UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Assessment and improvement of energy use in wastewater systems

Catarina Nunes Jorge Benavente

Supervisor: Doctor Maria do Céu de Sousa Teixeira Almeida

Co-Supervisor: Doctor Dídia Isabel Cameira Covas

Thesis approved in public session to obtain the PhD Degree in Civil Engineering

Jury final classification: Pass with Distinction

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Abstract

This research aims at developing a comprehensive approach for assessing the energy use and efficiency in wastewater systems, considering the water-energy-greenhouse gas (W-E-G) emissions nexus supported by methods and tools, such as a tailored energy balance and a performance assessment system (PAS). This approach is aligned with continuous improvement principles and allows carrying out the diagnosis of energy efficiency in wastewater systems supporting the building of a portfolio of energy use improvement measures responding to strategic objectives and attending to the systems' characteristics and factors influencing performance. The impact of undue inflows into these systems is addressed specifically. This approach is intended to support utility managers in managing the referred nexus.

The first step was the development of an energy balance scheme for assessing energy efficiency in wastewater systems. It provides a consistent method to calculate the energy components associated with wastewater transport processes, allowing the quantification of the main water-energy inefficiencies. Three assessment levels (macro, meso and micro-level) can be used for applying the energy balance, depending on available information and scope. As a second step, a comprehensive PAS to assess energy efficiency was developed, incorporating criteria related to energy consumption, undue inflows, operation and maintenance costs, and environmental impacts, such as untreated discharges and W-E-G nexus, among others. A comprehensive diagnosis of wastewater systems can be carried out by combining both developed tools (the energy balance and the PAS). As a third step, a portfolio of measures for energy use improvement in wastewater systems was developed based on literature and on a survey of the wastewater utilities. This portfolio facilitates the identification of the measures by the wastewater utilities. The proposed global framework allows to carry out the diagnoses of the current situation, to evaluate the applicable measures, using the referred tools, to set priorities and to prepare an implementation plan. The approach requires operational data; when data are limited, it enables a simple analysis, whereas when data are complete, an advanced analysis with the option of mathematical modelling is carried out. The current research is novel and innovative, adopting a holistic view of the energy efficiency in wastewater systems, and addressing significant gaps in the literature and current practice.

The main outcomes of this research are: i) *an integrated approach for the energy efficiency diagnosis in wastewater systems*; ii) a *novel energy balance for wastewater systems with different assessment levels*; iii) a *tailored and objective-oriented PAS composed of several new metrics*;

and iv) *a portfolio of energy efficiency improvement measures for wastewater systems*. The developed tools have been applied to real case studies to explore the applicability and the advantages and disadvantages of different calculation methods and metrics, attending to the limitations faced by the wastewater sector.

Keywords: energy balance, energy efficiency, performance assessment, water-energy-greenhouse gas emissions nexus, wastewater systems

Resumo

Este trabalho tem como objetivo desenvolver uma abordagem abrangente para avaliar a eficiência no uso de energia em sistemas de águas residuais, considerando o nexo água-energia-emissões de gases de efeito estufa, suportada por ferramentas como um balanço energético e um sistema de avaliação de desempenho (SAD) específicos. Esta abordagem está alinhada com os princípios de melhoria continua e permite efetuar um diagnóstico de eficiência energética em sistemas de águas residuais e incluir um portfólio de medidas para melhorar o uso de energia desenvolvido para apoiar a seleção das mesmas, respondendo a objetivos estratégicos e atendendo às características dos sistemas e fatores que influenciam o desempenho. O impacto das afluências indevidas no consumo de energia nestes sistemas é especificamente analisado. Esta abordagem constitui-se assim como um suporte ao desenvolvimento do planeamento da atuação para melhor gerir o nexo referido.

O primeiro passo foi o desenvolvimento de um balanço energético para avaliar a eficiência energética em sistemas de águas residuais. Este balanço afigura-se um método consistente para calcular as componentes de energia associadas ao processo de transporte de águas residuais, permitindo a quantificação das principais ineficiências energéticas. Três níveis de avaliação (nível macro, meso e micro) podem ser usados para aplicar o balanço energético, dependendo do contexto e informação disponível. Num segundo passo, foi desenvolvido um SAD para avaliar a eficiência energética, adaptado aos sistemas de águas residuais, incorporando critérios relacionados com o consumo de energia, afluências indevidas, custos de operação e manutenção e impactos ambientais, como descargas de água não tratada e o nexo água-energia-emissões de gases de efeito de estufa, entre outros. Utilizando as duas primeiras ferramentas (balanço energético e SAD), é possível efetuar um diagnóstico adequado dos sistemas. Num terceiro passo foi construído um portfólio de medidas para a melhoria do uso de energia em sistemas de águas residuais, com base em revisão bibliográfica e numa inquirição direcionada às entidades gestoras de águas residuais. Este portfólio facilita a identificação das medidas pelas entidades gestoras. A abordagem global proposta permite não só efetuar o diagnóstico da situação atual, mas também avaliar as medidas aplicáveis, com recurso às ferramentas referidas, selecionar as prioridades de atuação e preparar um plano de implementação. Esta abordagem requer dados operacionais; quando limitados, esta permite uma análise simples, caso contrário, permite uma análise detalhada, recorrendo a modelação matemática para simular o comportamento dos sistemas. Esta abordagem afigura-se inovadora, adotando uma visão holística da eficiência energética em sistemas de águas residuais, endereçando lacunas significativas existentes na literatura e nas práticas atuais.

Os principais resultados são: i) *uma abordagem integrada para o diagnóstico da eficiência energética em sistemas de águas residuais*; ii) *um novo balanço energético para sistemas de águas residuais com diferentes níveis de avaliação*; iii) u*m SAD adaptado e orientado por objetivos composto por novas métricas*; e iv) *um portfólio de medidas de melhoria do uso de energia em sistemas de águas residuais*. As ferramentas desenvolvidas foram aplicadas a um conjunto de casos de estudo reais para explorar a sua validade e as vantagens e desvantagens dos diferentes métodos de cálculo e métricas, atendendo às diversas limitações de dados do setor de águas residuais.

Palavras-chave: balanço energético, eficiência energética, avaliação de desempenho, nexo água-energia-emissões de gases de efeito de estufa, sistemas de águas residuais

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E_{AR_1}	Energy supplied per unit of authorised or due inflows…..………………	kWh/m^3
E_{AR_2}	Energy supplied over the minimum energy required by the system………………………………………………………………	kWh
E_D	Dissipated energy…………………………………………………..	kWh
E_E	External energy…………………………………………………….	kWh
E_{EAI}	External energy associated with authorized or due inflows………….	kWh
E_{ED}	Total dissipated energy associated with external energy.……………	kWh
E_{EDE}	Dissipated energy associated with pumps inefficiency.………………	kWh
E_{EDL}	External energy dissipated in friction losses and local head losses......	kWh
E_{EE}	Elevation associated energy……….....………………………………	kWh
E_{EUI}	External energy associated with undue inflows.…………...…………	kWh
E_{exc}	Energy in excess in the system, typically associated with undue inflows…………………………………………………………...	kWh
E_F	Friction energy……………………………………………………..	kWh
E_I	Total inflow intrinsic energy……………………………………….	kWh
E_i	Energy consumption associated with the type of energy……...……...	kWh/year
E_{IAI}	Total inflow intrinsic energy associated with authorized or due inflows………………...…………………...…………………….	kWh
E_{ID}	Total dissipated energy associated with inflow intrinsic energy...…...	kWh
E_{IDE}	System downstream energy……………..………………………….	kWh
E_{IDL}	Energy dissipated in pipe friction and local head losses.....…………	kWh
E_{IDT}	Dissipated energy in turbines……………….……………………...	kWh
E_{IEV}	Energy associated with exceedance volumes………………………	kWh
E'_{IEV}	Energy equivalent to exceedance volumes potentially inflowing to an energy consuming component……………………………………...	kWh
E''_{IEV}	Energy equivalent to exceedance volumes not connected to an energy consuming component.………………………………......	kWh
E_{INP}	Total input energy………………………………………………….	kWh
E_{IRE}	Recovered energy…..……………………………………………….	kWh
E_{IUI}	Total inflow intrinsic energy associated with undue inflows...……….	kWh
E_L	Outgoing energy through leaks…………………………………….	kWh
E_{min}	Minimum energy required by the system, associated with the operation at dry weather……………………………………………	kWh
E_N	Natural input energy………………………………………………..	kWh
E_{out}	Output energy………………………………………………………	kWh
E_S	Energy supplied to the system……………………………...…	kWh

E_{SUR}	Surplus energy…………………………………………………………..	kWh
E_T	Total energy in the system for transport and treatment……………….	kWh
E_{Teq}	Total equivalent energy consumption ……………………………….	kWh
E_U	Unit average energy consumption per unit of volume……………….	kWh/m^3
E_V	Local head losses in valves…………………………………………...	kWh
f	Dry weather inflow factor.……………………………………………	-
F_i	Emission factor of the type of energy………………………………...	kgCO_2 eq/kWh
g	Gravity acceleration ………………………………………………….	m/s^2
H	Hydraulic head………………...……………………………………...	m
H_{MIN}	Minimum required head……………………………………………….	m
H_{REC}	Recovered head……………………………………………………….	m
H_{ps}	Manometric head of the pumping station…………………………….	m
H_t	Net head of the turbine………………......…………………………….	m
N	Number of nodes with inflow………………………………………...	-
N_p	Number of pipes……..………………………………………………...	-
N_{ps}	Number of pumping stations………………………………………….	-
N_t	Total number of energy recovery devices.…………………………….	-
p	Pressure……………………………………………………………….	Pa
P_h	Hydraulic power of the turbine……………………………………….	kWh
P_{EXC}	Hydraulic power in excess…………………………………………….	W
P_{INP}	Hydraulic power supplied …………………………………………….	W
P_{MIN}	Minimum hydraulic power ……………………………….……….	W
P_{REC}	Recovered hydraulic power………………………………………….	W
Q_{INP}	Supplied flow……………………………………………………….	m^3/s
Q_{ps}	Flow of the pumping station………….……………………………....	m^3/s
Q_t	Flow of the turbine…………………………………………………....	m^3/s
T	Number of time intervals………………………….…………………	-
v	Mean flow velocity…………………………………………………...	m/s
V_{AI}	Volume of authorized or due inflows…………………………………	m^3
V_{AI}^t	Total authorized or due inflow volume during the whole year……….	m^3
V_{EV}	Exceedance volume….……………………………………………….	m^3
V_T	Total transported wastewater volume ……………….…………….….	m^3
V_{Tb}	Volume generated in the PS served area in the period of analysis.…..	m^3
V_{UI}	Volume of undue inflows……………………………………………..	m^3
V_{ws}^s	Monthly water consumption………………………………………….	m^3
V_{ws}^t	Total water supply volume…….……….………………………….…..	m^3
V_{ww}^s	Monthly wastewater production………………………………………	m^3
V_{ww}^t	Total wastewater volume …………………………………………….	m^3

z	Node elevation…………………………………………………………..	m
z_0	Zero elevation………...……………………………………………	m

Greek

γ	Water specific weight…………………………………………………..	9800 N/m^3
α	Unit conversion factor from Ws to kWh……………………………..	2.78x10^{-7}
η_{p_s}	Global efficiency of the pumping station………………………………	-
η_t	Global efficiency of the turbine………………………………………..	-
Δt	Time interval…………………………………………………………...	s

List of Abbreviations

ADENE	Portuguese Agency for Energy
CC	Capital Costs
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
COP	Conference of the Parties
DGEG	Directorate-General for Energy and Geology
DWSS	Drinking Water Supply Systems
EB	Energy Balance
ECAM	Energy Performance and Carbon Emissions Assessment and Monitoring Tool
EIM	Energy use Improvement Measure
EnPIs	Energy efficiency metrics
EPA	Environmental Protection Agency
ERSAR	Portuguese Water and Waste Services Regulation Authority
FCT	Portuguese National Funding Agency for Science, Research, and Technology
GHG	Greenhouse Gas
GIZ	Deutche Gesellschaft für Internationale Zusammenarbeit
GT24	ERSAR Technical Guide no. 24
HVAC	Heating, Ventilation, and Air Conditioning
IAM	Infrastructure Asset Management
IBNET	International Benchmarking Network for Water and Sanitation Utilities
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
IWA	International Water Association
LCA	Life Cycle Assessment
LNEC	National Laboratory for Civil Engineering
N_2O	Nitrous Oxide
NES	*Núcleo de Engenharia Sanitária*
NH_4	Ammonium
NPV	Net Present Value
O&M	Operation & Maintenance
O-C-M	Objective-Criteria-Metrics
PAS	Performance Assessment System
PAT	Pumps Operating as Turbines
PBP	Payback Period

PDCA	Plan-Do-Check-Act
PS	Pumping Station
PSWS	Pumping Station Water Supply
RV	Reference Value
SAD	*Sistema de Avaliação de Desempenho*
SDGs	Sustainable Development Goals
SGCIE	*Sistema de Gestão de Consumos Intensivos de Energia*
SWMM	Storm Water Management Model
UI	Undue Inflows
UN	United Nations
USEPA	United States Environmental Protection Agency
VFD	Variable Frequency Device
W-E-G	Water-energy-greenhouse gas
WTP	Water Treatment Plant
WU	Wastewater Utility
WWTP	Wastewater Treatment Plant

List of Publications

Several papers have been published and submitted in peer-reviewed journals and international or national conference proceedings during the development of this research work. These papers are listed by chronological order as follows:

National and International Peer-Reviewed Journals

(i) **Jorge, C.**; Almeida, M.C.; Covas, D. (2021). Impacto de afluências indevidas no consumo energético em instalações elevatórias em sistemas de drenagem urbana. Águas & Resíduos, Serie IV.9, pp. 29-40. DOI: 10.22181/aer.2020.0903.

(ii) **Jorge, C.**; Almeida, M.C.; Covas, D. (2021). Performance Assessment System for Energy Efficiency in Wastewater Systems. Water, 13, 1807. https://doi.org/10.3390/w13131807.

(iii) **Jorge, C.**; Almeida, M.C.; Covas, D. (2021). Energy Balance in Wastewater Systems with Energy Recovery: A Portuguese Case Study. Infrastructures, 6, 141. https:// doi.org/10.3390/ infrastructures 6100141.

(iv) **Jorge, C.**; Almeida, M.C.; Covas, D. (2022). A novel energy balance tailored to wastewater systems. Urban Water Journal, 1-12, https://doi.org/10.1080/1573062X.2022.2035409.

(v) **Jorge, C.**; Almeida, M.C.; Brito, R.S.; Covas, D. (2022). Water, energy, and emissions nexus: effect of inflows in urban drainage systems. Water, 14(6), 868. https://doi.org/10.3390/w14060868.

(vi) **Jorge, C.**; Almeida, M.C.; Covas, D. (2022). From assessment to a decision: a global framework to manage energy use in wastewater systems. International Journal of Environmental Science and Technology (*submitted in September 2022*).

National and International Peer-Reviewed Conferences

(i) **Jorge, C.**; Almeida, M.C.; Covas, D. (2019). Impacto de afluências indevidas no consumo energético em instalações elevatórias em sistemas de drenagem urbana. SEREA19, 15-17 de julho de 2019, Lisboa, Portugal.

(ii) **Jorge, C.**; Almeida, M.C.; Covas, D. (2021). Balanço energético em sistemas de águas residuais. ENEG 2021, 23-26 de novembro de 2021, Vilamoura, Portugal.

(iii) **Jorge, C.**; Almeida, M.C.; Covas, D. (2022). Uma abordagem integrada para gerir o uso de energia em sistemas de águas residuais. 20º ENASB, 24-26 de novembro de 2022, Cascais, Portugal (*accepted*).

To my husband and son

Chapter 1 – Introduction

1.1 Research context

Water and energy are two critical natural resources necessary for human society. Substantial amounts of water and energy are required, increasing pressure on natural resources and the environment. Increasing water consumption and water shortages are aggravated by climate change. Furthermore, energy-related emissions associated with the use of large amounts of fossil energy worldwide also have major impact on global climate change (IEA, 2021; Ke *et al.*, 2022). For many years, water and energy were managed as independent resources. Today, the water-energy nexus is widely recognised, acknowledging their interdependence, both in terms of water needs for energy use and production and energy needs for the water sector. Ensuring water and energy availability and decreasing greenhouse gas (GHG) emissions are critical issues on the agenda of cities and national governments today. Increasing water and energy consumption implies the rise in production of GHG emissions with a massive impact on climate change. The world urgently needs to use less energy more efficiently (Wakeel *et al.*, 2016).

Water and wastewater services providers face a double challenge to save water and energy concurrently, not only because of technical and economic reasons, but because of the environmental and societal concerns associated with climate change, including carbon emissions and greenhouse effects reduction. In the urban water cycle, water supply, wastewater transportation, wastewater treatment, and disposal are services that consume a considerable amount of energy. The urban water cycle comprises water catchment, abstraction, drinking water treatment, distribution, water use, wastewater collection and transport, wastewater treatment, recycling, and rainwater collection and transport. Three main parts can be distinguished: before, during and after use (drinking water system, water consumption, and wastewater system, respectively). The share of energy consumption in this stage during transportation varies according to factors such as level difference in urban zones, precipitation, proximity to the wastewater treatment plant (WWTP), type of sewer (combined or separate) and population density (Elías-Maxil *et al.*, 2014). For instance, in Sydney, the percentage of energy consumed in sewer systems is close to 7% of the total energy spent in the urban water cycle (Lundie *et al.*, 2004), while in the Netherlands, the percentage is approximately 10% (Blom *et al.*, 2010). Moreover, the energy used to provide water and wastewater services contribute directly and indirectly to GHG emissions.

Energy consumed by water and wastewater services providers is directly associated with the level of service to ensure the quantity and quality of the supplied water and treated wastewater to achieve a good level of service provided to consumers and to reduce the deleterious effects on the environment, respectively (Venkatesh and Brattebø, 2011). The steady increase in energy prices, population growth and environmental concerns related to GHG have drawn attention for improving energy efficiency in the urban water sector (Twomey Sanders, 2016).

Energy consumption from external sources in the water sector can be reduced by 15% by 2040, if energy efficiency measures are implemented (IEA, 2016). Approaches to improve energy efficiency in urban water systems focusing on equipment abound, and intervention priorities are established accordingly (Coelho and Andrade-Campos, 2014; Nowak *et al.*, 2018). Conversely, adopting a holistic view of urban water systems composed of interacting and interdependent stages is not frequent. Only in recent years systemic approaches to assess sources of inefficiency in water supply systems, such as inadequate layout and operation and energy associated with water losses, have been explored and shown a high potential for improving efficiency (e.g., Duarte *et al*., 2009; Cabrera *et al*., 2010; Mamade *et al*., 2017; 2018). For wastewater systems, existing approaches mainly focus on wastewater treatment processes and equipment (e.g., Nowak *et al*., 2015; Silva *et al*., 2016). There remains a need to adapt and explore these approaches to wastewater and stormwater systems to identify the main inefficiencies associated with sewer inflow, infiltration, and network layout and adopt measures to reduce the associated energy consumption.

Undue inflows are identified as one of the main problems in wastewater and stormwater systems, leading to several performance issues in urban drainage systems, such as flooding, decreased efficiency in water and energy use and reduced treatment efficiency in wastewater treatment plants (WWTP), among others (ERSAR, 2014). These inflows can also contribute to the increased total system operating costs because of higher operating and maintenance costs, such as pumping, and treatment costs and other costs associated with discharges or flooding. Thus, every measure to increase energy efficiency can have a significant economic impact (Metro Vancouver, 2014; Carne and Le, 2015; Almeida *et al*., 2017).

The energy balance for water and wastewater transport processes is valuable for identifying and analysing the effects of implementing energy efficiency improvement measures and identifying their potential. It aims to evaluate how much energy enters the transport system and how much is consumed and dissipated during the water path through the system. Applying the energy balance in drainage systems is not a straightforward task, mainly because of the lack of available and reliable data, poor knowledge of networks, and specific issues associated with these systems (e.g., undue inflows). Urban water systems are complex, and management needs to carry out performance assessments and account for multiple factors (infrastructure, operational, economic, social, environmental, or legal). The last is a key management tool defined as an approach that allows evaluating the process, activity efficiency, or effectiveness through performance measures (SINTEF, 2008).

This concept shifts in assessing energy efficiency in wastewater systems at the system level rather than only at the equipment level, taking advantage of the water-energy-greenhouse gas emissions nexus as a driver of this research. The development of a robust framework to support decision-making regarding energy efficiency, using a comprehensive and tested energy balance with tailored performance assessment and specific measures to improve energy use in wastewater systems, is necessary to face the upcoming management challenges and is the primary motivation for this thesis.

1.2 Thesis objectives and adopted approach

1.2.1 Objectives

The primary objective of this research is to develop a robust approach for assessing the energy use and efficiency in general wastewater transport systems, considering the water-energy-greenhouse gas emissions nexus supported by a tailored performance assessment system. The results purpose is to guide wastewater utilities in undertaking systems diagnosis and analysing options to reduce energy consumption and GHG emissions, while improving the overall performance of the systems. Management and control of undue inflows into these systems are specifically addressed to provide a systemic overview as well as to assess its impact on energy consumption. The proposed method requires operational data; when data are limited, it enables a simple analysis, whereas data are complete, an advanced analysis with the option of mathematical modelling can be carried out. This approach can also contribute to increase awareness of benefits derived from adopting operational and monitoring practices that allow more rational energy management in wastewater systems.

To achieve this purpose, the thesis specific objectives are:

(i) To compile a comprehensive state-of-the-art review, including existing energy balance approaches, energy efficiency metrics and energy use improvement measures.
(ii) To develop a novel energy balance scheme for wastewater systems, with different assessment levels for systems with different maturities in terms of available and reliable data and the existence of mathematical models.
(iii) To develop a performance assessment system (PAS) tailored for energy-related issues in wastewater systems (consumption, costs, and environmental impact, e.g., untreated discharges, GHG emissions).
(iv) To validate the proposed energy balance and the proposed PAS in a set of systems to explore their applicability and discuss the advantages and disadvantages of the calculation methods and metrics.
(v) To create a portfolio of measures to improve energy use in wastewater systems, considering those mentioned in scientific publications, those applied and envisaged by wastewater utilities, and those resulting from the application and validation of the approach proposed in this thesis.
(vi) To validate the benefits and limitations of energy improvement measures compiled, quantitatively when feasible, based on tailored surveys addressed to multidisciplinary teams from wastewater utilities and specialists.

