# How to assess the effectiveness of energy management processes in water supply systems

Nelson Carriço, Dídia Covas, Helena Alegre and Maria do Céu Almeida

## ABSTRACT

The main objectives that generally motivate the implementation of energy management strategies, suggestions of possible assessment criteria and corresponding performance measures are presented in a systematic way. A methodology based on the hydraulic energy balance along water pipe systems and four performance indices to assess energy efficiency is established. This methodology is applied to a real-life water supply system for two consumption scenarios and two operating schemes. The calculation of index E4 and the comparison between scenarios and schemes rely on the hydraulic simulation of the system. The application of this methodology has demonstrated the robustness and practicality of the proposed new performance indices, being particularly relevant for the comparison of different measures for the improvement of energy efficiency, such as the use of variable speed pumps and the installation of micro-turbines. More applications are needed for systems with different sizes, layouts and elevations in order to identify and to overcome practical application difficulties.

**Key words** | energy efficiency, energy management, performance indicators, water supply

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## INTRODUCTION

The current paper presents criteria and performance measures for the assessment of the effectiveness of energy management processes in water supply systems. Energy consumption costs, together with the manpower costs, represent a significant part of operating costs of the water supply utilities. The efficient use of energy is, therefore, critical for the global economic efficiency of utilities. In addition, it has an increasing environmental importance in order to reduce $CO_2$ emissions.

The implementation of projects aiming at the optimization of energy resources and costs, by reducing energy losses, reducing peak electricity consumption and minimizing the environmental emissions footprint is, therefore, increasingly common among water utilities. Assessing the efficiency of energy use is important to establish priorities of intervention and to monitor the effectiveness of the implemented measures. However, this task is far from being trivial. The use of performance metrics is advisable. The selection of the performance measures to adopt should follow the general service assessment principles established in ISO 24510 2007 standards, namely: objectives identification, assessment criteria establishment and adequate performance measures selection.

The International Water Association (IWA) performance indicators (PI) system includes indicators adequate for assessing energy efficiency (Alegre *et al*. 2006). These PI are a good starting point, but they are not always appropriate or sufficient. They allow the utility to assess, for example, if the pumping equipment is efficiently operating, but they do not provide information on the potential for savings derived from other factors.

The main challenge in terms of energy assessment relates to the diagnosis phase. How energy efficient is the system currently? Which system is the less efficient one? What is the potential for improvement? How should the analysis and selection of alternative intervention solutions be carried out? What is the ideal system layout (configuration) in terms of energy efficiency? How can long-term planning take into account the ideal layout?

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This paper addresses these aspects. It presents, in a systematic way, the main objectives that generally motivate the implementation of energy management strategies, suggestions of possible assessment criteria and corresponding performance measures. Performance indices comparing the energy used in the scenario under analysis with the minimum energy theoretically necessary under the existing external context are analysed. A case study is used to illustrate the proposed measures and to compare different operating schemes for two consumption scenarios.

## ENERGY MANAGEMENT

Infrastructure asset management in urban water services can be carried out at three levels of planning: strategic, tactical and operational (Alegre & Covas 2010; Alegre *et al.* 2012). At the strategic level, global, long-term targets are identified; at the tactical level, the means for achieving targets are established; finally, operational objectives define and schedule actions to be taken.

Among the strategic objectives identified in ISO 24510: 2007 standards, some greatly depend on energy management: provision of services under normal and emergency situations; sustainability of the water utility; and protection of the environment. The first objective means that water shall be available with a minimum pressure at every demand point. The utility's economic sustainability is affected by energy costs. Protection of the environment depends on the amount and type of energy used.

Increasing concerns over the environment require effective actions for reducing the carbon footprint. Energy management should make careful choices on the types of energy used, avoiding as much as possible gas emissions that contribute to the greenhouse effect.

