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ORIGINAL PAPER

From assessment to a decision: a global framework for the management of energy use in wastewater systems

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Abstract

A global framework to assess the energy use and efficiency in wastewater systems is presented, focusing on the development of a portfolio of energy use improvement measures specifically tailored to these systems. The framework includes a performance assessment system for energy efficiency in wastewater systems and an energy balance scheme. The development and analysis of the portfolio of measures included the following steps: (i) an extensive review and compilation of existing energy improvement measures on the urban water cycle, (ii) a tailored survey addressed to multidisciplinary teams of wastewater utilities, (iii) the consolidation of the portfolio of measures for wastewater systems with the identification of main benefits and drawbacks of each measure and (iv) the discussion of the application of the improvement measures. Results from the survey for the different assessed dimensions (e.g., priority, importance) of each measure are presented together with a specific analysis of wastewater utilities. The final portfolio is instrumental for utilities to select measures, decide on the priority ones and prepare an implementation plan.

Keywords Energy efficiency · Improvement measures · Portfolio · Wastewater systems

Introduction

The management of energy use is essential in urban water systems. The efficient use of energy is associated with the environmental and economic sustainability of these systems (Bylka and Mroz 2019). The International Energy Agency reports a use of 4% of the worldwide energy by the water sector; 30–40% of the overall global energy cost is spent on wastewater and water supply systems (IEA 2019). Adequate measures can reduce costs by 15% until 2040 in the sector (UN 2014; IEA 2019). Reducing energy use is a priority in the management of urban water systems (Gómez et al. 2018).

Energy efficiency measures are essential to achieve consistent reductions in energy consumption and greenhouse gas (GHG) emissions (Moadel et al. 2022). A clear understanding of such measures can help gathering and capitalizing the information needed by utilities, when analysing and selecting ways forward, as well as by policymakers in developing strategies supporting their effective use (Trianni et al. 2014). Measures such as the installation of hydropower recovery equipment, the use of renewable energy, the use of efficient pumping systems, and the implementation of improved operation and maintenance practices are essential for enhancing energy efficiency (Nazemi et al. 2015; Ahmad et al. 2020).

The installation of energy-efficient pumping equipment can have a significant impact in energy consumption since pumping equipment uses 80–90% of the energy consumed by the water industry (Brandt et al. 2012). Upgrading existing pumping systems can save about 20% of energy (Greenberg 2011). It involves matching pump requirements, optimizing the distribution networks, eliminating unnecessary valves, and controlling pump speed. In water supply systems, improving pumping systems is essential to reduce energy costs associated with pipe friction and leakage and these practices lead to measures with different

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associated costs (ranging from low-cost to higher-cost measures). In drainage systems, energy consumption for pumping in different processes depends on the pump time scheduling (Castro-Gama et al. 2017), the hydraulic head (Behandish et al. 2014), the stormwater volume (Ostojin et al. 2011), the use of the appropriate pump type (Sperlich et al. 2018) and the use of recovery and renewable energy solutions (Charlesworth et al. 2017). A better design of water drainage systems and optimization of pipe diameter, length and valve location can generate 5–20% energy savings (EPRI 2009). The installation of variable frequency drives to control pump speed also allows for improving the system's energy performance (Vilanova and Balestieri 2015).

Gravity flows can reduce energy use in drainage systems in locations with higher slopes. An effective way to reduce sewage overflow by taking advantage of optimal control saves energy in the water system. The use of renewable energy sources, (e.g., solar and wind) significantly improves the performance of urban water systems (Trianni et al. 2014).

A systematic understanding of the relationship between the energy efficiency diagnosis and assessment and the identification of energy solutions is lacking, especially for the wastewater subsector, where limited data exist. To bridge this gap, previous studies (Jorge et al. 2021; 2022) were developed to identify the main energy inefficiencies in wastewater systems. A novel energy balance was proposed, tailored to transport processes and types of flows of wastewater systems and to the lack of data and analysis tools in these systems (Jorge et al. 2022). A specific performance assessment system (PAS) was proposed, customized to assess energy efficiency in wastewater systems, accounting for existing methodologies, the long-term objectives for energy efficiency, and identified knowledge gaps (Jorge et al. 2021).

The energy balance and the PAS allow the identification of the system's inefficiencies and of specific elements requiring improvement, supporting the planning of corrective actions. However, these diagnosis tools do not directly impact energy consumption, though these allow to identify, analyse, and support the selection of energy efficiency improvement measures attending to the specificities of each system (e.g., single components, energy recovery, system-wide improvement measures).

This paper proposes a portfolio of measures to improve energy use tailored to wastewater systems, considering existing methodologies, previous diagnoses of energy inefficiencies, the long-term objectives on energy efficiency and the identified knowledge gaps to support decision-making in utility management. The main novelties are the development of a tailored portfolio of energy use improvement measures for wastewater systems and its integration into a comprehensive energy efficiency framework, innovatively adopting a holistic view of the energy efficiency in wastewater systems.