1.2.2 Adopted approach

The adopted approach for this research work to assess energy use and efficiency in wastewater systems follows the planning steps proposed by Almeida and Cardoso (2010). The correspondence between the latter and the methods and tools developed in the current research is schematically presented in Figure 1.1. In this context, a comprehensive framework is proposed as a tool to wastewater utilities to carry out the diagnosis of energy efficiency in wastewater systems and to support the selection of measures to improve energy use. The framework allows responding to strategic objectives and attending to systems' characteristics and other factors influencing the organization performance.

This framework, including the energy balance, a tailored PAS and a portfolio of energy use improvement measures is flexible to be applied to stormwater systems considering their specificities (e.g., stormwater systems have fewer energy consumption processes and have different magnitude and typology of undue inflows inflowing to the networks). In this work, treatment processes and other sources of energy self-production (e.g., biogas, solar, heat transfer) are not included but the framework is compatible with their inclusion.

Amongst most relevant characteristics and factors influencing the systems' performance are the relevance of undue inflows and overflows, limitations of inventory and flow data, and availability of modelling tools. This holistic framework differs from existing energy management practices since it focuses on the entire system, or subsystems, and not on individual components; it is objective-oriented and allows utilities to carry out a structured assessment from short to long-term time horizons.

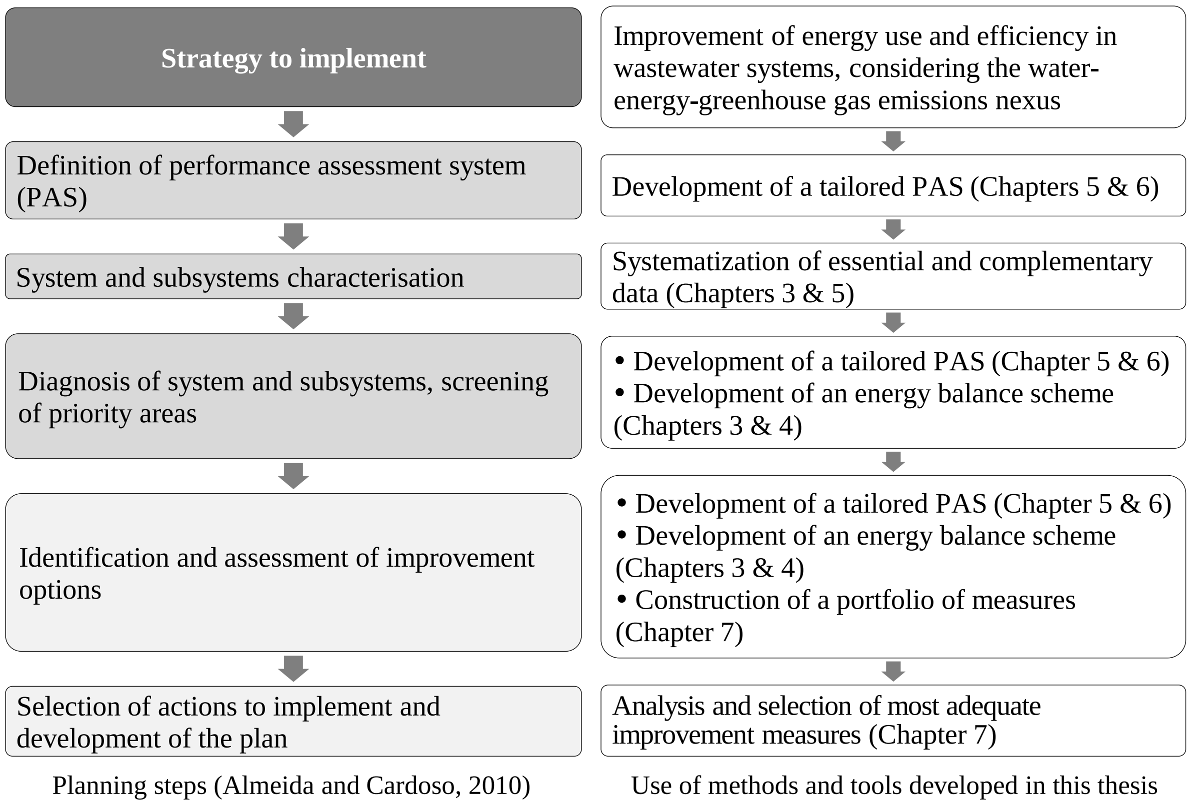


Figure 1.1 – Global framework to assess energy use and efficiency in wastewater systems.

To respond to the objectives and to develop the methods and tools mentioned in Figure 1.1, an **energy balance scheme** tailored to wastewater transport processes is developed, accounting for systems' characteristics and factors influencing the systems' performance. The systemic energy balance comprises the complete system, including the sewer network and pumping stations, among other components. System layout, energy losses, the energy associated with undue inflows, and wastewater outflowing the system because of capacity exceedance, are incorporated.

Data availability and reliability often are limited in wastewater systems (e.g., inventory, wastewater flows or analysis tools, e.g., modelling). In such case, building an energy balance for these systems is challenging; to overcome these issues, throughout all the research, flexible and complementary methods are adopted (such as different assessment levels and wide-ranging performance assessment system), where applicable, to allow and encourage wastewater utilities with different maturities to apply the methods and tools.

Three assessment levels are proposed to apply the energy balance, depending on data and the use of mathematical models. These assessment levels (macro, meso and micro-level) differ in data requirements. In short, if a utility only has global data, it can only apply the macro-level, focusing on the external energy calculation; if the utility has detailed data on the pumping systems, the meso-level assessment can be used, allowing the estimation of different energy components of the external energy; when both the pumping systems and the gravity networks are well known, detailed measurement data and mathematical modelling are available, micro-level assessment allows calculating all energy balance components.

The results of the energy balance highlight systems' inefficiencies and specific elements that need to be improved, supporting the planning of corrective actions. However, by itself, an energy balance will not change energy consumption. Thus, it is of utmost importance to align and to complement the proposed energy balance with a performance assessment system to structure the diagnosis of energy efficiency in wastewater utilities and support the selection of measures.

Therefore, a **performance assessment system (PAS)** for energy efficiency tailored for wastewater systems is developed, incorporating specific objectives, criteria related to energy consumption, operation and maintenance costs, and environmental impact, such as untreated discharges and directed and extended to the water-energy-greenhouse gas (W-E-G) emissions nexus, among others. The proposed PAS is comprehensive and adopts the same principles and structure used for other purposes, such as in strategic utility management or infrastructure asset management (EN 752:2017; ISO 24500 series). The application of the PAS can be adapted by each utility to be aligned with organisation characteristics and data.

Both development and validation of the PAS involved utilities and sector experts. The process for constructing a specific PAS to evaluate energy efficiency in wastewater systems builds on an accepted Objective-Criteria-Metrics (O-C-M) structure (Alegre and Covas, 2010; Almeida and Cardoso, 2010), ensuring the alignment with typical strategic objectives of the utilities. The focus is on the wastewater-energy use associated with the collection and transport of wastewater throughout the system and in current operation and maintenance activities. The system allows evaluating energy consumption globally and in pumping stations, the efficiency in the use of resources, the impact of undue inflows on energy consumption, and organisational and environmental sustainability. The first part of this process consists of the definition of the specific objectives, by identifying the relevant points of view to assess the performance of wastewater systems in terms of energy use efficiency and associated aspects. Once the objectives are set, the second part focuses on the selection of the criteria or points of view for evaluation of each objective. The third part is the identification of a set of metrics to assess each criterion. The last part of the process involves the definition of reference values. Performance metrics are selected to incorporate relevant aspects of energy efficiency in wastewater systems and the dimensions of performance, risk, and cost.

Analysis of energy efficiency in wastewater systems using a tailored PAS allows utilities to have a holistic view of their system's performance and increases utilities awareness of data needs and advantages associated with better knowledge of the system performance.

Combining the first and second methods described above allows to carry out a proper diagnosis of the systems, by using the energy balance and a tailored PAS. Subsequently, these tools also facilitate the assessment of potential measures for improvement.

To proceed with the identification and the assessment of improvement options, **an investigation of measures to improve performance** according to set objectives for energy use in wastewater systems is carried out. For this purpose, an extensive literature review is carried out in scientific publications, followed by a survey of wastewater utilities and specialists on the subject area. The survey allows the validation of the set of measures to include in the resulting portfolio and to collect further information to characterise them.

The final portfolio of measures is instrumental for wastewater utilities to select the measures (as in Figure 1.1), to decide which are the priority ones and to prepare an implementation plan. The same procedure is applicable in the plan revision cycle, ensuring continuous improvement.

The proposed framework is novel and innovative, adopting a holistic view of the energy efficiency in wastewater systems and associated emissions, addressing significant gaps in the literature and current practice. The continuous improvement framework with the tools developed allows carrying out the diagnosis and investigating the potential of improvement measures for energy use in wastewater systems. The framework has been applied to a set of real national case studies from representative wastewater utilities, depending on the method and level of assessment, to explore its validity and the advantages and disadvantages of different calculation methods and metrics, attending to the several described limitations faced by the wastewater sector.

The current doctoral project is based on extensive research focused on improving energy efficiency in wastewater systems. The research carried out in this project is detailed in Chapters 3 to 7.

1.3 Thesis structure

The thesis is organised in eight chapters, mostly corresponding to papers published or submitted to international peer-review journals. A brief description of each chapter is presented below.

Chapter 1 introduces the scope and background of this research, describes the main and specific objectives, and explains the overall approach of the thesis.

Chapter 2 presents a state-of-the-art review in relevant areas, namely existing energy management standards and methodologies, energy balance approaches and performance metrics for urban water systems, including examples of tools and measures for improving energy efficiency in the scope of the water-energy-emissions nexus. Gaps of knowledge in this domain are identified. The motivation for the development of this research is highlighted.

Chapter 3 presents a novel energy balance scheme for wastewater systems. Three assessment levels for the energy balance application are described (macro, meso and micro-level), depending on available information and scope. The energy balance is applied to real case studies using the three assessment levels.

Chapter 4 explores one selected case study to illustrate a detailed application (micro-level) of the energy balance for wastewater systems. The energy balance is demonstrated with a Portuguese real-life case study, using mathematical modelling to estimate the different energy components and compute two energy efficiency indices. The potential for energy recovery is analysed.

Chapter 5 presents a tailored performance assessment system (PAS) for energy efficiency, specific for wastewater systems, incorporating criteria related to energy consumption, operation, and maintenance (O&M) costs, and environmental impacts, such as untreated discharges and GHG emissions, among others. Results from the application of the PAS to Portuguese utilities are discussed.

Chapter 6 explores the magnitude of the impact of undue inflows in the water-energy-greenhouse gas (W-E-G) emissions nexus using three levels of analysis: at a national level, by calculating performance metrics with yearly data; at the utility level, by calculating performance metrics using yearly, monthly, and sub-daily data; at the subsystem level, using calculations from mathematical modelling. The significance of undue inflows in the W-E-G nexus is sustained by results from three case studies in Portugal. Results show the implications of undue inflows on energy and GHG emissions, including the effect of flooding and discharges.

Chapter 7 presents the development of a portfolio of measures to improve the energy use in wastewater systems, embedded in a complete energy efficiency framework to enhance energy efficiency in wastewater systems, considering system specificities. Results from validation of the measures by Portuguese wastewater utilities are presented, as well as some use cases applications and general characterization.

Chapter 8 contains the main conclusions of this research work and recommendations for further developments.

Chapters 3 to 6 correspond to published papers in referenced journals, respectively, Urban Water Journal (Chapter 3), Infrastructures (Chapter 4) and Water (Chapters 5 and 6) and to one submitted paper to International Journal of Environmental Science and Technology (Chapter 7). Additional information complementing the published or submitted journal papers is presented in appendices A1 to A4, respectively, to Chapter 3 to Chapter 7. Therefore, some repetitions in these chapters result from the need to provide the context in each paper.

Chapter 2 – Literature review

2.1 Introduction

This chapter presents a state-of-the-art review of energy use and efficiency assessment in urban water systems, with highlights on wastewater transport systems. The most important aspects of the water, energy, and greenhouse gases (W-E-G) emissions nexus are reviewed. Management methodologies to assess and improve energy efficiency are explored, followed by the identification and discussion of different approaches to calculate energy balances and performance metrics in the urban water sector. A specific section is dedicated to undue inflows, a process in wastewater systems that significantly affects energy consumption and the W-E-G nexus. Finally, energy improvement solutions in urban water systems are also reviewed. This background review is of the utmost importance to assess the state-of-the-art in this research area, clarify the missing research issues and the water industry needs and supports the motivation and the main objectives of this research work.

Chapter 3 to Chapter 7 are also supported with additional and specific literature reviews, since these chapters correspond to published and submitted independent journal papers.

2.2 Water, energy, and greenhouse gas emissions nexus

The United Nations (UN) 17 Sustainable Development Goals (SDG) establish a universal agenda to call for action and achieve sustainability in essential aspects of human life, such as food or health (Delanka-Pedige *et al.*, 2021; Elavarasan *et al.*, 2021). One of them is SDG 6 ”Clean water and sanitation”, which includes targets that are also critical for achieving other SDG (Delanka-Pedige *et al.*, 2021; Garcia *et al.*, 2021). At the same time, some SDG demand actions to preserve natural resources, provide affordable and clean energy and tackle climate change (Elavarasan *et al*., 2021). Although the UN annual climate summits, known as Conference of the Parties (or COP), started almost three decades ago, tackling climate change has become a global priority in recent years, particularly since the Paris Agreement (COP21) in 2015. Under this agreement, countries are being asked to significantly reduce their GHG emissions by 2030 aiming at net zero carbon emissions by 2050. To achieve these goals, countries are encouraged to implement several strategies, including investments in renewable energy generation technologies (Elavarasan *et al.*, 2021).

Several urban water supply and wastewater utilities worldwide (e.g., Amsterdam, Melbourne, New York) are setting GHG emissions reduction or carbon neutrality goals to contribute to climate change mitigation (Lam and van der Hoek, 2020). For urban water and wastewater services, low-carbon or carbon-neutral operation can be achieved through improving operational energy efficiency, generating electricity onsite from renewable sources, biogas valorisation, capturing fugitive emissions, optimizing treatment processes, and purchasing carbon offsets (Lam and van der Hoek, 2020). Therefore, sustainable management of water networks and treatment facilities is becoming a crucial issue for policymakers, as the needs are expected to soar in the near future (WWAP, 2017). Water should not be regarded just as a consumer product, but as a valuable resource that must be protected, a social responsibility (EurEau, 2020). As such, opportunities to improve wastewater management should not be neglected (WWAP, 2017; Kehrein *et al.*, 2020).

Although it is not obvious at once, water and wastewater services provided by urban water and wastewater utilities consume a considerable amount of energy (Venkatesh *et al.*, 2014). The water-energy nexus is typically characterized in resource use efficiency terms, such as energy intensity (Lee *et al.*, 2017). Water is used to produce, transport, and use all forms of energy and energy is required for the abstraction, treatment, transport, and distribution of water, as well as for the wastewater collection, transport, and treatment. Furthermore, the current challenges of infrastructure ageing, population growth, urbanization increase, and climate change mean that water and energy will be resources with competition to meet the increasing demands in the near future. Improving energy efficiency in water services have, therefore, become a key priority for politicians, decision makers and operators (IEA, 2016).

The water sector requires 4% of the worldwide electric energy consumption for abstracting, treating, and distributing water as well as collecting and treating wastewater (IEA, 2016). This energy consumption comes with an associated carbon footprint: nearly 5% (290 million tons) of total annual GHG emissions in the USA are generated by the water sector (Nair *et al.*, 2014). Considering environmental and economic damage concerns related to climate change, any reduction in energy consumption is highly relatable with GHG emissions reduction (mainly carbon dioxide, CO_2, methane, CH_4, and nitrous oxide, N_2O), drawing attention to the water, energy, and greenhouse gas emissions nexus (Stern, 2007).

In Portugal, the water sector is responsible for approximately 1.1 TWh of energy consumption annually, which corresponds to 169 million tons of indirect GHG emissions associated with water and wastewater pumping. Energy costs typically represent the second highest expense of operational costs in water utilities (around 30%-40%), according to the WWAP (2014).

Assessing energy consumption and related GHG emissions in urban water systems has been globally recognised in the 2030 Agenda for Sustainable Development, particularly with the targets defined for goals 6 (Clean water and sanitation), 7 (Affordable and clean energy), 9 (Industry, innovation, and infrastructure) and 11 (Sustainable cities and communities) (UNDP, 2015). In 2016, the European Union established the required legislation to achieve carbon neutrality in 2050, as a direct result of the Convention on Climate Change in Paris (COP21). In Portugal, the integrated Plan for Energy and Climate (PNEC 2030) is the most recent political instrument that sets the targets for energy savings and improved efficiency for each sector of activity to meet the European goals.

For urban water services providers, improving operational efficiencies or even becoming net energy producers, could be as much an ethical imperative as a service goal. In countries of all income levels, energy use for water services provision is a rather significant budget item. This, along with rising population densities and increased climate change vulnerabilities, makes efficiency gains at all stages of the urban water system fundamental for municipalities around the world (Venkatesh *et al.*, 2014).

GHG emissions are considered as an accelerating factor for climate change. The global warming potential of the total energy consumption in the water industry sector is 934 800 tons CO_2eq per year. Energy use accounts for 56% of the carbon footprint of the water sector. The other contributions to the carbon footprint are from process emissions (methane and nitrous oxide) and indirect emissions (energy used for chemicals and the organisation) (Frijins *et al.*, 2013).

The primary energy per capita consumed in the urban water cycle multiplied by an emission factor (corresponding to the type of delivered energy) results in the amount of emitted greenhouse gases (Elías-Maxil *et al.*, 2014). It should be considered that biogas (mainly methane and carbon dioxide) is produced during the biological treatment of wastewater. In the Netherlands, assuming that almost all biogas is completely flared, every person produces annually 324 kg CO_2eq by using the urban water cycle. This amount represents more than 3% of the total CO_2eq produced per inhabitant. This amount could be higher if methane from sewer networks is included in the balance (UNDP, 2011). Frijns *et al.* (2008) estimated a contribution of CO_2 emissions from waterworks and the overall urban water cycle of 0.8% and 3.3%, respectively. In regions where the gas is not flared, the mass of emitted methane will contribute to higher greenhouse emissions, since methane has 21 to 23 times higher greenhouse gas effects than carbon dioxide (EPA, 2011). Gases produced in the sewer network are not captured or treated in most places in the world, however Guisasola *et al.* (2008) have suggested that the emission of methane in sewers could have a comparable greenhouse gas effect to that produced in WWTP. Measurement results of greenhouse gas production in sewer systems of Amsterdam have a similar conclusion (de Graaff *et al.*, 2012).

Furthermore, an experiment tracing the carbon isotopes in four treatment plants in Australia, showed that fossil organic carbon contributes 4% to 7% of the total carbon balance from domestic wastewater (Law *et al.*, 2013). According to Washington *et al.* (2009), to mitigate half of the effects of climate change, a global reduction of 70% in the emission of greenhouse gases must be achieved by the year 2100, which implies that activities involved in the urban water cycle should be improved.

Also in Australia, there is increased emphasis on the water-energy nexus of urban water systems and associated environmental impacts, where the energy supplied to the urban water systems is electricity which is produced by coal combustion with large amounts of GHG emissions. The Australian water sector is trying to reduce carbon emissions from its water utilities as a part of climate change mitigation strategies that have led to carry out significant and comprehensive studies by several Australian researchers (Lundie *et al.*, 2004; Kenway *et al.*, 2008; Marsh, 2008; Sharma *et al.*, 2008; Fagan *et al.*, 2010). The studies focused on water-energy-GHG emissions nexus encompass various aspects that include impacts of political, social, technological, environmental, and economic changes on the urban water system (Nair *et al.*, 2014). In the USA, around 5% (290 million tons) of total annual GHG emissions originate in the water sector as reported by Sattenspiel and Wilson (2009). In the UK, the annual GHG emission in 2006/2007 from energy use of the water sector is 5.03 million tons of CO_2eq, which is almost one million ton over previous years (Environmental Agency, 2008).

Therefore, it is of utmost importance to reduce the total use of energy from fossil fuels used in the urban water cycle including the substitution of fossil fuels by renewable energy sources, extraction of energy from urban water and optimization of processes in water sector, especially the energy-intensive processes.

The studies reported in the literature consider several components of the urban water cycle as individual entities to report the energy and carbon footprints of each but have ignored the urban water cycle as single systems to establish the W-E-G nexus, which can provide useful information for planning low-carbon and less energy-intensive urban infrastructure. Singh and Kansal (2018) conducted a study in India and presented the main urban wastewater infrastructure components (including wastewater transport and treatment) for energy use and GHG emissions (Figure 2.1). The region selected was the National Capital Territory of Delhi divided into 12 drainage zones with 35 WWTP, 105 wastewater pumping stations and 13 common effluent treatment plants. These authors found an average value of net GHG emissions from wastewater infrastructure (excluding emissions from the open drains) of 1.046 kg CO_2eq/m^3. Direct emissions from open drains are estimated as 0.38 kg CO_2eq/m^3, whereas from sewers as 0.56 kg CO_2eq/m^3. Hence, the average net GHG emissions of the contributing drainage zones from wastewater network (including emissions from open drains) are estimated as 1.426 kg CO_2eq/m^3. This study has found that the transport of wastewater consumes a total of 203.6 MWh/day, which is influenced by the mode of transport, topography, and population density of the catchment area (it is important to highlight that the context of the country should be considered when analysing these values). However, it is important to highlight that this approach do not consider undue inflows and overflows (the latter either at overflow structures or flooding not returning to the system).

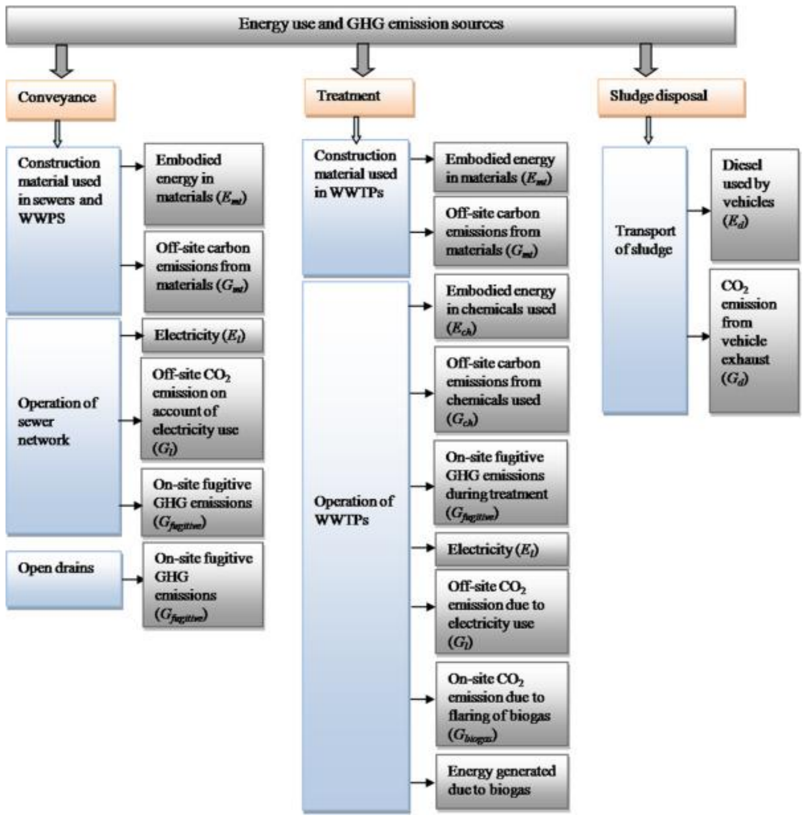


Figure 2.1 – Urban wastewater infrastructure components considered for energy use and GHG emission (Singh and Kansal, 2018).

