



# Energy efficiency assessment in collective irrigation systems using water and energy balances: methodology and application

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## Abstract

Many collective irrigation systems have been operating for decades, facing high degradation of existing infrastructures and huge water-energy efficiency problems. Predominantly composed of open canals, they have been partially or entirely converted into pressurised pipe systems, implying a considerable increase in energy consumption and operation and maintenance costs. Simple, easy-to-use, and comprehensive approaches for energy efficiency assessment in collective irrigation systems are needed for diagnosis and assisting decision-making on implementing adequate improvement measures. This research proposes and demonstrates an innovative approach based on the water and energy balances and performance indicators to assess the effect of water losses, network layout and operation, energy recovery, and equipment on energy efficiency. A novel methodology for energy balance calculation is proposed for open canal, pressurised and combined systems. The application to a real-life open canal system and network areas allowed the identification of efficiency problems mainly due to water losses in canals, followed by the dissipated energy in friction losses. Less critical are pumping and manoeuvring equipment inefficiencies. Also, a considerable excess of gravity energy is recovered in hydropower plants. In raising pipe systems, in which shaft input energy predominates and costs for pumping play a key role, surplus and dissipated energy in friction losses are the most relevant issues. Significant energy is lost in the water conveyance and distribution in both systems. Consequently, the potential to improve energy efficiency through water loss management, network layout, and operation improvement, besides pumping and manoeuvring equipment replacement, is considerable.

## Introduction

In 2022, agriculture accounted, on average, for 70% of all freshwater withdrawals worldwide (The World Bank 2022). In Europe, this sector requires 44% of freshwater resources, mainly used for irrigation, fertiliser and pesticide application, crop cooling, and frost control (EEA 2020). In Portugal, the agriculture and livestock sector used 74% of the available water volume, and the overall irrigation water efficiency was 60–65% between 2012 and 2016 (DR 2016).

The irrigation systems might be classified into two groups: collective irrigation system (CIS), including the infrastructure for water intake, transport, and distribution to

irrigators and the irrigation plot (i.e., the infrastructure and equipment for culture irrigation, operated by each irrigator). Several methodologies have been proposed for optimizing irrigation plots by combining agro-hydrological modelling, ground and satellite information, and water-energy balance modelling (Corbari and Mancini 2023).

In operation for several decades, CIS faces high degradation levels and huge water and energy efficiency problems being, consequently, partially or entirely converted into pressurised pipe systems. This significantly increases energy consumption and operation and maintenance (O&M) costs (Belaud et al. 2020; Rocamora et al. 2013; Pardo et al. 2013). Although the transformation from open canals to pressurised systems provides a more flexible service with lower water losses, it ought to have also contributed to Portugal's observed energy consumption increase (Fenareg 2022). Therefore, for a clear contribution of irrigation for national targets (i.e., 11% reduction of agriculture greenhouse gas emissions by 2030), by improving energy efficiency and promoting clean energy production is fundamental (EDIA 2021).

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More comprehensive water and energy efficiency assessment approaches should be adopted to support the diagnosis and to assist decision-making on adequate improvement measures. Besides evaluating pumping stations' efficiency (Luc et al. 2006; IDAE 2008; Lamaddalena and Khila 2013), initial studies (Abadia et al. 2008, 2010; Moreno et al. 2010; Rocamora et al. 2013) gave the first steps towards the energy balance calculation in CIS. Besides pumping energy efficiency, these studies also considered supply energy efficiency, determined by the spatial distribution of irrigated areas and the network layout, to assess efficiency in pressurised irrigation systems. Although the impact of head losses and water losses on system energy efficiency was implicit, they were not calculated in these previous studies. Cabrera et al. (2010) proposed an energy balance for pressurised systems based on the time integration of the energy conservation equation applied to a known water control volume (i.e., supply system), dividing the input energy into energy delivered to users and outgoing energy due to leaks and friction losses. Pardo et al. (2013) extended this energy audit to pressurised irrigation networks, decomposing the dissipated energy by friction into three independent terms: dissipated energy in pipelines, control valves, and irrigation hydrants. This energy auditing scheme requires hydraulic modelling to estimate energy associated with leakage, which may be data-demanding and not applicable to open canals. Pérez-Sánchez et al. (2016) proposed an energy balance to quantify the potential energy recovery. The total input energy equals the sum of the energy required for irrigation, the dissipated energy in friction losses, the theoretical recoverable energy at the irrigation point, and the theoretical non-recoverable energy in lines and hydrants. Yet, this work did not consider leakage in the energy balance.

Mamade et al. (2017, 2018) proposed an energy balance for pressurised drinking water systems using results from the water balance to separate the energy associated with authorised consumption and water losses. This provides an initial perception of efficiency improvements that can be achieved by reducing water losses (real and apparent losses) without requiring hydraulic modelling. Moreover, it allows a first assessment of the main excess energy components: water losses, equipment inefficiencies, the energy associated with surplus energy at delivery points, and network head losses. However, hydraulic modelling is typically required to calculate the energy balance (Cabrera et al. 2010; Pardo et al. 2013; Mamade et al. 2018). Monteiro et al. (2021) proposed new water and energy balances for assessing the water use and energy efficiency in urban green spaces, considering landscape water requirements and other uses besides irrigation and losses. Jorge et al. (2022) proposed an energy balance specifically tailored for wastewater systems. All these studies highlight the importance of presenting tools

for comprehensively assessing energy efficiency in water infrastructures.

To the authors' knowledge, no energy balance methodology adequately addresses the specificities of CIS and considers all contributions for system the energy outputs in canals and pipe systems (e.g., water delivered to users, apparent/real water losses, equipment inefficiencies, friction losses, and recovered energy). Moreover, the development of straightforward methodologies, aligned with the water balance calculation to estimate the main inefficiency components and the impact of water losses, followed by complementary and more data-intensive methods (e.g., hydraulic modelling) for a more detailed analysis and measures' planning, is valuable to improve water and energy efficiency in these systems. Finally, a novel energy balance methodology applicable to gravity, pressurised, and combined systems to identify the major energy efficiency issues and to prioritise the most problematic network areas is of the utmost importance.

The energy balance also allows the calculation of relevant energy efficiency performance indicators (PIs). These PIs have been traditionally expressed in kWh/m<sup>3</sup> as the ratio between the billed energy consumption for pumping and some metered water volume (e.g., system input volume, billed authorised consumption). There are also several specific PIs for assessing equipment efficiency (Luc et al. 2006; IDAE 2008; Liu et al. 2015; ERSAR and LNEC 2021).

Abadia et al. (2008) proposed an initial methodology for calculating the global energy efficiency performance indicator, including both the pump and system energy efficiency. Abadia et al. (2010) concluded that global energy efficiency PI was inadequate for assessing irrigation systems with two or more water inputs at different locations and elevations. This limitation was corrected by Abadia et al. (2018) using a generalized model for the calculation of supply energy efficiency. Moreover, Cabrera et al. (2010) proposed a set of energy efficiency PIs for pressurised networks calculated based on the energy balance: “Excess of supplied Energy” and “Standards compliance” relative to minimum useful energy, and “Network energy efficiency”, “Dissipated energy through friction”, and “Dissipated energy through leakage energy”, comparative to input energy. Pardo et al. (2013) proposed new PIs for irrigation water networks: energy losses in pipelines, hydraulic valves and irrigation hydrants relative to energy wasted through leakage and friction. Cabrera et al. (2014) suggested three other PIs for assessing the energy efficiency of a pressurised water system: “Ideal efficiency”, “Real efficiency”, and the “Target energy efficiency” linked to a target energy loss associated with pumping stations, leakage, and friction losses.

Mamade et al. (2017) proposed new PIs based on minimum energy and energy in excess. In this study, the energy in excess derives from the difference between input energy,

minimum required energy, and recovered energy. More recently, Cabrera et al. (2018) proposed a new metric to assess the energy efficiency of a pressurised water network from the point of view of friction losses by comparing the average optimum hydraulic gradient and current value. Further on, Cabrera et al. (2021) proposed a new energy intensity indicator that includes all factors that impact the total energy consumption, based on system data and operating conditions, for a realistic approximation of the energy needs of water transport. Despite several studies having proposed specific PIs to address system energy efficiency, the focus of the analysis was only on pressurised networks, disregarding gravity and combined networks, such as CIS. Moreover, calculating most PIs is data-demanding and complex in several studies.

Using the energy balance and adequate PIs allows for a robust diagnosis and establishing energy efficiency improvement measures in CIS. Two types of measures can be taken: (i) measures based on the improvement of the design, operation, and maintenance of the irrigation infrastructure and (ii) measures based on the improvement of the pumping and energy-recovery equipment. Moreno et al. (2010) found an average energy saving of 10% after implementing pump efficiency measures and a higher energy saving related to improving pump wells. Substantial energy savings were also obtained with preventive maintenance of pump wells. Recent studies also proposed infrastructural measures (e.g., canal rehabilitation to reduce water losses and head losses) to improve water and energy efficiency in CIS (Loureiro et al. 2023).

The current paper proposes a new approach for energy efficiency assessment in CIS. It demonstrates the respective application to real case studies. The proposed method for calculating the energy balance in open canal, pressurised, or combined collective irrigations is inspired by previous studies developed for urban pressurised drinking networks (Mamade et al. 2017, 2018). Existing and additional performance indicators are also tested to assess CIS energy efficiency supporting the system diagnosis, prioritising intervention areas and decision-making on improvement measures.

## Energy efficiency assessment

### Approach for energy efficiency assessment

The proposed energy efficiency assessment approach identifies and calculates the energy inherent to water input and output flows in CIS, considering elevation differences due to topography and following the energy equation principle. For energy efficiency assessment in CIS, from system to equipment, the following steps are proposed:

- (a) Definition of system boundaries, irrigation period for water and energy balance and reference elevation for energy balance calculation.
- (b) Data collection for water and energy balances calculation and context characterisation of the CIS (Table 4).
- (c) Calculation of the water balance (Table 1) to estimate the volume associated with the system input, authorised consumption and water losses necessary for the energy balance.
- (d) Calculation of the proposed energy balance (Table 2) to estimate system input energy, minimum required energy and components of energy in excess relative to reference elevation.
- (e) Calculation of the energy performance indicators to identify the system's major problems in terms of efficiency.
- (f) Identification of network areas that integrate the system, where the water and energy balances can be calculated.
- (g) For each network area, calculation of the water and energy balances and the energy efficiency performance indicators to identify critical areas with lower performance and the major causes for the inefficiency problems.
- (h) For the areas with higher priority, a more detailed analysis of equipment efficiency (i.e., pump, turbines) should be carried out to identify the equipment with lower performance and the major causes.

The first step is to define the period of analysis for the water and energy balances, which corresponds to the period in which the WUA provides the service (i.e., the irrigation period). Also, the system boundaries should be established considering all system input energy points (e.g., reservoirs, wells, and pumping stations) and the delivery points to irrigators, agreeing with those adopted in the water balance for the same infrastructure dedicated to abstraction, transport, storage, and distribution, as illustrated in Fig. 1.

The reference elevation,  $Z_{ref}$ , for calculating the energy components must also be defined. Previous studies (Cabrera et al. 2010; Mamade et al. 2017) considered the minimum system elevation as the reference elevation. The reference elevation should be unique when the system integrates several interconnected network areas. However, when the system comprises separate areas with no possibility of interconnection, the energy balance must be separately calculated for each network area and different reference elevations can be considered.