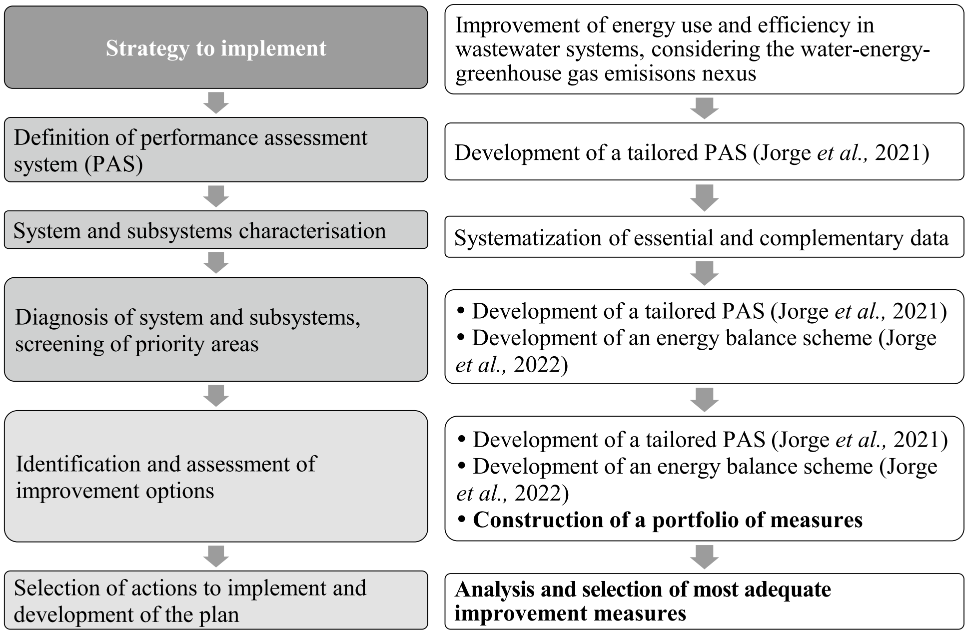
Background and proposed framework

The paper focuses on the development of a portfolio of measures intended to support the improvement of energy use in wastewater systems as part of a global framework for this purpose. The framework provides a path for tactical level planning and is aligned with similar management processes in organisations, e.g., infrastructure asset management (IAM) (Alegre and Covas 2010; Almeida and Cardoso 2010) and ISO standards (IPQ 2012; ISO 2014a, b, c series). These publications provide a standardized procedure for evaluating actual performance and appraising intervention options over an analysis period. It involves full alignment between objectives, criteria, metrics, and targets at three planning levels: strategic, tactical, and operational. Relevant tactical areas include IAM, adaptation to climate change, control of water losses and undue inflows, and energy management. This type of planning path was initially proposed to provide utilities with the know-how and tools needed for efficient decision-making in IAM of urban water services (Alegre and Covas 2010; Almeida and Cardoso 2010).

Typically, water utilities should carry out the steps presented in Fig. 1a in any planning process. At each level, a diagnosis based on a pre-defined PAS is the foundation for evaluation and priority setting that, together with a set of courses of action, leads to further developments. The process should be periodically reviewed to ensure continuous improvement (Almeida et al. 2021).

A global framework for assessing energy use and efficiency in wastewater systems is proposed (Fig. 1b) and aligned with the planning process (Fig. 1a). It allows the application of a proper diagnosis and a performance evaluation of energy efficiency in wastewater systems based on a tailored energy balance and on a PAS. These two tools support the selection of measures to improve energy use, attending to the specificities of each system, for instance, the control of undue inflows, overflows, limitations of inventory data, flow data, or modelling tools. The framework focuses on the system and not on single components, being objective-oriented and allowing water utilities to carry out a structured assessment for long-term time horizons. The novel contributions of this paper are highlighted in bold in Fig. 1b.

The energy balance (see Online Resource 1, Table O.R.1.1) is proposed and described by Jorge et al. (2022). It provides a systemic approach, looking globally at the wastewater system, considering the system layout, the energy losses in pipes and manholes, the energy associated with undue or excessive inflows, and wastewater outflowing the



(a) (b)

Fig. 1 Global framework to assess energy use and efficiency in wastewater systems: **a** planning steps and **b** use of methods and tools developed in the proposed framework

system because of capacity exceedance, among others. Different assessment levels can be applied depending on data and mathematical model availability. Three assessment levels are proposed (macro, meso and micro-level). In short, if a utility only has global data, it can apply the macro-level (external energy calculation); if the utility has detailed data on the pumping systems, the meso-level assessment applies, allowing the estimation of different components of the external energy; the micro-level assessment can be applied when pumping systems and gravity networks are well known and detailed data and mathematical modelling are available. The energy balance highlights systems' inefficiencies and specific elements that need to be improved, supporting the planning of corrective actions, but, by itself, an energy balance will not affect energy consumption. The energy balance, together with a PAS, supports the energy efficiency diagnosis and the development of energy efficiency improvement measures. Jorge et al. (2021) developed a PAS for energy efficiency tailored for wastewater systems, incorporating criteria related to energy consumption, operation and maintenance costs, and environmental impacts, such as untreated discharges and GHG emissions. The PAS comprises a complete objective, criteria, and metrics structure, system independent. The PAS has four objectives, 10 criteria and 35 metrics (Jorge et al. 2021). The objectives, criteria and complete metrics are presented in Online Resource 1 (Figure O.R.1.1 and Table O.R.1.2, respectively).

Based on the results of the diagnosis carried out using the described tools, the portfolio of measures resulting from this paper supports the identification of corrective actions to address the weak areas in terms of energy use in the system under analysis. The results allow utilities to plan the implementation of selected measures and to estimate the impact on the performance. This process should be periodically reviewed to ensure continuous improvement.

Materials and methods

General approach

A method for developing and characterizing a portfolio of energy use improvement measures is presented. An energy use improvement measure (EIM) is understood as any action or set of actions, that has a direct impact on improving efficiency in the use of energy in wastewater systems.

The development and the analysis of the portfolio of measures are based on four main steps: (i) an extensive review and compilation of existing energy use improvement measures on the urban water cycle, (ii) a tailored survey addressed to teams and experts of wastewater utilities, (iii) the consolidation of the portfolio of measures for wastewater systems with the identification of the main benefits and drawbacks of each measure and (iv) the discussion of the application of the measures.

Review of existing energy use improvement measures for urban water systems

As a first step, this research used a systematic review of the literature to explore published energy efficiency measures in urban water systems. Online databases Web of Science, Google Scholar and ScienceDirect were used to search scientific literature to find relevant research papers and other scientific publications on the topic as books, book chapters, conference abstracts, mini-reviews, short communications, case studies, and reports. The database search of publications in English was carried out using the following keywords: water; energy; nexus; water-energy nexus (water supply systems, water distribution systems, water drainage systems, urban water system); energy-water nexus; water and energy efficiency; energy efficiency; energy efficiency measures; energy efficiency solutions (water supply systems, water distribution systems, water drainage systems, urban water system). About 100 references were found. Analysis of these references was carried out to compile relevant data and produce an initial portfolio.

Energy use improvement measures survey

In a second step. a survey was designed and sent to wastewater utilities to validate the initial portfolio. This allowed a broader understanding of problems and verification of the feasibility and completeness of the portfolio.