Earlier studies on the W-E-G nexus have used various approaches that differ in terms of boundary conditions, the scope of analysis, and methodology. For example, Plappally and Lienhard (2012) and Nair *et al.* (2014) developed a meta-analysis of published data on the W-E-G nexus and presented a comprehensive analysis of energy consumption of different components of the urban water cycle, although they limited their focus to electrical energy and excluded all other sources of energy including diesel, labour, and resource recovered (biogas). They also excluded carbon and fugitive emissions from the purview of their study. Risch *et al.* (2015) used Life Cycle Analysis (LCA) of an urban water system to quantify the environmental impact of sewers on the entire system, and Loubet *et al.* (2014) reviewed 18 LCA case studies to recommend different ways of assessing the environmental impact of urban water systems. Also, Zhang *et al.* (2010) demonstrated the use of process-based and input-output based LCA in reducing the discharge of secondary effluent. Strokes and Horvath (2010) estimated energy consumption and GHG emissions from the collection, treatment, and discharge of wastewater and, also, investigated the options to offset energy consumption. Tran *et al.* (2015) found biogas recovery to produce electricity to offset the energy footprint of wastewater infrastructure and Hoek *et al.* (2016) explained such methods for recovery of biogas from sludge. Garcia *et al.* (2011) estimated the electricity consumption (for operations) of the oxidation ditch process, activated sludge process, and activated sludge process with lime stabilization. Venkatesh and Brattebø (2011) considered the water and wastewater system (operation and maintenance) to estimate the consumption of electricity and heat. Other studies, such as those by Hospido *et al.* (2008), Shahabadi *et al.* (2010) and Siddiqi and Anadon (2011), emphasized the importance of systems analysis for the W-E-G nexus in their study of carbon emissions.

Different models and tools were used in the above-mentioned studies to estimate the energy footprint and GHG emissions from wastewater processing, and the estimates have also varied, depending on other factors such as the technology used and topography.

2.3 Assessment methodologies and tools to evaluate and to promote energy efficiency in the urban water cycle

2.3.1 Introduction

Energy assessment is one of the most important parts of water sector utility performance assessment. In recent years, many methods for the evaluation of energy transformation in urban water systems have been presented in the literature (e.g., Carlson and Walburger, 2007; US EPA, 2008; McGuckin *et al.*, 2013). Energy assessment of a water supply and sewage utility can involve all processes from the abstraction, transport, treatment, and distribution of water, and sewage collection, transport, treatment, and disposal. The different methodologies provide information on issues related to the classification of methods, energy balancing, the use of supporting computer tools, and the importance of data reliability (Bylka and Mroz, 2019). Some of the most relevant methodologies and approaches are revised in the following sections.

2.3.2 The US EPA energy management approach and tool

In 2008, the United States Environmental Protection Agency (US EPA) launched a free guidebook that defines a step-by-step methodology for energy management based on the Plan-Do-Check-Act (PDCA) method (US EPA, 2008). The main goal of this guidebook is to identify, to implement, to improve energy efficiency and to identify renewable energy investment opportunities in water supply systems.

The plan phase is composed of four steps, including a preliminary evaluation, the assessment of the current energy baseline status, the establishment of an energy vision and priorities for improvement and the identification of energy objectives and targets. The do phase involves the implementation of energy improvement programmes. An energy improvement programme is a structured document that should assign responsibilities, tasks, timeframes, and resources (who, what, by when and how much) for achieving the objectives and targets with a set of specific identifiable actions. The check and act phases are presented altogether and include monitoring and measuring energy improvement and keeping the energy improvement programmes. To do so, performance metrics should be defined and calculated. Efforts are easier to demonstrate when current and reliable performance data are available and referenced against a defined baseline. These data can help to demonstrate the value of energy management activities from the top management to the community (US EPA, 2008; Mamade, 2019). Figure 2.2 illustrates the PDCA cycle.

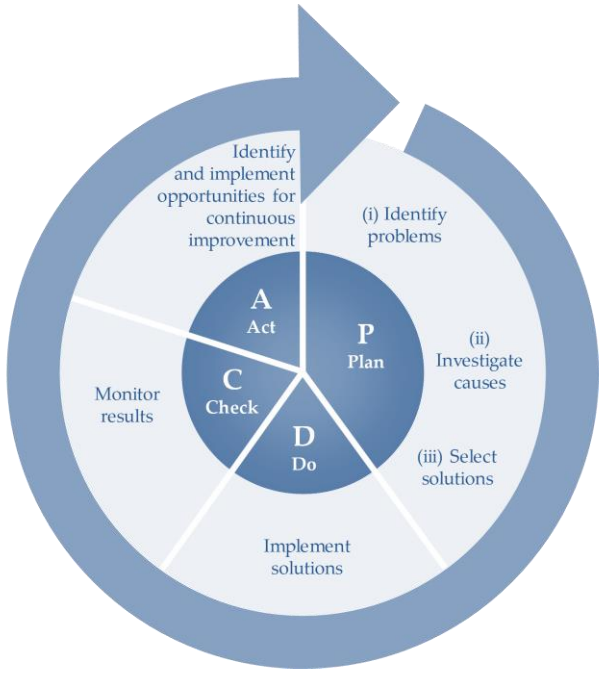


Figure 2.2 – PDCA cycle (Alegre and Covas, 2010).

A comprehensive tool for energy assessment in water utility was developed by US EPA: the EPA's Energy Use Assessment Tool. This tool aimed to support small and medium-sized water or wastewater utilities in conducting energy audits to their systems, taking a key step in gathering data to understand and to reduce energy usage. The main targets were buildings and treatment plants (US EPA, 2008).

The assessment is based on data on electricity consumption for all devices, such as pumps, blowers, heating, ventilation, and air conditioning (HVAC) installations, lighting, etc, showing energy consumption over time compared with the volume of treated water. The data are assigned to processes (e.g., distribution pumping, filtration, clarification, HVAC, low service pumping, etc.). It also allows to determine the baseline of energy consumption and associated costs, in total and broken down to the process level and to the equipment level. The tool also highlights areas of energy inefficiency that a utility can consider for identifying and prioritizing energy improvement projects. The audit is recommended for a minimum period of one year. As part of the assessment, the trend of changes in the value of energy consumption is checked, and the most energy-consuming processes are selected. The audit enabled the assessment of changes in the value of energy consumption indicators within the utility (US EPA, 2008; Bylka and Mroz, 2019).

This approach has been the predecessor of other similar approaches in the USA, namely WEF (2009) and American Water Works Association (AWWA, 2015). These methodologies have a broad scope in terms of energy consumption assessment (pumps, HVAC, lighting) which proves to be useful. However, starting by the definition of single processes or equipment types can be limiting to carry out a more systemic analysis. For instance, in this methodology, the water distribution stage is only evaluated in terms of energy consumption in pumps, although other components may dissipate energy (*e.g.*, valves).

Furthermore, the methodical calculation of performance metrics since the beginning of the evaluation, instead of just at the end, might be more beneficial, since it promotes a more coherent analysis (Mamade, 2019).

2.3.3 Energy index development for benchmarking water and wastewater utilities

The American Water Works Association (AWWA) Research Foundation, California Energy Commission, and New York State Energy Research and Development Authority jointly conducted a study about energy usage and water supply. The result of the work was a report "The Energy Index Development for Benchmarking Water and Wastewater Utilities". The objective of the research was to review existing energy data and assessment methods used by utilities, to develop a statistical model and characteristics of energy use, to apply and to evaluate a benchmark score system, which is similar to the EPA's Energy Star rating system, and to present case studies to show the use of the metrics. During the research, information characterizing utilities was collected using a survey (Carlson and Walburger, 2007).

The statistical model was tested to find the correlation between different parameters and energy consumption in water utilities. About 100 parameters were considered in the investigation. A combination of the six best-represented model parameters was found. The water utility energy model was developed by integrating these parameters (Carlson and Walburger, 2007). However, it should be highlighted that results can be biased owing to the USA particular conditions and contextual factors associated with the country reality.

2.3.4 Toolbox for water utility energy and greenhouse gas emission management

The Water Research Foundation developed a complex report about energy assessment called "Toolbox for Water Utility Energy and Greenhouse Gas Emission Management" (McGuckin *et al.*, 2013). The main objective of the toolbox was to present a framework for energy and GHG emission assessments for water utilities. The document contains a review of energy and GHG emissions assessment programmes and presents currently used models and algorithms and future research needs for energy evaluation. The sources and types of GHG emissions from water and wastewater treatment facilities were distinguished. Emissions were classified by scope designation, ownership level (direct/indirect), and contribution sources. Strategies and best practices for utilities were also presented under the project. Energy benchmarking and management tools and software were reviewed.

The report also includes the results of a survey on the use of energy assessment tools by different water utilities. Results have shown that it was not possible to develop a single methodology for energy and GHG emissions assessment for all water utilities. A methodology should always be selected, considering the local conditions and aims. It was only possible to lay down general standards and good practices. The report presented a decision framework for GHG emissions accounting and reporting (McGuckin *et al.*, 2013; Bylka and Mroz, 2019).

2.3.5 Energy Performance and Carbon Emissions Assessment and Monitoring Tool

Energy Performance and Carbon Emissions Assessment and Monitoring Tool (ECAM) is a tool developed under the Wastewater Companies for Climate Mitigation project, implemented by the Deutche

Gesellschaft für Internationale Zusammenarbeit (GIZ) and the International Water Association (IWA). The tool could be used to evaluate all processes in both water and wastewater systems (ECAM, 2015).

The ECAM tool is a free web-based tool designed for assessing the carbon emissions that utilities can control within the urban water cycle and preparing these utilities for future reporting needs on climate mitigation. It can be used for GHG emissions assessment and energy performance assessment and for identifying opportunities for reducing CO_2eq emissions. ECAM also allows to consider scenarios and model reduction impacts of future measures, and to monitor the GHG reduction results after their implementation.

The ECAM tool follows a tiered approach. The quick assessment refers to an initial GHG assessment that helps utilities to understand their overall energy usage and total GHG emissions at a system-wide level (water supply and wastewater). Data that are readily known, or accessible by utility managers and operators, are used and allow a first look at the potential opportunities that exist for reducing GHG emissions. The detailed assessment focuses on a detailed GHG assessment. Energy use and GHG emissions at the individual stage level of the urban water cycle (i.e., abstraction, drinking water treatment, distribution, collection, and wastewater treatment) are analysed, providing utilities with a more thorough assessment of their GHG emissions and energy usage. This tier helps utilities to identify areas of improvement and to evaluate solutions and scenarios for developing a feasible carbon reduction strategy in line with their current and future needs (ECAM, 2015; Bylka and Mroz, 2019; Mamade, 2019).

2.3.6 WATERGY project

The Alliance to Save Energy conducted a study about the relation between water and energy presented in the report “WATERGY: Energy and Water Efficiency in Municipal Water Supply and Wastewater Treatment – Cost-Effective Savings of Water and Energy” (WATERGY, 2014).

WATERGY is a project concerning the relationships between water and energy in all elements of a water and wastewater system. The report described all elements of the system (devices and processes) in which significant amounts of energy are consumed. The report recommended an energy audit for all devices. It assumed that to increase energy efficiency, three elements are necessary: political will, technical and economic analysis, and implementation. Attention was also paid to ways of financing investments related to improving energy intensity, e.g., through performance-based contracts. The study did not present an energy assessment methodology but described general principles for conducting these types of audits.

2.3.7 Energy efficiency auditing scheme for industry

Portugal has an energy efficiency auditing scheme for industry – *Sistema de Gestão de Consumos Intensivos de Energia* (SGCIE), in Portuguese – defined in the Decree-law 71/2008 and, later, updated by the Law 7/2013 and the Decree-law 68-A/2018. This legislation is mandatory to facilities with an energy consumption above or equal 500 tep[1] (or 2.33 GWh) in the previous year. Facilities with lower

[1] Tep is the Portuguese abbreviation for tons of oil equivalent (*i.e.*, *toneladas equivalentes petróleo*).

energy consumption can voluntarily apply this management system and define energy consumption rationalization agreements with the Directorate-General for Energy and Geology (DGEG).

This auditing scheme determines that energy audits should be carried out every 8 years to reduce energy consumption, to improve efficiency and to incorporate renewable energies. It also determines the elaboration and implementation of plans to rationalise energy consumption. These plans include the establishment of minimum goals for energy efficiency that, once approved, are an agreement of rational energy consumption. A report documenting the agreement implementation status as well as deviations and mitigation measures is required every two years.

For facilities with annual energy consumption below 1000 tep, a 4% reduction of energy intensity (i.e., the ratio between total energy consumption and gross benefit) and specific energy consumption (i.e., the ratio between total energy consumption and production) is required, whereas for facilities with annual energy consumption above 1000 tep, a 6% reduction is expected. In both cases, the carbonic intensity (i.e., the ratio between emissions and total energy consumption) should not increase.

2.3.8 The ISO 5000x standards

Management systems are systematic frameworks designed to help organizations in the management of their policies, procedures and processes and promote continuous improvement. Concerning energy, the ISO standards have published the ISO 5000x intending to leverage the integration of energy management into the overall efforts to improve quality and environmental management in a company. The main standards within the ISO 5000x are: NP EN ISO 50001:2012 which defines the basic requirements of an Energy Management System; ISO 50002:2014 (E) which sets out the basic principles and requirements for carrying out energy audits; ISO 50004:2014 (E) providing guidance for the implementation, maintenance and improvement of an energy management system; ISO 50006:2014 (E) which provides guidance on measuring energy performance using energy baselines and energy efficiency metrics (EnPIs) (International Organizational for Standardization, 2014b).

The NP EN ISO 50001:2012 specifies requirements for energy management systems follows the PDCA methodology. The plan step refers to the elaboration of an energy management plan for improving energy performance. The do step refers to the implementation of energy action plans and is well documented in the ISO 50004:2014 (E). The check step involves the monitoring and measurement of the key characteristics and processes that determine energy performance based on the energy policy and objectives. It also includes the reporting of results. The act step refers to carrying out the measures that contribute to the continuous improvement of the energy management system.

The objective of the NP EN ISO 50001:2012 is to leverage the establishment of systems and procedures to improve energy performance including efficiency in the use and consumption of energy.

The implementation of the standards should lead to a reduction in GHG emissions and energy costs through a systemic energy management. It applies to all types and dimensions of organizations. The generic process of energy planning is depicted in Figure 2.3. Firstly, data related to energy use and variables affecting consumption are collected and analysed. Secondly, the areas with significant energy consumption are identified and, thirdly, opportunities for improving energy efficiency are identified. As a result of this process, a baseline of energy consumption can be drawn as well as energy efficiency metrics, objectives, targets, and action plans can be established.

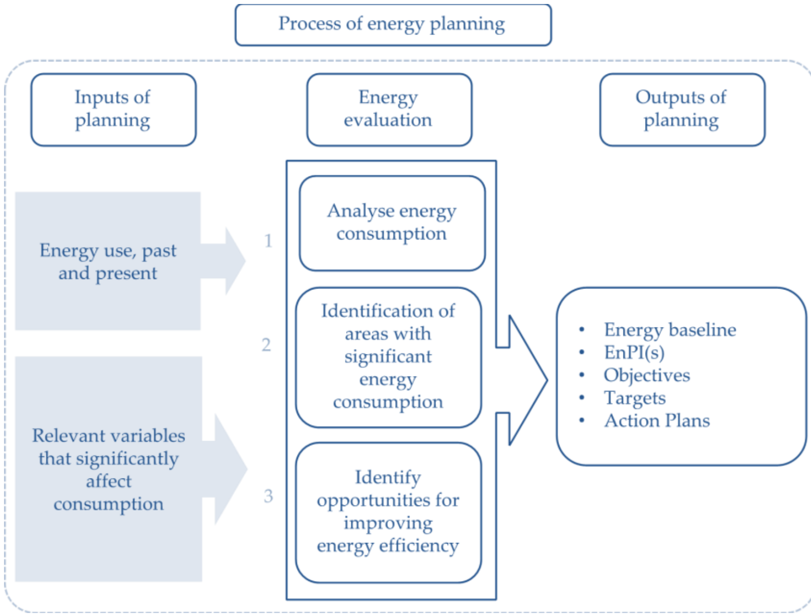


Figure 2.3 – Conceptual diagram of energy planning process (ISO 50001:2012).

A strong emphasis is also given on the top management involvement and the existence of a management representative who is responsible to communicate across the organization. The top management commitment is demonstrated by the existence of an energy policy that sets the roadmap for the improvement of energy performance. Main steps of energy planning provided in the ISO 50004:2014 are: legal and other requirements, energy review, energy baseline, energy efficiency metrics, energy objectives and targets and action plans.

The legal requirements related to the organisation energy consumption or energy efficiency and other requirements should be well known. Energy review involves the analysis of energy use and consumption to identify the current energy sources (*e.g.*, electricity, natural gas, solar, wind) as well as the current energy uses (*e.g.*, pumping, lighting, HVAC) and their consumption including past and present trends. It is good practice to analyse data at least one year to account for seasonal effects. The areas with significant energy use should be identified to support definition of priorities for energy management, energy performance improvement and resources allocation. These can be identified by carrying out energy balances and energy audit interviews with personnel and can be iterative procedures. Then, opportunities for improving energy performance should be identified, prioritized, and evaluated. Examples of criteria for prioritizing opportunities include energy savings, return on investment, cost implementation, environmental impacts, and funding opportunities, among others.

The ISO 50006 provides guidance on the establishment of an energy baseline and the energy efficiency metrics. An energy baseline is the reference for measuring energy performance over time. The energy efficiency metrics are the metrics defined by the organization to measure energy performance. The definition of objectives and targets put the energy policy into action. Finally, the action plans include the allocation of resources necessary to accomplish the objectives.

2.4 Energy balances in the urban water cycle and performance metrics

2.4.1 Energy balances for water supply systems

According to the ISO 50002:2014, an energy balance consists of accounting for the inputs and energy recovery or generation versus the energy outputs based on energy consumption by energy use. The energy balance reconciles all the energy that enters the system boundaries against all energy that leaves the system boundaries. Many authors have suggested the development of the energy balance for water supply systems; the most relevant contributions are described in the following paragraphs.

Duarte et al. (2009) approach

Duarte *et al.* (2009) carried out a systemic evaluation of several types of hydraulic power in a pressurized water transmission system without pumping stations. Supplied hydraulic power quantifies the total power entering the system in the period of analysis. The minimum power refers to the sum of the minimum power required at each consumption node to meet minimum pressures. The power in excess represents the difference between the supplied and the minimum powers. Dissipated power quantifies the dissipated power in the flow (i.e., in friction and local head losses). Available power is given by the difference between the supplied power and the dissipated power. Surplus power corresponds to the power supplied to the system beyond the sum of the minimum power and the dissipated power. Each hydraulic power should be calculated using the same reference elevation.

Assuming, for a better understanding of the concept, that energy provided to the system has a single source (e.g., storage tank) with the head *H*, the hydraulic power supplied at time *t* is given by:

$$P_{INP}(t) = \gamma . Q_{INP}(t) \, . H(t) \tag{2.1}$$

where γ is water specific weight (N/m^3), $P_{INP}(t)$ is the hydraulic power supplied at time t (W), $Q_{INP}(t)$ is the supplied flow rate at time *t*, including revenue water, water losses and unbilled authorised consumption (m^3/s), and $H(t)$ refers to the head at the storage tank at time *t* expressed in terms of the zero-reference elevation (m). In case of more than one water source (*e.g.*, several storage tanks or pumping stations), the total hydraulic power is the sum of each provided power expressed in terms of the zero-reference elevation.

The minimum hydraulic power at time *t* corresponds to the sum of the minimum hydraulic powers at each node *i* that satisfy the respective consumption with the minimum pressure (Alegre, 1992):

$$P_{MIN}\,(t) = \sum_{i=1}^{n} P_{MIN}^{i}\,(t) = \gamma . \sum_{i=1}^{n} \left[Q^{i}\,(t) . \; H_{MIN}^{i} \right] \tag{2.2}$$

in which $P_{MIN}^{i}\,(t)$ refers to the minimum hydraulic power at node i and at time t (W), $Q^{i}\,(t)$ is the consumption at node *i* and at time *t* (m^3/s), H_{MIN}^{i} refers to the minimum required head at node *i* (m) and *n* is the number of consumption nodes.

In situations in which there is energy recovery by means of the installation of turbines, the recovered hydraulic power at time *t* is given by:

$$P_{REC}\,(t) = \sum_{k=1}^{N_T} P_{REC}^{k}\,(t) = \gamma. \sum_{k=1}^{N_T} \left[Q^{k}\,(t).\ H_{REC}^{k}\,(t) \right] \tag{2.3}$$

in which $P_{REC}^{k}\,(t)$ is the recovered hydraulic power at node *k* and at time *t* (assuming turbine efficiencies of 100%) (W), $Q^{k}\,(t)$ is the turbinated flow rate at node *k* and at time *t* (m^3/s), $H_{REC}^{k}\,(t)$ is the recovered head at node *k* and at time *t* (m) and N_T is the number of nodes with turbines installed.

The hydraulic power in excess has the advantage of being independent of the zero-reference elevation and can be calculated as follows:

$$P_{EXC}\,(t) = P_{INP}\,(t) - P_{REC}\,(t) - P_{MIN}\,(t) \tag{2.4}$$

Since the flow rate is time-dependent, the energy corresponding to the above-referred hydraulic powers can be obtained by their time integration for a given period of analysis. It is demonstrated that there is always a dependency on the reference elevation.

Cabrera et al. (2010) approach

Cabrera *et al.* (2010) proposed an energy balance based on the time integration of the energy conservation equation applied to a known water control volume. This energy balance shows that the energy provided to the system (by reservoirs and/or pumps) can be divided into the energy delivered to the consumers and the outgoing energy through leaks plus the dissipated energy due to the friction losses. Table 2.1 shows the proposed balance on a longer period (i.e., one year). The adaptations for shorter periods are also presented, whenever the networks have compensation tanks that accumulate water during low consumption hours while releasing it in peak hours. The net flow of water and energy in one of these tanks, when integrated through a long enough period, is zero, as well as their contribution to the longer-term analysis. During normal operation, with shorter periods, the tanks can be considered mass and energy sources and sinks and must be included in the audit.