**Table 1** Water balance for CIS

Abstracted water	System input volume (corrected from known errors)	Authorised consumption	Billed authorised consumption	Billed metered consumption (including water exported) Billed unmetered consumption	Revenue water
			Unbilled authorised consumption	Unbilled metered consumption Unbilled unmetered consumption	Non-revenue water
		Water losses	Evaporation losses	Evaporation losses in canals* Evaporation losses in intermediate reservoirs*	
Imported water			Apparent losses	Unauthorised consumption Metering inaccuracies Errors in estimating unmetered consumption** Errors throughout the data acquisition process**	
Precipitation in canals*			Real losses	Leakage on the pipe network Leakage in canals* Leakage in intermediate reservoirs	
Precipitation in intermediate reservoirs				Discharge in intermediate reservoirs	
Runoff				Discharges in canals*	
Intermediate storage					

\*Components not applicable to pressurised networks

\*\*New components not proposed initially by Cunha et al. (2019)

**Table 2** Energy balance for CIS (components that require hydraulic modelling in grey)

Natural input energy	Total input energy (a)	Energy associated with authorised consumption (b)	Energy associated with water delivered to users	Minimum required energy (c)		
			Dissipated energy	Surplus energy	Surplus energy and dissipated due to head losses (h)	Energy in excess (e)
				Continuous head losses in pipes and canals and singular head losses in gates and valves		
				Pump inefficiency (f <sub>1</sub> )	Dissipated energy in equipment (f)	
Turbine inefficiency (f <sub>2</sub> )						
Shaft input energy	Energy associated with water losses (b)	Recovered Energy (d)	From authorised consumption (d <sub>1</sub> )	Recovered energy (d)		
			From water losses (d <sub>2</sub> )			
			Energy associated with water losses (without recovered energy) (g)			Energy in excess (e)

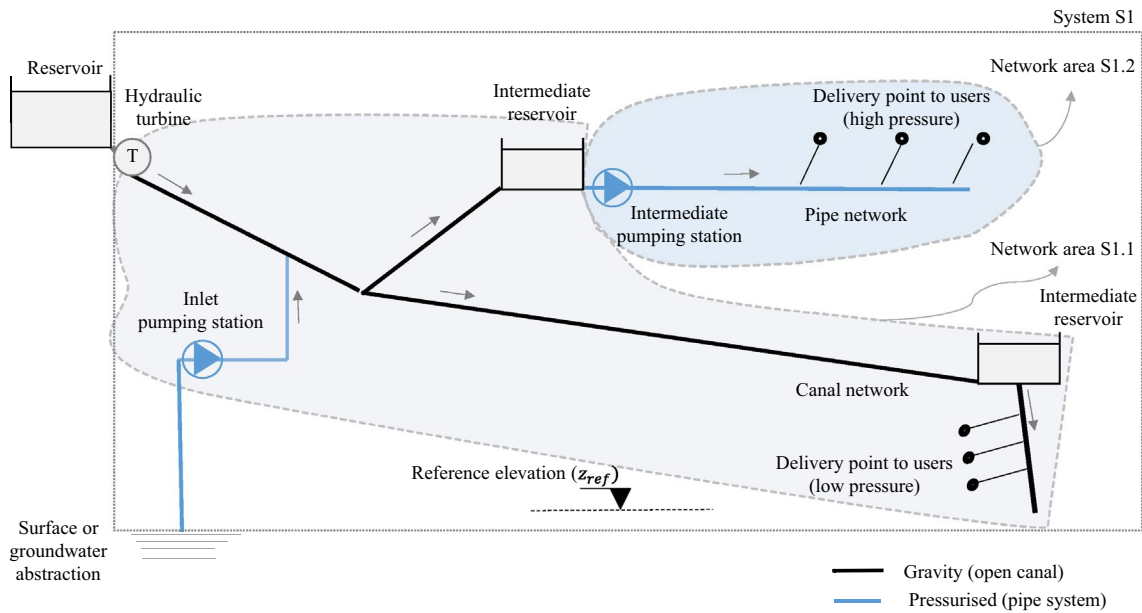


Fig. 1 Example of CIS boundaries and main infrastructure components

## Water balance calculation

The water balance proposed by Cunha et al. (2019) for CIS, as presented in Table 1, is based on the water balance for drinking water systems (Alegre et al. 2017). The main difference between approaches is that CIS' transport, storage, and distribution are mainly carried through canals and intermediate reservoirs with free surface flows, which does not apply to urban water systems with pressurised networks. The provision of service through these infrastructures implies the consideration of new components in the system input volume (e.g., precipitation, surface runoff in intermediate reservoirs), in the authorised consumption (i.e., minimum operational volume), and in water losses (e.g., evaporation and canal leaks), which do not exist in pressurised systems (Cunha et al. 2019).

First, the methodology estimates system input components indicated in Table 1 for the irrigation periods. Imported water from other utilities, abstracted water from reservoirs, groundwater sources or watercourses, and input volume from intermediate storage correspond to components more easily calculated, since the WUA measures most of these. In the case of precipitation in canals and intermediate reservoirs, the input volume is estimated based on the cross-section characteristics of these components of infrastructure and precipitation data from the nearest weather station. Surface runoff to intermediate reservoirs is due to the contribution of the respective watershed and can be estimated through hydrologic modelling (US Army Corps of Engineers 2010; Neitsch et al. 2011) or by empirical methods (Thorthwaite and Matter 1957). Concerning canals, it is assumed in this study that they are equipped with lateral surface drainage to prevent inflows due to surface

runoff. Before entering components of system input volume in the water balance, this study recommends identifying and correcting systematic metering or estimative errors, according to Vermersch et al. (2016). This correction limits apparent losses to authorised consumption errors.

Second, authorised consumption is divided into billed and unbilled consumption. Billed authorised consumption data, or revenue water, can be obtained from the billing and customer management systems. It corresponds to metered or unmetered (i.e., estimated) volume delivered to customers (i.e., irrigators, industry, and other users). Non-revenue water is obtained by subtracting billed authorised consumption from the system input volume. Unbilled authorised consumption corresponds to water delivered to users and unbilled (e.g., for firefighting) or to water used by the WUA for the network cleaning, maintenance, rehabilitation, and operation (e.g., minimum operation volume in canals that is discharged at the end of the irrigation season). The total volume of water losses is obtained by subtracting authorised consumption from the system input volume.

Third, in terms of water losses, besides the components covered for drinking water systems (i.e., apparent and real losses), the water balance for CIS also considers the evaporation losses. Evaporation in canals and intermediate reservoirs can be estimated using the Penman–Monteith equation (Allen et al. 1998) or experimental data (Rodrigues et al. 2020). This study proposes a more detailed breakdown of apparent losses compared to Cunha et al. (2019), as Vermersch et al. (2016) recommended. Summarising, apparent losses include:

- Unauthorised consumption due to unregistered connections to the CIS or fraud in water use in registered connections).
- Customers' metering errors, associated with error generated by the water meters (e.g., paddle water meters, hydrometers, Neyrpic modules).
- Errors in estimates of unmetered consumption, generated by the estimates of consumption, significant in systems that are neither metered nor fully metered.
- Errors throughout the data acquisition process associated with errors generated through data collection, transmission, and processing and storage stages.

The subtraction of evaporation and apparent losses from the total volume of water losses gives a first estimation (top–down approach) of real losses. Afterwards, real loss components should be assessed by complementary methods (bottom–up approach), and the results cross-checked with the top–down approach for comparative analysis.

Leakage in canals can be estimated through different methods, namely the inflow–outflow direct method, the direct ponding method, electromagnetic and acoustic flowmeters, empirical equations for regional application, and analytical approaches (Barkhordari and Shahdany 2022). Most techniques can be adapted to estimate leakage in existing intermediate reservoirs. Zonal metering combined with the minimum flow analysis is a well-established method for pipe networks to estimate leakage in pressurised networks (Farley and Trow 2003). Finally, discharges in canals and intermediate reservoirs should be monitored to assess these components in the water balance.

## Energy balance calculation

### General procedure

A novel energy balance specifically tailored for CIS is presented in Table 2. In comparison to studies (Cabrera et al. 2010; Pardo et al. 2013; Mamade et al. 2017), the proposed balance scheme has the following novel features:

- The balance requires the previous calculation of water balance components, where system input volume is disaggregated into authorised consumption and water losses (i.e., apparent, evaporation, and real losses).
- The energy associated with water losses equals the percentage of water losses in the water balance, assuming that water losses are distributed proportionally to water demand. This provides a clear perception of excess energy reduction with water loss reduction. This assumption was also adopted by Mamade et al. (2017, 2018) in pressurised drinking water systems, being distinct from previous energy balances (Cabrera et al. 2010), in which

only energy associated with real losses was considered and given by the product of leak discharge and the head at each node integrated into time and space.

- Several energy balance components can be calculated without a hydraulic simulation, with the following exceptions: energy associated with water delivered to users; dissipated energy associated with authorised consumption; surplus energy; and continuous head losses in pipes and canals and singular head losses in gates and valves (Table 2).
- New components are considered to estimate total input energy (i.e., energy associated with precipitation and surface runoff volume), the minimum required energy (i.e., energy related to minimum operational volume), and the dissipated energy throughout the system, which considers the energy associated with friction losses in pipes and canals and singular head losses in gates and valves, providing more information about the inefficiencies of these assets.

After defining the system boundaries, the irrigation period, and the reference elevation, the following procedure is recommended for calculating the energy balance. The corresponding step (a–h) in Table 2 identifies the different components.

- Calculate the total input energy (a), considering natural input energy components (i.e., input energy due to water abstraction from reservoirs, rivers, precipitation in canals and intermediate reservoirs, surface runoff in intermediate reservoirs, volume variation in intermediate reservoirs, and imported water from another system) and shaft input energy (i.e., the electrical energy in the inlet and intermediate pumping stations), see Eqs. (1) to (7).
- Estimate the energy associated with authorised consumption and water losses (b), using information about the respective volumes given from the water balance, see Eqs. (8) and (9), respectively.
- Calculate the minimum required energy to supply users (c), see Eq. (10).
- Estimate the recovered energy (d), see Eq. (12), and obtain the components associated with consumption ( $d_1$ ) and water losses ( $d_2$ ), described by Eqs. (13) and (14), respectively.
- Estimate the energy in excess (e) as the difference between input energy (a), the minimum required energy (c), and recovered energy (d), see Eq. (15).
- Estimate the dissipated energy due to pump inefficiencies (f), see Eq. (16), and hydraulic turbines inefficiencies (g), see Eq. (17), and obtain the components associated with consumption, see Eq. (18), and water losses, see Eq. (19) and estimate the total dissipated

- energy in equipment, related to authorised consumption (f).
- (g) Estimate energy associated water losses without recovered energy (g), see Eq. (20).
- (h) Estimate aggregated surplus energy and dissipated energy due to continuous and singular head losses (h), see Eq. (21).

### Formulation for each component of the energy balance

**Total input energy** Natural input energy,  $E_N$  (kWh), described by Eq. (1), results from the summation of the following components: input energy associated with water abstraction from reservoirs, rivers, or wells,  $E_{Res}$  (kWh), Eq. (2); input energy associated with the volume variation in intermediate reservoirs,  $E_{Vol}$  (kWh), Eq. (3); input energy associated with water imported from other systems,  $E_{Imp}$  (kWh), Eq. (4); input energy associated with precipitation,  $E_P$  (kWh), Eq. (5); and input energy associated with surface runoff in intermediate reservoirs,  $E_{SR}$  (kWh), Eq. (6)

$$E_N = E_{Res} + E_{Vol} + E_{Imp} + E_P + E_{SR}, \quad (1)$$

$$E_{Res} = \gamma \cdot \alpha \sum_{i=1}^N V_i (H_i - Z_{ref}), \quad (2)$$

$$E_{Vol} = \gamma \cdot \alpha \sum_{l=0}^{N_l} \sum_{t=t_0}^{t_f} (V_l(t_f) - V_l(t_0)) \cdot \left( \frac{H_l(t_f) + H_l(t_0)}{2} - Z_{ref} \right), \quad (3)$$

$$E_{Imp} = g \cdot \alpha \sum_{n=1}^{N_{Imp}} V_n (H_n - z_{ref}), \quad (4)$$

where  $\gamma$  is the specific weight of water (9800 N/m<sup>3</sup>);  $\alpha$  is a conversion factor from W s to kWh,  $1/(1000 \times 3600) = 2.78 \times 10^{-7}$ ;  $i$ ,  $l$ , and  $n$  refer to the inlet reservoir or river, the intermediate reservoir, and connection to other systems, respectively;  $N$ ,  $N_l$ , and  $N_{Imp}$  are the total number of inlet points through reservoir or river, intermediate reservoirs, and connections to other systems, respectively;  $V$  is the volume abstracted (m<sup>3</sup>) and  $H$  is the average hydraulic head in the period of analysis (m) from the inlet point  $i$ , stored in the intermediate reservoir  $l$  and imported from another system  $n$ ;  $z_{ref}$  is the reference elevation (m);  $t_f$  and  $t_0$  are the initial and final instants of the analysis.

In addition to the components applicable to pressurised networks (Pardo et al. 2013; Mamade et al. 2017, 2018), the proposed energy balance also includes the input energy associated with precipitation in canals and intermediate reservoirs,  $E_P$  (kWh), and with surface runoff in intermediate

reservoirs,  $E_{SR}$  (kWh), described by Eqs. (5) and (6), respectively

$$E_P = \gamma \cdot \alpha \sum_{m=1}^{N_m} V_{Pm} \times \left( \frac{H_m^{up} + H_m^{dw}}{2} - Z_{ref} \right) + \gamma \cdot \alpha \sum_{l=1}^{N_l} V_{Pl} \times (NPA_l - Z_{ref}) \quad (5)$$

$$E_{SR} = \gamma \cdot \alpha \sum_{l=1}^{N_l} V_{SRI} \times (H_l - Z_{ref}), \quad (6)$$

where  $m$  is the stretch of canal;  $N_m$  is the number of stretch of canals;  $H_m^{up}$  and  $H_m^{dw}$  are the upstream and the downstream depths in each stretch of canal, assuming full storage (m);  $NPA$  is the head at the intermediate reservoir for full storage (m),  $V_{Pm}$  is the volume associated with precipitation in each stretch of canal (precipitation head multiplied by the canal surface area),  $V_{Pl}$  is the volume associated with precipitation in intermediate reservoir (precipitation head multiplied by the reservoir surface area),  $V_{SRI}$  is the runoff volume, and  $H_l$  is the average head in the intermediate reservoir.