For each measure, the survey included the following dimensions: priority, importance, applicability, level of implementation, possible quantification of benefits, data allowing the quantification of benefits and the possibility of providing information as case studies. An open field was included for comments, further information on measures implemented, and suggestions on other measures. The priority relates to the reality of the utility. Importance refers to the measure in global terms and not specifically in the utility. The applicability is understood as the implementation feasibility in absolute terms, regardless of being considered a good or bad option for the respondents. The implementation applies when the measure was found applicable by the wastewater utilities (WU); the same applies to quantification of benefits and data availability and provision. For each dimension, the following options were available:

- Priority: 1 – high priority; 2 – medium priority; 3 – non-priority; 4 – don't know/no information available.
- Importance: 1 – not important; 2 – little important; 3 – important; 4 – very important; 5 – extremely important; 6 – don't know/no information available.
- Applicability: 1 – not applicable; 2 – partially applicable; 3 – applicable; 4 – don't know/no information available.
- Implementation: 1 – foreseen; 2 – unforeseen; 3 – already implemented.
- Possible quantification of benefits: 1 – yes; 2 – no; 3 – don't know/no information available.
- Data allowing benefits quantification: 1 – yes; 2 – no; 3 – don't know/no information available.
- Possible to provide information as a use case: 1 – yes; 2 – no; 3 – don't know/no information available.

Twenty-six WU, representative of the Portuguese wastewater sector, were invited to participate in the survey. In the Portuguese wastewater sector, utilities can handle wastewater bulk transport and treatment (type A utilities); collection and transport, sometimes including treatment (type B utilities); or both. Fifteen complete responses were received. Some information about the responders is shown in Online Resource 1 (Table O.R.1.3).

Portfolio consolidation

The initial portfolio of improvement measurements was further completed and consolidated. The main benefits and drawbacks of energy use improvement measures application are analysed based on a literature review and wastewater utilities practice and testimonies.

Discussion of the application of selected measures

Selected use cases allow discussion and quantitative analysis of some energy use improvement measures provided by utilities and described in the literature.

Results and discussion

Consolidated portfolio

The consolidated portfolio includes 17 measures (Table 1). The measures are divided into six categories: equipment; systems optimization; reduction of inflows to pumping systems; operation and maintenance; energy recovery; and reduction in GHG emissions. The contributions of each measure to the energy balance components and the PAS criteria are included in Table 1.

Energy use improvement measures survey

Survey results for 15 WU are presented in Fig. 2 for the classification of measures by priority and importance. Three out of 17 measures are considered a priority (i.e., high priority): EIM3.1. (87%); EIM3.2. (80%); EIM4.3. (67%). Conversely, three measures were considered not a priority by most utilities: EIM2.3. (73%); EIM2.2. (67%); and EIM6.2. (60%).

Measures found as most important are EIM3.1. (47% considered extremely important); EIM3.2. (33% considered

Table 1 Portfolio of energy use improvement measures (EIM) for wastewater systems

Energy use improvement measure (EIM)	Description	References	Energy balance component $^{(*)}$	PAS criterion $^{(**)}$
1. Equipment				
EIM1.1 Rehabilitation or replacement of electromechanical equipment replacement: complete replacement	Complete replacement of electromechanical equipment due to deterioration, oversizing, low efficiency, or inadequacy to existing flow rates/heads. For example, replacing pump groups by more adequate and efficient ones (e.g., equal heads but different ranges of pumped flow rates and higher efficiencies)	Greenberg (2011), Cabrera et al. (2017), ERSAR and ADENE (2018), Batista (2020)	E_E	C1.1, C2.1, C4.1, C4.2
EIM1.2 Rehabilitation or replacement of components of electromechanical equipment	Replacement of components of the electromechanical equipment (e.g., motors, impellers), rehabilitation of equipment components (e.g., application of coatings to reduce the materials roughness) or introduction of new components (e.g., variable speed drives)	Brandt et al. (2012), Cabrera et al. (2017), ERSAR and ADENE (2018)		
2. Systems' optimization				
EIM2.1 Resizing or reconfiguration of the systems	Resizing or reconfiguration of the pipe system profile and layout to minimize pumping and to reduce pump heads, whenever possible deactivating pumping stations	Brandt et al. (2011), Trianni et al. (2014), Cabrera et al. (2017)	E_I, E_E	C1.1, C3.3, C4.2
EIM2.2 Continuous or local head losses reduction in pumping systems	Reduction of the roughness of raising pipes (e.g., through the application of interior coatings, pipe lining or replacement with smoother pipes) or reduction of local head losses (e.g., curves, pipe blockages, partially closed or malfunctioning valves)	Brandt et al. (2011), Batista (2020)	E_{ED}	C1.1., C1.2, C4.2
EIM2.3 Increase of the storage volume of pumping wells	Increase of the storage volume upstream of the pumping system by building additional storage volume	Based on practical experience of Portuguese wastewater utilities	E_E	C1.1, C4.1
EIM2.4 Improvement of the solids' removal procedure	Replacement or new installation of effective solids removal systems for retaining and removing several types of solids from the fluid (e.g., sediments, wet wipes, other solids)	Batista (2020)	E_{EDL}, E_{IDL}	C1.1, C1.2, C4.2

Table 1 (continued)