The main assumptions considered are the following (Cabrera *et al.*, 2010): water is incompressible; there is no heat flow transfer through the boundaries; the kinetic term is neglected; energy inside the boundaries remains constant in each extended period integration; the flow regime is uniform. When calculating the outgoing energy through leaks, leaks are modelled as concentrated nodal consumptions and behave as pressure-driven demands. Apparent losses are not considered in this analysis. When calculating the friction energy, the additional losses due to leakage are determined through the difference between a simulation with and without leaks.

In this balance, the dissipated energy in pumping stations and valves is not accounted for and only real losses are considered. Furthermore, the energy associated with water losses is given by subtracting energy in a simulation with and without real losses. Recently, Cabrera *et al.* (2018) suggested an updated energy balance including the pump inefficiencies and the dissipated energy in valves that can be recovered.

Table 2.1 – Energy balance for a water supply network on the long term proposed by Cabrera *et al.* (2010).

<table>
<tr><td rowspan="4">Total input energy
(E_{INP})</td><td rowspan="2">Natural input energy
(E_N)</td><td>Energy delivered to users
(i)</td><td rowspan="3">Output energy
(E_{out})</td></tr>
<tr><td rowspan="2">Outgoing energy through leaks
(E_L)</td></tr>
<tr><td rowspan="2">Shaft input energy
(E_S)</td></tr>
<tr><td>Friction energy
(E_F)</td><td>Dissipated energy
(E_D)</td></tr>
</table>

Souza et al. (2011) approach

Souza *et al.* (2011) proposed an energy balance (Table 2.2), using the same assumptions as Cabrera *et al.* (2010). The main novelties of this balance are the quantification of the dissipated energy associated with valve head losses, the energy recovery and the separation of the energy delivered to consumers in the minimum required energy and surplus energy. Dissipated energy in pumping stations is not evaluated and energy losses associated with leakage are calculated using two simulations.

Table 2.2 – Energy balance in kWh/m^3 proposed by Souza *et al.* (2011).

<table>
<tr><td rowspan="3">Natural input energy
(E_N)</td><td rowspan="6">Total input energy
(E_{INP})</td><td rowspan="4">Dissipated energy
(E_D)</td><td>Friction energy (E_F)</td></tr>
<tr><td>Outgoing Energy Through Leaks – Real Losses (E_L)</td></tr>
<tr><td>Local Head losses in Valves (E_V)</td></tr>
<tr><td rowspan="3">Shaft input energy
(E_S)</td><td>Recovered Energy (E_{REC})</td></tr>
<tr><td rowspan="2">Energy delivered to users
(E_U)</td><td>Minimum energy required (E_{MIN})</td></tr>
<tr><td>Surplus Energy (E_{SUR})</td></tr>
</table>

Walski (2016) approach

Walski (2016) proposed another energy balance (Table 2.3) more targeted for short-term periods (*i.e.*, 24 hours). The energy balance is obtained using the energy conservation law. The main difference from the previous balances is that the energy delivered to consumers is divided into two terms: "Energy used to raise the water to node elevation" and "ΔEnergy at tanks". The first accounts for the energy involved in pumping the water to the elevation of the customers and the second represent the energy that is accumulated in storage tanks when the tank is filling, or re-enters the system when tanks are draining. Regarding the reference elevation, this author suggests it can be set to sea level, some offset from sea level or the elevation of the lowest customer. However, this can influence the results of performance metrics.

Table 2.3 – Energy balance in kWh/m^3 proposed by Walski (2016).

<table>
<tr><td rowspan="2">Energy at sources</td><td rowspan="6">Total Energy Input</td><td>Energy lost in pipe friction</td></tr>
<tr><td>Energy lost in valves</td></tr>
<tr><td rowspan="4">Energy at pumps</td><td>Energy recovered at turbines</td></tr>
<tr><td>Energy used to raise the water to node elevation</td></tr>
<tr><td>Energy delivered to customers or leaks</td></tr>
<tr><td>ΔEnergy at tanks</td></tr>
</table>

The energy balance can be used to better describe the network, but the balance itself does not increase the energy efficiency of the system. This is only possible through the implementation of corrective actions. In some cases, the calculation of the balance supports the identification and planning of such actions. It can facilitate finding the subsystems where energy use can be reduced. For example, if energy is dissipated through pressure-reducing valves, there is potential to install turbines to recover energy. If most of the energy is lost in pipe friction, then piping rehabilitation can be used to reduce head losses. If the energy delivered to customers is excessive, pressure-reducing valves or variable-speed pumps can be introduced to reduce pressure and, consequently, reduce leakage volume. Walski (2016) concludes that the energy balance can be used to compare systems, though it can be a difficult task because of systems' specific characteristics.

Mamade et al. (2017) approach

The methodology presented by Mamade *et al.* (2017) has three stages: (i) system characterization and data collection, (ii) energy balance calculation and (iii) performance metrics assessment. The authors described the novel features of their energy balance and of the previous ones (e.g., Cabrera *et al.*, 2010) and audit method. The energy balance proposed by Mamade *et al.* (2017) was improved and further demonstrated by Mamade (2019), and it is presented in Table 2.4.

Before the energy balance calculations, the first step is to clearly define the system boundaries, layout, and main components (pipes, tanks, pumping stations). The energy balance analysis can include the whole system from the intake to the delivery point, or part of the system (e.g., a network sector), depending on the scope of the analysis. Each component of the energy balance scheme should be calculated with respect to a reference level. It is recommended to adopt as a reference level the average elevation weighted by authorised consumption (Mamade *et al.*, 2017; Mamade, 2019).

Table 2.4 – Energy balance scheme for water supply systems (Mamade, 2019).

<table>
<tr><td rowspan="13">Natural Input Energy (E_N)

Shaft Input Energy (E_S)</td><td rowspan="13">Total system input energy (E_{INP})</td><td rowspan="7">Energy associated with authorised consumption (E_{AC})</td><td rowspan="2">Energy associated with water supplied to consumers (E_{SUP})</td><td>Minimum required energy (E_{MIN})</td></tr>
<tr><td>Surplus energy (E_{SUR})</td></tr>
<tr><td rowspan="4">Dissipated energy ($E_{DIS,AC}$)</td><td>Pipe friction ($E_{diss,f\ AC}$)</td></tr>
<tr><td>Valve head losses ($E_{diss,v\ AC}$)</td></tr>
<tr><td>Pumping stations' inefficiency ($E_{diss,p\ AC}$)</td></tr>
<tr><td>Hydro power plants' inefficiency ($E_{diss,T\ AC}$)</td></tr>
<tr><td rowspan="2">Recovered energy (E_{REC})</td><td>Associated with authorised consumption ($E_{REC\ AC}$)</td></tr>
<tr><td rowspan="6">Energy associated with water losses (E_{WL})</td><td>Associated with water losses ($E_{REC\ WL}$)</td></tr>
<tr><td colspan="2">Dissipated energy in nodes with water losses ($E_{N,WL}$)</td></tr>
<tr><td rowspan="4">Dissipated energy ($E_{DIS,WL}$)</td><td>Pipe friction ($E_{diss,f\ WL}$)</td></tr>
<tr><td>Valve head losses ($E_{diss,v\ WL}$)</td></tr>
<tr><td>Pumping stations' inefficiency ($E_{diss,p\ WL}$)</td></tr>
<tr><td>Hydro power plants' inefficiency ($E_{diss,T\ WL}$)</td></tr>
</table>

☐ Components that do not require mathematical modelling
■ Components that require mathematical modelling

Two approaches for the energy balance calculation were proposed by these authors. The first is the top-down approach, which includes the calculation of the components in Table 2.4, except those in grey. This approach requires fewer data and can be applied at a system level, providing a global overview of the main components of energy consumption in the system. It is also useful when utilities do not have hydraulic models. The second is the bottom-up approach, which allows detailed assessment of energy consumption in every component of the balance and requires a calibrated hydraulic model of the network. Calculations can be carried out using EPANET software simulation results (Mamade *et al.*, 2017; Mamade, 2019).

In comparison with previous studies, the proposed balance scheme has three main novel features. First, this balance uses information from the system to separate the energy associated with authorised consumption and water losses, providing an intuitive perception of the efficiency improvements that can be achieved by reducing water losses (real and apparent losses). Accordingly, the percentage of energy associated with water losses equals the percentage of water losses in the system, assuming that the losses are distributed throughout the system proportionally to water demand. In other words, given a certain percentage of water losses (real and apparent) in the system (e.g., 20%), the total system input energy is divided as follows: 80% is the energy associated with authorised consumption and 20% is the energy associated with water losses. This is a completely different approach from previous energy balances (Cabrera *et al.*, 2010; Souza *et al.*, 2011) in which this component was uniquely due to real losses and was given by the product of leak discharge and the head at the node integrated with time and space.

Second, the calculation of the proposed energy balance in a bottom-up approach requires running two hydraulic simulations: one including water losses and another one without water losses. However, several energy balance components can be calculated without a hydraulic simulation, when following the top-down approach. Examples of these components are the energy associated with authorised consumption, the energy associated with water losses and the minimum required energy. This is important as it allows a preliminary assessment of energy consumption in the system.

Finally, new components (not existing in previous balances) have been introduced to better understand where the energy is dissipated throughout the system (e.g., valves, pumps, and turbines), providing complementary information about the inefficiencies of these components.

2.4.2 Energy balances for irrigation systems

The agricultural sector is responsible for ca. 70% of the freshwater consumed volume in the world (Cunha *et al.*, 2019). Collective irrigation systems are infrastructures composed of a set of components, which ensure the abstraction, storage, conveyance, and distribution of water to the users, and are also intensive energy consumers (Cunha *et al.*, 2019).

A methodology to calculate the energy balance in irrigation systems, including canals and pressurised pipes was roughly developed by Cunha (2018). Fernandes (2020) refined the proposed energy balance, which is presented in Table 2.5. The energy balance developed for urban water supply systems (Mamade, 2019) was the basis to the approach.

The first step for the energy balance calculation is to select the period for the energy balance, usually the period in which the irrigation system provides the service. The system boundaries are defined considering all system energy input points (e.g., reservoirs, wells, pumping stations) and the delivery point to irrigators, according to those adopted in the water balance for the same system. The reference elevation in relation to which the energy components associated are calculated, must be selected. Fernandes (2020) recommended that the reference elevation should be unique when the system integrates several interconnected subsystems. However, when the system is composed of separated subsystems with no possibility of interconnection between them, the energy balance can be calculated separately for each subsystem and then, by adding the various components, to reach the global energy balance.

Table 2.5 – Energy balance for collective irrigation systems (Fernandes, 2020).

<table>
<tr><td rowspan="6">Natural input energy</td><td rowspan="13">Total energy input</td><td rowspan="7">Energy associated with authorised consumption</td><td rowspan="2">Energy associated with water delivered to consumers</td><td>Minimum energy</td></tr>
<tr><td>Surplus energy</td></tr>
<tr><td rowspan="4">Energy dissipated associated with consumption</td><td>Continuous head losses in pipes and canals</td></tr>
<tr><td>Singular head losses in gates and valves</td></tr>
<tr><td>Pump inefficiency</td></tr>
<tr><td>Turbine inefficiency</td></tr>
<tr><td rowspan="7">Shaft input energy</td><td rowspan="2">Energy recovered</td><td>From authorised consumption</td></tr>
<tr><td rowspan="6">Energy associated with water losses</td><td>From water losses</td></tr>
<tr><td rowspan="5">Energy dissipated due to water losses</td><td>In locations where water losses occur</td></tr>
<tr><td>Singular head losses in gates and valves</td></tr>
<tr><td>Continuous head losses in pipes and canals</td></tr>
<tr><td>Pump inefficiency</td></tr>
<tr><td>Turbine inefficiency</td></tr>
</table>

2.4.3 Performance assessment evaluation

Performance assessment provides a systematic way to undertake the diagnosis of systems and services performance over time (Neely *et al.*, 2002). Organizational performance assessment in the water sector has been a topic of growing attention since the 1990s, following the increase in the role of regulators (economic, environmental, health, and quality of service) and tighter legislation (Ganjidoost *et al.*, 2018; Molinos-Senante *et al.*, 2018; Akimov *et al.*, 2019; Santos *et al.*, 2019). Assessing performance in alignment with the mission and strategic objectives of the utility, using reliable and up-to-date data, is of the utmost importance to enable effective and continual improvement management while allowing benchmarking (Ganjidoost *et al.*, 2018; Molinos-Senante *et al.*, 2018; Burdescu *et al.*, 2020; Almeida *et al.*, 2021a). Proactive utilities are incorporating sustainability, resource efficiency, resilience, and continual improvement principles into their practices (Alegre *et al.*, 2011; EEA, 2014; EPA, 2018).

As detailed by Almeida *et al.* (2021a), a structured performance assessment system focuses on the definition of objectives, assessment criteria, and metrics (O-C-M), complemented with reference values, and allows a robust comparison between utilities and systems. Such a system facilitates the implementation of continual improvement principles typically used in quality systems standards (Alegre *et al.*, 2011). It allows consistent utility assessment over time, targets fine-tuning, implementation of systematic benchmarking within a water utility to compare the performance of different systems in similar or different locations and contexts, and externally for comparison with other similar utilities in the same context (Alegre and Covas, 2010; Almeida and Cardoso, 2010). The objectives for water sector utilities are well defined by international standards (EN 752:2017; ISO 24500 series). The criteria allow the evaluation of several aspects or principles of these objectives. The metrics are parameters or functions used to assess the criteria. Reference values are used to classify and judge the metrics' results, preferably after validation by utilities. Performance metrics are typically expressed as ratios between variables, where the numerator expresses quantities to be assessed by the respective performance metric and the denominator expresses a relevant system dimension (e.g., m^3 of treated water). Performance assessment requires comparing each performance metric with a reference value for its judgment. Reference values can be given by existing legislation (such as water quality compliance), best practice guidelines from water regulators, literature references or water utilities' historical data.

Performance assessment can be integrated in other management approaches, such as infrastructure asset management (IAM) to support effective and robust management of urban water systems (e.g., Matos *et al.*, 2003; Cardoso *et al.*, 2004; Cabrera and Pardo, 2008; Cardoso, 2008; van den Berg and Danilenko, 2011; Alegre *et al.*, 20169). IAM of urban water infrastructures consists of the set of processes that utilities need to have in place to ensure that infrastructure performance corresponds to service targets over time, that risks are adequately managed and that the corresponding costs, in a lifetime cost perspective, are as low as possible (Alegre and Coelho, 2012).

The IAM methodology proposed by Alegre and Covas (2010) and by Almeida and Cardoso (2010) is an integrated approach that is aligned with the PDCA methodology supported by the ISO standards and is organised in three levels of planning – strategic, tactical, and operational – that should be fully aligned. A successful infrastructure asset management planning requires meeting the methodology's main principles. These include that the infrastructure, composed of a set of individual assets, behaves as a single system, i.e., each individual pipe or sewer is not a functional unit as this cannot provide a service by itself and does not have a value (in terms of service) by itself (Burns *et al.*, 1999). Secondly, planning should be carried out taking into account a long-term horizon, considering that the infrastructure has an indefinite life, that goes beyond generations and, thus, all phases of the asset's lifecycle coexist in a mature infrastructure. Finally, these methodologies should address performance, risk, and cost.

The strategic level looks a long-term planning horizon and the whole organisation. The strategic plan includes: 1) identification of the utility's vision and mission, 2) definition of strategic objectives and the correspondent assessment systems – criteria, metrics, and reference values, 3) diagnosis with assessment results of the metrics for the current situation combined with an internal and external context evaluation, and 4) identification of strategies to be implemented (Almeida and Cardoso, 2010).

The tactical level of planning looks at a medium-term planning horizon, up to 3 to 5 years. Tactical plans include the definition of tactical objectives and the corresponding assessment system – criteria, metrics, and reference values – as well as the diagnosis, with results from the current situation characterisation. Following the methodology, and by comparing the assessment results obtained in each of the sectors, it is possible to assess the priority subsystems that require a more detailed analysis. Intervention options are assessed and compared using the assessment system. Based on the results, the decision of the best alternative intervention can be selected, and implementation planned (Almeida and Cardoso, 2010).

The operational level refers to a short-term horizon, typically one year, and it is where implementation of interventions is done by organisational sectors (Almeida and Cardoso, 2010).

In summary, the strategic objectives should determine where the utility would like to be at the end of the defined long-term planning horizon and the tactical objectives should define the path, they need to follow to achieve those strategic objectives (Cardoso *et al.*, 2016). At each management and planning level, a structured loop initially proposed by Cardoso *et al.* (2016), comprises the following steps: (i) definition of objectives, assessment criteria, metrics, and targets; (ii) diagnosis; (iii) plan production; (iv) plan implementation; and (v) monitoring and review. Figure 2.4 presents the methodology.

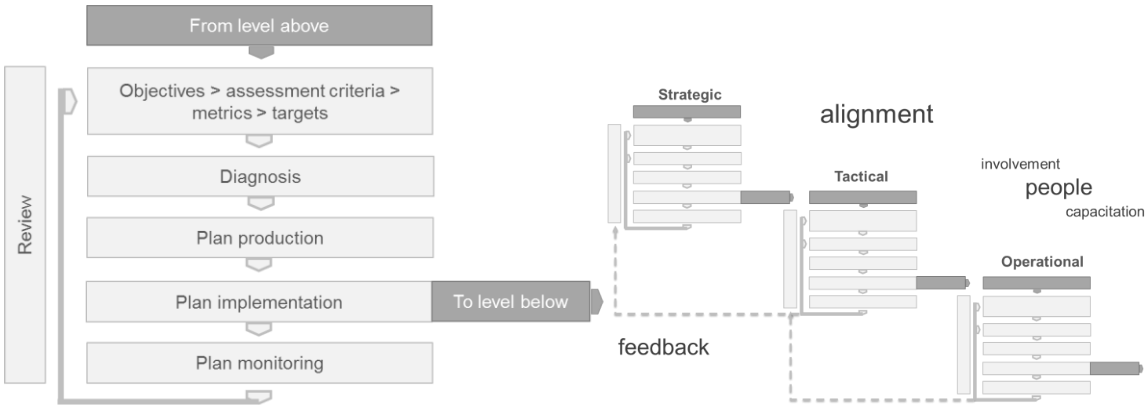


Figure 2.4 – AWARE-P IAM methodology: the planning process at each planning level and its alignment (Cardoso *et al.*, 2016).

Two widely known methodologies of performance assessment for water utilities are described in the IWA Manuals of Best Practice Performance Indicators for Water Supply Services and Wastewater Services (respectively, Alegre *et al.*, 2016 and Matos *et al.*, 2003). Alegre *et al.* (2016) is a standard for the development of a performance assessment system for water utilities, including 166 indicators, divided into six groups. The following indicators related to energy were specified in the physical indicators group: percentage of pump capacity used, standardized energy consumption, reactive energy consumption, and energy recovery. The only energy-related indicator was classified under economic and financial indicators: electrical energy costs. Using the IWA manual, several computer applications in which this methodology is implemented were developed (e.g., Sigma software and AWARE-P). The manual presents a guide for implementing a performance assessment system.

Another relevant project on performance assessment of a water utility was The International Benchmarking Network for Water and Sanitation Utilities (IBNET) developed by the World Bank project (Danilenko *et al.*, 2014). The main aim was to provide data about water utilities worldwide for utility managers, regulators, authorities, investors, and the public. The performance indicators in IBNET concerned 14 areas: service coverage, water consumption and production, operating costs and staff, non-revenue water, meters, network performance, quality of service, billings and collections and financial performance, and assets. For energy assessment, two performance indicators were calculated: electricity consumption per m^3 sold (kWh/m^3) and electrical energy costs as a percentage of operational costs. All data were free and publicly available via an Internet application (https://www.ib-net.org/). The platform is an appropriate tool allowing to carry out macroeconomic analyses, but the possibilities of assessing single utilities can be limited.

Comprehensive methodologies of water utility performance assessment were also developed in the AquaRating project. The project involving the IWA and the Inter-American Development Bank, includes 112 assessment factors organized into eight groups. The result of the evaluation was an aggregated "rating" of a utility's performance. The evaluation uses both performance indicators (quantitative assessment) and good practices (qualitative assessment). The good practices are a set of recommendations for water utilities related to management. Methods of assessment are specified for each indicator and good practice, as well as the method for aggregating all criteria results into a single "rating". The energy assessment was carried out as part of the assessment of the implementation of eight good practices and two indicators. In the project, much attention was paid to data reliability. During the assessment, documents that confirmed data reliability should be collected. The methodology defined which documents should be checked and with what frequency.

Regarding the water supply sector, Table 2.6 provides a list of energy efficiency metrics selected from the literature review (Mamade, 2019). Metrics are presented in alphabetical order.

Table 2.6 – Selected energy efficiency metrics (adapted from Mamade, 2019).

Energy efficiency metrics, ID	**Description**	**Source**
Average electricity expenditure, *MEEXP* ($\$/m^3$)	Average electricity expenditure per cubic meter of produced water	Nogueira Vilanova and Perrella Balestieri (2015)
Electrical energy costs, *Fi46* (%)	Percentage of the running costs corresponding to electrical energy	Alegre *et al.* (2016)
Energy dissipated through friction, *I3* (-)	Ratio between friction energy and input energy	Cabrera *et al.* (2010)
Energy in excess per authorised consumption, *E2* (-)	Theoretical potential for energy reduction per m^3 of the authorised consumption volume	Duarte *et al.* (2019)
Energy in excess per system input volume, *E1* (-)	Theoretical potential for energy reduction per m^3 of the input volume	Duarte *et al.* (2019)
Energy in excess per unit of authorised consumption (kWh/m^3)	Theoretical potential for energy reduction per unit volume. The denominator of this index changed from being the revenue water (Duarte *et al.*, 2009) to the authorised consumption. E2 can also be assessed in terms of natural input energy, E2 (natural), and shaft input energy, E2 (shaft)	Mamade *et al.* (2017)
Energy recovery, *Ph7* (%)	Percentage of the total energy consumption for pumping that is recovered using turbines of reverse pumps	Alegre *et al.* (2016)
Excess of supplied energy, *E3*, *I1* (-)	Theoretical energy in excess that is provided to the system (minus recovered energy)	Duarte *et al.* (2019), Cabrera *et al.* (2010)
Indirect GHG emissions (ton CO_2eq)	Indirect CO_2eq emissions associated with pumping stations	GIZ/IWA (2015)
Leakage energy, *I4* (-)	Ratio between energy associated with leakage and friction losses due to leaks and input energy	Cabrera *et al.* (2010)
Network energy efficiency, *I2*(-)	Ratio between useful energy and input energy	Cabrera *et al.* (2010)
Power failures, *Op34* [hours/(pumping station.year]	Average number of hours per year pumping stations are out of service due to power supply interruptions	Alegre *et al.* (2016)
Pump failures, *Op30* [days/(pump.year)]	Average number of days per year system pumps are out of order	Alegre *et al.* (2016)
Pump refurbishment, *Op21* (%/year)	Percentage of pumps that were subject to overhaul per year	Alegre *et al.* (2016)
Pump replacement, *Op22* (%/year)	Percentage of pumps replaced per year	Alegre *et al.* (2016)
Pumping stations energy efficiency [$kWh/(m^3.100m)$], *AA13ab; AR10ab*	Average pumping energy consumption in the system per 1 m^3 at 100 m of head	ERSAR (2018)

Table 2.6 (cont.) – Selected energy efficiency metrics (adapted from Mamade, 2019).