The shaft input energy,  $E_s$  (kWh), includes the inlet and intermediate pumping stations. The former corresponds to groups installed for groundwater (wells) or surface abstraction (reservoir, river) to the system. In contrast, the latter raises water to transport and distribute along the system (e.g., between canals with different topographic levels), Eq. (7)

$$E_s = \sum_{j=1}^{N_j} E_j, \quad (7)$$

where  $j$  is the pumping station;  $N_j$  the total number of pumping stations, respectively;  $E_j$  (kWh) the electrical energy consumed (electricity bill) at each pumping station  $j$  in the analysis period.

The sum of natural input energy components,  $E_N$  (kWh), Eq. (1), with the shaft input energy,  $E_s$  (kWh), Eq. (7), allows obtaining the total input energy,  $E_{IN}$  (kWh), along the analysis period.

### Energy associated with authorised consumption and water losses

From the total input energy (natural and shaft), part is used to deliver authorised consumption,  $E_{AC}$  (kWh), and another part is associated with water losses,  $E_{WL}$  (kWh), as described by Eq. (8) and Eq. (9), respectively

$$E_{AC} = \frac{V_{AC}}{V_{IN}} \cdot E_{IN}, \quad (8)$$

$$E_{WL} = E_{IN} - E_{AC}, \quad (9)$$

where  $V_{AC}$  is the volume associated with authorised consumption ( $m^3$ ) and  $V_{IN}$  is the input volume ( $m^3$ ), both calculated in the water balance (Cunha et al. 2019). Water losses include apparent losses (i.e., unauthorised consumption and metering errors) and real losses (i.e., leakage in canal and pipe networks and intermediate reservoirs and discharges in canals and intermediate reservoirs) and evaporation losses, as explained in Cunha et al. (2019).

### Minimum required energy to supply users

Energy associated with water delivered to users can be divided into two components: the minimum required energy to ensure the service to users,  $E_{min}$ , and the surplus energy,  $E_{sur}$ . The minimum required energy to ensure water to the irrigators is given by Eq. (10), being independent of the system characteristics (e.g., network length, head losses)

$$E_{min} = \gamma \cdot \alpha \times \sum_{r=1}^{N_r} V_r \times \left( Z_r + \frac{P_{min,r}}{\gamma} - Z_{ref} \right), \quad (10)$$

where  $r$  is the delivery point to each irrigation user,  $N_r$  is the total number of delivery points,  $V_r$  is the volume delivered (billed or unbilled) to irrigation at each delivery point  $r$  ( $m^3$ );  $Z_r$  is the topographic elevation at the delivery point  $r$  (m);  $p_{min,r}/\gamma$  is the minimum pressure-head required at each delivery point  $r$  (m). In the case of gravity systems, the minimum pressure-head can be given by the water level above the weir crest in Neyrpic-modules' measurement devices at each delivery point. In low-pressure systems (e.g., equipped with paddle wheel meters at each delivery point), the minimum pressure-head might be very low (1–2 m). In high-pressurised systems (e.g., equipped with hydrometers in each delivery point), the minimum pressure-head can range between 30 and 40 m. However, in a pressurised system, the service pressure-head at each delivery point can be higher than the minimum pressure-heads, corresponding to surplus energy,  $E_{sur}$ . The system is divided into homogenous areas of pressure and consumption, where the annual volume delivered to users is known for a more straightforward analysis of minimum energy required. After that, the average elevation is estimated, and a minimum required pressure-head is assumed for the whole area.

In the case of gravity systems, the energy associated with the minimum operational volume in canals, given by Eq. (11), should be considered in the energy balance. The minimum operational volume corresponds to the minimum volume in the canals to start discharge and supply at each delivery point, Eq. (11)

$$E_{V_{min}} = \gamma \cdot \alpha \sum_{m=1}^{N_m} V_{min,m} \left( \frac{H_m^{up} + H_m^{dw}}{2} - Z_{ref} \right), \quad (11)$$

where  $V_{min,m}$  is the minimum volume required in the canal stretch  $m$  ( $m^3$ );  $H_m^{up}$ ,  $H_m^{dw}$  are the upstream and downstream heads corresponding to the stretch of canal minimum volume (i.e., flow is null), respectively (m).

Since the minimum volume required is usually discharged at the end of the irrigation season, it is considered an authorised unbilled consumption for the water balance. Although this minimum volume is associated with system operation, not corresponding to the energy delivered to users, it has a minimal contribution to the water balance (Cunha et al. 2019). Therefore, the energy associated with minimum operational volume was included in the minimum energy required, and authorised consumption has only energy related to water delivered to users and dissipated energy (Table 2).

### Energy recovery

In locations with energy in excess (e.g., in water intakes in reservoirs with high dams), part of the energy can be recovered by installing small hydropower plants. Recovered energy,  $E_T$  (kWh), described by Eq. (12) includes the components associated with authorised consumption,  $E_{T_{AC}}$ , and with water losses,  $E_{T_{WL}}$  given by Eqs. (13) and (14), respectively

$$E_T = \gamma \cdot \alpha \sum_{t=1}^{N_t} V_t \cdot H_u, \quad (12)$$

$$E_{T_{AC}} = \gamma \cdot \alpha \sum_{t=1}^{N_t} V_t \cdot H_u \cdot \frac{V_{AC}}{V_{IN}}, \quad (13)$$

$$E_{T_{WL}} = E_T - E_{T_{AC}}, \quad (14)$$

in which  $t$  is the hydropower plant,  $N_t$  is the total number of hydropower plant and  $V_t$  is the turbined volume, and  $H_u$  is the average net head in the analysis period.

### Energy in excess

The difference between input energy, the minimum required energy and recovered energy gives energy in excess, as follows:



$$E_{\text{exc}} = E_{\text{IN}} - E_{\text{min}} - E_{\text{T}}. \quad (15)$$

### Dissipated energy in pumps and hydraulic turbines

Dissipated energy components due to inefficiencies in pumps,  $E_{\text{disP}}$ , and in hydraulic turbines,  $E_{\text{disT}}$ , are given by Eq. (16) and Eq. (17), respectively

$$E_{\text{disP}} = \sum_{j=1}^{N_j} E_j \cdot (1 - \eta_j), \quad (16)$$

$$E_{\text{disT}} = \gamma \cdot \alpha \sum_{t=1}^{N_t} V_t \cdot H_{u_t} \cdot (1 - \eta_t), \quad (17)$$

where  $\eta_j$  and  $\eta_t$  are the efficiency of pumping stations and hydraulic turbines, respectively. Afterwards, dissipated energy due to pumping stations and hydraulic turbines' inefficiencies and associated with authorised consumption,  $E_{\text{disP}_{\text{AC}}}$  and  $E_{\text{disT}_{\text{AC}}}$  are described by Eqs. (16), (18), and the homologous dissipated energy values associated with water losses,  $E_{\text{disP}_{\text{WL}}}$  and  $E_{\text{disT}_{\text{WL}}}$ , respectively, are given by Eq. (19)

$$E_{\text{disP}_{\text{AC}}} = E_{\text{disP}} \cdot \frac{V_{\text{AC}}}{V_{\text{IN}}}, \text{ for pumping stations} \quad (18)$$

$$E_{\text{disT}_{\text{AC}}} = E_{\text{disT}} \cdot \frac{V_{\text{AC}}}{V_{\text{IN}}}, \text{ for hydropower plants,}$$

$$E_{\text{disP}_{\text{WL}}} = E_{\text{disP}} - E_{\text{disP}_{\text{AC}}}, \text{ for pumping stations} \quad (19)$$

$$E_{\text{disT}_{\text{WL}}} = E_{\text{disT}} - E_{\text{disT}_{\text{AC}}}, \text{ for hydropower plants.}$$

### Dissipated energy due to water losses (without recovered energy)

The energy associated with water losses, without recovered energy, can be obtained by Eq. (20)

$$E'_{\text{WL}} = E_{\text{WL}} - E_{\text{T}_{\text{WL}}}. \quad (20)$$

Hydraulic simulation is required for a disaggregated energy analysis related to water losses. Table 3 indicates the components that should be considered and the necessary data.

### Surplus energy and dissipated energy due to continuous and singular head losses

The summation of the surplus energy,  $E_{\text{sur}}$ , and the dissipated energy due to continuous and singular head losses,

$E_{\text{dis}\Delta H}$ , can be obtained without hydraulic modelling by subtracting to energy associated with authorised consumption,  $E_{\text{AC}}$ , in Eq. (8), the minimum required energy to supply users,  $E_{\text{min}}$ , in Eq. (10), the dissipated energy (associated with authorised consumption) due to pump inefficiencies,  $E_{\text{disP}_{\text{AC}}}$ , and due turbine inefficiencies,  $E_{\text{disT}_{\text{AC}}}$ , in Eq. (18), and the recovered energy associated with authorised consumption,  $E_{\text{T}_{\text{AC}}}$ , Eq. (13), as follows:

$$E_{\text{sur}} + E_{\text{dis}\Delta H} = E_{\text{AC}} - E_{\text{min}} - E_{\text{disP}_{\text{AC}}} - E_{\text{disT}_{\text{AC}}} - E_{\text{T}_{\text{AC}}}. \quad (21)$$

If this component is relevant relative to system input energy, a more detailed analysis using hydraulic modelling is required to separate the surplus energy from dissipated energy due to continuous and singular head losses.

### Application of the energy balance to network areas

Besides a global assessment of system energy efficiency, the energy balance can be applied to diagnosing network areas. Network areas might operate separately, with independent water sources or dependent on water transference between areas. In the case of hydraulic-dependent network areas (e.g., S1.1 and S1.2 share water and energy sources in Fig. 1), it is necessary to estimate the input energy associated with the volume transferred to another network area (e.g., downstream network area S1.2 in Fig. 1) and the input energy available in the upstream network area (e.g., S1.1 in Fig. 1), following the energy footprint from the different sources until each network area.

Each input energy component (natural or shaft),  $E_{\text{INexp}}$ , that contributes to the transference between network areas (e.g., between S1.1 and S1.2 in Fig. 1) is given by Eq. (22) and each input energy component available in the upstream network area (e.g., S1.1 in Fig. 1),  $E_{\text{IN}a}$ , is obtained using (23)

$$E_{\text{INexp}} = \frac{V_{\text{exp}}}{V_{\text{IN}}} \cdot \left( \sum_{i=1}^N E_{\text{Res}_i} + \sum_{l=1}^{N_l} E_{\text{Vol}_l} + \sum_{n=1}^{N_{\text{imp}}} E_{\text{Imp}_n} + \sum_{m=1}^{N_m} E_{\text{P}_m} + \sum_{l=1}^{N_l} E_{\text{SR}_l} + \sum_{j=1}^{N_j} E_{\text{S}_j} \right), \quad (22)$$

$$E_{\text{IN}a} = E_{\text{IN}} - E_{\text{INexp}}, \quad (23)$$

where  $V_{\text{exp}}$  is the volume transferred between network areas ( $\text{m}^3$ );  $V_{\text{IN}}$  is the input volume in the upstream network area that contributes to volume transfer ( $\text{m}^3$ );  $E_{\text{IN}}$  (kWh) is input energy component in the upstream network area component that contributes to volume transfer;  $E_{\text{INexp}}$  and  $E_{\text{IN}a}$  are the input energy component transferred to the downstream

**Table 3** Component of energy associated with water losses

Main component	Components	Additional data
Energy associated with the occurrence of water losses in the network	Evaporation in canals and intermediate reservoirs	Evaporation volume in each canal stretch $m$ and in each intermediate reservoir $l$ Average head in each canal stretch $m$ and in each intermediate reservoir $l$
	Unauthorised consumption	Volume associated with unauthorised consumption at each delivery point $r$ with illegal uses Service head/pressure at each delivery point $r$ with illegal uses
	Metering inaccuracies, errors in estimating unmetered consumption, errors through the data acquisition process	Volume associated with metering inaccuracies, errors in estimating unmetered consumption and/or errors through the data acquisition process at each delivery point $r$ with authorised consumption errors Service head/pressure at each delivery point $r$ with authorised consumption errors
	Leakage in canals	Leakage volume in each canal stretch $m$ Average head in each canal stretch $m$
	Leakage in pipe network	Volume associated with leakage at each network node Service head/pressure at network node
	Discharges in canals and intermediate reservoirs	Volume associated with discharges in each canal stretch $m$ and intermediate reservoir $l$ Head associated with each discharge
Dissipated energy associated with water losses	Head losses in canals and pipe networks (continuous and singular head losses)	Volume associated with authorised consumption and water losses in each canal or pipe network Continuous and singular head losses at each canal or pipe network Requires running two hydraulic simulations to estimate dissipated energy associated with water losses: i) with authorised consumption plus water losses and then ii) only with authorised consumption. The difference between both simulations gives the dissipated energy due to friction losses, associated with water losses, for each canal or pipe network
	Inefficiencies in pump equipment	See Eq. (19)
	Inefficiencies in hydraulic turbine equipment	See Eq. (19)

network area and the input energy component available in the upstream network area, respectively (kWh).

Additionally, in the case of dependent network areas (e.g., S1.1 and S1.2 in Fig. 1), it is required to calculate the recovered energy associated with the volume transferred to another area (e.g., downstream network area S1.2 in Fig. 1) and the recovered energy and available in the upstream network area (e.g., S1.1 in Fig. 1), following the energy footprint and using the same rationale as presented in Eqs. (22) and (23). Also, part of the input energy involved with water transferred to the downstream network area is dissipated through friction losses and equipment inefficiencies in the upstream network, being transferred to the downstream systems following the same rationale.