Energy use improvement measure (EIM)	Description	References	Energy balance component $^{(*)}$	PAS criterion $^{(**)}$
3. Reduction of inflows to pumping systems				
EIM3.1 Reduction of undue inflows: undue connections	Reduction of drains improperly connected to the wastewater system (e.g., rainwater, industrial drains)	Metro Vancouver (2014), Carne and Le (2015), Almeida et al. (2017)	E_{IUI}, E_{EUI}, E_{IEV}	C1.1, C1.3, C4.1
EIM3.2 Reduction of undue inflows: infiltration in sewer systems' components	Rehabilitation of sewers that are vulnerable to infiltration due to insufficient watertightness (e.g., repair of joints or cracks, or replacement of components)			
EIM3.3 Reduction of undue inflows: inflows of saline and fluvial waters	Reduction of inflows from saline and fluvial waters through the installation or replacement of valves (e.g., tide valves, duckbill valves)			
4. Operation and maintenance (O&M)				
EIM4.1 Programming the operating mode of pumping systems	Optimization of the operation and of the operating rules of pumping systems (e.g., minimization of the number of starts/stops, optimization of operating rules)	Brandt et al. (2011; 2012), Napolitano et al. (2016)	E_E	C1.1, C1.2, C4.2
EIM4.2 Optimization of the useful storage volume of pumping wells	Maximization of the use of the storage volume upstream of pumping systems by improving the cleaning procedures of wells, which allows a reduction of the number of pumps starts/stops	Based on practical experience of Portuguese wastewater utilities		
EIM4.3 Improvement of pumping station maintenance procedures	Improvement of cleaning procedures (e.g., grids) and maintenance of components in pumping stations (e.g., maintenance of valves, motors, and pumps)	Brandt et al. (2011)		
5. Energy recovery				
EIM5.1 Installation of energy recovery equipment downstream WWTP	Installation of energy recovery equipment at downstream of WWTP (e.g., inverted Archimedes screw), benefiting from the wastewater having already some level of treatment (e.g., after solids removal or downstream WWTP)	Mcnabola et al. (2014), Power et al. (2017), Garcia et al. (2021), Sinagra et al. (2022)	E_{IRE}	C3.2
EIM5.2 Installation of energy recovery equipment at locations throughout the system	Installation of energy recovery equipment at locations with higher elevation drops in the wastewater system (e.g., at downstream manholes)	Berger et al. (2013), Jain et al. (2014), Delgado et al. (2019)		

Table 1 (continued)

Energy use improvement measure (EIM)	Description	References	Energy balance component (*)	PAS criterion (**)
6. Reduction of GHG emissions				
EIM6.1 Installation of solar energy systems	Installation of solar energy systems (e.g., photovoltaic panels)	Kusakana (2016), EPA (2018), Bailey et al. (2021), Capelo (2022)	E_E	C2.1, C2.2, C3.1
EIM6.2 Installation of wind energy systems	Installation of wind energy systems (e.g., wind turbines)	Kusakana (2016), EPA (2018)		
EIM6.3 Use of other energy sources	Use of other self-energy production energy sources (e.g., biogas)	Vakilifard et al. (2018), Limaye and Welsien (2019), Bailey et al. (2021)		

(*) presented in Online Resource 1, Table O.R.1.1

(**) presented in Online Resource 1, Figure O.R.1.1

extremely important); EIM1.2. (53% found it very important); EIM4.3. (33% considered very important); EIM4.1. (67% considered important). The least important measures for most utilities are: EIM2.3. (30%); and EIM6.2. (30%).

The results for applicability and implementation are in Fig. 3. For applicability, the measures considered more feasible to apply by wastewater utilities are EIM4.3. (93%); EIM3.1. (87%); EIM1.2. (80%); EIM3.2. (80%). Measures found not applicable are: EIM2.3. (53%); and EIM5.2. (47%).

Energy use measures more widely implemented in wastewater systems are EIM1.2. (73%); EIM1.1. (60%). Measures planned to be implemented in the short to medium term by wastewater utilities are EIM4.3. (40%); EIM3.2. (40%); and EIM2.4. (40%). Measures not planned to be implemented in the medium term are EIM6.2. (73%); and EIM2.3. (67%).

To summarize, the wastewater utilities that have taken part in the survey are aware of the problem of undue inflows, an issue often neglected. This is important since undue inflows have a direct influence on the system performance, affecting system processes' efficiency, the total energy consumption, and the energy-associated costs (among other variables). Utilities implement more often measures focusing on individual components (e.g., pumps, treatment equipment) rather than system-wide measures, despite acknowledging their importance. Investment in renewable energies and energy recovery is not yet a priority for these utilities.

Regarding data availability, utilities recognise not having data for measures EIM2.2., EIM5.2., EIM6.2. and EIM6.3. Most utilities have data regarding equipment-related measures (EIM1.1. and EIM1.2.), reduction of undue inflows (EIM3.1) and pumping stations maintenance improvement procedures (EIM4.3).

Benefits and drawbacks of the measure's portfolio

The major benefits and drawbacks of implementing each energy use improvement measure were identified and analysed, to better characterize the portfolio of the energy use measures. The primary dimensions considered are energy efficiency improvement, performance, economic, environmental, and societal concerns.

Globally, most measures lead to the reduction of energy consumption and associated costs; many have environmental benefits (e.g., reduction of untreated discharges and GHG emissions). Major drawbacks correspond to high financial efforts in terms of capital costs, functional problems, or application difficulties. This analysis has been developed based on the literature review and on the fruitful discussions with the wastewater utilities and their comments on the survey. The major benefits and drawbacks are summarised in Table 2.