Table 1 establishes assessment criteria for each of the above-mentioned objectives and PI for each criterion. Some indices were selected from the IWA PI system (Alegre *et al.* 2006). Others frequently used refer to the specific energy

**Table 1** | Strategic objectives, assessment criteria and PI relevant for energy management (adapted from Duarte *et al.* 2009)

| Strategic objective | Assessment criteria | Performance measures |
|---|---|---|
| Provision of services under normal and emergency situations | Maintenance of adequate pressures in the bulk supply and distribution systems | QS10 – Pressure of supply adequacy (%)<br>% of delivery points that receive pressure equal or above the required |
| Sustainability of the water utility | Adequate size of infrastructures | Ph4 – Pumping utilisation (%)<br>*Maximum percentage of the available pumping capacity (that can be used simultaneously) that was effectively used* |
| | Economic and financial sustainability | Fi10 – Electrical energy costs (%)<br>*% of running costs corresponding to electric energy*<br>Energy consumed per revenue water (kWh/m$^3$ of revenue water)[a]<br>Energy consumed per revenue water in peak consumption periods (kWh/m$^3$ of revenue water)[a]<br>Energy consumed per revenue water in off peak consumption periods (kWh/m$^3$ of revenue water)[a] |
| Protection of the environment | Minimize energy consumed | Ph5 – Standardised energy consumption (kWh/m$^3$/100 m)<br>*Average amount of energy consumed/m$^3$ at a pump head of 100 m*<br>Ph6 – Reactive energy consumption (%)<br>% of the total energy consumed that corresponds to reactive energy<br>Ph7 – Energy recovery (%)<br>*% of the total energy recovered in turbines or reverse pumps*<br>Energy consumed per revenue water (kWh/m$^3$ of revenue water)<br>Energy consumed per pumped water (kWh/m$^3$ of pumped water) |
| | Use of renewable energy | Percentage of energy consumed from fossil fuels (%)[b] |

[a]Same indicators for pumped water (€/m$^3$ of pumped water).
[b]Same indicators for other sources.

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consumption. However, none of these fully responds to the criteria established, being unable to compare alternatives, to define priorities or to monitor achieved results.

## ENERGY EFFICIENCY PERFORMANCE INDICES

The energy efficiency indices presented were first presented by Duarte *et al.* (2009). These are based on the concepts of minimum energy and of energy in excess (Alegre 1992), which allow identification of the systems with higher potential for energy efficiency improvement. The minimum theoretical energy corresponds to the ideal situation of a frictionless system. It is assumed that for each system the zero-reference elevation corresponds to the elevation of the lower network node, which can be a consumption node, a tank level or a pump elevation. Other authors have used these energy balance concepts (Cabrera *et al.* 2009; Souza *et al.* 2011).

For a better understanding of the proposed indices, and since nodal consumptions vary with time, the concepts are explained in terms of energy per unit time (i.e. hydraulic power). There are different types of hydraulic power in a water supply system as presented and described in Table 2 and in Figure 1.

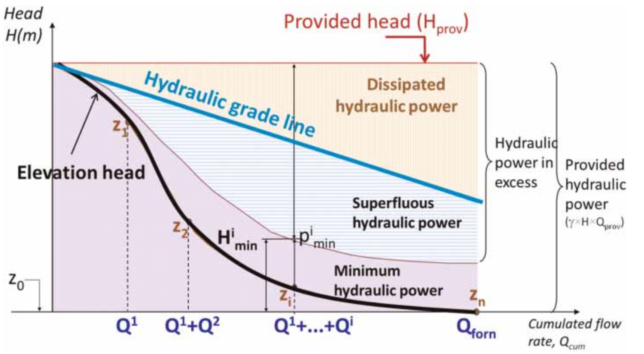


**Figure 1** | Schematic representation of the provided power, dissipated power and minimum power.

The higher the difference in elevation between demand nodes, the higher the value of $P_{\min}$. When subtracting from the provided hydraulic power, the component that refers to the elevation ($P_{\min}$), the resulting parameter allows for the comparison between different systems. Additionally, the hydraulic power in excess, $P_{\text{exc}}$, has the advantage of being independent of the zero-reference elevation. Since flow is time-dependent, the energy corresponding to these parameters can be obtained by their time-integration for a given period of analysis.

Based on the previous equations, four different indices were defined to assess the energy efficiency.