### Context characterisation and energy performance indicators in CIS

The water and energy balances enable the systematic calculation of variables relevant to energy performance indicators. Necessary data for energy balance calculation are the following: data related to network mapping and operation characteristics and data associated with the entry points (e.g., input volume, elevation, and pressure), storage tanks (e.g., input/output volume, elevation, and water level), pumping stations (e.g., elevation, upstream and downstream pressures, pump head, shaft volume, and electricity bill), and delivery points (e.g., elevation, minimum pressure required, and authorised consumption). A summary context and infrastructure characterisation regarding assets, irrigated areas, reference elevation,

**Table 4** Context characterisation of CIS with relevance for energy efficiency assessment

Variable	Description or formulation
Surface water intake from reservoirs (no.)	Number of surface water intakes from reservoirs in the CIS
Surface water intake from watercourses (no.)	Number of surface water intakes from watercourses in the CIS
Groundwater intakes (no.)	Number of underground water intakes in the CIS
Pumping stations (no.)	Number of pumping stations in the CIS
Hydraulic turbines (no.)	Number of hydraulic turbines in the CIS
Intermediate reservoirs (no.)	Number of compensation and control reservoirs in the CIS
Conveyance and distribution canal network for collective irrigation (km)	Total canal length for water conveyance and distribution to end-users
Conveyance and distribution pipe network for collective irrigation (km)	Total pipe length for water conveyance and distribution to end-users
Area equipped with collective irrigation system (ha)	Total area equipped with infrastructure for abstraction, conveyance and collective water distribution to end-users
Minimum elevation (m)	Minimum system elevation
Minimum required pressure-head (m)	Minimum required pressure-head to ensure the service to end-users
Average elevation at delivery points (m)	Average elevation at delivery points for irrigation
System input volume ( $10^6$ m <sup>3</sup> )	Input water volume associated with abstract water, imported water, precipitation in canals and intermediate reservoirs, runoff, and intermediate storage
Energy consumption from electric grid ( $10^6$ kWh)	Energy consumption from electric grid for system operation
Average billed authorised consumption for irrigation [ $\text{m}^3/(\text{irrigation user}\cdot\text{year})$ ]*	Ratio between average billed authorised consumption and the number of irrigation users in the year of analysis
Shaft energy consumption (kWh/m <sup>3</sup> )	Ratio between shaft input energy and billed authorised consumption
Shaft input energy (%)	Ratio between shaft input energy and system input energy
Indirect greenhouse gas emissions [ $\text{kgCO}_{2\text{eq}}/(\text{ha}\cdot\text{year})$ ]	Ratio between indirect emission with acquired energy for CIS operation (e.g., pumping, cleaning) and area equipped with collective irrigation system
Shaft energy costs (%)	Ratio between shaft energy costs and operational costs $\times 100$
Energy production (%)	Ratio between produced energy and shaft input energy $\times 100$

minimum required pressure-head, energy consumption, costs, production, and greenhouse gas emissions supports a better understanding about performance assessment of CIS (Table 4). The characterisation refers to the infrastructure between the input energy points (e.g., reservoirs, wells, pumping stations) and the delivery points to irrigators considered for the water and energy balance calculation. Shaft energy (kWh/m<sup>3</sup>, %) and indirect emissions [ $\text{kgCO}_{2\text{eq}}/(\text{ha}\cdot\text{year})$ ] refer only to the irrigation period. In contrast, shaft energy costs (%) are relative to annual operational costs, and energy production (%) refers to yearly production.

Besides quantifying the different sources of inefficiencies, the systematic calculation of the energy balance provides valuable data for calculating energy performance indicators (PIs). Based on previous studies for pressurised urban water systems (Cabrera et al. 2010; 2014; Mamade et al. 2017, 2018) and for pressurised irrigation networks (Pardo et al. 2013), this study proposes two key PIs specific for CIS to assess the energy in excess (E2 and E3). Furthermore, new complementary PI to assess the components of energy in excess (i.e., associated the water losses, E21, equipment inefficiency, E22, head losses,

and surplus energy, E23) are presented in Table 5. Proposed PIs apply to gravity, pressurised, and combined CIS.

## Case studies' description

The proposed methodology for the energy balance calculation is tested in two CIS—one gravity open canal system and another pressurised pipe system. In the gravity, CIS predominates rice and maize crops and gravity and centre pivot irrigation systems, whereas in the pressurised CIS predominates maize and vineyards crops, olive orchards, and centre pivot and drip irrigation systems. The main characteristics of both CIS, relevant for the water and energy balances, are presented in Table 6.

The gravity CIS system, in operation for about 60 years and mostly composed of open canals, corresponds to one of the longest systems in Portugal, with a network of over 400 km and an average irrigation period of 190 days in 2016–2018. Despite having 13 pumping stations, energy costs only represented 7% of the total operational costs in 2018. Three hydraulic turbines yearly produce 8.5 times

**Table 5** Proposed energy efficiency performance indicators specific for CIS

Performance indicator	Formulation
E1p—Energy efficiency of pumping equipment (%)	Useful energy/input energy to the pump $\times 100$
E1t—Energy efficiency of hydraulic turbines equipment (%)	Energy available at the turbine shaft/ Energy available from water jet $\times 100$
E2—Energy in excess per authorised consumption (kWh/m <sup>3</sup> )	(Input energy – Recovered energy – Minimum required energy)/volume associated with authorised consumption
E21—Energy in excess associated with water losses per authorised consumption (kWh/m <sup>3</sup> )	Energy in excess associated with water losses (without recovered energy)/volume associated with authorised consumption
E22—Energy in excess associated with equipment inefficiency per authorised consumption (kWh/m <sup>3</sup> )	Dissipated energy in equipment and associated with authorised consumption/volume associated with authorised consumption
E23—Energy in excess associated with head losses and surplus energy per authorised consumption (kWh/m <sup>3</sup> )	Energy associated with head losses and surplus energy/volume associated with authorised consumption
E3—Energy in excess index (-)	(Input energy – Recovered energy – Minimum required energy)/minimum required energy

**Table 6** Gravity and pressurised CIS characteristics in 2018

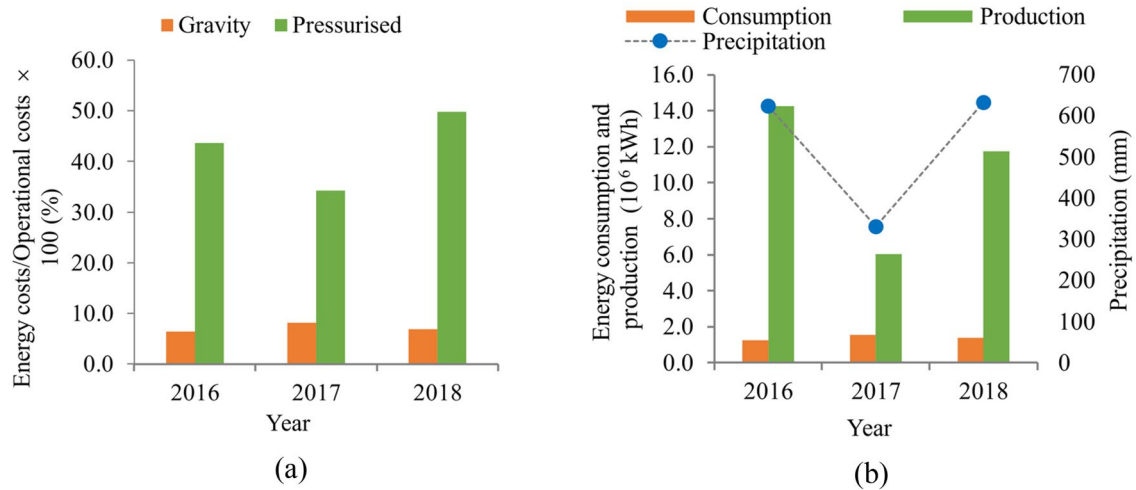
Variable   Type of CIS system	Gravity (open canals)	Pressurised (pipe systems)
Operation start date (–)	1959	1981
Surface water intakes in reservoirs (no.)	3	1
Surface water intakes in watercourses (no.)	6	–
Pumping stations (no.)	13	1
Hydraulic turbines (no.)	3	–
Intermediate reservoirs (no.)	1	–
Conveyance and distribution canal network for collective irrigation (km)	208.5	–
Conveyance and distribution pipe network for collective irrigation (km)	193.9	41.3
Area equipped with collective irrigation system (ha)	16 351	1 500
Minimum elevation (m)	0.23	181.7
Minimum required pressure-head (m)	1	40
Average elevation at delivery points (m)	23.1	211.4
System input volume (10 <sup>6</sup> m <sup>3</sup> )	166.5	4.3
Energy consumption from electric grid (10 <sup>6</sup> kWh)	1.2	1.2
Average billed authorised consumption for irrigation [m <sup>3</sup> /(irrigation user·year)]*	237 724.5	38 564.2
Shaft energy consumption (kWh/m <sup>3</sup> )	0.01	0.28
Shaft input energy (%)	2.8	74.1
Indirect emissions of GHG [kgCO <sub>2eq</sub> /(ha year)]*	17.9	193.1
Shaft energy costs (%)	6.9	49.8
Energy production (%)	8.5	–

\*User registered by the WUA for irrigation in the year of analysis

\*\*The national emission factor in 2018 was 0.247 kgCO<sub>2eq</sub>/kWh

the energy required for pumping during irrigation. This is a determinant for economic sustainability, since the WUA sells the produced energy to the national electric grid. However, energy recovery depends on climate conditions and can be severely affected in years with lower precipitation (e.g., see the year 2017 for gravity CIS in Fig. 2). According to more recent agrometeorological data provided by the

CIS, between 2019 and 2021, the precipitation was similar to 2017. In 2017 and between 2019 and 2021, a reduction between 23 and 47% in precipitation and an increase in temperature between 1.7 °C and 2.2 °C relative to 30 years (between 1976 and 2006) were observed. Therefore, a reduction in the water volume and associated energy recovery is expected between 2019 and 2021.



**Fig. 2** Comparison of gravity and pressurised systems during the irrigation period between 2016 and 2018: **a** pumping energy consumption, annual energy production and precipitation for the gravity

system; **b** energy costs with pumping stations relative to annual operational costs for the gravity and the pressurised systems

**Table 7** Gravity and pressurised collective irrigation network area profile in 2018

Variable   Type of CIS system	Gravity system					Pressurised system	
	S1	S2	S3	S4	S5	C1	C2
Surface water intakes in reservoirs (no.)	1	1	–	–	1	1	–
Surface water intakes in watercourses (no.)	0	1	1	3	1	–	–
Water intake from other network areas (no.)	0	1 (S1)	1 (S1,S2)	1 (S1,S2)	0	0	–
Inlet pumping stations (no.)	0	1	1	3	1	1	–
Intermediate pumping stations (no.)	4	3	–	–	–	–	–
Hydraulic turbines (no.)	2	1	–	–	–	–	–
Intermediate reservoirs (no.)	2	1	–	–	–	–	–
Conveyance and distribution canal network (km)	37.4	114.9	20.8	26.9	8.5	–	–
Conveyance and distribution pipe network (km)	39.4	91.1	26.2	33.7	3.3	25.8	15.4
Area equipped with collective irrigation system (ha)	2755	8041	2675	2368	521	873	627

The pressurised system, in operation for less than 40 years, is composed of pipes and corresponds to one of the smallest CIS in Portugal, in which the minimum required pressure-head is significantly high (40 m) compared with the gravity system (1 m). Although, with a single pumping station (Table 7), energy efficiency is an essential driver for CIS sustainability, since the costs of pumping energy represent almost 50% of the operational costs between 2016 and 2018, whereas, in the gravity system, this component is lower than 10% (Fig. 2b). Moreover, the pressurised system, with a significant shaft energy contribution to input energy (74.1%) and shaft energy consumption (0.28 kWh/m<sup>3</sup>), in agreement with the previous studies (Abadia et al. 2010) and without any energy production, is responsible for the indirect emission of 193.1 kgCO<sub>2eq</sub>/(ha year) from the

purchased electricity for pumping. This comparative analysis corroborates previous studies (Rocamora et al. 2013), highlighting that substituting open channels with pressurised pipes without a comprehensive assessment of water and energy consumption and efficiency substantially increases the energy used in irrigated agriculture.

The gravity system is composed of five network areas (S1–S5). The network area S2 is dependent on input water from S1, whereas network areas S3 and S4 are dependent on input water from S1 and S2 (Table 7). Regarding water balance, part of the input water in S2 (ca. 46%) is imported from S1, and part of the input water in S3 and S4 is imported from S1 and S2. Relative to the energy balance, part of the input, dissipated, and produced energy in S1 is associated with water transferred to S2, S3 and S4. The same rationale

applies to the input, dissipated, and produced energy in S2 associated with water transferred to S3 and S4. All network areas in the gravity system have inlet pumping stations at the water intakes from the river, except S1. Only network areas S1 and S2 have intermediate pumping stations for water transport between canals.