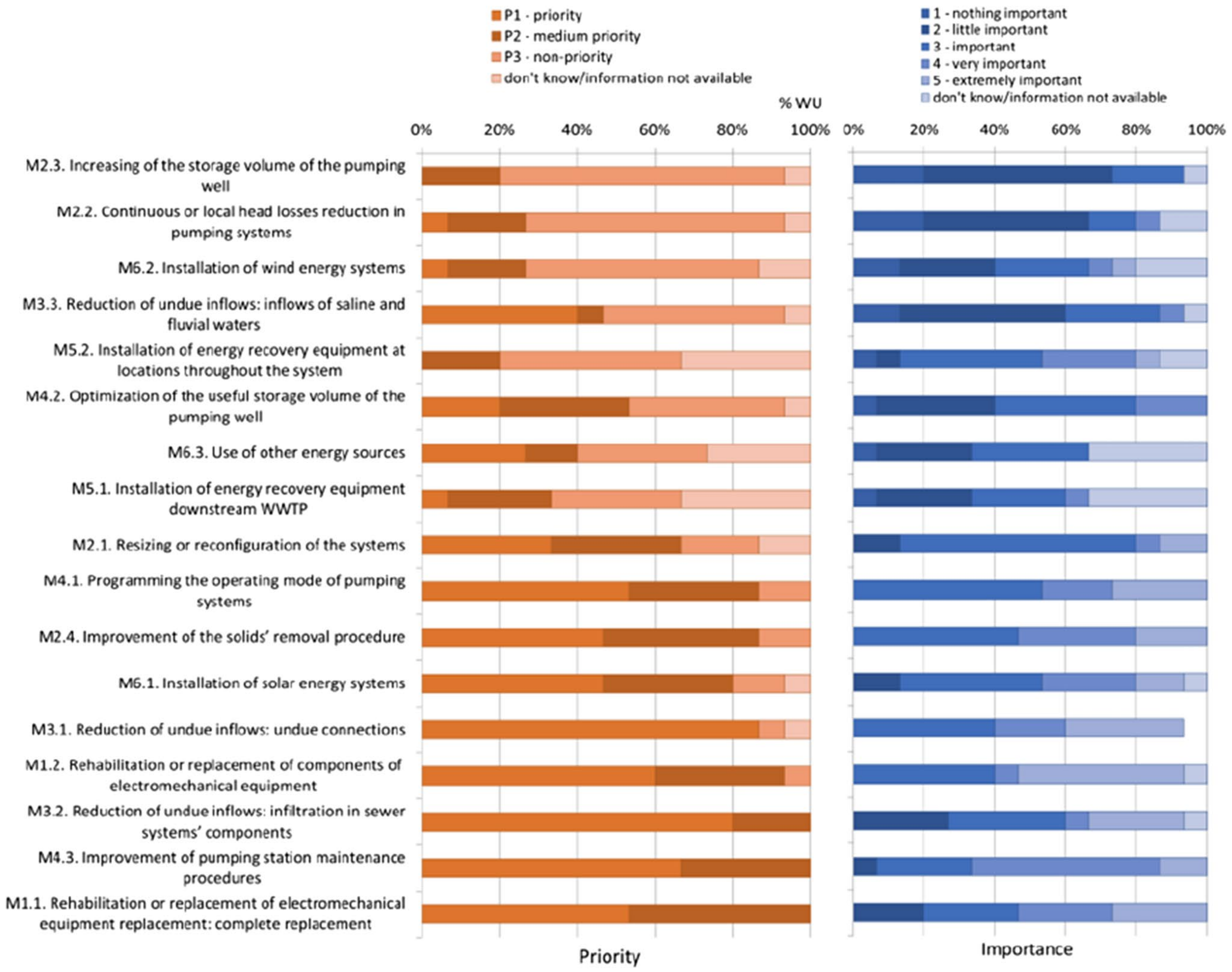


Fig. 2 Survey results: priority and importance

Application of selected energy use improvement measures

Introduction

Four use cases were selected based on existing publications and on available and reliable data provided by WU to illustrate the implementation of measures. These cases show the application of two measures of the equipment category (EIM1.1 and EIM1.2), one of the reduction of GHG emissions category (EIM6.1) and the fourth on energy recovery category (EIM5.1). The latter is a reliability study of an energy recovery solution installed at downstream of a WWTP in a Portuguese utility (Capelo 2022).

Complete replacement of electromechanical equipment (EIM1.1)

The WU2 provided relevant data regarding the results of implementing the energy improvement measure EIM1.1. One of the two pumps of the pumping station PS1 was replaced in April 2019. The WU provided data on the total energy consumption, the total energy costs, the energy consumption for pumping, the pumped volume in this pump and the pumping energy costs for 2018 (before pump replacement) and for the period 2019–2021 (Table 3). Monthly data were provided and analysed to better understand the impact of the pump replacement (data for 2019, Table 3). The pump replacement date (April 2019) is indicated.