**Table 2** | Different types of hydraulic power in a water supply system

| Type | Formula |
|---|---|
| Hydraulic power (in general) | $P = \gamma \cdot Q \cdot H$ where $P$ = hydraulic power ($W$); γ = specific water weight (9800 $\text{Nm}^{-3}$); $Q$ = flow rate ($\text{m}^3/\text{s}$); $H$ = hydraulic head expressed in terms of the zero-reference level (m) |
| Minimum hydraulic power | $P_{\min}(t) = \sum_{i=1}^{n} P^i_{\min}(t) = \gamma \sum_{i=1}^{n} \left[Q^i(t) \cdot H^i_{\min}\right]$ where $P^i_{\min}(t)$ = minimum hydraulic power at node $i$ and at time $t$ ($W$); $Q^i(t)$ = consumption at node $i$ and at time $t$ ($\text{m}^3/\text{s}$); $H^i_{\min}$ = minimum required head at node $i$ ($m$); $n$ = number of consumption nodes |
| Provided hydraulic power | $P_{\text{prov}}(t) = \sum_{i=1}^{n} P^i_{\text{prov}}(t) = \gamma \cdot \sum_{i=1}^{n} \left[Q^i(t) \cdot H^i_{\text{prov}}\right]$ where $P^i_{\text{proc}}(t)$ = provided hydraulic power at node $i$ and at time $t$ ($W$) related to initial storage tank level or PS; $Q^i(t)$ = flow rate at node $i$ and at time $t$ ($\text{m}^3/\text{s}$); $H^i_{\min}$ = minimum required head at node $i$ ($m$); $n$ = summation of the number of water sources and the number of PS |
| Recovered hydraulic power | $P_{\text{rec}}(t) = \sum_{k=1}^{N_T} P^k_{\text{rec}}(t) = \gamma \sum_{k=1}^{N_T} \left[Q^k(t) \cdot H^k_{\text{rec}}(t)\right]$ where $P^k_{\text{rec}}(t)$ = recovered power through a turbine at node $k$ at time $t$; $Q^k$ $(t)$ = turbine flow at node $k$ at time $t$ ($\text{m}^3/\text{s}$); $H^k_{\text{rec}}(t)$ = recovered head at node $k$ and at time $t$ ($m$); $N_T$ = number of nodes with turbines installed |
| Hydraulic power in excess | $P_{\text{exc}}(t) = \left[P_{\text{prov}}(t) - P_{\text{rec}}(t) - P_{\min}(t)\right]$ |

### E1 – Energy in excess per unit of input volume (kWh/m$^3$)

$$E1 = \frac{E_{\text{exc}}}{V_{\text{prov}}} = \frac{\int P_{\text{exc}}(t)\text{d}t}{\int Q_{\text{prov}}(t)\text{d}t} \quad (1)$$

This index represents the theoretical potential for energy reduction per m$^3$ of the provided volume, $V_{\text{prov}}$. It should be as low as possible, though it is always a positive value. It is an adequate index to assess the impact of different energy management measures; however, it does not allow for the assessment of the impact of leakage control measures in energy efficiency. For this reason, E1 is not adequate for the comparison of systems with different water loss levels.

### E2 – Energy in excess per unit of the revenue water (kWh/m$^3$)

$$E2 = \frac{E_{\text{exc}}}{V_{\text{rev}}} = \frac{\int P_{\text{exc}}(t)\text{d}t}{\int Q_{\text{rev}}(t)\text{d}t} \quad (2)$$

This index represents the theoretical potential for energy reduction per m$^3$ of revenue water. E2 is always a positive value, ideally as low as possible. The aim of using the revenue water, $V_{\text{rev}}$, in the denominator (instead of the provided flow) is to allow the index to reflect the impact of leakage control measures in terms of energy. If real losses are improved, the index will have a lower (better) value, since the numerator diminishes ($V_{\text{prov}}$ is lower) and the denominator is the same. Therefore, E2 has advantages in comparison with E1 and should be preferred. Interventions that result in the improvement of the dissipated energy (e.g. pipe rehabilitation) will only be reflected in indices E1 and E2 if changes result in reduction of the total provided head at the source (i.e. provided hydraulic power).

### E3 – Ratio of the maximum energy in excess (dimensionless)

$$E3 = \frac{E_{\text{prov}} - E_{\text{rec}}}{E_{\text{min}}} = \frac{\int (P_{\text{prov}} - P_{\text{rec}})(t)\text{d}t}{\int P_{\text{min}}(t)\text{d}t} \quad (3)$$

This index quantifies the theoretical energy in excess that is provided to the system (minus recovered energy) in comparison with the minimum energy necessary. Similarly to the previous two indices, the provided hydraulic head includes the head losses component, which is why it is always higher than 1. It depends on the zero–reference elevation.