The hydraulic turbines in S1 and S2 produce energy using distributed water for irrigation downstream. Network area S5 is independent of the other network areas and corresponds to the smallest network. The pressurised system comprises only

two network areas: C2, entirely rehabilitated and C1, partially rehabilitated recently (less than 4 years relative to 2018).

## Results and discussion

### Water balance calculation

The first step is the calculation of the water balance for the gravity system (Table 8). Most system input volume (87.8%)

**Table 8** Water balance components (expressed in  $10^6$  m<sup>3</sup> and as a percentage of system input volume) for the gravity CIS in 2018

Abstracted water 146.2 (87.8%)	System input volume 166.5	Authorised consumption 100.6 (60.4%)	Billed authorised consumption 100.2 (60.2%)	Billed metered consumption 95.7 (57.5%)	Revenue water 100.2 (60.2%)
				Billed unmetered consumption 4.5 (2.7%)	
			Unbilled authorised consumption 0.45 (0.3%)	Unbilled metered consumption n.a	Non-revenue water 66.3 (39.9%)
				Unbilled unmetered consumption 0.5 (0.3%)	
		Water losses 65.9 (39.6%)	Evaporation losses 0.62 (0.4%)	Evaporation losses in canals 0.5 (0.3%)	
Imported water n.a				Evaporation losses in intermediate reservoirs 0.097 (0.1%)	
			Apparent losses 10.9 (6.5%)	Unauthorised consumption 1.0 (0.6%)	
Precipitation 0.068 (<0.1%)				Metering inaccuracies 9.8 (5.9%)	
				Unmetered consumption estimation errors n.a	
				Acquisition, transmission, and data processing errors n.a	
			Real losses 54.4 (32.7%)	Leakage on pipe network 0.2 (0.1%)	
Runoff 20.2 (12.1%)				Leakage in canals 3.5 (2.1%)	
				Leakage in intermediate reservoirs n.a	
Intermediate storage n.a				Discharges in intermediate reservoirs 2.5 (1.5%)	
				Discharges in canals 48.2 (28.8%)	

*n.a.* not applicable or not available

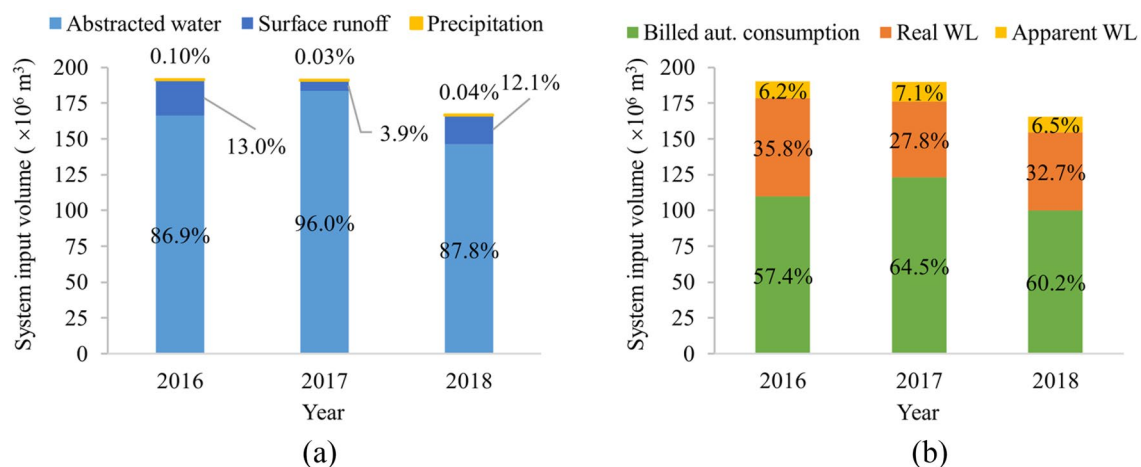
is due to abstracted water from three reservoirs (Table 7), followed by surface runoff (12.1%) estimated by the water balance proposed by Thornthwaite and Matter (1957). In 2018, system input volume decreased (Fig. 3a), since most precipitation occurred during the irrigation period and irrigation needs were lower. However, surface runoff contribution is variable, reaching the minimum value in 2017 when the annual precipitation is lower than 300 mm (Fig. 2a and Fig. 3a). According to more recent agrometeorological data provided by the CIS, between 2019 and 2021, with precipitation similar to 2017 as described in 3, a low surface runoff contribution is expected in these last three years. The contribution of precipitation to the input water in canals and intermediate reservoirs is also negligible (i.e.,  $<0.1\%$ ), and from intermediate storage is null, since the water level is constant in the intermediate reservoirs in S2 (Table 7). Billed authorised consumption for irrigation and industry represents 60.2% of the system input volume, whereas billed unmetered consumption represents only 2.7%. Billed unmetered consumption is estimated by the WUA using reference values for crop water requirements. Although unmetered consumption is reduced, the WUA should install water meters in all delivery points to minimise uncertainty in billed authorised consumption.

Only the minimum operational volume in canals is considered in unbilled authorised consumption, representing only 0.3% of the system input volume. However, well-established procedures to estimate other possible components of authorised consumption should be implemented by the WUA (e.g., volumes associated with network cleaning, maintenance and rehabilitation, and firefighting).

Water losses include evaporation losses in canals and intermediate reservoirs, and apparent and real losses. In agreement with previous studies (Mutema and Dhavu 2022), evaporation losses are the less relevant component of water

losses, representing only 0.4% of system input volume in this CIS. Apparent losses include unauthorised consumption, metering inaccuracies, unmetered consumption estimation errors and acquisition, transmission, and data processing errors. Since the WUA has an extensive staff for daily network control (60 operators), illegal water use is assumed to be very small, representing only 1% of billed consumption (or 0.6% of system input volume, Table 8). In the gravity system, 81% of billed consumption is metered using Neyrpic modules and 19% with paddle wheel meters. Most Neyrpic modules have been operating for about 60 years, except those installed in S5, less than 20 years since the infrastructure was completely rehabilitated in 2001. The paddle wheel meters' maximum age is 20 years. Some in situ tests were carried out on paddle water meters to estimate the equipment error. Preliminary results indicate a small error in equipment uncertainty (2%) that increased with age, with a -1%/year degradation rate. In the Neyrpic modules, carrying out tests to estimate metering errors was impossible. Combining some information from previous studies (Rijo and Pereira 1987) with indications given by the WUA, where the volume delivered to irrigators can be higher than the volume metered due to settlement problems in the infrastructure at the delivery point, an initial estimate of -10% is considered for the metering error in Neyrpic modules. Yet, further work is necessary to improve the estimate of the metering error, which depends on the meter size and trademark and the water demand profile (Arregui et al. 2006).

Relatively to real losses, leakage was estimated in canal or pipe network stretches limited by closed gates or valves. Besides the geometric characteristics of each network stretch under test, precipitation and water-level data were collected over 24 h and used to calculate leakage by applying the water balance proposed in this study. It was estimated 14 L/(m<sup>2</sup> day) for rehabilitated canals, and for non-rehabilitated



**Fig. 3** Water balance components for the gravity CIS: **a** system input volume components, and **b** consumption and apparent and real water losses

canals 25 L/(m<sup>2</sup> day). In the case of pipe network (with low pressure), it was estimated in 1.5 m<sup>3</sup>/(km day) for rehabilitated pipes and 7.0 m<sup>3</sup>/(km day) for non-rehabilitated pipes. Leakage in intermediate reservoirs was not applicable, since those were recently built (2014) with waterproof material. A first estimate of water discharges in reservoirs and canals was obtained from the water balance (Table 8) by subtracting leakage components from the total volume of real losses. In this WUA, monitoring water discharges is critical, since only a few are currently measured. Therefore, it was not possible to compare the monitoring results of discharges with the value given by the difference between the total volume of real losses and the volume associated with leakage in pipes, canals, and reservoirs.

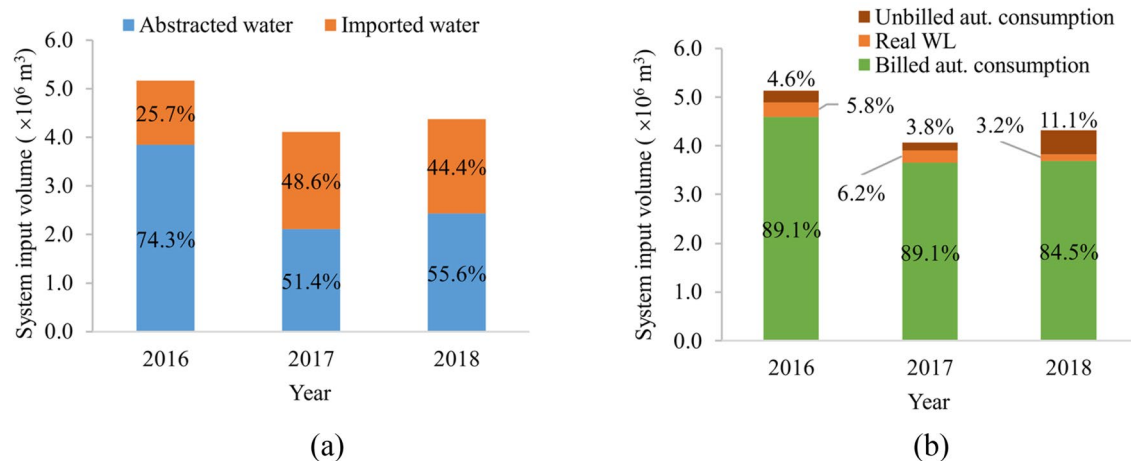
The water balance for the pressurised system (Error! Reference source not found.a) shows major differences relative to the gravity system. Imported water represents almost 50% of the system input volume in 2017 and 2018, years with lower annual precipitation (359.20 mm) relative to 2016 (559.80 mm), indicating a lack of water from own resources and additional costs with imported water, in opposition to the gravity system (Fig. 3a). In the pressurised CIS, water scarcity problems in 2017 and 2018 have limited water availability, and consequently, authorised billed consumption has decreased (Fig. 4b). Moreover, estimated unbilled authorised consumption has increased in 2018 due to the need to use water for network flushing to solve pipe network, valve, and water meter blockage due to the poor water quality during the scarcity period. In 2018, unbilled authorised consumption is the most relevant component of system input volume in the pressurised CIS (11.1%), followed by real losses (3.2%) and a reduced value of apparent losses (1.3%) (Fig. 4b), which contributed to 15.6% in non-revenue water in this year. In contrast, in the gravity system, non-revenue water is much higher in 2018 (39.9% of the system input

volume, Table 8), and the most relevant component is due to real losses (32.7% of the system input volume, Table 8). In the pressurised system, a significant part of the pipe system and water meters were recently rehabilitated (< 4 years), and leakage and discharges do not exist, contributing to the main differences relative to the gravity CIS (Figs. 3 and 4).

### Energy balance calculation

The energy balance is calculated for the same system, and the period of analysis considered for the water balance.

Results of the energy balance for the gravity CIS (Table 9) show that the contribution of shaft input energy to total input energy is minimal (2.8%), mainly associated with intermediate pumping stations to transport water between canals. Recovered energy represents 15% of total input energy, which is relevant for the economic and environmental sustainability of the WUA. The minimum pressure required at each delivery point is lower than in pressurised systems. The conveyance and distribution network, generally in canals, may comprise some pipes operating with low pressure-head (e.g., 1 m). Minimum required energy represents only 14.8%, whereas energy in excess represents 70% of total input energy. This high excess energy value, comprising surplus energy at delivery points, continuous and singular head losses, equipment inefficiencies, and water losses, indicates a significant potential for energy efficiency improvements. Therefore, these results demonstrated that improving energy efficiency in gravity CIS is crucial. Although energy consumption is reduced, energy efficiency improvement and cost reduction are fundamental in water scarcity to ensure CIS's infrastructure and economic and environmental sustainability. The proposed energy balance (Table 2) has allowed a comprehensive assessment of the total input energy, the minimum required energy, the recovered energy,



**Fig. 4** Water balance components for the pressurised CIS: **a** system input volume components, and **b** consumption and water loss components



and the energy in excess without the need for more detailed data or hydraulic modelling, which is a step forward for CIS concerning other studies (Cabrera et al. 2010; Pardo et al. 2013; Mamade et al. 2017, 2018).

The most relevant components of excess energy in the gravity CIS are water losses (33.6% of system input energy) and surplus energy combined with dissipated energy due to continuous and singular head losses (30.0%). These results suggest that reducing water loss will improve the overall system energy efficiency. In this CIS, the surplus energy is expected to be low due to water delivery to the atmosphere or low-pressure delivery points. Therefore, dissipated energy due to continuous and singular head losses is expected to be the most relevant component (*j*) in Table 2. Dissipated energy in equipment (i.e., pumps and hydraulic turbines) associated with authorised consumption represents only 6.6% of the total input energy. However, the dissipated energy in turbines, associated with authorised consumption (2.4 GWh), is similar to shaft input energy (2.8 GWh). These results suggest that it is valuable to improve turbine efficiency. The dissipated energy with pumping and hydraulic turbines, associated with water losses, will be necessarily reduced with measures used to control real losses.