Energy efficiency metrics, ID	**Description**	**Source**
Pumping utilisation, *Ph4* (%)	Percentage of the maximum pumping capacity (that can be used simultaneously) that was actually used	Alegre *et al.* (2016)
Ratio of the available energy in excess, *E4* (-)	Theoretical effective energy in excess that is provided to the system (minus recovered energy and head losses)	Carriço *et al*. (2014)
Reactive energy consumption, *Ph6* (%)	Percentage of the total energy consumption for pumping that corresponds to reactive energy consumption	Alegre *et al.* (2016)
Specific energy consumption, *SEC* (kWh/m^3)	Electricity consumption per cubic meter of produced water	Nogueira Vilanova and Perrella Balestieri (2015)
Specific energy consumption associated with water losses, *SECWL* (kWh/m^3)	Implicit electricity in each cubic meter of water losses in the city	Nogueira Vilanova and Perrella Balestieri (2015)
Specific GHG emissions, SCO_2eq (kg CO_2eq/m^3)	CO_2 equivalent emissions associated with direct electricity consumption in the DWSSs of the city	Nogueira Vilanova and Perrella Balestieri (2015)
Specific GHG emissions associated with water losses, $WLSCO_2eq$ (kg CO_2eq/qm^3)	CO_2 equivalent emissions associated with direct electricity consumption in the DWSSs of the city resulted from the water losses	Nogueira Vilanova and Perrella Balestieri (2015)
Standardised energy consumption, *Ph5* [$kWh/(m^3.100m)$]	Average pumping energy consumption in the system per $1m^3$ at 100 m of head	Alegre *et al.* (2016)
Standards compliance, *I5* (-)	Ratio between useful energy and input energy	Cabrera *et al.* (2010)
Supplied energy index (-)	Ratio of the theoretic energy in excess that is supplied to the system in comparison to the minimum energy required. The index E3 can be assessed in terms of energy in excess due to network operation and layout, E3 (network), pump improvement potential, E3 (pumps) and energy associated with water losses, E3 (losses)	Mamade *et al.* (2017)
Water-energy efficiency, *WEE* (%)	Implicit electricity percentage in each cubic meter of consumed water in relation to the electricity consumption per produced cubic meter	Nogueira Vilanova and Perrella Balestieri (2015)

These performance metrics have been applied to many systems, described by several authors (e.g., Feliciano *et al.*, 2013; Lenzi *et al.*, 2013; Carriço *et al.*, 2014; Dziedzic and Karney, 2015; Mamade *et al.*, 2017; Lapprasert *et al.*, 2018; Mamade, 2019; Fernandes, 2020).

In Portugal, the national Regulator of Public Water Supply, Urban Wastewater, and Urban Waste Management Services, ERSAR (acronym in Portuguese) undertakes a national quality of service assessment, based on a performance assessment system. ERSAR incorporates the legal and economic, quality of service, drinking water quality, and user interface regulation of the utilities (ERSAR, 2019). This system allows a yearly assessment and national benchmarking.

Almeida *et al.* (2021a) developed a specific performance assessment system to support strategic management of wastewater, stormwater, and combined systems, bolstering these systems' assessment. The methodology adopted considers existing assessment approaches and is aligned with current challenges expressed in international standards. Innovative aspects of the methodology comprise: the adoption of a holistic view of the urban water systems (regarding, e.g., interactions of water supply and drainage systems); flexibility in the application (e.g., depending on the utility, the type of systems, or data availability); valorisation, at the strategic level, of common tactical concerns; and the contribution of utilities in a co-creation and validation approach.

Loureiro *et al.* (2020) developed an approach focusing on the energy efficiency integrated management of the urban water cycle. Its novelty relied on allowing the evaluation of all stages of the urban water systems and the interactions between stages in terms of energy consumption and efficiency while also assessing the systems' effectiveness. It was structured by efficiency and effectiveness criteria, and the performance metrics and their reference values evaluate: (i) equipment efficiency (e.g., pumps, equipment for sewer cleaning, aerators), (ii) system efficiency (i.e., because of water losses, undue inflows) and (iii) the system effectiveness.

Similarly, recent developments and applications for assessing energy efficiency in wastewater treatment plants also show that there is a high potential to promote efficiency through better operation and adequacy of treatment capacity (Nowak *et al.,* 2015; Silva and Rosa, 2015; Castellet-Viciano *et al.*, 2018; Vaccari *et al.,* 2018).

Following this review, a need for a global methodology is identified allowing the identification of the main inefficiencies of wastewater transport systems and supporting selection of measures to improve energy use and attending to the specificities of each system and to the overall management objectives (e.g., control of undue or excessive inflows, overflows, limitations of inventory data, flows data, or modelling tools).

2.5 Undue inflows in wastewater systems

Undue inflows into sewers or natural drainage systems are a known source of functional problems. These can relate to water volume increase, water quality issues, or both. These inflows contribute to the poor performance of systems and to the deterioration of natural and built environments throughout the world (EPA, 1977; Brown *et al.,* 2004; York, 2010; Metro Vancouver, 2014; Carne and Le, 2015). The dimension of the problem is often unknown, even if identified by managers and academia as decisive for the performance deterioration of their drainage and treatment systems. The large volume of undue inflows remains a challenge to quantify because of the limited availability of measurements for drainage systems (Almeida *et al.*, 2021a). The problem results from several typical cause-effect mechanisms, varying with predominant undue inflows, some depending on local factors, others intrinsic to the type of system (e.g., separate or combined) (Almeida *et al.,* 2021a). Some authors found that undue inflows from extraneous and illicit water can be up to 50% of the wastewater volume (Langeveld *et al.,* 2012; Beheshti *et al.*, 2015; 2018a).

Inflows can be illicit, excessive, or have detrimental effects on overall system performance. In urbanized areas, they can occur in both separate (wastewater or rainwater) and combined sewer systems or natural drainage systems, such as urban streams, or coastal waters. For each of these systems, different inflows can be undue if they are not supposed to convey into a specific system or lowers the quality of the service. For instance, household wastewater is undue in separate stormwater systems but should be conveyed to separate wastewater or combined systems. Knowledge of causal mechanisms is essential in identifying adequate solutions and preventing future occurrences (Almeida and Cardoso, 2010).

Managers of water utilities often acknowledge some symptoms, consequences, or signs of undue inflows in everyday operation. However, effective identification of the causes and mechanisms of undue inflows is a complex task, requiring expertise, time, and resources frequently not available. For built systems, problems are noticeable in structural and operational conditions, such as manhole surcharge, discharge at pumping stations, or flooding. For natural systems, these are repeatedly related to pollution (Almeida *et al.*, 2017).

Overall, undue inflows can have effects on the wastewater systems' performance from several points of view, such as (Almeida and Cardoso, 2010): (i) hydraulic and structural performance, because of reduction of transport and treatment capacity, an increase of anomalies and continued degradation of assets materials; (ii) environmental performance, because of discharges into the natural environment (leading to soil and water pollution) and to the decreased efficiency of treatment facilities; (iii) social performance, including potential effects on health and public safety, because of to increased flooding (in frequency, duration or peak flow), with ensuing inconvenience to traffic, damages to public or private property, and potential increase in the likelihood of contact with polluted waters; (iv) economic and financial performance, because of an increase in operating costs (e.g. increase in pumped flows and treatment costs) and costs to third parties; and (v) non-compliance issues and reduction of utility overall performance. Undue inflows can cause sanitary sewer overflows in urban areas (e.g., discharges and flooding), unnecessary transport of water, decreased efficiency in water and energy use and reduced treatment efficiency in WWTP, among others, since these directly affect pumping (e.g., escalating pumping operation time) and treatment processes and total energy consumption (Metro Vancouver, 2014; Carne and Le, 2015; Almeida *et al.*, 2017).

Together with flooding and discharges, assessment of undue inflows is not a common practice in water utilities. The quantification of these undue inflows, overall and per type, is of utmost importance to assess the effect on systems performance, to identify intervention needs and to select intervention priorities on subsystems and classes of components. However, the quantification of these undue inflows is complex and not carried out systematically (Almeida *et al.*, 2021a). Several methodologies have been proposed to address specific undue inflows, such as infiltration, rainwater inflows, high salinity water and industrial effluents, among others (De Bénédittis, 2004; Becouze-Lareure, 2010; Flood and Cahoon, 2011; Metro Vancouver, 2014; Carne and Le, 2015; Saletti *et al.*, 2021).

Accurate quantification of undue inflows from individual sources into a sewer system is an essential task for assessing the status of the sewer network and conducting rehabilitation measures. Representing a high asset value (Beheshti and Saegrov, 2018b), urban sewer systems in most cities all over the world are undergoing deterioration with service time (Rehan *et al.*, 2014). Thus, accurate monitoring, maintenance and rehabilitation are necessary for their preservation (Beheshti and Saegrov, 2018a). Undue inflows can be reduced by sewer rehabilitation measures, e.g., relining, or chemical grouting, by measures to control the inflows, e.g., separating combined systems or disconnecting private stormwater laterals from the sanitary sewer system, or by reducing the sources (Almeida and Cardoso, 2010). Measures can also be carried out to decrease the adverse effects of undue inflows after entering the system, e.g., increasing the capacity in the piping system and the wastewater treatment plant (Salleti *et al.*, 2021).

Climate change most likely will contribute to increase the undue inflows (Sola *et al.*, 2021). These undue inflows can increase the footprint of wastewater systems, having a direct impact on the W-E-G nexus. However, few studies consider the implications of undue inflows in the nexus and, when included, the issue is not approached comprehensively, and the relevance and uncertainties of undue inflows are not recognized. It was found by Chhipi-Shrestha *et al.* (2017) that the infiltration and inflow to the sewer network are major contributors to the water footprint but did not account for overflows (either at overflow structures or flooding not returning to the system).

The component related to the energy associated with overflows potentially inflowing to energy-consuming component represents energy that would be consumed additionally if the total volume that left the system was also pumped. Therefore, this component should not be mistreated since it highlights to wastewater utilities that, while they do not reduce these exceedance volumes, the impact of actions in the control of undue inflows to reduce energy consumption is compromised. This makes it difficult to document the efficiency of mitigating measures.

2.6 Energy use improvement measures in the urban water cycle

2.6.1 General

The focus on energy efficiency measures is very much needed to reduce the carbon footprint of the water sector (Frijins *et al.*, 2013). The number of examples of energy efficiency improvement measures in water production and treatment is rapidly growing (Plappally and Lienhard, 2012; IEA, 2016). However, more substantial improvements will be necessary as it is expected that more advanced and energy-intensive treatment will be required to meet future demands and quality standards and to adapt to climate change (Frijins *et al.*, 2013).

The Global Water Research Coalition (Brandt *et al.*, 2012) prepared a compendium of best practices for energy efficiency in the water industry and concluded that there is a direct correlation between energy demand and the location, availability and quality of natural resources and treatment and disposal of sewage and sludge disposal. The key energy demand processes are pumping from distant or deep-water sources, distributing potable water over wide areas, asset condition and pipe leakage, treatment of sewage by aeration and pumping raw and treated effluents (Brandt *et al.*, 2012).

Aware of the need to reduce energy consumption and the associated costs, water utilities are currently looking for innovative ways to improve energy efficiency in their services, by improving equipment efficiency, by optimizing pump scheduling and by changing the system layout (Mamade *et al.*, 2017), as well as by recovering the excessive energy, whenever feasible (Williams *et al.*, 1998; Fecarotta and McNabola, 2017). However, a significant potential for water-energy saving can be found when analysing the whole system, since energy is dissipated not only in pumping stations but also in the system layout, pipes, water losses, among others.

For water supply systems leakage reduction and demand conservation represent significant opportunities to improve energy efficiency. Reducing the water demand implies the decrease in the abstracted, treated and distributed volumes and a corresponding reduction in wastewater volumes to be collected, transported and treated. Brandt *et al.* (2012) found that a 5% reduction in consumer demand will be mirrored by energy reductions through all components of the water cycle, including actions such as consumer education, installation of water-saving devices and maintenance, and replacement of the infrastructure.

Although some categories of energy use improvement measures were most found for water supply systems, especially the ones described in sections 2.6.2, 2.6.3, 2.6.4 and 2.6.6 are easily extendable to wastewater and stormwater systems.

2.6.2 Equipment-related improvement measures

Pumps use between 80% and 90% of the total energy consumed by the water industry. Many of the parameters and problems concerning energy efficiency are generic so the subject is covered below from the principles governing the appropriate selection of a pump and its system, rather than by application. This should allow rapid diagnosis of problems and identification of solutions. Pumping represents more than 70% of water supply energy demand and, at least, 30% of wastewater energy needs (Brandt *et al.*, 2012).

Both in water supply and wastewater networks, the selection of the most suitable pumps is crucial, as the efficiency and reliability of the system largely depend on it. The selection should consider system characteristics and needs (e.g., type of system, topographic level) (Baptista, 2020).

The most common measures associated with equipment to improve energy efficiency include pump refurbishment, pump component replacement, complete pump replacement and variable frequency drives (VFD) installation (Liu *et al.*, 2012). These solutions can be taken as reactive rehabilitation interventions or integrated in a maintenance programme and represent potential improvements of 5%-30% of consumed energy in water and wastewater systems (Liu *et al.*, 2012). According to Cabrera *et al.* (2017) the use of more efficient pumps (i.e., old pumps refurbished or replaced by new ones) can lead to savings of up to 30%.

The most common pump component replaced is the impeller. The replacement of inefficient motors by higher efficiency models is also a common and effective way for energy performance improvement. Maintenance measures, such as keeping ventilation and temperature control to the optimal operating conditions provided by the motor manufacturer, can be carried out with very little capital expenditure (US EPA, 2013).

There are few examples of pumps replaced solely on energy efficiency grounds. Most replacements are for other reasons, such as reducing blockages, operating regime changes from the original design and incorrect original selection but impacting indirectly on energy consumption. The small number of examples reflects the relatively high cost of replacement and the payback time involved. Some utilities have reported situations where pump refurbishment or replacement had been proposed but postponed because of uncertainty and risk. It is expected that rising energy prices will increase the viability of schemes that are currently only marginal (Brandt *et al.*, 2012).

Another possible improvement is by the installation of variable-frequency drives (VFD), also referred to as variable-speed drives. A VFD is an electronic control device that allows a continuous matching of the motor speed to the load requirements for the pump. VFDs easily accommodate fluctuating flow rate demands, avoiding losses when using throttled valves and bypass lines. VFDs also allow slow and smoother pump start-up and shutdown, reducing wear and tear on the motor. US EPA (2013) suggests that when VFDs are properly installed with premium efficiency motors, savings up to 10%-50% can result in a payback of 1-8 years. Brandt *et al.* (2011) reported two case studies where energy consumption was reduced by 12%-20%, with payback periods of 2.5 years. However, it should be noted that the correct sizing of constant speed pump can result in lower life-cycle costs than when using VFD in typical water distribution systems (Walski, 2001).

The efficiency of VFDs can be calculated by using the pump affinity laws (Jones *et al.,* 2006). Walski *et al*. (2003) tested a small pump with a VFD and measured its efficiency against the efficiency calculated using pump affinity laws at different points with the pump working from full speed to 30% of full speed. While the affinity laws worked quite well for adjusting the pump head characteristic curves, the pump efficiency curves fell significantly lower (5%-15%) than those predicted by the affinity laws and this deviation increased as the speed decreased from full speed. This is most likely explained by the loss of efficiency in the variable-frequency drive. Since VFDs cost almost as much as the pumps themselves, this efficiency loss needs to be accounted for. Manufacturers do not readily provide data on loss of efficiency as the drives deviate from loads that would give the peak efficiency (Walski *et al*., 2003).

Brandt *et al.* (2012) indicated that some VFDs have enabled turn down of machinery to match operating conditions, with one example allowing an energy-wasting throttling valve to be removed. Where only one pump is expected to cope with a wide duty range or seasonal or diurnal variations a VFD is an economical solution. Modern VFDs include power factor management and one case study showed an 83% saving. However, VFDs use power to drive their electronics and take typically 4 to 5% of the rated motor power. There are examples of pumps being replaced to allow efficient fixed-speed operation thus dispensing with VFDs (Brandt *et al.,* 2012).

Other important part of pump efficiency loss is related to the impeller and casing wear rings degradation. The degradation rate tends to be much higher in pumps operating far from the best-efficiency point due to increased shaft deflection. Most of the loss in efficiency is normally caused by a build-up of corrosion products in cast iron casing (Brandt *et al.,* 2012). Periodic pump refurbishment is a maintenance practice that involves the application of an internal coating and replacement of wearing parts. Internal coatings for pumps have been an accepted practice for some years and can be a convenient addition to a routine or major maintenance overhaul including, for example, replacing packed glands with mechanical seals or sleeve bearings with roller elements on older pumps (Brandt *et al.,* 2012). The coating can prevent corrosion and reduce water friction losses by more than 40%. This periodic maintenance measure can return pump efficiency close to a new pump (Cardoso *et al.,* 2017). Brandt *et al.* (2011) describe a case study in which epoxy coating was applied to the pump impeller and the pump body, and the investment had a payback period of 3.2 years.

Energy efficiency gains from new pumping technology (e.g., supervisory control, data acquisition software and installation of smart pumps) will probably be less than 5% since the technology is generally mature. However, more significant improvements should be feasible in submersible and borehole pumps where hydraulic and electrical configurations are more challenging (Brandt *et al.,* 2012).

In Portugal, the ERSAR Technical Guide no. 24 (GT24) also presents some of the most frequently applied measures to improve the equipment energy efficiency, such as: the installation of variable speed drives to improve and to adapt the operation of the motor to variations in consumption; replacement of conventional motors by more efficient class motors; the adjustment of the operating points of pumps to approach their best-efficiency point; replacement of oversized pumps; application of coatings in interior walls of pump cases and impellers, to reduce frictional losses and to improve the pump efficiency; implementation of an energy management system that allows monitoring the operation of the pumping system; verification of the correct lubrication and wear of the pump bearings; verification if the impeller is worn or damaged; verification of the conditions of the seals; verification of air leaks during operation (ERSAR and ADENE, 2018).

2.6.3 Optimization of system operation

Other energy improvement measures can be adopted and implemented in the pipe system design, by avoiding sharp edges with high velocities, using appropriate valves for check and isolation duties, and incorporating flow rate and head measurement in the pumping stations (Brandt *et al.*, 2011).

Regarding pipe friction, regular pigging, and cleaning, especially in raw water and wastewater mains, can be economically viable and can considerably reduce friction losses. This technique comes from the oil industry and consists of inserting a piston into the pipe during a short pump stop. When the pump restarts, the pig is driven by the pump, while taking the sediments that can be removed at a terminal point. This approach has been successfully applied in Krefeld, Germany and resulted in a head loss reduction of 30 m. Another common measure is pipe relining using smooth pipes with much lower roughness that are inserted in the main pipe (Brandt *et al.*, 2011).

Other important measures are the system-wide improvement measures, which involve acting at the system level instead of focusing on a single equipment. Examples of these measures include the maximization of gravity flows and the minimization of water losses and of pipe friction, which indirectly consume energy. Other opportunities, such as water conservation or energy recovery on the demand side, can also be found to improve energy efficiency. The adoption of a combination of these measures is less common despite these may yield higher energy savings than acting on individual components (Mamade, 2019). Cabrera *et al.* (2017) indicated that by improving old designs and layouts expected savings can be 30%.

The maximization of gravity flows can be achieved by finding alternative water sources that remove or reduce the need for water pumping. Brandt *et al.* (2011) have reported that Bristol water has been managing its water sources holistically: with increased rainfall, reservoirs have been used for water supply instead of pumping water from water canals.

In systems requiring water pumping, high water losses represent an opportunity for saving both water and energy. It is commonly verified that any reduction in the demand for water from a system which includes pumping within the cycle will have a proportional reduction in energy consumption. In the Netherlands, a pipe has been installed to reduce water losses between the water intake and the pre-treatment facility (KWR and STOW, 2010). Water losses have been reduced by 5%, resulting in more than 0.7 GWh/year of energy savings. Sydney Water has implemented a pressure management programme combined with pipe replacement, flowmeter upgrade and active leakage control. This combination of water loss measures has resulted in a 6.6 GWh of energy savings in 5 years. Improved flow metering allowed the identification of opened valves that were letting water pass and, therefore, requiring more pumping.

Baptista (2020) also indicated that small corrective actions, such as replacement of pumps' motor oil and cleaning actions (e.g., equipment cleaning, solids removal) can be very effective.

2.6.4 Operation and maintenance measures

Pumping scheduling optimisation is another improvement measure, aiming mostly at energy cost reduction, though it may also lead to an energy consumption improvement. It involves better management of the water flows in the system to reduce the costs associated with the electricity bill. This can be achieved by maximizing the use of existing tanks, the installation of additional storage capacity and rescheduling of water pumping times to take advantage of time-of-use energy rates, avoiding electricity tariffs at peak hours (Mamade, 2019).

Jung *et al.* (2014) presented a near-real-time optimal pump scheduling for South Korea, in which 19%-27% of energy cost savings have been achieved. Cherchi *et al.* (2015) explored an optimisation framework that integrates pump optimisation and water quality and has been successfully applied in 20 water supply systems, distributed around the world, having reported operating cost savings of 8%-15%. Ghaddar *et al.* (2015) developed an optimisation model to account for dynamic pricing. Kusakana (2016) considered the optimisation by considering photovoltaic and wind power generation in rural water supply systems. Napolitano *et al.* (2016) presented a cost-risk balancing approach aimed at energy cost minimization and simultaneous reduction of damage caused by water shortages in South Italy. Coelho (2016) developed an optimisation approach that simultaneously deals with valves and fixed and variable-speed pumps to minimise associated energy costs. Menke (2017) proposed a novel convex formulation and exported it to variable speed pumps, exploring the trade-offs between costs and emission reduction. Vakilifard *et al.* (2018) concluded that the main gap is the absence of models for optimising the long-term planning of water supply systems considering renewable energy within the urban context and the lack of models considering uncertainties associated with water demand. Luna *et al.* (2019) obtained an average 15% cost reduction through the adoption of knowledge-based solutions, that is the incorporation of information about the water network and respective limitations to locally improve or find solutions known to be feasible, together with water storage risk management.