### E4 – Ratio of the available energy in excess (dimensionless)

$$E4 = \frac{E_{\text{prov}} - E_{\text{rec}} - E_{\text{headlosses}}}{E_{\text{min}}} = \frac{\int (P_{\text{prov}} - P_{\text{rec}} - P_{\text{headlosses}})(t)\text{d}t}{\int P_{\text{min}}(t)\text{d}t} \quad (4)$$

This index quantifies, in a straightforward way, the effective energy in excess that is provided to the system. Unlike the previous indices, it does not include the head losses component, being more realistic than E3 for the potential energy available for recovery in comparison with the minimum required.

## CASE STUDY

The analysed case study is a subsystem of the Multi-Municipal Water Supply System (MMWSS) for the Algarve region in Portugal: the Eastbound system. The Algarve region is Portugal's most popular destination for tourists, particularly in the summer. MMWSS supplies 450,000 inhabitants from October to May, a value that almost triples in the high season (HS) to 1,190,000. MMWSS has four surface water sources (reservoirs): Odeleite/Beliche, Bravura, Funcho, and Odelouca.

The Eastbound system is supplied by Beliche reservoir and water is treated in both Tavira and Beliche Water Treatment Plants (WTP). This reservoir aims at irrigation and water consumption uses. The system has two operating schemes due to the seasonality of tourism: one for the HS from June to September; and the other for the low season (LS) from October to May. During the LS, only Tavira WTP is operating and water is conveyed from Beliche to Tavira by a raw water main of 28 km total length (Figure 2(a)). In the HS, both Tavira and Beliche WTPs operate and part of the water is conveyed to Beliche WTP through a 1 km long pipe (Figure 2(b)). The raw water main from Beliche to Tavira WTP has two pumping stations (PS). At the upstream end of Beliche WTP, there is a micro-hydro power plant with two pumps-as-turbines installed.

The system downstream of Tavira WTP has four PS, four in-line storage tanks and delivers water to 20 municipal