For the pressurised CIS, shaft input energy represents more than 70% of input energy (Fig. 5a), and energy costs represented almost 50% of operational costs (Fig. 2b). Therefore, energy efficiency is a key driver for sustainability in the pressurised CIS. The minimum required energy is higher than in gravity CIS, varying between 55.0 and 61.7% of the total input energy (Fig. 5b). Pressurised systems have high operating pressure-heads (e.g., > 30 m) for water conveyance and distribution. In terms of energy in excess, the

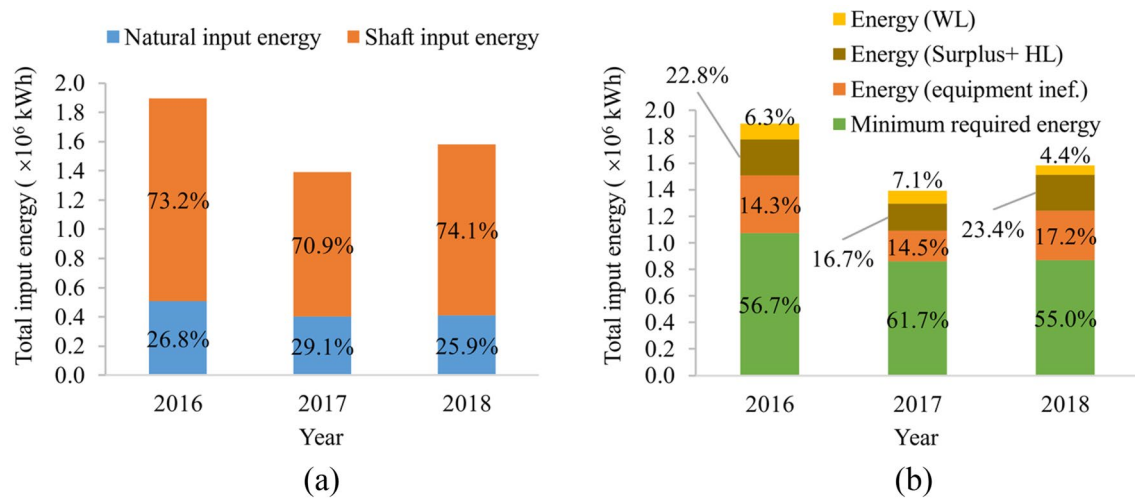
most relevant component is associated with surplus energy and dissipated energy due to continuous and singular head losses, varying between 16.7 and 23.4% of system input energy in 3 years. The second most relevant component is dissipated energy in equipment, ranging between 14.3 and 17.2% of the total input energy (Fig. 5b). Energy lost through water losses (real and apparent losses) varies between 4.4 and 7.1% of the overall input energy, a low value relative to the gravity CIS, and previous studies (Pardo et al. 2013). These results agree with earlier studies for pressurised irrigation networks where more than half of the input energy is lost in the pumping systems and through pipe friction (Moreno et al. 2010). Since these components are aggregated, future work should be developed to estimate surplus energy and dissipated energy due to continuous and singular head losses. In agreement with previous studies (Pardo et al. 2013), it is recommended to use hydraulic modelling to understand better surplus energy, energy losses in pipes, hydraulic valves and hydrants, and the effect of improving efficiency measures. In this case study, efforts to enhance pressure management through network sectorization, combined with better pumping design and operation, should be explored. This recommendation aligns with previous studies (Moreno et al. 2010) which indicated that the energy efficiency of CIS with higher elevation differences tends to be lower, and it is necessary to establish different pressure zones to manage irrigation networks.

In the pressurised system, where part of the infrastructure was recently rehabilitated (pipes, valves, and flowmeters), the energy associated with water losses is significantly lower than the gravity CIS indicated in Table 9.

**Table 9** Energy balance components (10<sup>6</sup> kWh) for the gravity CIS in 2018 (components that require hydraulic modelling in grey)

	Total input energy 41.8	Energy associated with authorised consumption 25.3 (60.5%)	Energy associated with water delivered to users	Minimum required energy 6.2 (14.8%)		
			Dissipated energy	Surplus energy		Energy in excess 15.3 (36.6%)
Natural input energy 40.6 (97.2%)	Energy associated with water losses 16.5 (39.5%)	Recovered energy from authorised consumption 3.8 (9.1%)		Continuous head losses in pipes and canals and singular head losses in gates and valves 12.5 (30.0%)	Dissipated Energy in equipment 2.8 (6.6%)	
Shaft input energy 1.2 (2.8%)				Pump inefficiency 0.4 (0.9%)		Recovered energy from water losses 2.5 (5.9%)
			Turbine inefficiency 2.4 (5.7%)			Energy in excess 14.0 (33.6%)
			Energy associated with water losses (without recovered energy) 14.0 (33.6%)			

Energy balance components are calculated considering the reference elevation, 0.23 m



**Fig. 5** Energy balance components for the pressurised CIS between 2016 and 2018: **a** natural and shaft input energy and **b** minimum required energy and energy in excess components

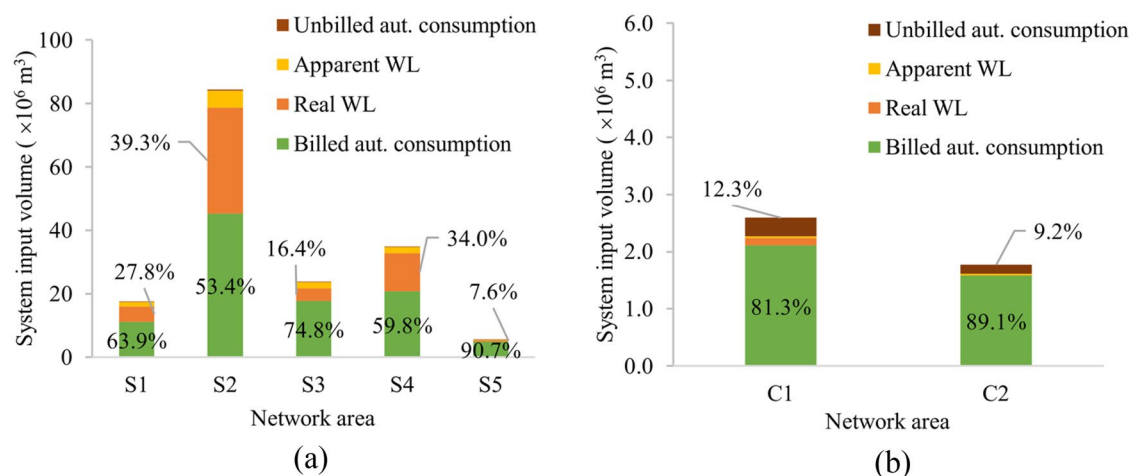
### Water and energy balance calculation in network areas

Applying the water balance to network areas, results indicate that non-revenue water ranges between 9.3 (S5) and 46.6% (S2) in the five network areas of the gravity CIS. Real losses are the most relevant component of non-revenue water in this CIS (Fig. 6a), except S5 entirely rehabilitated in 2001 (where non-revenue water is lower than 10%). In the pressurised CIS (Fig. 6b), with authorised billed consumption above 80%, the most relevant component of non-revenue water, 18.7% in C1 and 10.9% in C2, is associated with authorised unbilled consumption in both networks.

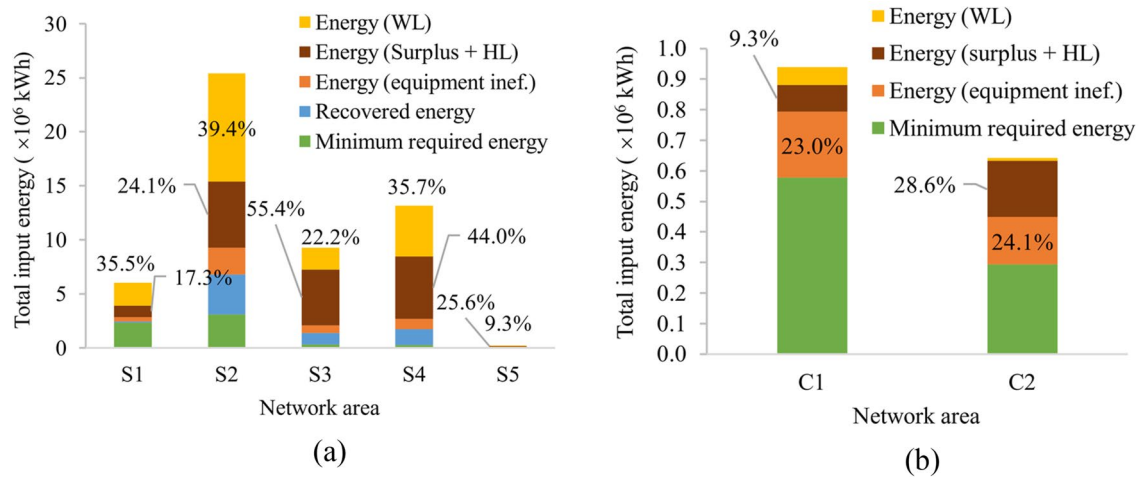
The gravity network areas' most relevant excess energy components are surplus energy, head losses, and water

losses (Fig. 7a). In network areas S3 and S4, most of the energy in excess, 55.4% and 44.0%, respectively, is due to surplus energy and head losses. These results are consistent, since both network areas are dependent on S2 and S1, and part of the dissipated energy in these upstream network areas is associated with transferred water. In agreement with the water balance (Fig. 5a), network areas S1, S2, and S4 have more than 30% of energy in excess associated with water losses. Energy in excess due to equipment inefficiencies associated with authorised consumption is reduced in the gravity network areas, whereas in the pressurised is very relevant (above 20% in both areas).

In the pressurised network area with a low percentage of energy in excess associated with water losses (Fig. 7b), the second most relevant component of energy in excess



**Fig. 6** Water balance components for each network area in 2018: **a** gravity CIS and **b** pressurised CIS



**Fig. 7** Energy balance components for each network area in 2018, with the most relevant components of energy in excess quantified relative to input energy: **a** gravity CIS and **b** pressurised CIS

is due to the surplus energy and head losses, particularly in network area C2 (rehabilitated recently). These results indicate that energy efficiency improvement measures focused on network layout and sectorization should be further studied.

Total input energy from the different water sources in S1 corresponds to  $25.3 \times 10^6$  kWh in 2018 (Table 10). From the total input volume in S1 ( $81.9 \times 10^6$  m<sup>3</sup>), some water sources (i.e., abstracted water from reservoirs, surface runoff, and precipitation from intermediate reservoirs) contributed to the water transference of  $64.3 \times 10^6$  m<sup>3</sup> in 2018 to S2. Precipitation in canals and shaft input energy in S1 do not contribute to water transference. Therefore, when using Eq. (8), part of the input energy in S1 is associated with the water transference ( $19.2 \times 10^6$  kWh) and the available input energy in S1 is given by Eq. (23), corresponding only to  $6.1 \times 10^6$  kWh. Moreover, from the recovered energy in S1 (ca. 3.3 GWh), most is associated with water transferred downstream to S2, S3, and S4 (ca. 3.2 GWh), as illustrated in Fig. 7a. Similarly, a part of the dissipated energy in the S1 network and in turbines installed in S1 is due to water transference.

### Effect of reference elevation on energy efficiency performance indicators

A sensitivity analysis is carried out to test the adequacy of PIs proposed in this study to assess the global system and the network areas' energy efficiency (Table 5) and the effect of different reference elevation values.

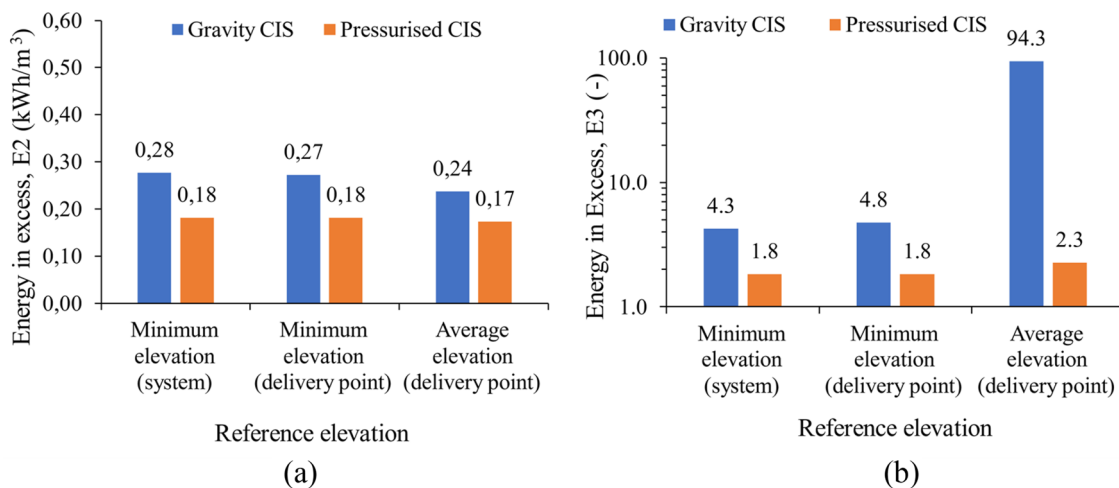
This analysis consisted first of comparing the Energy in excess per authorised consumption (E2) and Energy in excess (E3) for the canal and the pressurised system,

using three alternative values for the reference elevation,  $z_{ref}$ : the minimum system elevation (canal—0.23 m, pressurised—181.7 m), the minimum delivery point elevation (canal—3.1 m, pressurised—181.7 m), and the average delivery point elevation (canal—23.1 m, pressurised—211.4 m). Results are presented in Fig. 8.