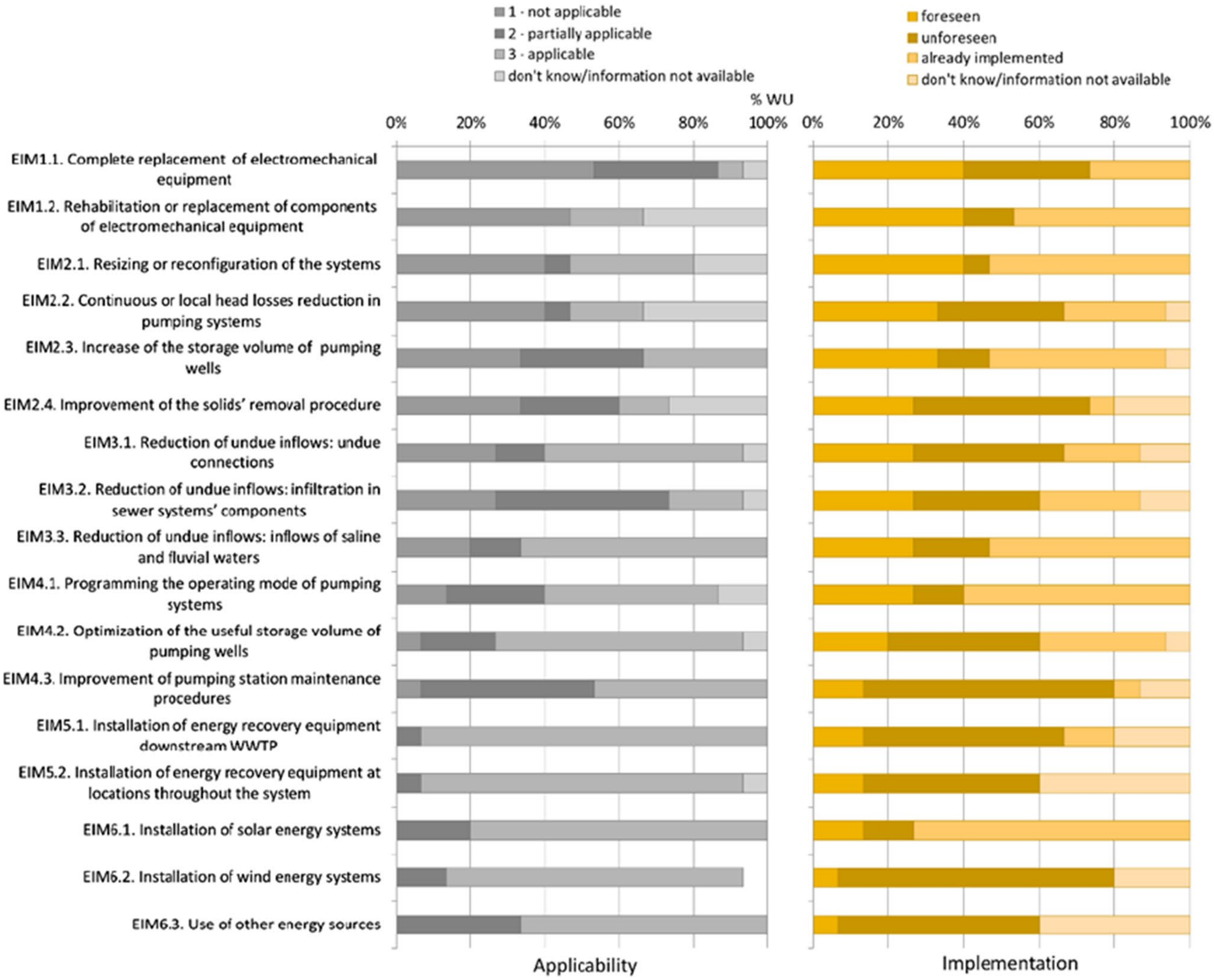


Fig. 3 Survey results: applicability and implementation

Two PAS metrics are calculated to quantify energy efficiency improvements, namely: M1.1.2. Specific energy per total pumped volume and M4.1.3. Percentage of the cost of total energy consumption used for pumping (see Online Resource 1, Table O.R.1.2). These metrics and respective reference values are presented in Table 3. Performance is classified using a three colour-grid in good (green), fair (yellow) and poor (red).

Results from metrics M1.1.2 and M4.1.3 have improved after pump replacement. Other factors influencing energy consumption in PS1 are seasonality and undue inflows (e.g., rainfall) that should be analysed. The replacement of groups for reasons other than the high energy consumption often has a positive impact on energy efficiency. Regarding data quality and reliability, it is important that energy measurements per pump are carried out to better understand each pump efficiency and the effect of the implementation of energy use improvement measures.

The application of measure EIM1.1 will influence the energy balance calculation, namely the external energy (E_E) and the respective sub-components.

Replacement and repair of electromechanical equipment components (EIM1.2)

The WU2 provided the following data regarding measure M1.2: total energy consumption, energy costs, energy consumption for pumping, total pumped volume, and pumping energy costs from January 2016 to May 2022 (Table 4). During this period, several pump components were replaced and repaired in PS2, namely: pump impellers, bearings, rectified shafts, bushings, rubbers, sealing rings, brakes, and rewinds. Data were not

Table 2 Main identified benefits and drawbacks of EIM in wastewater systems

EIM		Benefits	Drawbacks
1. Equipment			
EIM.1.1	Rehabilitation or replacement of electromechanical equipment replacement: complete replacement	Reduction of energy consumption Improvement of the equipment energy efficiency Reduction of equipment degradation Reduction of operational costs Reduction of maintenance costs Reduction of GHG emissions	Relevant capital costs Eventual service interruption (it can be done during equipment failures or maintenance) Inaccurate benefits quantification due to insufficient/unavailable water/energy meters
EIM1.2	Rehabilitation or replacement of components of electromechanical equipment		
2. Systems' optimization			
EIM.2.1	Resizing or reconfiguration of the systems	Reduction of energy consumption Reduction of equipment degradation Reduction of operational costs Reduction of maintenance costs	Very high capital costs Service interruption Limited by elevation constraints Easier application in new systems
EIM2.2	Continuous or local head losses reduction in pumping systems	Reduction of energy losses Reduction of material deterioration Reduction of equipment degradation	Relevant capital costs Service interruption Easier application in new systems
EIM2.3	Increase of the storage volume of pumping wells	Reduction of pumping equipment degradation Reduction of the number of pump start/stops	Very high capital costs Service interruption Longer wastewater retention times (which can deteriorate the characteristics of the effluent and release gases)
EIM2.4	Improvement of the solids' removal procedure	Reduction of energy losses Reduction of material deterioration (reduction of abrasive action) Prevention of clogging and obstructions (e.g., in retention valves) Improvement of the dehydration of sludge process (solids increase the load to be treated in the WWTP) Reduction of maintenance costs Reduction of the number of periodic cleaning of wells and equipment (avoiding breakdowns and stoppage)	Relevant capital costs Eventual service interruption (it can be done during equipment failures or maintenance)
3. Reduction of inflows to pumping systems			
EIM3.1	Reduction of undue inflows: undue connections	Reduction of energy consumption Reduction of flooding and discharges Reduction of material deterioration Reduction of pumping and treatment costs Reduction of GHG emissions	Very high capital costs Service interruption
EIM3.2	Reduction of undue inflows: infiltration in sewer systems' components		Very high capital costs
EIM3.3	Reduction of undue inflows: inflows of saline and fluvial waters	Reduction of energy consumption Reduction of flooding and discharges Reduction of material deterioration Reduction of pumping and treatment costs Reduction of GHG emissions Not affecting the reuse of water	Very high capital costs
4. Operation and maintenance (O&M)			
EIM4.1	Programming the operating mode of pumping systems	Reduction of the number of pump start/stops Improvements of systems' operation Reduction of equipment degradation	Overall positive impact
EIM4.2	Optimization of the useful storage volume of pumping wells	Reduction of the number of pump start/stops Improvements of systems' operation Reduction of equipment degradation	Relevant capital costs Service interruption Longer wastewater retention times

Table 2 (continued)