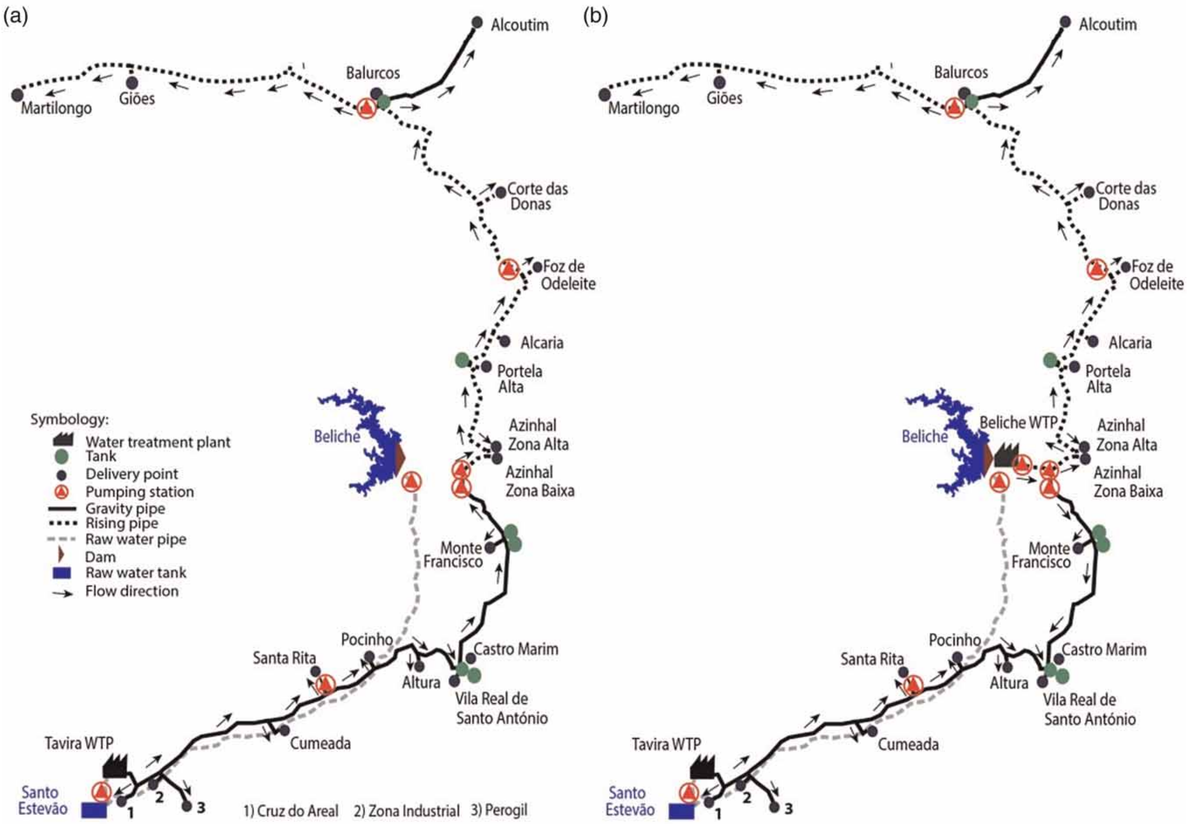


**Figure 2** | Operating schemes of the Eastbound system: (a) OS1 and (b) OS2.

tanks as shown in Figure 2. It is composed of 115 km of pipes with diameters ranging from 40 to 1,500 mm.

The aim of this analysis is to compare the energy efficiency of the Eastbound system for two operating schemes using the four energy indices defined above.

- Operation Scheme 1 (OS1): water is treated only in the Tavira WTP; neither Beliche WTP nor the micro-hydro power plant is operating.
- Operation Scheme 2 (OS2): 78% of water is treated at Tavira WTP and 22% is treated at Beliche WTP; the micro-hydro power plant is operating.

The hydraulic simulator EPANET was used to assist the calculation of the energy efficiency performance indices. The hydraulic model was provided by the water utility Águas do Algarve. Flow rate data were collected at each delivery point during 2012 and used to calculate delivery water volumes per month (Figure 3).

Two representative months were selected: January for the LS and July for the HS. These two demand scenarios were considered for each operating scheme (OS1 and OS2) to assess energy efficiency, and four situations were simulated: OS1-HS, OS2-HS, OS1-LS, OS2-LS.

The energy balance was calculated using the hydraulic model for each scenario. The dissipated energy along the system is given by the difference between the provided energy and the delivered energy at the consumption nodes. The surplus energy corresponds to the difference between the delivered energy and the minimum required energy. The dissipated and superfluous energies, expressed in terms of head, for the subsystem considering the Operation Scheme 2 with the HS demand (OS2 HS) are presented in Figure 4. The upper bound to the area corresponds to the provided head (hydrostatic head) and the three sections at which it suddenly increases correspond to PS. The limit between the dissipated power and the surplus power corresponds to the hydraulic grade line.