Results for both PIs (E2 and E3) show that the Energy in excess is higher for the canal system, regardless of the reference elevation. Considering the PI Energy in excess per authorised consumption (E2), the values are quite similar for the three reference elevation values. This evidence indicates that the variable in the numerator of this PI (Energy in excess = input energy - recovered energy - minimum required energy) is not very sensitive to reference elevation. For the canal system, E2 varied between 0.24 and 0.28 kWh/m<sup>3</sup>; the pressurised varied between 0.17 and 0.18 kWh/m<sup>3</sup>. The Energy in excess (E3) shows a higher variability with the reference elevation, ranging between 4.3 and 94.3 for the canal system and between 1.8 and 2.3 for the pressurised system. For the reference elevation equal to the average elevation, the minimum required energy decreases significantly, and therefore, E3 (ratio between Energy in excess and minimum required energy) increases. These results suggest that E2 might be more robust PI for system energy efficiency assessment and almost independent of adopted reference elevation values. The results in both case studies are similar for minimum system elevation or minimum delivery point elevation. However, the Energy in excess (E3) provides a clear perception of both systems' potential for energy improvement. Therefore, when considering the Energy in excess (E3), this study recommends not using the average elevation as a reference. Previous studies (Cabrera et al. 2010; Mamade et al. 2017) considered that piezometric

**Table 10** Energy balance components ( $\times 10^6$  kWh) for the network area S1 in the gravity CIS in 2018 (components that require hydraulic modelling in grey)

	Natural input energy 24.6 (97.3%)	Total input energy 25.3	Input energy associated with water transference 19.2 (76.0%)				
			Input energy available 6.1	Energy associated with authorised consumption 3.9 (64.0%)	Energy associated with water delivered to users	Minimum required energy 2.4 (39.0%)	
Shaft input energy 0.7 (2.7%)							Dissipated energy
			Pump inefficiency 0.2 (3.7%)	Dissipated energy in equipment 0,2 (4.3%)			
						Recovered energy from authorised consumption 0.05 (0.9%)	Recovered energy 0.08 (1.4%)
					Recovered energy from water losses 0.03 (0.5%)		
				Energy associated with water losses 2.2 (36.0%)	Energy associated with water losses (without recovered energy) 2.1 (35.5%)		Energy in excess



**Fig. 8** System energy performance indicators for the gravity and the pressurised systems in 2018 using three reference elevation values: **a** Energy in excess per authorised consumption, E2 (kWh/m<sup>3</sup>) and **b** Energy in excess, E3 (-)

heads are calculated concerning the lowest system node elevation, considered the reference elevation in this study.

Second, regarding network areas in the gravity system (Fig. 9), although both PIs indicate that the network area with higher energy in excess is S4, prioritising network areas in terms of Energy in excess (E3) depends on the assumption considered for the reference elevation. The energy in excess (E3) provides different results for the same reference

elevation hypotheses, with large variability for average consumption node elevation. Considering the Energy in excess per authorised consumption (E2), the values are similar for the three reference elevation assumptions. Using E2, the network areas with the highest value are: S4, S3, and S2, independent of the reference elevation. Therefore, E2 is the recommended PI in this study to assess CIS energy efficiency. Moreover, considering the authorised consumption

in the PI calculation, the absence of water losses becomes a clear advantage for comparative analysis, as recommended by previous studies (Cabrera et al. 2010).

### Energy performance assessment

For the gravity CIS, most of energy in excess per authorised consumption ( $E2 = 0.29 \text{ kWh/m}^3$ ) is associated with water losses ( $0.14 \text{ kWh/m}^3$ ; 48% of energy in excess) and with dissipated energy due to head losses and surplus energy ( $0.12 \text{ kWh/m}^3$ ; 41% of energy in excess). Energy in excess associated with equipment inefficiencies is minimal ( $0.03 \text{ kWh/m}^3$ ; 1% of energy in excess), as depicted in Fig. 10a.

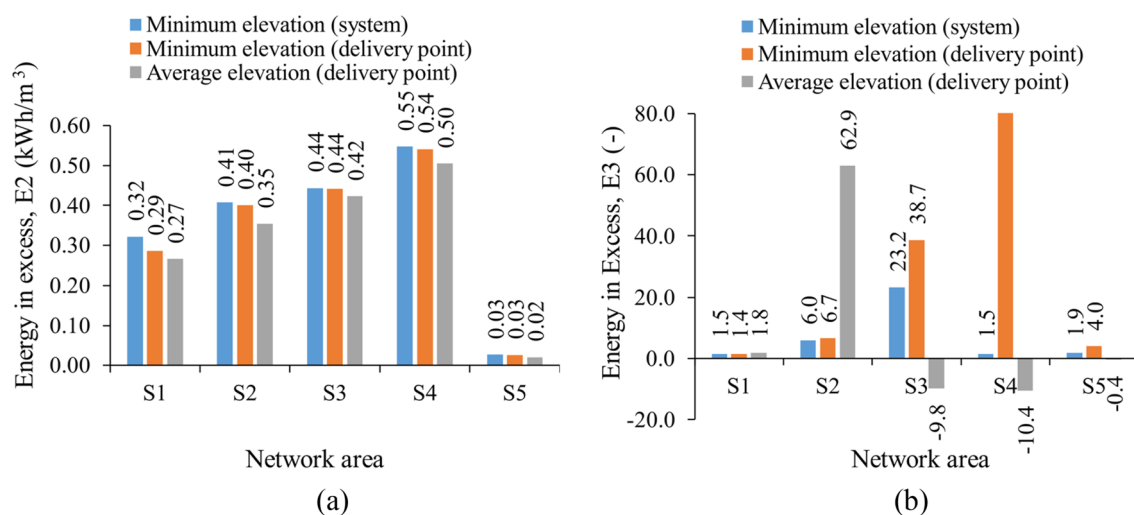
From the energy balance in network areas, S3 ( $E2 = 0.44 \text{ kWh/m}^3$ ) and S4 ( $0.55 \text{ kWh/m}^3$ ; 50%) are the most critical in terms of energy in excess per authorised consumption, being the main problem of energy in excess due to head losses and surplus energy ( $0.30 \text{ kWh/m}^3$ ).

Since both network areas receive water from S1 and S2, a significant part of the energy in excess is due to head losses and surplus energy in these upstream areas associated with water transference ( $0.14 \text{ kWh/m}^3$ ). The excess energy is minimal in network area S5, rehabilitated in the last 20 years and with a reduced network length ( $E2 = 0.03 \text{ kWh/m}^3$ ).

These results highlight that the energy in excess per authorised consumption allows for identifying the areas with higher priority for a more detailed diagnosis analysis of improvement measures (i.e., S3 and S4) besides a global assessment. Additionally, the components of energy in excess per authorised consumption allow a first identification of the main causes of energy inefficiency. Although

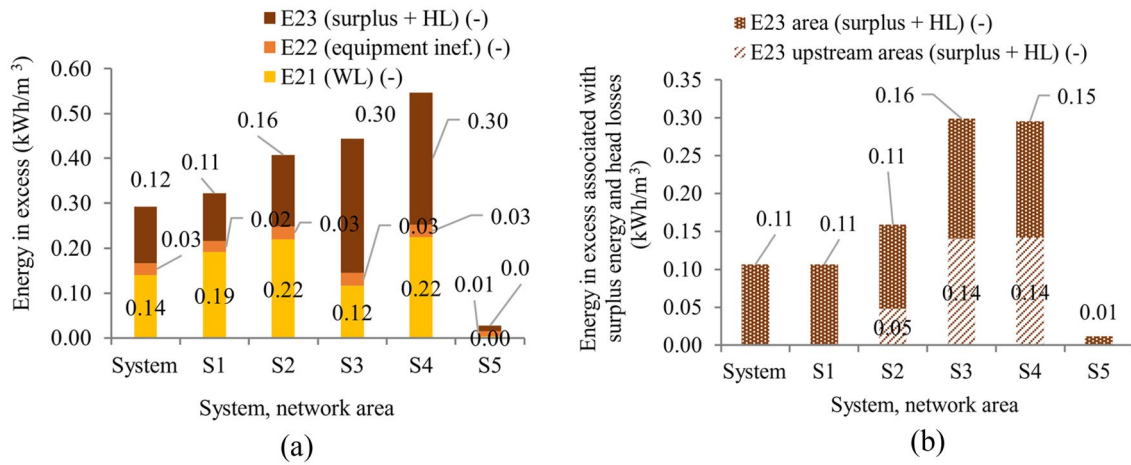
energy consumption in pumping stations in S3 and S4 is reduced (Fig. 12), three pumping stations in these areas (BIL, BOR, and PES) have poor performance in terms of pump efficiency (i.e., below 40%), according to IDAE (2008) and ERSAR and LNEC (2021). From these pumping stations, only pumps in BOR have reached the end of their service life considered by WUA. Therefore, adequate flow rate and pressure monitoring (e.g., energy audits) of these pumping stations should constitute a first step to implementing well-succeed operational measures in the equipment (e.g., variable speed pump installation), as recommended in the previous studies (Lamaddalena and Khila 2013). These results illustrate that calculating adequate performance indicators allows for more robust global diagnoses and identifying the area or equipment with higher priority for a more detailed analysis (Fig. 11).

In terms of equipment (Fig. 12), the average pump efficiency is 48%, varying between 17 and nearly 80%, whereas the average efficiency of turbines is 58%, ranging between 48 and 90% in the 3 years of analysis. Several turbines are installed in the system: the Kaplan turbine has the highest average efficiency of 81%, and the two Francis turbines have a lower average efficiency of 57%. These efficiencies are under expected behaviours of these turbines. Kaplan has double regulation (adjustable runner blades and wicket gate), allowing higher efficiencies for a wide range of flow rates. Francis turbines have single regulation (only wicket gate) that does not allow such a good performance. Still, these results indicate that the turbines' efficiency is low relative to the maximum expected efficiency for Francis (80–95%) and Kaplan turbines (94–100%) (Liu et al. 2015). The precipitation variability in years of analysis (Fig. 2a) and the fact that



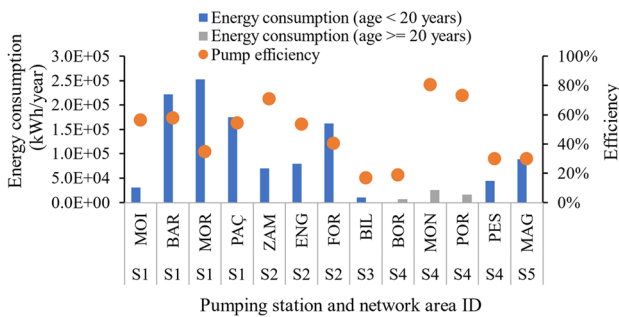
**Fig. 9** Energy performance indicators for the canal network areas in 2018 calculated using three reference elevation levels: system minimum elevation, system minimum consumption node elevation, and

system average node elevation: **a** Energy in excess per authorised consumption,  $E2 \text{ (kWh/m}^3)$  and **b** Energy in excess,  $E3 \text{ (-)}$



**Fig. 10** Energy performance indicators for the canal network areas in 2018: **a** energy in excess associated with water losses, E21, equipment inefficiency, E22, and head losses and surplus energy, E23 **b** energy in excess associated with head losses and surplus energy, E23,

disaggregated into energy in excess in the upstream areas associated with water transference and energy in excess in the network area in analysis

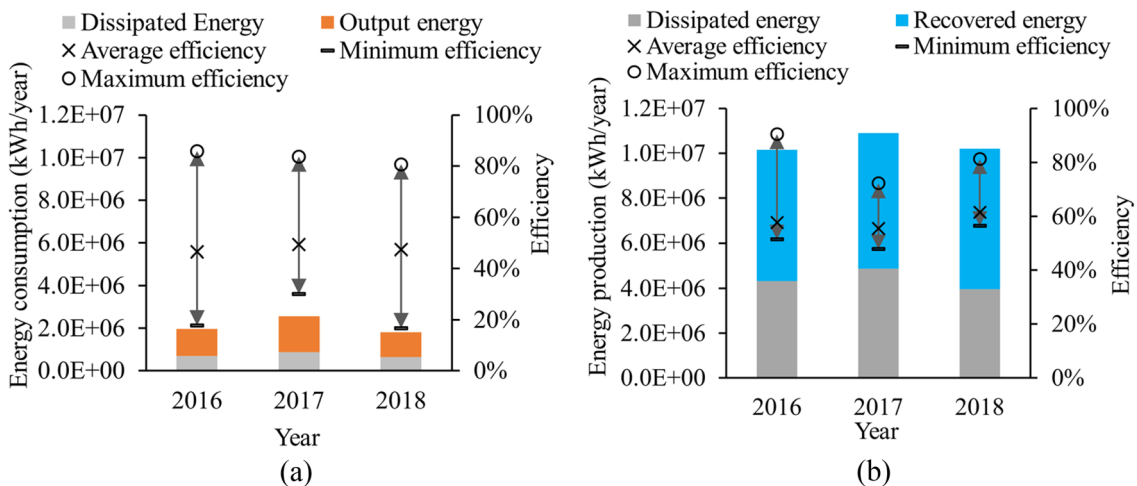


**Fig. 11** Pumping energy consumption and efficiency per network area and equipment in the gravity CIS in 2018

during the irrigation period, the priority of the WUA is to ensure the service to users might contribute to the observed efficiency values. Therefore, a more detailed diagnosis is necessary to identify improvement measures for hydraulic turbines.