EIM		Benefits	Drawbacks
EIM4.3	Improvement of pumping station maintenance procedures	Reduction of the number of breakdowns Improvements of systems' operation Reduction of equipment degradation Reduction of alarms (thermal trips) related to the obstruction of pumps Prevention of clogging and obstructions	Relevant capital costs Service interruption
5. Energy recovery			
EIM5.1	Installation of energy recovery equipment downstream WWTP	Increase of the recovered energy Reduction of electricity consumption from the national grid Reduction of GHG emissions	Very high capital costs
EIM5.2	Installation of energy recovery equipment at locations throughout the system		Very high capital costs Service interruption Need to remove solids before implementation Possible equipment damage due to the corrosive effluent Most difficult application in wastewater systems due to lower heads
6. Reduction of GHG emissions			
EIM6.1	Installation of solar energy systems	Increase of energy self-production and self-consumption Reduction of electricity consumption from the national grid Reduction of GHG emissions	Very high capital costs High probability of equipment robbery High space requirement
EIM6.2	Installation of wind energy systems		Very high capital costs High probability of equipment robbery High space requirement Not applicable in non-windy areas
EIM6.3	Use of other energy sources		Very high capital costs Application limited to largest plants due to the higher complexity of the anaerobic processes required to generate biogas

Table 3 EIM1.1 application in WU2/PS1: annual and monthly (for 2019)

Year/Month	Total energy consumption (kWh/year)	Total energy costs (€/year)	Total energy consumption for pumping (kWh/year)	Total pumped volume (m^3/year)	Total energy costs for pumping (€/year)	M1.1.2 (kWh/m^3) (*)	M4.1.3 (%)
2018	1,688,386	236,374	164,181	370,498	22,287	0.44 🟢	9.4
2019	1,529,396	214,115	117,479	347,306	16,706	0.34 🟢	7.8
Jan	–	–	15,325	29,126	2107	0.53 🟡	–
Fev	–	–	13,103	29,078	1792	0.45 🟢	–
Mar	–	–	11,780	30,629	1618	0.38 🟢	–
Apr	–	–	10,428	35,348	1442	0.30 🟢	–
Mai	–	–	7288	30,240	1043	0.24 🟢	–
Jun	–	–	6476	25,866	951	0.25 🟢	–
Jul	–	–	5669	23,437	881	0.24 🟢	–
Aug	–	–	3995	16,256	637	0.25 🟢	–
Sep	–	–	5467	18,439	825	0.30 🟢	–
Oct	–	–	8019	21,719	1178	0.37 🟢	–
Nov	–	–	12,641	37,362	1807	0.34 🟢	–
Dec	–	–	17,288	49,806	2426	0.35 🟢	–
2020	1,630,246	228,234	145,330	443,945	19,939	0.33 🟢	8.7
2021	–	–	106,383	351,940	13,534	0.30 🟢	–

(*) Reference values: type A WU [0, 0.5] 🟢; [0.5, 1.7] 🟡; [1.7, +∞] 🔴

Table 4 Annual data from EIM1.2 application in WU2/PS2

Year	Total energy consumption (kWh/year)	Total energy costs (€/year)	Total energy consumption for pumping (kWh/year)	Total pumped volume (m^3/year)	Total energy costs for pumping (€/year)	M1.1.2 (kWh/m^3) (*)	M4.1.3 (%)
2016	1,811,271	253,578	269,934	2,347,663	28,488	0.11 🟢	11.0
2017	1,680,576	235,281	188,580	1,759,239	20,340	0.11 🟢	9.0
2018	1,688,386	236,374	214,410	2,032,111	23,759	0.11 🟢	10.0
2019	1,529,396	214,115	196,084	1,735,417	22,518	0.11 🟢	11.0
2020	1,630,246	228,234	226,527	2,568,794	22,145	0.09 🟢	10.0
2021	–	–	213,942	2,558,750	19,274	0.08 🟢	–
2022	–	–	83,633	1,164,815	11,080	0.07 🟢	–

(*) – Reference values: type A WU [0, 0.5] 🟢; [0.5, 1.7] 🟡; [1.7, +∞] 🔴

Performance is classified using a three colourgridin good (green), fair (yellow) and poor (red)

available per pump (the pumping system was composed of three pumps installed in parallel, one group as reserve pump). Replacements and repairs were carried out in the three pump groups for several months along the 6-years (April 2016, June and October 2017, December 2018, February, July and October 2019, June 2020, April and July 2021 and June 2022). Metrics M1.1.2. and M4.1.3. were calculated (Table 4).

The effect of the replacement and repair of pump group components is not clear in metric M4.1.3. However, metric M1.1.2 has improved from 2020 onwards. Given the works being carried out over the years, it is difficult to assess the specific impact on energy consumption and efficiency, and only accumulated effects can be observed. It is recommended to analyse these results together with other factors as previously mentioned.

Installation of photovoltaic panels (EIM6.1)

Measure EIM6.1 is analysed by looking at two cases: WU2 installation of photovoltaic panels in two WWTPs (WWTP1 and WWTP2) in 2016; WU14 installation of photovoltaic panels in four WWTPs (WWTP1 to WWTP4), one water treatment plant (WTP1), one water supply pumping station (PSWS1), and on the roof of a mechanic's workshop (WS1). The latter, composed of 224 photovoltaic modules (60 kW) was installed in 2019. Data provided by utilities WU2 and WU14 are presented in Tables 5 and 6, respectively.

Metric M.3.2.1. Energy self-production (see Online Resource 1, Table O.R.1.2) was calculated. Results for WU2 highlight a fair performance for WWTP1 (Table 5), allowing to conclude that energy self-sustaining is possible in the future, with quick recovery of the investment on the equipment. Variations in annual data result from gaps in data series (e.g., due to equipment breakdowns and cloudy days).

Results of metric M3.2.1 for WU14 sometimes show poor performance however, globally, an increasing performance trend from 2019 to 2021 is observed (Table 6). This increase is mainly due to the installation in 2019 of the solar energy recovery equipment at WS1. WWTP2 and WWTP4 values show a fair to good performance, indicating possible energy self-sufficiency in the future. Annual variations result from factors like cloudy days and equipment breakdowns.

This renewable energy source contributes to increase the energy recovered component (E_{IRE}), influencing energy inefficiencies diagnosis, and reducing GHG emissions.

Hydro-energy recovery (EIM5.1)

For measure EIM5.1, Capelo (2022) analysed the installation of energy recovery equipment downstream of a WWTP from a Portuguese WU. The inverted Archimedes screw was selected as the best cost-effective technology for energy recovery in systems with low available heads and operating for a wide range of flow rates. This equipment has a long service life, low maintenance costs, high efficiencies (> 70%) and allows the passage of large solids without compromising equipment integrity and efficiency (Capelo 2022). The recovery equipment was installed downstream of the WWTP, in a bypass channel connecting to a manhole, being the available head 1.5 m.