An energy audit carried out in India estimated that an annual saving of US$670 000 can be achieved through power factor correction, contract demand management, and shifting pumping loads from peak to off-peak periods by pumping water to storage reservoirs during off-peak periods (Brandt *et al.*, 2012).

Limaye and Welsien (2019) pointed out that avoiding throttling pumps, optimizing distribution-side voltage, replacing the delivery pipe, and operating lower capacity and lower head pumps resulted in significant annual energy savings.

2.6.5 Reduction of undue inflows

As previously described in section 2.5, undue inflows represent a significant part of water volumes in wastewater systems and can have effects on hydraulic and structural performance, because of reduction of transport and treatment capacity, leading also to a decreased efficiency of pumping and treatment facilities (Almeida and Cardoso, 2010). In pumping stations, undue inflows lead to increased expenses related to maintenance and energy use; in sewer networks (including weirs) these inflows lead to payments related to basement flooding and to wastewater transported to recipients; and in WWTP (including weirs), undue inflows lead to increased expenses related to maintenance, energy use and wastewater transported to the receiving waters (Jenssen Sola *et al.*, 2018).

Therefore, reducing undue inflows directly impacts the total energy consumption. Bilateral effects related to flooding and discharges reduction and their impact on energy consumption should also be analysed (Metro Vancouver, 2014; Carne and Le, 2015; Almeida *et al.*, 2017).

2.6.6 Energy recovery measures

Hydropower is a well-known technology, applied worldwide for electricity generation from renewable sources. Some studies (e.g., Pereira, 2018; Llácer-Iglesias *et al.*, 2021; Mérida Garcia *et al.*, 2021; Mitrovic *et al.*, 2021) have started to consider its application to existing urban water systems, to harness an excess of energy that otherwise would be wasted (Llácer-Iglesias *et al.*, 2021).

Water supply systems have a significant potential for energy recovery, through the installation of turbines and pumps operating as turbines (PAT) in locations with excessive pressures, e.g., at locations with pressure or flow control valves or at the inlet of storage tanks supplied by gravity (Jain and Patel, 2014; Delgado *et al*., 2019).

The assessment of the energy recovery potential for water supply systems requires the identification of the locations where energy is dissipated, the estimation of available hydraulic power and the development of technical and economic feasibility studies (MacNabola *et al.*, 2014; Gallagher *et al.*, 2015; Su *et al.*, 2015; Oliveira *et al.*, 2021). The main potential of energy recovery in water supply and irrigation systems is in the range of the mini and micro hydropower schemes (5 kW – 1 MW), according to the classification proposed by Williams and Porter (2006).

Among several solutions to recover the excessive hydraulic power, pumps operating as turbines, typically installed in parallel with the control valve, are pointed as a cost-effective solution for energy production (Ramos and Borga, 1999). One of the general barriers to the installation of such a solution is the fact that flow rate and pressure vary constantly in water supply systems, which significantly complicates the operation of these devices and reduces their efficiency. Monteiro *et al.* (2018) developed a methodology for assessing the energy recovery potential to overcome this issue. Results have shown that installing PAT can be a feasible solution at the inlet of storage tanks only if available hydraulic power is higher than 50 kW and operating times (during the tank filling) at the maximum power are higher than 100 days/year.

Delgado (2018) proposed a new methodology for predicting the PAT performance and for modelling the variable speed performance hill chart of a PAT. The variable speed operation has been proven effective for both increasing the energy recovered and for avoiding the operation in off-design conditions. The rotational speed control provides, thus, greater flexibility to the operation of a PAT power plant under the variable discharge conditions of drinking water supply systems (DWSS) (Delgado *et al*., 2019).

Given the nature of wastewater systems, the inlet or the outlet of wastewater treatment plants (WWTP) are preferentially used as potential sites to install an energy recovery solution to generate electricity in the wastewater system fields and thermal energy applications (Nowak *et al.,* 2015). In wastewater systems, the use of energy recovery devices is more difficult, due to the nature of the fluid that contains solid materials and has corrosive properties. It is typical to have low heads with high flow rates. Whenever the installation of a turbine is already planned during the infrastructure construction, this significantly reduces the capital costs and the hydraulic design of the system can be optimized (Berger *et al.*, 2013).

The development of energy recovery feasibility studies involves key steps: the identification of potential locations, the identification of the most suitable turbine and the prediction of its performance, given specific head and flow values, the simulation of the energy recovery during a period and a cost-benefit analysis (Oliveira *et al.,* 2021). The Archimedes screw was originally developed to pump water from a low to a high-level section; this equipment is composed of a helical array of simple blades that wound on a central cylinder. Recently, this equipment has been used in reverse mode (inverted Archimedes screw) serving as a turbine – Archimedes screw turbine – to generate energy for low-heads and high flow rates (Pereira 2018; Oliveira *et al.,* 2021).

Regarding treatment processes, there are also opportunities for energy generation from waste and sludge through combined heat and power technology (Brandt *et al.,* 2012).

2.6.7 Renewable energies

The growing pollution levels caused by fossil fuels as well as their continuously changing prices, warrants the need for energy conservation and a transition from fossil fuels to renewable energy (Gormus *et al.*, 2015; Bukhary *et al.*, 2018). Therefore, to decrease the GHG emissions and dependency on fossil fuels, the use of renewables as energy sources has become popular (Bailey *et al.,* 2021).

Water utilities may also reduce energy costs by deploying renewable energy resources (Lisk, *et al.*, 2012; DESL, 2017; EPA, 2018), for instance by (i) solar photovoltaic generation; (ii) generation of electricity from small hydropower; (iii) use of combined heat and power (cogeneration) when both heat and electricity are required; and (iv) generation of electricity from biogas in wastewater treatment facilities (Limaye and Welsien, 2019).

In the United States, in 2019, energy consumption through renewable energy resources (11.5% of total energy consumption) exceeded the consumption of energy through coal (11.3%), predominantly because of the increased growth rate of solar and wind installations, since 2015. In 2019, 2% of the total electricity generation was solar (USEIA, 2020).

The costs of solar photovoltaics have decreased substantially (from US$2 to US$1 per watt), and solar generation is becoming competitive in many areas. Water utilities could install solar photovoltaics to reduce their purchased electricity needs. Solar energy can be captured in two forms: thermal through circulating fluid, or electrical through photovoltaic panels. Thermal panels are relatively efficient and are available in various states of technological development roughly in proportion to their efficiency. The simplest and cheapest will generally only release energy from direct sunlight, whereas the most expensive technology with concentrators and vacuum tubes will be effective even on cloudy days (Brandt *et al.*, 2012). Solar photovoltaic panels have the advantage of being employed for both utility-scale and distributed generation. Further, with the development of new technology, solar energy has become more cost-effective and efficient (Bailey *et al.,* 2021).

Methane gas produced by anaerobic sludge digestion is another source of renewable energy (Bailey *et al.,* 2021). Electricity generation from biogas is usually the main option at WWTP. Biogas production certainly is a very profitable technology for this industry and ongoing research is continuously improving its performance and possibilities. Nevertheless, the still high complexity of the anaerobic processes required to generate biogas limits their application to the largest plants (Llácer-Iglesias *et al.,* 2021). Biogas in the form of sludge gas from digesters has been extensively used for some decades. In some business models, it can be viewed as only marginally cost-effective but rising energy prices and carbon reduction strategies can change this perception (Brandt *et al.,* 2012).

One difficulty with using renewable energy is that its availability rarely matches demand for water or wastewater installation. Power demands are usually concentrated in larger centres, whereas renewable sources are diffuse and there are always periods when they are not available. Grid connections are essential for most applications. Energy storage becomes a major issue and technology developments are required to be feasible at any scale. An exception is the use of combinations of small-scale wind and solar energy to charge uninterruptible power supplies which can be beneficial for remote small power applications such as monitoring instruments (Brandt *et al.,* 2012).

Opportunities for other renewable energy sources are usually site-specific, in geographic and financial terms. Large wind turbines have been used and some applications exist for small solar and wind packages combined with battery storage, usually for remote instruments. Their requirements include site space and wind resource availability, positive local planning and public attitudes, local grid connection availability and a suitable financial and business model for capital and operational expense (Brandt *et al.,* 2012).

2.7 Motivation and gaps of knowledge

The wastewater sector still faces several limitations and challenges regarding energy efficiency. Wastewater utilities strongly need to foster the improvement of energy use in these systems. It is of the utmost importance to provide clearer guidance, at the tactical level, for energy management in the wastewater sector, comparing different systems for priority setting as well as identifying, analysing, and comparing improvement measures. The energy management framework proposed in the ISO 5500x standards is intentionally very general and applicable to any type of organisation and in any field. More specific guidelines for wastewater systems are necessary including details on how the main energy inefficiencies should be addressed and on how the potential for energy recovery should be evaluated. The infrastructure asset management (IAM) methodology facilitates dealing with some of the mentioned issues by integrating the organisation´s objectives and by ensuring a diagnosis that is based on performance. Nevertheless, the IAM methodology is too broad and does not focus on energy efficiency.

Also, less data-demanding and flexible approaches, capable of allowing the identification of the main energy inefficiencies are necessary, since most utilities have a low maturity level regarding available and reliable information for application of the energy balance, calculation of performance metric and selection of energy improvement measures. To the author's knowledge, specific energy balances and tailored performance assessment systems for wastewater systems do not exist. Developments reported in the literature mainly focus on individual assets (e.g., pumps, wastewater treatment plants) and are predominantly associated with water supply and wastewater treatment. The fact is that an extensive application of the energy balance to the whole system, complemented with performance metrics specific to wastewater systems, can yield a deeper establishment and understanding on improvement opportunities. The W-E-G nexus should also be further highlighted and explored in these systems, mainly because most studies do not consider undue inflows and overflows. The latter component should not be mistreated since it highlights that the impact of actions in the control of undue inflows to reduce energy consumption is compromised, while wastewater utilities do not reduce these exceedance volumes. This also makes it difficult to assess the efficiency of mitigating measures.

Overall, there is a need for user-friendly tools that provide a systemic analysis of energy efficiency and that deal with uncertainties associated with collected variables to identify the main energy inefficiencies and to enable the analysis of new solutions. As mentioned, current tools for assessing energy efficiency are mostly directed to water supply systems and treatment processes and are mainly focused on equipment (i.e., pumps, lights, HVAC); others are too complex to use, not allowing a straightforward assessment of energy efficiency.

This reinforces the need to develop and explore new approaches to wastewater systems to assess energy efficiency, associated with sewer inflow and network layout, and to identify and evaluate new solutions with potential to improve energy efficiency. A gap is identified in terms of a global methodology allowing the assessment of the main inefficiencies of wastewater transport systems and supporting selection of measures to improve energy use, attending to the specificities of each system and to the overall management objectives, for instance, the control of undue or excessive inflows, overflows, limitations of inventory data, flow rates' data, or modelling tools.

Therefore, the following specific gaps of knowledge related to energy efficiency assessment and improvement in wastewater systems have been identified, and are key drivers for the development of the current research:

(i) A need of an integrated approach that allows the application of a comprehensive diagnosis of energy efficiency in wastewater systems, allowing to attend to the specificities of each system and to the overall management objectives, for instance, the control of undue or excessive inflows, overflows, limitations of inventory data, flow data, or modelling tools.

(ii) A lack of a structured and well-tested energy balance applicable to wastewater and stormwater systems that facilitates the identification of the main energy inefficiencies.

(iii) A lack of approaches for the assessment of energy use and efficiency in wastewater systems, using a tailored and objective-oriented performance assessment system, considering the water-energy-greenhouse gas emissions nexus and implications of undue inflows in the water, energy, and emissions nexus and in the global energy consumption and efficiency.

(iv) A lack of a structured portfolio of energy efficiency solutions tailored for wastewater systems.

Table 2.7 identifies the chapters in which these gaps of knowledge are addressed.

Table 2.7 – Gaps of knowledge associated with energy efficiency and corresponding chapters.

Gap of knowledge	**Chapter**
1. Lack of a comprehensive approach to assess energy efficiency in wastewater systems	Chapter 1 – Introduction and Chapter 7 – From assessment to a decision: a global framework to manage energy use in wastewater systems
2. Lack of a structured and tested energy balance for wastewater systems	Chapter 3 – Energy balance for wastewater systems and Chapter 4 – Micro-level application of the energy balance with energy recovery
3. Lack of a tailored energy efficiency performance assessment system	Chapter 5 – Performance assessment system for energy efficiency in wastewater systems and Chapter 6 – Water, energy, and emissions nexus in wastewater systems
4. Lack of a structured portfolio of energy use improvement measures in wastewater systems	Chapter 7 – From assessment to a decision: a global framework to manage energy use in wastewater systems

Chapter 3 – Energy balance for wastewater systems

This chapter corresponds to the research paper:

C. Jorge, M.C. Almeida and D. Covas (2022), *A novel energy balance tailored to wastewater systems*. Urban Water Journal. https://doi.org/10.1080/1573062X.2022.2035409.

Author contribution: The author co-developed the conceptual idea and the methodology and carried out the data analysis and investigation.

Abstract

This paper presents a novel energy balance scheme tailored for assessing energy efficiency in wastewater systems. It provides a consistent method to calculate the energy components associated with wastewater transport processes, allowing the quantification of the main water-energy inefficiencies. Three assessment levels are described (macro, meso and micro-level), depending on available information and scope. This balance allows a holistic approach of wastewater systems energy efficiency, including the system layout, losses in pipes/manholes, energy associated with undue inflows, exceedance volumes and energy recovery. The energy balance is applied to real case studies. The energy associated with undue inflows represents from 20% to 44% of the external energy, with low average efficiencies of wastewater pumping systems (34%) and inflow intrinsic energy representing 64% of the total energy. This energy balance supports the performance diagnosis and the development of energy efficiency improvement measures.

Keywords: energy balance, energy efficiency, pumping stations, wastewater systems.

3.1 Introduction

Energy efficiency is key for the water sector as urban water systems are energy-intensive worldwide (Basupi *et al.,* 2014; Twomey Sanders, 2016; Wakeel *et al.*, 2016; Venkatesh *et al.*, 2017) with implications to utilities and to the society in terms of economic and financial sustainability and environmental performance, mainly in the use of natural resources and in the reduction of greenhouse gas (GHG) emissions (Nair *et al.*, 2014; Singh and Kansal, 2018). The United Nations (WWAP, 2014) estimate that energy costs represent 30% to 40% of operational costs in water supply and wastewater services worldwide, while the Directive (EU) 2018/2002 of 11 December 2018, amending Directive 2012/27/EU on energy efficiency, reports that water and wastewater sectors account for 3.5% of electricity use in the EU in 2018. This directive requires Member States to achieve cumulative end-use energy savings, setting ambitious targets to 2030, mandating large organisations to complete energy audits every four years and emphasises “the effective management of water can make a significant contribution to energy savings”.

In Portugal, the urban water systems also represent 3% to 4% of the total national electricity consumption (PENSAAR, 2020) and has increased steadily 10% over the 5-years period from 2011 to 2015. Despite this figure being quite low, this energy proportion represents 1.1 TWh/year, thus efforts should be done to address this issue in the water sector. The wastewater subsector has about 40% share of this consumption (ERSAR and ADENE, 2018). Moreover, the water sector is one of the sectors with the highest number of energy-intensive facilities at the national level (ADENE, 2016).

Globally, management methodologies to assess and improve energy efficiency are explored, followed by the identification and discussion of different approaches to calculate water and energy balances and performance metrics in these systems (US EPA, 2008; AWWA, 2009; WEF, 2009). The ISO have published the ISO 5000x series (IPQ 2012; ISO 2014a; 2014b; 2014c) intended to leverage the integration of energy management into their overall efforts to improve companies’ quality and environmental management. However, the energy management framework proposed in the ISO 5000x standards is intentionally very general and applicable to any field and to any type of organisation. Therefore, it is beneficial to develop specific approaches for assessing energy efficiency in wastewater and stormwater systems, not only focused on the electrical energy associated with equipment but also considering a holistic system evaluation of energy consumption and efficiency, allowing to highlight main inefficiencies and impacts of excessive flows associated with undue inflows.

Energy consumption in wastewater transport and treatment depends strongly on (i) collected and treated volumes, (ii) groundwater infiltration and rainfall flowing into the wastewater system (typically undue inflows), (iii) required level of treatment and (iv) energy efficiency of operation and maintenance (O&M) works (IEA, 2016; ERSAR and ADENE, 2018). The undue inflow volumes are identified as a factor that significantly affects energy consumption (Jorge *et al.*, 2021a), since these directly affect pumping and treatment processes. These inflows are recognised as one of the main causes for many problems occurring in wastewater and stormwater systems, such as flooding, insufficient hydraulic capacity, low pumping and treatment efficiency and high O&M costs, globally contributing to their poor performance (Metro Vancouver, 2014; Carne and Le, 2015; Almeida *et al.*, 2017).

Several research studies have been conducted for assessing energy use efficiency in water supply systems (e.g., Duarte 2008; Cabrera *et al.*, 2010; Gay *et al.*, 2013; Lenzi *et al.*, 2013; Dziedzic *et al.*, 2015;

Walski, 2016; Mamade *et al.,* 2017; 2018). In the wastewater sector, hardly any research on the energy efficiency has been found with existing studies mostly focused on the integrated management of the urban water cycle (Loureiro *et al.,* 2020); treatment processes (Nowak *et al.*, 2015; Silva *et al.*, 2016); the improvement of individual assets' efficiency, like pumps (Hou *et al.,* 2015; Zhang *et al.,* 2016); and reducing energy costs (Hashemi *et al.*, 2014; Menke *et al.*, 2015). However, a significant potential for water-energy savings can be found when analysing the whole system, including explicitly the energy required for the transport of wastewater. This reinforces the need to develop and explore new approaches to wastewater systems to assess energy efficiency, associated with sewer inflow and network layout, and identification and evaluation of new solutions with potential to improve efficiency. A gap is identified in terms of a global methodology allowing the identification of the main inefficiencies of wastewater transport systems and supporting selection of measures to improve energy use, allowing to attend to the specificities of each system and to the overall management objectives, for instance, the control of undue or excessive inflows, overflows, limitations of inventory data, flows data, or modelling tools.

In this paper, a novel energy balance is presented, aiming at bridging the identified gap, specifically tailored to wastewater system transport processes, types of flows and scarcity of data and analysis tools. By itself, an energy balance will not affect energy consumption, but its definition highlights systems' inefficiencies and specific elements that need to be improved, supporting the planning of corrective actions. The proposed energy balance has a new structure and several new components, when compared with the ones proposed for water supply systems (Cabrera *et al.*, 2010; Mamade *et al.*, 2017) and irrigation systems (Fernandes, 2020), but the main structure is aligned as much as possible to facilitate a broader analysis of the water cycle. Main differences derive from the hydraulics in wastewater systems where free surface flows predominate justifying the division of the energy balance in two components – inflow intrinsic energy and external energy. Other aspects considered are data availability and calculation constraints; overflows not returning to the system are pointed as one of the main issues in wastewater systems (e.g., discharges and floods); and limitations derived from limited data on wastewater flows implying the use of estimates in many situations, even acknowledging the implications of this procedure. This energy balance intends to overcome the limitations related to the information gaps in inventory data or in flow measurements, by proposing three assessment levels. The energy balance for each assessment level is demonstrated and discussed using real case studies.

3.2 Energy balance scheme for wastewater systems

3.2.1 General description

A novel energy balance scheme tailored to wastewater systems is presented herein, with application focusing on the networked part of the system, including pumping stations, and compatible with incorporation of other components such as treatment works. Wastewater systems are composed of gravity sewers and pressurized pipes that collect and convey wastewater to a delivery point, typically a wastewater treatment plant (WWTP). The energy balance aims at calculating the amount of energy supplied to a system, consumed by the electromechanical equipment, and dissipated during the transport. This balance does not focus only on energy consuming components, as traditional energy audits, but aims to be a systemic approach, looking globally at the wastewater system, considering the system layout, the energy losses in pipes and manholes, energy associated with undue or excessive inflows, wastewater outflowing the system due to capacity exceedance, among others.

The proposed energy balance is applicable to combined sewer systems, for assessing the effect of excessive inflows in the energy consumption as well as to separate sewer systems, for assessing the effect of both excessive and undue inflows. Undue inflows are understood as those that should not enter into the system (e.g., rain derived inflows in separate wastewater systems). Excessive inflows are due in the system but globally are causing systems exceedance, typically above design capacity, and source of structural, hydraulic, or environmental performance problems. In this paper, the term “undue inflows” is used herein to refer both inflow types (i.e., excessive and undue inflows). The concept of “undue inflows” includes inflows, such as, infiltration, rainwater inflows, high salinity water, industrial effluents, commercial, basement drainage, among others (Almeida *et al.*, 2018). The energy balance can also be applied to stormwater systems, although these are less energy demanding.

Figure 3.1 illustrates the interaction between the energy components associated with the energy balance calculation. The energy balance is presented in Table 3.1. Application can be undertaken to a wastewater system or subsystems, ensuring well-defined boundaries. The energy balance has two main blocks: (i) “energy inflows”, including intrinsic energy, associated with system layout and characteristics, and external energy supplied to the system; (ii) “energy outflows” understood as energy dissipated, used or associated with exceedance flows (i.e., outflows from the system).

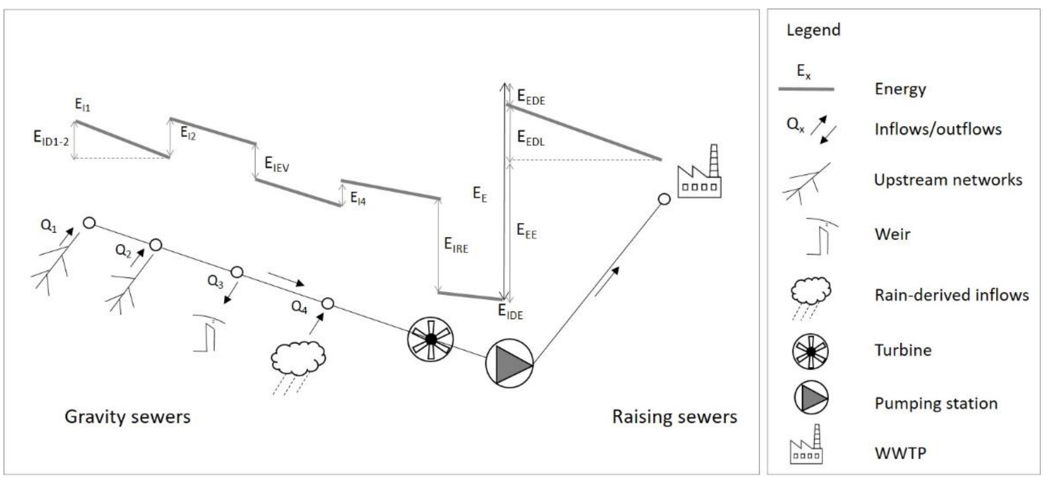


Figure 3.1 – Water-energy interactions scheme for wastewater systems.