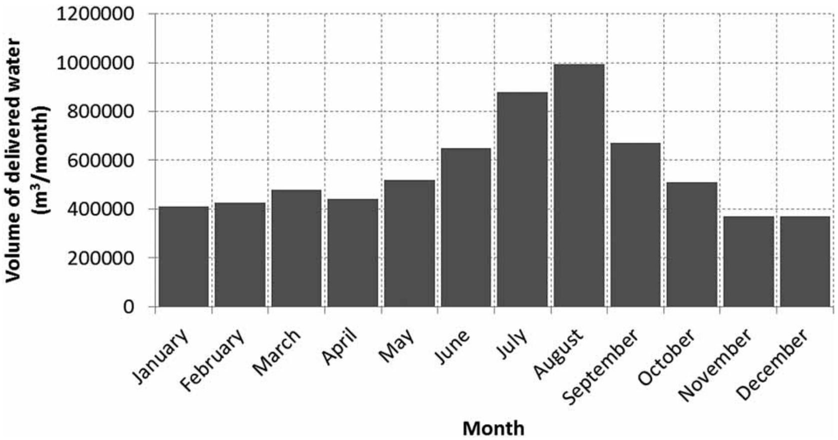


**Figure 3** | Volume of delivered water per month in 2012.

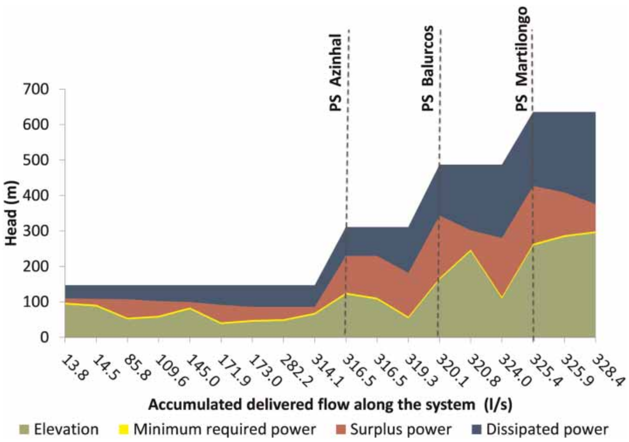


**Figure 4** | Minimum, surplus and dissipated power.

To determine the total provided power, it is necessary to calculate the hydraulic power at the PS as shown in Table 3 for the four situations.

The raw water main that conveys water from Beliche dam to Tavira WTP has two PS, necessary to sum the provided hydraulic power of each to the total provided power (Table 4).

There is a micro-hydro power plant in Beliche; the recovered hydraulic power was calculated assuming the turbine operates with a 15 m head (Table 5).

The energy efficiency performance indices obtained are presented in Figure 5.

The values of indices E1 and E2 are almost the same for both operating schemes and consumption scenarios,

**Table 3** | Hydraulic power of the PS

| | OS1-HS | | | OS2-HS | | | OS1-LS | | | OS2-LS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pumping station** | ***Q* (l/s)** | ***H* (m)** | **$P_{prov}$ (*W*)** | ***Q* (l/s)** | ***H* (m)** | **$P_{prov}$ (kW)** | ***Q* (l/s)** | ***H* (m)** | **$P_{prov}$ (kW)** | ***Q* (l/s)** | ***H* (m)** | **$P_{prov}$ (kW)** |
| Santa Rita | 3.1 | 38 | 1,168 | 3.1 | 38 | 1,168 | 1.8 | 39 | 6,694 | 1.8 | 39 | 669 |
| Beliche I | – | – | – | 36.7 | 69 | 24,776 | – | – | – | 36.6 | 69 | 24,678 |
| Beliche II | – | – | – | 36.7 | 69 | 24,776 | – | – | – | 36.6 | 69 | 24,678 |
| Azinhal I | 7.1 | 164 | 11,456 | 14.3 | 148 | 20,656 | 4.0 | 168 | 65,715 | 8.0 | 163 | 12,745 |
| Azinhal II | 7.1 | 164 | 11,456 | – | – | – | 4.0 | 168 | 65,715 | – | – | – |
| Balurcos I | 9.0 | 176 | 15,614 | 4.5 | 300 | 13,291 | 6.1 | 267 | 15,863 | 3.0 | 323 | 9,585 |
| Balurcos II | – | – | – | 4.5 | 300 | 13,291 | – | – | – | 3.0 | 323 | 9,585 |
| Martilongo | 4.4 | 148 | 6,381 | 4.4 | 148 | 6,381 | 3.3 | 207 | 67,598 | 3.3 | 207 | 6,760 |

**Table 4** | Provided hydraulic power

| | OS1-HS | | | OS2-HS | | | OS1-LS | | | OS2-LS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Raw water main** | ***Q*** **(l/s)** | ***H*** **(m)** | $P_{prov}$ **(W)** | ***Q*** **(l/s)** | ***H*** **(m)** | $P_{prov}$ **(W)** | ***Q*** **(l/s)** | ***H*** **(m)** | $P_{prov}$ **(W)** | ***Q*** **(l/s)** | ***H*** **(m)** | $P_{prov}$ **(kW)** |
| Beliche reservoir | 332.21 | 45 | 25,720 | 153.26 | 45 | 11,865 | 332.21 | 45 | 25,721 | 153.26 | 45 | 11,865 |
| Pumping station 1 | 332.21 | 87 | 283,242 | 153.26 | 87 | 130,669 | 259.12 | 87 | 220,926 | 73.13 | 87 | 68,319 |
| Pumping station 2 | 332.21 | 15 | 48,835 | 153.26 | 15 | 22,529 | 259.12 | 15 | 38,091 | 73.13 | 15 | 11,779 |

