses at consumption nodes (kWh)
$E_{diss_p,WL}$	Dissipated energy in pumping stations associated with water losses (kWh)
$E_{diss_w,WL}$	Dissipated energy in micro-hydro power plants associated with water losses (kWh)
$E_{diss_v,WL}$	Dissipated energy in valves associated with water losses (kWh)
E_{min}	Minimum required energy (kWh)
E_p^t	Input energy of pump p at time t (kWh)
$E_{rec,AC}$	Recovered energy associated with authorised consumption (kWh)
E_S	Shaft Input Energy (kWh)
E_{sur}	Surplus Energy (kWh)
$E_{sur,2}$	Surplus energy index (-)
E_{WL}	Energy associated with water losses (kWh)
$E2$	Energy in excess per unit of authorised consumption (kWh/m^3)
H	Hydraulic head (m)
H_{tot}	Hydraulic head of the system with water losses (m)
$H_{tot,p}^t$	Pump head elevation (m)
j	Pipe
L_j	Length of pipe j (m)
N_r	Number of reservoirs
p	Pump
$q_{tot,j}^t$	Pipe flow rate (m^3/s)
$q_{tot,n}^t$	Node total demand (m^3/s)
$q_{tot,r}^t$	Reservoir flow rate (m^3/s)
r	Reservoir
tot	Value referent to model with authorised consumption and water losses
w	Micro-hydro power plants
z_0	Reference elevation (m)
$_{AC}$	Volume of authorised consumption (m^3)
γ	Water specific weight (N/m^3)
$\Delta H_{tot,v}^t$	Head loss at valve v (m)
η_p^t	Efficiency of pump p at time t
E	Energy (kWh)
$E_{diss,AC}$	Dissipated energy associated with authorised consumption (kWh)
$E_{diss_f,WL}$	Dissipated energy due to pipe friction associated with water losses (kWh)
$E_{diss_p,AC}$	Dissipated energy in pumping stations associated with authorised consumption (kWh)
$E_{diss_w,AC}$	Dissipated energy in micro-hydro power plants associated with authorised consumption (kWh)
$E_{diss_v,AC}$	Dissipated energy in valves associated with authorised consumption (kWh)
$E_{diss,WL}$	Dissipated energy associated with water losses (kWh)
E_N	Natural Input Energy (kWh)
E_{rec}	Recovered energy (kWh)
$E_{rec,WL}$	Recovered energy associated with water losses (kWh)
E_{sup}	Supplied energy (kWh)
$E_{sur,1}$	Ratio between surplus energy and energy in excess (-)
E_{tot}	Total System Energy (kWh)
$E1$	Energy in excess per unit of input volume (kWh/m^3)
$E3$	Energy in excess index (-)
H_{ac}	Hydraulic head relative to the authorised consumption simulation (m)
$H_{tot,n}^t$	Node total head (m)
$H_{tot,r}^t$	Reservoir total head (m)
$J_{tot,j}^t$	Unit head loss in pipe j (m/m) at time t
n	Node
N_t	Number of time steps
$\frac{p_{req,n}}{\gamma}$	Minimum required pressure head (m)
$q_{ac,n}^t$	Node authorised consumption (m^3/s)
$q_{tot,p}^t$	Pump flow rate (m^3/s)
$q_{tot,v}^t$	Valve flow rate (m^3/s)
t	Time
v	Valve
WL	Water losses
z_n	Node elevation (m)

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Data availability statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.8376917.

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Appendices

Appendix A

Computational tools have been developed to support the operation and management of water systems (Carriço, 2020; 2023a; 2023b). To support management in terms of energy balance, a computational tool of the water-energy balance, Energy Balance Tool, has been developed in Python, using the WNTR package (Klise et al., 2017) to run the EPANET (Rossman et al., 2020). Energy Balance Tool version 0.0.1 is available at Carneiro, Loureiro, and Covas (2023); this version does not incorporate the energy balance components related to the recovered energy or turbines.

The tool receives an EPANET file (.inp) and requests the input data presented and explained in Table A1. The energy balance is calculated with the suggested modifications. The tool also calculates the surrogate resilience metrics. The initial page of the tool is presented in Figure A1.

The computational energy balance tool works with both pressure driven and demand driven approaches. In demand driven approach, water losses are equally spatially distributed, since they are contemplated in the demand multiplier, in the EPANET hydraulic options. In pressure driven approach, water losses are computed as emitters, making nodes with higher pressure have more water losses. As default, the tool defines Minimum pressure and Pressure exponent as default as 0.1 and 1.18, respectively (Mamade 2019). This impacts the flow and water head in the nodes, though the energy balance calculations remain the same. Results vary slightly between approaches though the final results are similar to each other. The tool uses the minimum system elevation as the reference elevation.

Table A1. Input data required by the energy balance tool to run the water-energy balance.

Input parameter	Description
Directory	Selection of the working directory, to which the output files are extracted
INP file	Selection of the EPANET file
EPANET model has water losses	The tool asks if the model imported has water losses. Accordingly, the tool generates a new model with or without water losses, implementing or removing them, respectively, either as an increase in demand multiplier if the model runs with a demand driven analysis, or through emitters if the model runs with a pressure driven analysis.
Model Type	The tool asks the analysis method: Pressure Driven or Demand Driven. By default, the tool runs in demand driven analysis.
Water losses percentage [%]	Percentage of water losses of the system. The tool generates a new model with or without the percentage of water losses given.
Required pressure [mH_2O]	The minimum required pressure-head can be specified by the user; by default, it is assumed equal to 20 m.

The software outputs two Excel files and an INP file into the Directory selected on the Input page. The first Excel file exports the calculated component values of the energy balance and the percentage relative to the input energy. The second Excel file exports the energy efficiency performance metrics values. The INP file corresponds to the complementary network model needed to calculate the energy balance.

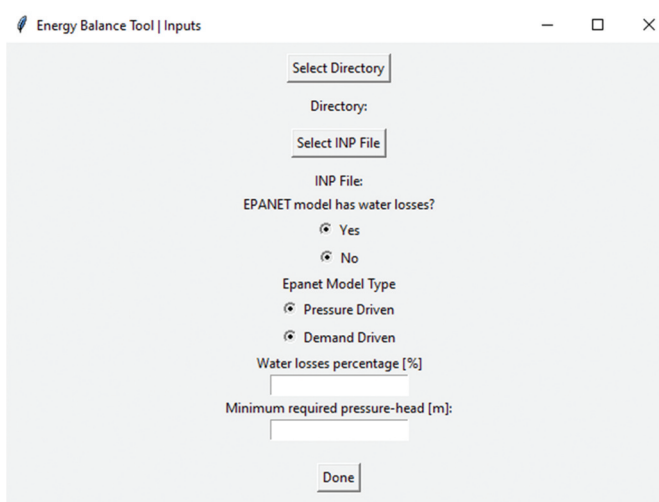

Figure A1. Energy balance tool input page.

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Appendix B

E2 (network) – natural energy in excess per unit of authorised consumption (kWh/m^3).

$$E2(network) = \frac{\left(E_{sur} + E_{diss_f,AC} + E_{diss_v,AC}\right)}{AC} \tag{B1}$$

E2 (pumps) – natural energy in excess per unit of authorised consumption (kWh/m^3).

$$E2(pumps) = \frac{E_{diss_p,AC}}{AC} \tag{B2}$$

E2 (losses) – shaft energy in excess per unit of authorised consumption (kWh/m^3).

$$E2(losses) = \frac{\left(E_{WL} - E_{rec,WL}\right)}{AC} \tag{B3}$$