Table 3.1 – Energy balance scheme for wastewater systems.

	ENERGY INFLOWS		ENERGY OUTFLOWS		
Total energy used for system processes (transport and treatment), E_T	Total inflow intrinsic energy (associated with gravity flow), E_I	Inflow intrinsic energy associated with authorized or due inflows, E_{IAI}	Total inflow intrinsic energy, E_I	System downstream energy, E_{IDE}	
				Recovered energy (e.g., micro-hydropower), E_{IRE}	
				Dissipated energy, E_{ID}	…due to inefficiencies in energy recovery equipment (e.g., turbines), E_{IDT}
					…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{IDL}
		Inflow intrinsic energy associated with undue inflows, E_{IUI}		Energy associated with exceedance volumes, E_{IEV}	…not connected to an energy-consuming component, E'_{IEV}
					…potentially inflowing to an energy-consuming component, E''_{IEV}
	External energy (electrical), E_E	External energy associated with authorized or due inflows, E_{EAI}	External energy, E_E	Elevation associated energy, E_{EE}	
				Dissipated energy, E_{ED}	…due to inefficiencies in electromechanical equipment (e.g., pumps), E_{EDE}
		External energy associated with undue inflows, E_{EUI}			…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{EDL}

The light grey boxes refer to the macro-level components, the dark grey boxes refer to the meso-level additional components to those in macro-level and the micro-level corresponds to all energy balance components (white and grey boxes).

The energy balance has two main components: the total inflow intrinsic energy associated with gravity systems and the external energy (i.e., supplied electrical energy) added to the system associated with pumping stations and WWTP. The total energy used in the system for transport and treatment is the summation of these two components according to equation (3.1).

$$E_T = E_I + E_E \tag{3.1}$$

in which E_T is the total energy in the system for transport and treatment (kWh), E_I is the total inflow intrinsic energy (kWh) and E_E is the external (electrical) energy (kWh). Despite the broad application, the present work will focus on energy consumed in the wastewater transport, typically the networked part of the system.

The main difficulty in applying the energy balance derives from the lack of data, for instance, network inventory data, flow measurements or energy measurements. While for water supply systems, it is common to have measurements at consumers' connections, it is not the case for wastewater systems.

Three assessment levels, macro, meso and micro-level (Table 3.1), are proposed to apply the energy balance depending on the available data and on the time horizon analysis; these levels will be further developed in section 3.2.4.

3.2.2 Total inflow intrinsic energy

The flow in wastewater systems is mainly free surface flow, except for a small number of situations including pressurised systems and rising mains or sewers immediately downstream a pumping station, where flow is pressurized. Different conditions from those of the water supply sector (pressurized pipe flows), result in use of hydraulics governing equations of open channel flows, more complex than those for pressurized flows. The basic energy equation used to estimate the available hydraulic head at each location of the gravity network is the Bernoulli's equation (3.2).

$$H = \frac{p}{\gamma} + \frac{v^2}{2g} + z \tag{3.2}$$

in which H is the hydraulic head (m), p is the pressure (Pa), γ is the water specific weight (9800 N/m^3), v is the mean flow velocity (m/s), g is the gravity acceleration (m/s^2) and z is the potential head (m).

Assuming a uniform flow regime, the hydraulic energy can be assumed as constant in each flow cross-section. Applying this equation to a point in the free surface of the flow, the first term in equation (3.2) is null, since it corresponds to the atmospheric pressure which is null in pressure gauges. Unlike in the balance applied to water supply systems, in free surface flows, the kinetic term is relevant for the balance as the pressure term is null. Thus, the total inflow intrinsic energy of the gravity network can be estimated by equation (3.3).

$$E_I = \gamma \left(\sum_{j=1}^{T} \sum_{i=1}^{N} Q_{i,j} H_{i,j} \Delta t_j \right) . \alpha \tag{3.3}$$

in which E_I is the total inflow intrinsic energy (kWh), $Q_{i,j}$ is the flow inflowing to node i and at time j (m^3/s), $H_{i,j}$ is the hydraulic head of the inflow to a node i and at time j (m), Δt_j is the time interval j (s), α is the unit conversion factor from Ws to kWh, α=1/(1000×3600) = 2.78×10^{-7} and N is the total number of nodes with inflow and T is the total number of time intervals.

From the perspective of energy inflows, the total inflow intrinsic energy is divided in (i) energy associated with authorized or due inflows, E_{IAI}, and (ii) energy associated with undue inflows, E_{IUI} (Table 3.1). These energy components can be estimated from the respective associated volumes calculated from wastewater measurements (despite the relationship between energy components and the respective wastewater volumes not being exactly linear), or on hydraulic models, by equations (3.4) and (3.5).

$$E_{IAI} = E_I \frac{V_{AI}}{V_T} \tag{3.4}$$

$$E_{IUI} = E_I \frac{V_{UI}}{V_T} \tag{3.5}$$

in which E_{IAI} is the inflow intrinsic energy associated with authorized or due inflows (kWh), E_{IUI} is the inflow intrinsic energy associated with undue inflows (kWh), V_{AI} is the volume of authorized or due inflows (m^3), V_T is the total transported wastewater volume (m^3), and V_{UI} is the volume of undue inflows (m^3). When wastewater measurements and hydraulic models are not available, these volumes can be estimated through simplified procedures.

For simple systems, with maximum one pumping station (when all the volumes are inflowing to the same energy consuming component), the volume of authorized or due inflows, V_{AI}, can be obtained from the average per capita water consumption and population served (dry weather wastewater volume) and the volume of undue inflows, V_{UI}, estimated using a sensitivity analysis procedure to determine the proportion of the runoff volume entering the system. The runoff volume can be obtained by applying the rational method described in Te Chow *et al.* (1962).

When monthly water consumption, V_{ws}^s, and wastewater, V_{ww}^s, volumes are known, an alternative is to estimate the dry weather inflow factor, *f*, representing the average proportion of this consumption discharged as wastewater, described by $f = \frac{V_{ww}^s}{V_{ws}^s}$, allowing to determine the total authorized or due inflow volume during the whole year V_{AI}^t. This volume is estimated by multiplying the factor by the water consumption volume, V_{ws}^t. The energy associated with this volume is estimated by equation (3.6), using the ratio between the total authorized inflow volume and the total collected or treated wastewater volume.

$$E_{IAI} = E_I \left(\frac{V_{AI}^t}{V_{ww}^t}\right) \tag{3.6}$$

in which V_{AI}^t is the total authorized or due inflow volume during the whole year (m^3) and V_{ww}^t is the total wastewater volume (m^3).

From a perspective of energy outflows, the total inflow intrinsic energy is divided in system downstream energy, recovered energy, dissipated energy and energy associated with exceedance volumes. The system downstream energy, E_{IDE}, represents the energy at the final section of the system, typically the connection to a WWTP or to an interceptor sewer, and is calculated by applying equation (3.3) at the final section of the system.

The recovered energy can be obtained at sites with installed energy recovery devices (e.g., Archimedes Screw or turbines), when there is a significant drop in elevation in the system, typically above 2 to 3 m, combined with high flows, for instance, at downstream of a WWTP. Despite the aggressiveness to materials of wastewater, there are several successful applications of turbines in wastewater systems (Berger *et al.*, 2013; Pereira, 2018). The recovered energy can be calculated by equation (3.7).

$$E_{IRE} = \gamma \left(\sum_{j=1}^{T} \sum_{i=1}^{N_t} \eta_{t_{i,j}} Q_{t_{i,j}} H_{t_{i,j}} \Delta t_j \right) . \alpha \tag{3.7}$$

in which E_{IRE} is the recovered energy (kWh), $\eta_{t_{i,j}}$ is the global efficiency of turbine *i* at time *j* (-), $Q_{t_{i,j}}$ is the flow of the turbine *i* at time *j* (m^3/s), $H_{t_{i,j}}$ is the net head of the turbine *i* and at time *j* (m) and N_t is the total number of energy recovery devices.

The dissipated energy consists of pipe friction and local head losses (e.g., in manholes, curves, valves) and of inefficiencies in turbines, as shown in equation (3.8). The energy dissipated in pipe friction and local head losses can be calculated by equation (3.9) and the dissipated energy in turbines can be calculated by equation (3.10).

$$E_{ID} = E_{IDL} + E_{IDT} \tag{3.8}$$

$$E_{IDL} = \gamma \left(\sum_{j=1}^{T} \sum_{i=1}^{N_p} Q_{i,j} \Delta H_{i,j} \Delta t_j \right) . \alpha \tag{3.9}$$

$$E_{IDT} = \gamma \left(\sum_{j=1}^{T} \sum_{i=1}^{N_t} \left(1 - \eta_{t_{i,j}} \right) P_{h_{i,j}} \Delta t_j \right) . \alpha \tag{3.10}$$

in which E_{ID} is the total dissipated energy (kWh), E_{IDL} is the energy dissipated in pipe friction and local head losses, E_{IDT} is the dissipated energy in turbines (kWh), $\Delta H_{i,j}$ is the total head loss in pipe *i* at time *j*, $P_{h_{i,j}}$ is the hydraulic power in turbine *i* at time *j* (kWh), and N_p is the number of pipes.

The energy associated with exceedance volumes not returning to the system, $E_{IEV,}$ such as overflows and flooding, can be calculated by equation (3.11).

$$E_{IEV} = E_I \frac{V_{EV}}{V_T} \tag{3.11}$$

in which E_{IEV} is the energy associated with exceedance volumes, V_{EV} is exceedance volume (m^3), and V_T is the total transported wastewater volume (m^3). The energy associated with exceedance volumes can be divided in two parts: (i) the energy equivalent to exceedance volumes potentially inflowing to an energy consuming component, thus pumped, or treated at some location downstream, leading to an energy consumption component, E'_{IEV}; and (ii) energy equivalent to exceedance volumes not connected to an energy consuming component, E''_{IEV}. If the exceedance occurs upstream of an energy consuming or recovery components (i.e., pumping stations, WWTP, turbines), the pumped, treated or turbined volumes will be lower, directly decreasing the energy consumption or recovery.

3.2.3 External energy

The electrical energy consumed in pumping systems corresponds to the external energy and can be estimated by equation (3.12).

$$E_E = \gamma\left(\sum_{j=1}^{T}\sum_{i=1}^{Np_s}\frac{Q_{p_{s\,i,j}}H_{p_{s\,i,j}}\Delta t_j}{\eta_{p_{s\,i,j}}}\right).\alpha \tag{3.12}$$

in which $Q_{p_{s\,i,j}}$ is the pumped flow of the pumping station i at time j (m³/s), $H_{p_{s\,i,j}}$ is the manometric head of the pumping station i at time j (m), assuming equal pumps are installed in parallel, $\eta_{p_{s\,i,j}}$ is the global efficiency of the pumping station i at time j (-) and N_{p_s} is the number of pumping stations. This component can be obtained from electricity measurements or bills of pumping stations, if the consumption for other uses (e.g., lighting) is excluded or is negligible.

From the perspective of energy inflows, the external energy can be divided in two components: one associated with authorized or due inflows and another associated with undue inflows. Ideally the calculation of these components should be obtained from flow measurements statistical processing; alternatively, the same simplified procedures described in section 3.2.2 can be used to estimate the part associated with authorised inflows. The external energy associated with undue inflows can then be obtained from the difference to the total external energy supplied by equation (3.13).

$$E_{EUI} = E_E - E_{EAI} \tag{3.13}$$

in which E_{EUI} is the external energy associated with undue inflows (kWh) and E_{IAI} is the external energy associated with authorized or due inflows (kWh).

From the perspective of energy outflows, the external energy can be divided in three components, namely: the energy associated with elevation, the energy dissipated due to inefficiencies in electromechanical equipment (mainly in pumps) and the energy dissipated due to friction and local head losses.

The elevation associated energy corresponds to the energy necessary to pump the wastewater volume from the water level in the pump well to the downstream delivery point, as given by equation (3.14).

$$E_{EE} = \gamma\left(\sum_{j=1}^{T}\sum_{i=1}^{Np_s}Q_{p_{s\,i,j}}\Delta z\Delta t_j\right).\alpha \tag{3.14}$$

in which E_{EE} is the elevation associated energy (kWh) and Δz is the geometric-head difference, between the pumping well and the delivery point (m).

The external energy is dissipated in friction losses and local head losses and in pumps as in equation (3.15). The energy dissipated due to friction losses and local head losses is calculated by applying equation (3.9) to each pumping system. The dissipated energy associated with pumps is calculated by equation (3.16).

$$E_{ED} = E_{EDE} + E_{EDL} \tag{3.15}$$

$$E_{EDE} = \gamma\left[\sum_{j=1}^{T}\sum_{i=1}^{Np_s}\left(\frac{1}{\eta_{p_s-1}}\right)Q_{p_{s\,i,j}}H_{p_{s\,i,j}}\Delta t_j\right].\alpha \tag{3.16}$$

in which E_{ED} is the total dissipated energy (kWh), E_{EDE} is the dissipated energy associated with pumps inefficiency (kWh) and E_{EDL} is the external energy dissipated in friction losses and local head losses (kWh).

The calculation of the different components of the energy balance depends on data availability; therefore, three levels of assessment are identified for the energy balance application.

3.2.4 Levels of energy balance application

The energy balance can be applied by utilities with different maturity levels, network layouts, data availability and operation modes. Three levels of assessment (macro, meso and micro-level) are proposed depending on objectives and available data. All assessment levels can be applied either to the whole or to parts of the system or subsystems. Utilities need to define the objectives, the system boundaries, layout, and main assets (e.g., sewers, pumping stations) and available information to proceed with selection of assessment levels.

The energy balance can be applied annually to have an overview of the energy consumption and efficiency, but it can also be applied monthly to attend to seasonality, or daily to understand weekly energy consumption patterns.

The annual analysis provides information to assessing overall system performance, for instance in the scope of global system performance assessments at strategic or tactical levels. Often measurement data is only available in a monthly basis, for instance for energy consumption. Data requirements and typical scale of application for each assessment level are presented in Table 3.2.

Table 3.2 – Data requirements for each assessment level.

Assessment level	Application time horizon	Required data
Macro-level	Year, Month	Collected or treated wastewater volume Water supply consumption volume Electric energy consumption
Meso-level	Year, Month	Same data of macro-level Electric energy consumption for pumping stations Pumped volume for pumping stations Pump heads Data from audits
Micro-level	Year, Month, Day, Week, Hour, Lower time steps	Same data of macro and meso-level Detailed drainage network maps and inventory data Calibrated hydraulic model

In the macro-level assessment, the external energy and the energy associated with undue and authorised inflows can be estimated annually. This assessment is significant, as it allows for a preliminary evaluation of energy consumption in the system. Results of the macro-level assessment used at the strategic management planning provides information on questions as: How much energy is consumed per cubic meter of wastewater? How much energy is consumed by all pumping stations or in other electromechanical components? How much energy is associated with authorized inflows and with undue inflows? Macro-level assessment information allows calculation of system energy performance metrics, such as the specific energy consumption and the energy efficiency of pumping stations.

The meso-level assessment requires additional data and allows a more detailed calculation of external energy components, namely, the elevation associated energy as well as the dissipated energy including the pumps inefficiencies, friction losses and local head losses. The estimation of the pumping stations' efficiencies can be carried out in a simplified way, unless data from energy audits are available allowing a more accurate estimation of the dissipated energy associated with pumps' inefficiency. For these two assessment levels, as explained in the previous sections, simplified procedures and ratios based on measured wastewater volumes are applied to determine the respective associated energy consumption components. Although these macro-level and meso-level assessments are mainly based on simplified calculations, the considered assumptions are reasonable and aligned with the current practice in wastewater utilities, depending on and adapting to available data. The uncertainties associated with these two levels are higher than for the micro-level. However, the benefit of having an approach compatible with currently available data and knowledge is considered positive, allowing to increase awareness to these issues and capacity building of the wastewater utility teams.

The micro-level assessment requires a calibrated hydraulic model of the network, especially for complex systems composed of several pumping stations. It provides a detailed assessment of each energy balance component (Table 3.1). Calculations can be carried out using commercial software (e.g., SWMM, MIKE URBAN). This analysis allows the calculation of all the energy components associated with the total inflow intrinsic energy, not feasible in the meso and macro-level assessments. Results allow identification of the main system inefficiencies and of improvement opportunities.

In short, if a utility only has global data, it can only apply the analysis at macro-level, focusing on the external energy calculation; if the utility has detailed data of the pumping systems, the meso-level assessments can be used, allowing the estimation of different energy components of the external energy; when both the pumping systems and the gravity networks are well-known, detailed measurement data are available and mathematical modelling is feasible, micro-level assessment can be applied allowing the calculation of all energy balance components.

3.3 Application and testing of the methodology

3.3.1 Energy balance application at macro-level and meso-level

Data available from the Portuguese regulator on a yearly basis allows application of the energy balance at macro-level to all 281 Portuguese wastewater utilities (ERSAR, 2018). A 4-years period (2015–2018) was available. There are two types of utilities: type A utilities (12 out of 281) are responsible for bulk wastewater transport and treatment systems whereas type B utilities (269 out of 281) manage wastewater collection and transport systems, sometimes, also, including treatment.

For application of both the macro and meso-level energy assessment, a set of six wastewater utilities (WU) provided data for testing the proposed methodology. These six utilities are responsible for urban water systems of different dimensions and characteristics as presented in Table 3.3: effective service households (19 772 to 488 725), network lengths for wastewater systems (32 to 1 549 km), pumping stations (3 to 380) and WWTP (9 to 176), being representative of the Portuguese reality. These utilities are classified in the two above mentioned types: type A and type B.

Table 3.3 – Selected WU characterization.

Identification	Type	Number of effective service households	Network extension (km)	Number of pumping stations	Number of WWTP
WU1	A	35 204	32	3	23
WU2	A	311 490	447	192	65
WU3	B	19 772	546	66	9
WU4	A	488 725	1 498	380	176
WU5	B	55 363	1 539	85	16
WU6	B	158 303	977	26	16

The data provided by the six utilities to calculate the energy balance both at the macro and the meso-level for the reference period of 2015 to 2019 were found to have limitations and were not sufficient to apply both assessments in all cases. Table 3.4 shows the data not available and assessment levels applicable to each utility.

Table 3.4 – Available and provided data for the selected WU.

WU	Missing data	Applied assessment level
WU1 / Type A	Water supply consumption monthly data	Meso-level
WU2 / Type A	Water supply consumption monthly data	Meso-level
WU3 / Type B	None	Macro-level and meso-level
WU4 / Type A	Pumping stations' pump heads	Macro-level
WU5 / Type B	None	Macro-level and meso-level
WU6 / Type B	None	Macro-level and meso-level

For four wastewater utilities (WU3, WU4, WU5 and WU6), rainfall data were available and relation of energy consumption with annual rainfall was analysed for the period of 2015-2019 to assess the impact on energy consumption of potential rain induced inflows.

3.3.2 Energy balance application at micro-level

The application of the energy balance at micro-level is carried out for a simplified case study, presented herein to illustrate the calculation and to discuss obtained results of the micro-level. This case study is based on the real-life domestic separate system of Venteira, located at Amadora, Portugal (Figure 3.2). The system has a network length of 2.60 km, sewer diameters varying between 200 and 500 mm, elevations between 105.50 m and 142.50 m, a total wastewater collected volume at dry weather of 868 700 m^3/year and a total rainfall derived volume of 856 655 m^3/year. The only pumping station has a manometric head of 3.00 m, a total pumped volume of 1 387 365 m^3/year and a total energy consumption of 37 767 kWh/year, representing a specific energy of 0.027 kWh/m^3. The wastewater exceedance volume (337 990 m^3/year) is given by the difference of the latter two volumes: the summation of the total volume generated at dry-weather and the total rainfall derived volume minus the pumped volume.

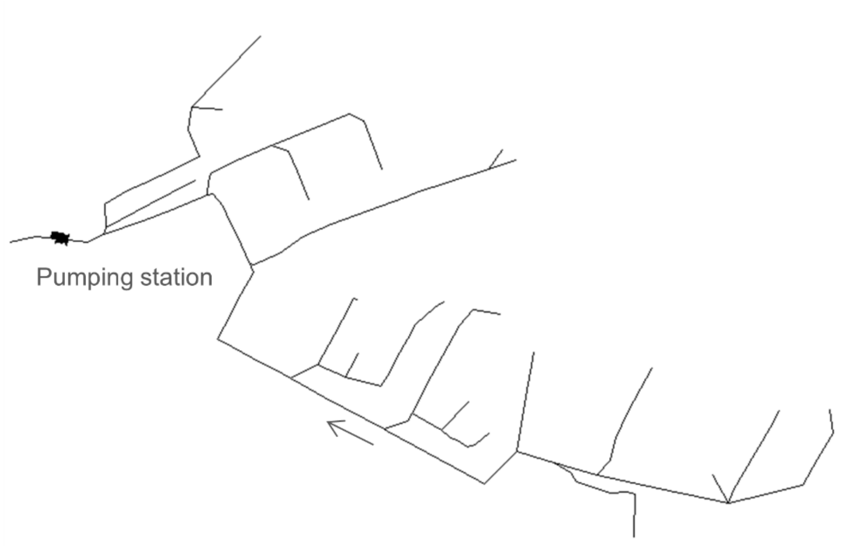


Figure 3.2 – Network scheme of the Venteira.

The micro-level assessment allows the calculation of both the external energy and the total inflow intrinsic energy components. The total inflow intrinsic energy is calculated by equation (3.3). The kinetic head associated with system inflows is neglected since it is low when compared to the elevation, thus the hydraulic head is given by z (potential head).

The system has no energy recovery; therefore, the recovered energy (equation (3.7) and the respective dissipated energy equation (3.10) are null). The dissipated energy in free surface systems is equal to the difference between the total inflow intrinsic energy and the energy at the downstream location. The energy at the downstream location is calculated by equation (3.2) with the hydraulic head given by the summation of the z at the delivery point (manhole drop equal to 1 m) and the kinetic head, $\frac{v^2}{2g}$.