### Conclusions

Existing studies on energy efficiency in CIS mainly focused on equipment or system efficiency in pressurised pipe systems. The main driver for this research was the need for a simple, robust, and comprehensive methodology for the



**Fig. 12** Analysis of energy consumption, pump efficiency for the set of pump equipment (13) (a), and energy production and turbine efficiency for the set of hydraulic turbines (3) in the gravity CIS between 2016 and 2018 (b)

energy balance calculation in gravity, pressurised and combined CIS. A methodology for the energy efficiency assessment specifically tailored CIS, applicable to the global system and individual network areas, is proposed herein. This methodology requires the previous water balance calculation to estimate system input volume, authorised consumption and water losses. Besides quantifying the different sources of inefficiencies, the energy balance provides valuable data for calculating energy performance indicators. This study also tests existing and additional performance indicators for energy efficiency assessment in CIS, namely, the “Energy in excess per authorised consumption”.

Applying the proposed energy balance methodology to real-life CIS has allowed identifying the most relevant energy components in excess in gravity and pressurised CIS. In the gravity CIS, these are due to water losses, followed by dissipated energy due to continuous and singular head losses. In the pressurised CIS, shaft input energy predominates, and pumping energy costs are a significant part of operational costs. In this system, the most relevant energy in excess component is the surplus energy and the dissipated energy due to friction losses, followed by the dissipated energy in pumping equipment. Applying the water and energy balances to network areas has allowed the identification of specific local problems. In the gravity system, network areas S3 and S4 are the more problematic, with energy in excess associated with head losses and water losses. The sensitivity analysis has shown that Energy in excess per authored consumption (E2) is an adequate and robust metric to assess the system's energy efficiency and to compare different network areas. This analysis also demonstrated that the minimum system elevation is the most robust reference elevation in the energy balance calculation.

Considering the water-energy efficiency diagnosis for the gravity CIS, the following non-infrastructure high-priority measures are suggested: monitoring and controlling discharges in canals and intermediate reservoirs and a more detailed diagnosis of turbines to optimize operation and energy production. Furthermore, infrastructural measures involving canal and pipe network rehabilitation of the most problematic components in leakage and replacement of old and low-efficiency pump equipment are recommended for the gravity CIS to improve energy efficiency. For the pressurised CIS, besides improving monitoring and controlling of authorised consumption for network operation (non-infrastructure measures), network sectorization, combined with pressure management, should be studied to reduce electricity energy consumption and surplus energy and prevent future leaks.

As future research, the methodology for energy balance should be further tested in more extensive and complex CIS. Future work should also include calculating all energy balance components based on the hydraulic modelling of the

CIS, to carry out a more detailed analysis of each excess energy component and to study improvement measures.

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**Data availability** Due to the nature of the research supporting data is not available.

## Declarations

**Conflict of interest** The authors declare no competing interests.

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## References

- Abadia R, Rocamora MC, Ruiz A, Puerto H (2008) Energy efficiency in irrigation distribution networks I: theory. *Biosys Eng* 101(1):21–27. <https://doi.org/10.1016/j.biosystemseng.2008.05.013>
- Abadia R, Rocamora MC, Corcoles JI, Ruiz-Canales A, Martínez-Romero A, Moreno MA (2010) Comparative analysis of energy efficiency in water users associations. *Span J Agric Res*. <https://doi.org/10.5424/sjar/201008S2-1356>
- Abadia R, Vera J, Rocamora C, Puerto H (2018) Generalisation of supply energy efficiency in irrigation distribution networks. *Biosys Eng* 175:146–155. <https://doi.org/10.1016/j.biosystemseng.2018.09.010>
- Alegre H, Baptista JM, Cabrera E, Cubillo F, Duarte P, Hirner W, Merkel W, Parena R (2017) Performance indicators for water supply services—manual of best practices, 3rd edn. IWA Publishing, London (ISBN 9781780406336)
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome

- Arregui F, Cabrera E Jr, Cobacho R (2006) Integrated water meter management. IWA Publishing, London (ISBN: 9781843390343)
- Barkhordari S, Shahdany MHS (2022) A systematic approach for estimating water losses in irrigation canals. *Water Sci Eng* 15(2):161–169. <https://doi.org/10.1016/j.wse.2022.02.004>
- Belaud G, Mateos L, Aliod R, Buisson MC, Faci E, Gendre S, Ghinassi G, Gonzales PR, Lejars C, Maruejols F, Zapata N (2020) Irrigation and energy: issues and challenges. *Irrigation Drainage*. <https://doi.org/10.1002/ird.2343>
- Cabrera E, Pardo MA, Cobacho R, Cabrera E Jr (2010) Energy audit of water networks. *J Water Resour Planning Manag* 136(6):669–677
- Cabrera E, Gómez E, Soriano J, Espert V (2014) Energy assessment of pressurized water systems. *J Water Resour Planning Manag*. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000494](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000494)
- Cabrera E, Gómez E, Cabrera E Jr, Soriano J (2018) Calculating the economic level of friction in pressurised water systems. *Water* 10:763. <https://doi.org/10.3390/w10060763>
- Cabrera E, del Teso R, Gómez E, Cabrera E Jr, Estruch-Juan E (2021) Deterministic model to estimate the energy requirements of pressurized water transport systems. *Water* 13:345. <https://doi.org/10.3390/w13030345>
- Corbari C, Mancini M (2023) (2022) Irrigation efficiency optimization at multiple stakeholders' levels based on remote sensing data and energy water balance modelling. *Irrig Sci* 41:121–139. <https://doi.org/10.1007/s00271-022-00780-4>
- Cunha H, Loureiro D, Sousa G, Covas D, Alegre H (2019) A comprehensive water balance methodology for collective irrigation systems. *Agric Water Manag*. <https://doi.org/10.1016/j.agwat.2019.05.044>
- DR (2016) Decree-law No. 76/2016. National Water Plan, Diário da República, 1.ª série, No. 215, 9th of november 2016 (in Portuguese)
- EDIA (2021) Irrigation 2030—Survey of public irrigation development potential on the horizon of a decade (in Portuguese). Available online: [https://agricultura.gov.pt/documents/78536/0/Regadio2030\\_ConsultaPublica\\_15dez2021.pdf/67382a6e-da4c-da69-e6a1-8ca03b582870?t=1639596544630](https://agricultura.gov.pt/documents/78536/0/Regadio2030_ConsultaPublica_15dez2021.pdf/67382a6e-da4c-da69-e6a1-8ca03b582870?t=1639596544630) (visited in 12/2022).
- EEA (2020) Water use by sectors. European Environmental Agency. <https://www.eea.europa.eu/archived/archived-content-water-topic/water-resources/water-use-by-sectors> (visited in 12/2022).
- ERSAR and LNEC (2021) Guide for assessing the quality of service in water and wastewater services, 3rd edition (in Portuguese). Lisbon, Portugal, 2021. Available online: <http://www.ersar.pt/publicacoes/publicacoestecnicas/guias> (visited in 12/2022).
- Farley M, Trow S (2003) Losses in water distribution networks. IWA publishing, London (ISBN 1900222116)
- Fenareg (2022) Irrigation in Portugal. Challenges for the next decades (in Portuguese). Seminar. Instituto Superior de Agronomia, 10th of January 2022
- IDAE (2008) Protocolo de Auditoría Energética en Comunidades de Regantes. Instituto para la Diversificación y Ahorro de la Energía (IDAE), ISBN: 978-84-96680-28-9
- Jorge C, Almeida MC, Covas D (2022) A novel energy balance tailored for wastewater systems. *Urban Water J* 19(5):441–452. <https://doi.org/10.1080/1573062X.2022.2035409>
- Lamaddalena N, Khila S (2013) Efficiency-driven pumping station regulation in on-demand irrigation systems. *Irrig Sci* 31:395–410. <https://doi.org/10.1007/s00271-011-0314-0>
- Liu X, Luo Y, Karney BW, Wang W (2015) A selected literature review of efficiency improvements in hydraulic turbines. *Renew Sustain Energy Rev* 51:18–28. <https://doi.org/10.1016/j.rser.2015.06.023>
- Loureiro D, Beceiro P, Moreira M, Arranja C, Cordeiro D, Alegre H (2023) A comprehensive performance assessment system for diagnosis and decision-support to improve water and energy efficiency and its demonstration in Portuguese collective irrigation systems. *Agric Water Manag*. <https://doi.org/10.1016/j.agwat.2022.107998>
- Luc JP, Tarhouni J, Calvez R, Messaoud L, Sablayrolles C (2006) Performance indicators of irrigation pumping stations: application to drill holes of minor irrigated areas in the Kairouan plains (Tunisia) and impact of malfunction on the price of water. *Irrig Drain* 55:85–98. <https://doi.org/10.1002/ird.210>
- Mamade A, Loureiro D, Alegre H, Covas D (2017) A Comprehensive and well tested energy balance for water supply systems. *Urban Water J* 14(8):853–861. <https://doi.org/10.1080/1573062x.2017.1279189>
- Mamade A, Loureiro D, Alegre H, Covas D (2018) Top-down and bottom-up approaches for energy balance in Portuguese supply systems. *Water* 10(5):577. <https://doi.org/10.3390/w10050577>
- Monteiro L, Cristina R, Covas D (2021) Water and energy efficiency assessment in urban green spaces. *Energies* 14:5490
- Moreno MA, Ortega JF, Córcoles JJ, Martínez A, Tarjuelo JM (2010) Energy analysis of irrigation delivery systems: monitoring and evaluation of proposed measures for improving energy efficiency. *Irrigation Sci*. <https://doi.org/10.1007/s00271-010-0206-8>
- Mutema M, Dhavu K (2022) Review of factors affecting canal water losses based on a meta-analysis of worldwide data. *Irrig Drain* 71(3):559–573
- Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2011) Soil and water assessment tool theoretical documentation (version 2009). Texas Water resources Institute Technical Report N. 406. Available at <https://swat.tamu.edu/media/99192/swat2009-theory.pdf> (visited in 12/2022).
- Pardo MA, Manzano J, Cabrera E, García-Serra J (2013) Energy audit of irrigation networks. *Biosys Eng* 115(1):89–101. <https://doi.org/10.1016/j.biosystemseng.2013.02.005>
- Pérez-Sánchez M, Sánchez-Romero FJ, Ramos HM, López-Jiménez PA (2016) Modeling irrigation networks for the quantification of potential energy recovering: a case study. *Water* 8:234. <https://doi.org/10.3390/w8060234>
- Rijo M, Pereira LS (1987) Measuring conveyance efficiencies to improve irrigation water management. *Irrigation Drainage Syst*. <https://doi.org/10.1007/BF01102935>
- Rocamora C, Vera J, Abadía R (2013) Strategy for efficient energy management to solve energy problems in modernized irrigation: analysis of the Spanish case. *Irrig Sci* 31:1139–1158. <https://doi.org/10.1007/s00271-012-0394-5>
- Rodrigues CM, Moreira M, Guimarães RC, Potes M (2020) Reservoir evaporation in a Mediterranean climate: comparing direct methods in Alqueva Reservoir, Portugal. *Hydrol Earth Syst Sci* 24(12):5973–5984. <https://doi.org/10.5194/hess-24-5973-2020>
- The World Bank (2022) Water in Agriculture. <https://www.worldbank.org/en/topic/water-in-agriculture> (visited in 12/2022).
- Thornthwaite CM, Matter JR (1957) Instructions and tables for computing potential evapotranspiration and the water balance. *Climatology* 10:311
- US Army Corps of Engineers (2010) Hydrologic Modelling System HEC-HMS—user's Manual. US Army Corps of Engineers, available at: [https://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS\\_Users\\_Manual\\_3.5.pdf](https://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS_Users_Manual_3.5.pdf) (visited in 12/2022).
- Vermersch M, Carteado F, Rizzo A, Johnson E, Arregui F, Lambert A. (2016) Guidance on apparent losses and water loss reduction planning. [https://www.pseau.org/outils/ouvrages/wlranda\\_free\\_guidance\\_notes\\_on\\_apparent\\_losses\\_water\\_loss\\_reduction\\_planning\\_2016.pdf](https://www.pseau.org/outils/ouvrages/wlranda_free_guidance_notes_on_apparent_losses_water_loss_reduction_planning_2016.pdf) (visited in 12/2022)