A preliminary assessment of the energy recovery potential was carried out. The Archimedes screw can work for a range of flow rate between 10 and 110% of best efficiency flow rate. Installed power ranges from 0.68 kW for the lowest flow rate (0.060 m^3/s) and 1.31 kW for the highest flow rate (0.116 m^3/s); energy recovery varies between 6.0 and 8.6 MWh/year. The device operates for the whole year.

Table 5 Results of the application of energy measure EIM6.1 (WU2)

Year	Solar energy production (kWh/year)	Energy consumption (kWh/year)	Metric M.3.2.1 (%) (*)
WWTP1			
2016	3123	24,074	13.0 🟡
2017	4567	24,423	19.0 🟡
2018 (**)	2414	27,618	9.0 🔴
2019 (**)	2887	25,993	11.0 🟡
2020 (**)	3325	18,876	18.0 🟡
2021	4322	24,775	17.0 🟡
WWTP2			
2016 (**)	3818	44,599	9.0 🔴
2017 (**)	3437	33,896	10.0 🟡
2018	3551	39,839	9.0 🔴
2019 (**)	3118	40,885	8.0 🔴
2020 (**)	4056	41,213	10.0 🟡
2021 (**)	3055	43,460	7.0 🔴

(*) Reference values: [20, 100] 🟢; [10, 20] 🟡; [0, 10] 🔴

(**) monthly data gaps mainly due to equipment breakdowns

Performance is classified using a three colourgridin good (green), fair (yellow) and poor (red)

The economic analysis included economic indicators, namely the net present value (NPV), the payback period (PBP) and the internal rate of return (IRR). The main assumptions were: prices remain constant over the project lifetime; discount rate of 5%; project lifetime 10 years; energy unit cost 0.10€/kWh; unit capital cost for the Archimedes screw turbine 3 000 €/kWh; annual O&M cost defined as a percentage of the capital cost (5%/year). The results obtained in the economic analysis are presented in terms of investment value, annual and O&M costs, annual revenues and the three economic indicators (NPV, PBP, and IRR) in Online Resource 1, Figure O.R.1.2.

The design flow rate leading to the maximum NPV value is 0.088 m^3/s, for an installed power of 1.0 kW; the respective economic indicators are NPV = 3014 €, PBP = 4 years and IRR = 23% (Capelo 2022). The investment is profitable since the IRR is higher than the discount rate. This solution proves to be cost-effective.

This energy source contributes to increase the energy recovered (E_{IRE}) on the energy balance, influencing energy inefficiencies diagnosis.

Conclusion

The paper presents a portfolio of energy use improvement measures specifically tailored to wastewater systems, as part of a framework to assess energy use and efficiency in these systems, involving several Portuguese wastewater utilities available to participate in the research and willing to improve the energy use efficiency in their systems. The application of the methodology was well received by the participating wastewater utilities and the alignment with the other utilities' methodologies was ensured. More awareness was created within the wastewater utilities for tackling the system as a whole and for novel renewable energy solutions. A portfolio of energy use improvement measures was developed and consolidated with the support of a survey to wastewater utilities.

The measures that were most importantly recognized by utilities were mainly related to the control of undue inflows, equipment and operation and maintenance practices. On the other hand, measures related to energy recovery and with the use of renewable energies have shown not to be a short-term priority for utilities. The main benefits and drawbacks of the measures were identified and discussed. As main benefits, it was possible to highlight energy consumption and costs reduction, equipment degradation reduction, increase of energy self-production, energy recovery and global environmental benefits (e.g., reduction of untreated water discharges and GHG emissions). As main drawbacks the following were identified: high capital costs, functional problems, application difficulties and service interruption.

Impacts on energy efficiency and consumption need to account for factors influencing energy efficiency and consumption. Deficits on data availability and reliability can hinder the benefits of measures and restrain utilities to proceed with what they have. The framework is instrumental to facilitate analysis and action by providing a path to use available information to proceed with diagnosis of energy efficiency in their systems context and limitations.

Table 6 Results of the application of energy measure EIM6.1 (WU14)

Facility	Solar energy production (kWh/year)	Energy consumption (kWh/year)	Metric M.3.2.1 (%) (*)
2019			
WWTP1	6282	290,391	2.2 🔴
WWTP2	4646	25,549	18.2 🟡
WWTP3	3629	208,387	2.9 🔴
WWTP4	2762	19,246	18.9 🟡
PSWS1	6242	–	–
WTP1	6078	–	–
WS1	37,819	–	–
WU total	67,458	3,041,443	2.2 🔴
2020			
WWTP1	6023	3,025,661	2.6 🔴
WWTP2	3951	229,836	17.6 🟡
WWTP3	6228	22,466	3.3 🔴
WWTP4	1369	188,650	7.2 🔴
PSWS1	6272	–	–
WTP1	6202	–	–
WS1	79,472	–	–
WU total	109,517	3,025,661	3.6 🔴
2021			
WWTP1	6077	275,088	2.2 🔴
WWTP2	4175	23,314	17.9 🟡
WWTP3	6791	380,437	1.8 🔴
WWTP4	2865	17,307	33.9 🟢
PSWS1	5954	–	–
WTP1	5864	–	–
WS1	89,424	–	–
WU total	121,150	3,150,292	3.8 🔴

(*) Reference values: [20, 100] 🟢; [10, 20] 🟡; [0, 10] 🔴

Performance is classified using a three colourgridin good (green), fair (yellow) and poor (red)

Ideally, the framework should be applied on an integrated manner, allowing wastewater utilities to establish a baseline diagnosis of the main energy inefficiencies in their systems, by calculating the energy balance components. This analysis can be complemented with the calculation of performance metrics proposed in the proposed PAS, to identify priorities based on the current and future performance. Finally, based on the two previous tools (energy balance and PAS), improvement solutions should be identified, evaluated, and compared with the baseline diagnosis (using the metrics or the sub-set of selected metrics and recalculating the energy balance components) to decide which are the priority ones and to prepare an implementation plan.

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