**Table 5** | Recovered hydraulic power of the micro-hydro power plant

| | OS1-HS | | | OS2-HS | | | OS1-LS | | | OS2-LS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Micro-hydro power plant** | ***Q*** **(l/s)** | ***H*** **(m)** | $P_{rec}$ **(W)** | ***Q*** **(l/s)** | ***H*** **(m)** | $P_{rec}$ **(W)** | ***Q*** **(l/s)** | ***H*** **(m)** | $P_{rec}$ **(W)** | ***Q*** **(l/s)** | ***H*** **(m)** | $P_{rec}$ **(W)** |
| Beliche | – | – | – | 73.1 | 15 | 10,750 | – | – | – | 73.1 | 15 | 10,750 |

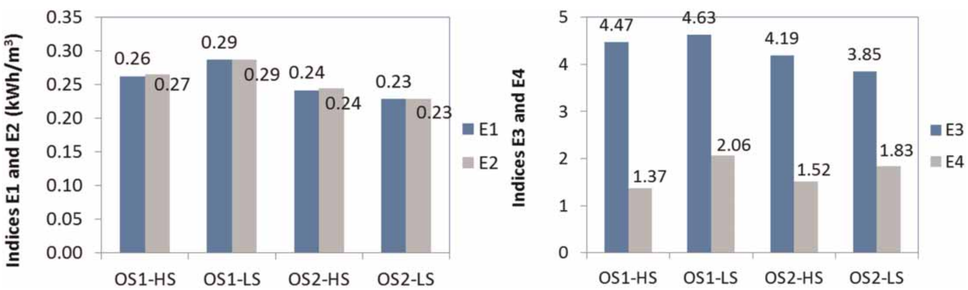


**Figure 5** | Energy efficiency performance indices.

because water losses are very small (i.e. 1–2%) and, consequently, provided water volume and revenue water volume are almost the same.

Operating scheme OS2 for both LS and HS has lower E1 and E2 indices (0.23–0.24 kWh/m$^3$) than the OS1 (0.27–0.29 kWh/m$^3$), meaning that it requires less energy per m$^3$ of delivered/provided water and has a better energy efficiency. This is because in OS2 part of the water is treated in Beliche WTP and another part is conveyed in the raw trunk main (with several PS); additionally, there is a hydro power plant at Beliche to recover energy.

Index E3 expresses the theoretical energy in excess that is provided to the system in comparison with the minimum energy necessary (i.e. 5 m): E3 is lower in OS2 than in OS1, as the other indices pointed out. E3 values vary between 3.9 and 4.6, which means that provided energy is approximately four times the minimum energy needed. As E3 values are lower in OS2 than in OS1, the former has lower potential for energy recovery than the latter.

Index E4 expresses the potential energy available for recovery in terms of the energy minimum required (i.e. 5 m). E4 varies between 1.4 and 2.1, which means that, on average, only between 2 and 5 m of energy can be recovered by the installation of microturbines in the delivery points (i.e. at the entrance of the storage tanks), or the reduction in pumping head by means of the use of variable speed pumps, for example. However, these indices do not take into account the existence of high sections in the pipe profile that may not allow this energy recovery. A more detailed analysis is necessary for the assessment of whether it is worth installing the speed variators at the existing PS and to identify the best points for the installation of micro-hydro power plants.

## CONCLUSIONS

This work contributes to the implementation of sustainable energy practices, by providing a procedure for identifying the systems with a higher potential for energy savings, quantifying this potential, and monitoring the results of the adopted interventions. A methodology based on energy balance and four perfomance indices has been presented. An example of application is presented to illustrate the recommended methodology and to demonstrate the robustness and practicality of the proposed new performance measures. Two operating schemes have been compared: it has been shown that OS2 is the most efficient as the water is supplied using less pumping energy, whereas OS1 has the highest potential for recovery. Although this is a real case study, more applications are needed with different sizes, layouts and elevations, in order to identify and to overcome practical difficulties that can occur in the application of this approach. Additionally, further work should be carried out to assess the cost of implementation of these solutions. A multicriteria analysis will be carried out including these energy efficiency indicators and other metrics associated with cost and risk.

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