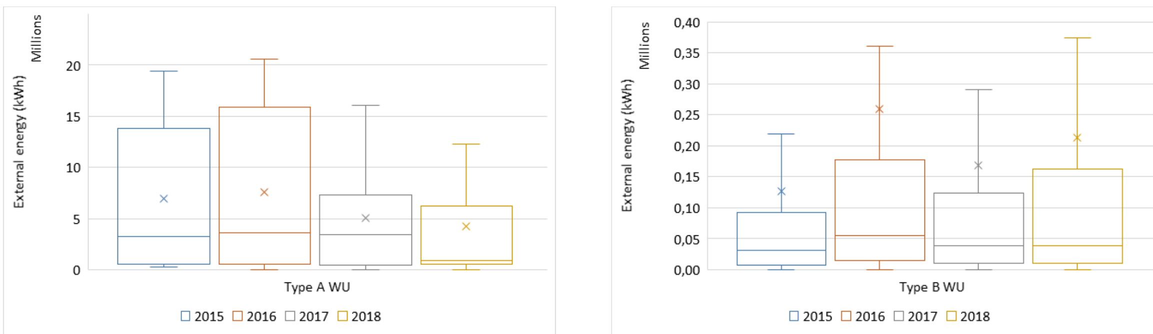
Calculations for the inflow intrinsic energy component associated with authorized or due inflows and associated with undue inflows use equations (3.4) and (3.5). The volumes are calculated using the simplified procedure based on per capita water consumption and population served described in section 3.2.2. Equation (3.11) is applied to calculate the energy associated with exceedance volumes (in this case, energy associated with exceedance flows not connected to an energy consuming component is null).

For the external energy associated components, the same procedure is used to obtain the volumes. The total external energy and the remaining components – elevation associated energy and dissipated energy – are calculated by equations (3.12), (3.14) and (3.15), respectively. The pump efficiency is assumed 30% since no auditing data are available. The period of analysis is one year.

3.4 Results and discussion

3.4.1 Macro-level energy balance

The external energy is calculated for 281 Portuguese wastewater utilities reporting to the Portuguese regulator (ERSAR, 2018) in the reference period of 2015-2018. Results are presented for the two types of utilities: 12 utilities of type A (Figure 3.3a) and 269 utilities of type B (Figure 3.3b). These results show that the wastewater bulk transport and treatment systems (type A) consume significantly more energy than collection and transport systems (type B), given the higher transported flows and a higher number of pumping stations and WWTP compared to type B utilities. Additionally, results for the type A utilities show a decreasing trend in the mean values of external energy and in dispersion over the 4-year period analysed (Figure 3.3a). These results show the impact of the increasing awareness and efforts done by utilities to improve their energy efficiency. Similar trend is not observed for type B utilities, typically managing older and more complex systems, and more vulnerable to undue inflows.

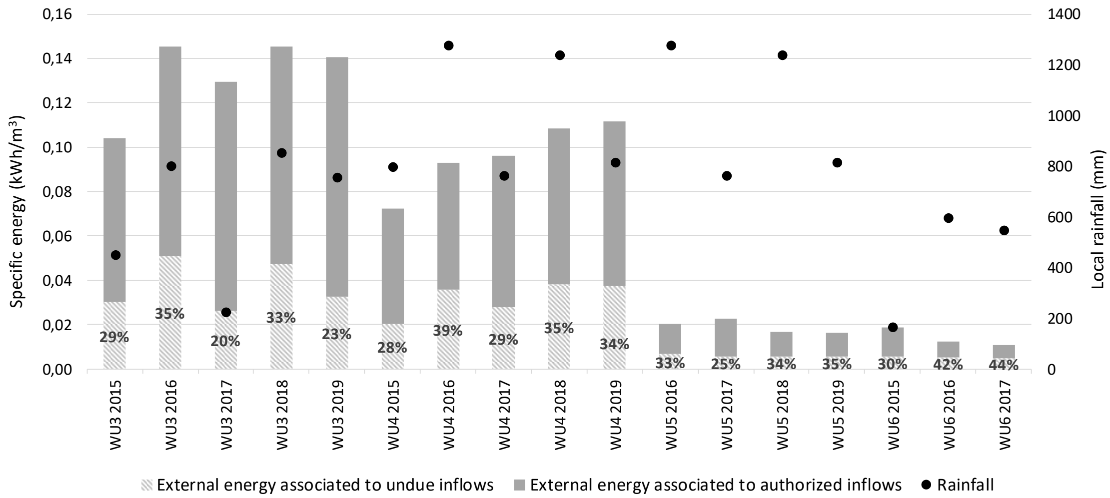


(a) (b)

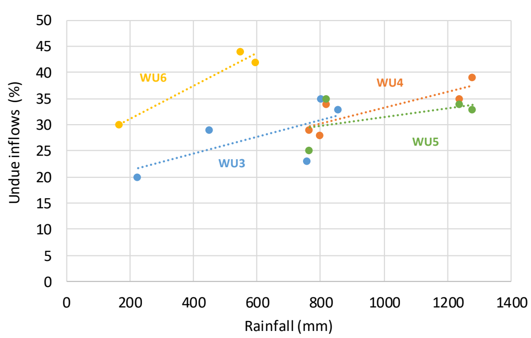
Figure 3.3. Distribution of the external energy for all Portuguese wastewater utilities: (a) Type A utilities; (b) Type B utilities.

The macro-level energy balance has been applied for four wastewater utilities (WU3, WU4, WU5 and WU6) that also provided rainfall data for the reference period of 2015-2019. The results for external energy associated with authorized inflows, external energy associated with undue inflows and local annual rainfall for each utility and year are shown in Figure 3.4a). The energy components significantly vary with the utility and with time; rainfall varies between 500 and 1200 mm depending on the local conditions. On average, the utilities have a percentage of energy associated with undue inflows between 20% to 44%.

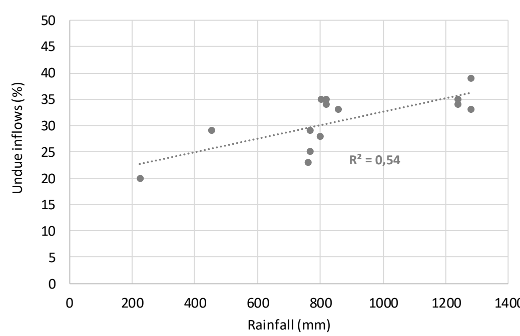
The variation of the percentage of undue inflows with the rainfall for each system is presented in Figure 3.4b). The percentage of undue inflows has an increasing trend with the local annual rainfall. This trend strongly depends on the quality of the data, on the integrity of the infrastructure and on the transport system capacity. The rainfall data of utility 6 (WU6) has a high uncertainty associated, which justifies a higher trend; thus, these data are excluded from the global estimated trend presented in Figure 3.4c).



(a)



(b)



(c)

Figure 3.4 – Energy balance application at a macro-level: (a) estimation of the external energy main components; (b) variation of undue inflows with local annual rainfall for each system; and (c) global variation of undue inflows with local annual rainfall.

The confidence in the results depends on the uncertainty associated with the rainfall data, on the unquantified exceedance volumes and on the energy measurements that can introduce several errors in the analyses. In addition, the component associated with undue inflows is often underestimated, since available measurements are normally carried out downstream of locations where exceedance occurs, and these flows are not accounted often at WWTP inlets.

Specific energy associated with undue inflows suggests a large energy saving potential by improving and investing on the control of undue inflows, particularly in systems located upstream of pumping stations and WWTP. Energy savings potential from reducing undue inflows will be fully effective only when exceedance volumes are eliminated. Reducing undue inflows is a long-term initiative, and benefits can be obtained in less severe events not resulting in exceedance volumes. If conditions allow installation of an energy recovery system, the extra energy obtained from undue inflows can also bring added value to recover the investment in the required equipment and in control actions to reduce undue inflows.

3.4.2 Meso-level energy balance

The meso-level assessment was applied to 15 pumping systems of five utilities for the period of 2015-2019. Table 3.5 presents the results for two pumping systems (PS1 and PS2) of WU1, in terms of the elevation energy and the dissipated energy, as a percentage of the total external energy per unit volume (kWh/m^3). The global pumping systems efficiencies and the manometric heads are also presented. Results for the other four utilities are presented in Appendix A1 (Table A1.1 – Table A1.4), as well as an overview of the global efficiencies for all WU (Figure A.1.1).

Results show that PS1 has a significantly higher global efficiency (51%) than PS2 (32%) and a smaller efficiency variation (48%-54%) with time than PS2 (16%-93%). PS2 results reflects major uncertainties in the flow and in the energy consumption measurements, not observed in PS1.

Table 3.5 – Energy balance: meso-level application for the wastewater utility WU1.

WU /PS	**Energy component**	**2015**	**2016**	**2017**	**2018**	**2019**	**Avg.**
WU1 /PS1	Elevation energy, E_{EE} (%)	46	47	51	51	50	**49**
	Dissipated energy pump inefficiency (%), E_{EDE}	51	51	46	46	47	**48**
	Dissipated energy friction losses (%), E_{EDL}	2	2	3	3	3	**3**
	External energy (kWh/m^3), E_E	0.118	0.115	0.107	0.106	0.109	**0.111**
	Manometric head (m)	21					
	Global efficiency (%)	48	50	53	54	52	**51**
WU1 /PS2	Elevation energy, E_{EE} (%)	16	15	88	14	19	**30**
	Dissipated energy pump inefficiency (%), E_{EDE}	83	83	7	86	80	**68**
	Dissipated energy friction losses (%), E_{EDL}	1	1	5	1	1	**2**
	External energy (kWh/m^3), E_E	0.386	0.402	0.070	0.443	0.326	**0.325**
	Manometric head (m)	24					
	Global efficiency (%)	17	16	93	15	20	**32**

The global efficiency of wastewater pumping systems for the analysed systems is quite low (34% on average, with percentile 25 and 75 varying from 21%-42%, respectively) with a slight trend to increase over the analysed period (Figure A.1.1). Results for global efficiency in the wastewater systems analysed are considerably lower than those typically found in water supply systems (Covas *et al.*, 2016b; Mamade *et al.*, 2017; 2018), mainly due to the type of groups used, to the higher degradation of the pump rotors due to aggressive characteristic of the wastewater and to the solids transported in the flow (Berger *et al.*, 2013; Covas *et al.*, 2016a).

Experience shows that utilities should invest in regularly auditing the pumping systems and replacing pump groups or components, when efficiencies are significantly lower than those provided by pump manufacturers. These measures allow reducing the energy consumption by improving pumping stations efficiency, though focusing only on the equipment. Other infrastructural interventions corresponding to rehabilitation works can be applied (e.g., replacing of pipe material to reduce continuous head losses), usually addressing more than one problem in the system. For example, the replacement of a pipe in poor condition improves infrastructure structural integrity while potentially reducing undue inflows and increasing sustainability.

Measures related with O&M practices can also be applied (e.g., improved solids removal operations). The layout of the systems should also be considered to find ways to optimize gravity flows and to deactivate pumping stations. Acting on the control of undue inflows can be very effective in reducing the external electrical energy. These measures can also contribute to reducing the dissipated energy, the energy associated costs and GHG emissions.

3.4.3 Micro-level energy balance

The micro-level assessment allows the identification of the main energy inefficiencies in the wastewater systems. Ideally, this assessment is undertaken using a calibrated and reliable network hydraulic model, in which the wastewater inflows are included together with rain induced and infiltration inflows (i.e., undue inflows). These models are a very useful tool for complex systems with several pumping stations.

Table 3.6 summarizes the results for the case study. The total inflow intrinsic energy is 64% of the total energy since the system is mainly composed of gravity sewers with only one pumping station. The energy associated with undue inflows is 49.7%. These components strongly depend on the length of gravity sewer and on the number of pumping systems. In this case, where transport is mainly by gravity, with one pumping station and 2.6 km of sewers, the total inflow intrinsic energy per unit length is 25 796 kWh/km. The available downstream energy does not indicate potential for energy recovery. This application successfully illustrates the proposed methodology for calculating all energy balance components.

Table 3.6 – Results for the micro-level of the energy balance for the current case study (in kWh and in % of the total energy used for system processes).

<table>
<tr><th></th><th colspan="2">ENERGY INFLOWS</th><th colspan="3">ENERGY OUTFLOWS</th></tr>
<tr><td rowspan="9">Total energy used for system processes (transport and treatment), E_T = 104 837 kWh (100%)</td><td rowspan="6">Total inflow intrinsic energy, E_I = 67 070 kWh (64%)</td><td rowspan="3">Inflow intrinsic energy associated with authorized or due inflows, E_{IAI} = 33 769 kWh (32.2%)</td><td rowspan="6">Total inflow intrinsic energy, E_I = 67 070 kWh (64%)</td><td colspan="2">System downstream energy, E_{IDE} = 5 218 kWh (5%)</td></tr>
<tr><td colspan="2">Recovered energy (micro hydropower), E_{IRE} = 0 kWh (0%)</td></tr>
<tr><td rowspan="2">Dissipated energy, E_{ID} = 48 713 kWh (46.4%)</td><td>…due to inefficiencies in energy recovery equipment (e.g., turbines), E_{IDT} = 0 kWh (0%)</td></tr>
<tr><td rowspan="3">Inflow intrinsic energy associated with undue inflows, E_{IUI} = 33 301 kWh (31.8%)</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{IDL} = 48 713 kWh (46.4%)</td></tr>
<tr><td rowspan="2">Energy associated with exceedance volumes, E_{IEV} = 13 139 kWh (12.6%)</td><td>…not connected to an energy consuming component, E'_{IEV} = 0 kWh (0%)</td></tr>
<tr><td>…potentially inflowing to an energy consuming component, E''_{IEV} = 13 139 kWh (12.6%)</td></tr>
<tr><td rowspan="3">External energy (electrical), E_E = 37 767 kWh (36%)</td><td rowspan="2">External energy associated with authorized or due inflows, E_{EAI} = 19 015 kWh (18.1%)</td><td rowspan="3">External energy, E_E = 37 767 kWh (36%)</td><td colspan="2">Elevation associated energy, E_{EE} = 11 104 kWh (10.6%)</td></tr>
<tr><td rowspan="2">Dissipated energy, E_{ED} = 26 664 kWh (25.4%)</td><td>…due to inefficiencies (in electromechanical equipment, e.g., pumps), E_{EDE} = 26 437 kWh (25.2%)</td></tr>
<tr><td>External energy associated with undue inflows, E_{EUI} = 18 752 kWh (17.9%)</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{EDL} = 227 kWh (0.2%)</td></tr>
</table>

3.5 Conclusions

This paper proposes and demonstrates the application of a novel energy balance scheme tailored for wastewater systems. This energy balance can be applied at three different assessment levels depending on available data and analysis objectives. These levels are intended to facilitate and promote the application of the proposed approach by utilities with different maturity levels and types of available data. To the authors knowledge, most utilities do not have specific data regarding energy use. It is also relevant to emphasize the low number of wastewater utilities using modelling even today. These three levels are relevant to utilities with scarce data to have a way forward to tackle this issue. This is also a contribution to support the sector action towards energy efficiency and CO_2 emissions reduction.

The energy balance allows wastewater utilities to identify the main energy inefficiencies of the system, allowing supporting the calculation of performance metrics and the comparison of the effects of the implementation of several energy efficiency measures.

This energy balance was successfully applied to different case studies, illustrating the potential use for responding to current challenges of wastewater utilities, even when data are scarce. Macro and meso-level assessment results allows concluding that: the energy associated with undue inflows can be quite significant, representing from 20% to 44% of the total energy consumption in analysed wastewater utilities; and the pumping systems efficiency are generally lower (34% on average, with percentiles 25 and 75 corresponding to 21% and 42%, respectively) than those in the water supply sector. Dissipated energy associated with undue inflows and pumping stations can be quite significant and improvement measures should focus both on the control of undue inflows and on the replacement and maintenance of existing pumps. Micro-level assessment application successfully illustrates the potential of the proposed methodology for calculating all energy balance components.

The current research is a step-forward contributing to increase energy efficiency in wastewater systems by providing a framework to support further developments. Additional performance assessment metrics can be developed to assess water-energy efficiency in wastewater systems (e.g., energy peak factor, percentage of pumps with acceptable efficiency), complementing the results of the energy balance, and further supporting the diagnosis of energy efficiency in wastewater utilities. Software development can facilitate automatic integration of results from the hydraulic model simulations in the energy balance calculation.

Chapter 4 – Micro-level application of the energy balance with energy recovery

This chapter corresponds to the research paper:

C. Jorge, M.C. Almeida, and D. Covas (2021), *Energy Balance in Wastewater Systems with Energy Recovery: A Portuguese Case Study*. Infrastructures, 6(10), 141. https://doi.org/10.3390/infrastructures6100141.

Author contribution: The author co-developed the conceptual idea and the methodology and carried out the data analysis and investigation.

Abstract

This paper presents and discusses the application of a novel energy balance scheme for assessing energy efficiency in wastewater systems. The energy balance is demonstrated with a Portuguese real-life case study, using mathematical modelling to estimate the different energy components and to compute two energy efficiency indices. The total inflow intrinsic energy can represent a significant amount (>95%) of the total energy used in systems mainly composed of gravity sewers. The total input energy is significantly (four-times) higher in the wet season than in the dry season, mostly due to undue inflows (e.g., direct rainfall and infiltration). The potential for energy recovery strongly depends on the available head and flow rate at the delivery point, being 0.01 kWh/m^3 in the current case, with a project payback period of 4 years. The energy balance components and the respective energy efficiency indices strongly depend on the considered reference elevation. Thus, a unique regional reference elevation is recommended in the calculations.

Keywords: energy balance, energy efficiency, energy recovery, hydraulic modelling, wastewater systems.

4.1 Introduction

Energy efficiency in the water industry is often regarded as an operational issue focused mostly on pumping and treatment equipment or processes improvement, simply regarded as a management efficiency target to be achieved (Lingireddy and Wood, 1998). However, due to the worldwide energy crisis and to the need of reducing greenhouse gas (GHG) emissions, there is an increasing motivation to minimize the energy requirements in sustainable water use (USDE, 2006). Climate change is challenging the water sector to optimize energy use and limit GHG emissions in the current daily operations. The number of examples of energy efficiency improvement measures in water production and treatment is rapidly growing (Frijins *et al.,* 2013; Wilson *et al.,* 2021).

Aware of the need to reduce energy consumption and the associated costs, water utilities are currently looking for innovative ways to improve energy efficiency in their services by improving equipment efficiency, optimizing pump scheduling, and changing the system layout (Mamade *et al.,* 2017), as well as recovering the excessive energy whenever feasible (Williams *et al.,* 1998; Fecarotta and McNabola, 2017). However, a significant potential for water-energy saving can be found when analysing the complete system, since energy is dissipated not only in pumping stations but also in the system layout, pipes, and water losses, among others. There remains a need to adapt and explore alternative approaches, mainly to wastewater and stormwater systems, to assess the inefficiencies associated with the sewer inflow and network layout.

The energy balance should account for all inputs and/or generation of energy supply versus energy outputs based on energy consumption by energy use (ISO 50002:2014(E)). The energy balance compares the total energy that enters the system boundaries with the total energy that leaves the boundaries. Many authors have suggested the development of energy balances in the urban water cycle (Duarte *et al.,* 2008; Cabrera *et al.,* 2010; Mamade *et al.,* 2017; 2018), but for wastewater systems, this concept has hardly been developed and explored.

Carrying out energy balances in the entire water system allows the understanding of which components are energy-intensive and, therefore, allows the identification of measures to increase the energy efficiency. Energy balances assessment also supports the tactical and operational levels of management. At the tactical level, these provide a diagnosis of the system, enable the comparison between systems and help to prioritize interventions in subsystems. At the operational level, critical subsystems can have their service improved by specific actions, such as changes in pumping operation according to demand profiles (e.g., daily pumping schedules, adoption of speed controllers). Therefore, mapping energy consumption through an energy balance scheme for the water systems is useful to identify critical components requiring action and to plan interventions to improve the energy efficiency (Mamade, 2019).

Water supply systems, which are mostly pressurized pipes, have a significant potential for energy recovery (Monteiro *et al.,* 2018) through the installation of turbines and pumps operating as turbines in locations with excessive pressures (e.g., near pressure or flow control valves, at the inlet of storage tanks) (Jain and Patel, 2014; Delgado *et al.,* 2019). Given the nature of wastewater systems, the inlet, or the outlet of wastewater treatment plants (WWTP) are preferentially used as potential sites to install an energy recovery solution to generate electricity in the wastewater system fields and thermal energy applications (Nowak *et al.,* 2015).

The assessment of the energy recovery potential for water supply systems requires the identification of the locations where energy is dissipated, the estimation of available hydraulic power and the development of technical and economic feasibility studies (McNabola *et al.,* 2014; Gallagher *et al.,* 2015; Su and Karney, 2015; Oliveira *et al.,* 2021). However, in wastewater systems, the use of energy recovery devices (herein, referred to as turbines) is more difficult not only due to the nature of the fluid, which contains solid materials and has corrosive properties, but also due to the existence of typical low heads with high flow rates. Whenever the installation of a turbine is already planned during the infrastructure construction, this will significantly reduce the capital costs and optimize the hydraulic design of the system (Berger *et al.*, 2013).

The development of energy recovery feasibility studies involves key steps: the identification of potential locations; the identification of the most suitable turbine and the prediction of its performance, given specific head and flow values; the simulation of the energy recovery during a period of time; and a cost-benefit analysis (Oliveira *et al.,* 2021). The Archimedes screw was originally developed to pump water from a low to a high-level section. This equipment is composed of a helical array of simple blades wound on a central cylinder. Recently, this equipment has been used in the reverse mode (inverted Archimedes screw) serving as a turbine – the Archimedes screw turbine – to generate energy for low heads and high flow rates (Pereira, 2018; Oliveira *et al.,* 2021).

A novel energy balance tailored for wastewater systems was proposed by Jorge *et al.* (2022). This balance has a different structure and several new components compared to water supply systems (Mamade *et al.,* 2017) and irrigation systems (Fernandes, 2020) and allows the identification of the main system inefficiencies and the potential for energy recovery. This energy balance aims to understand the energy transformation processes occurring in the integrated wastewater system, highlighting the most energy-consuming subsystems. This approach can be applied in three assessment levels (macro-, meso- and micro-level) depending on available information of the wastewater system in terms of the physical characteristics and flow rates.

The current paper aims to apply and discuss the energy balance developed for wastewater systems at the micro-level, using mathematical simulations to describe the flow throughout the system. A real Portuguese case study, composed of several systems, is used. The main innovative features are the detailed application of the micro-level energy balance to a wastewater system, supported by a hydraulic model to calculate the different energy balance components, the discussion of the main energy consumption components and the specific energy indices, and the analysis of the potential for energy recovery at the downstream manhole of the system.

4.2 Methodology

4.2.1 Energy balance for wastewater systems

The energy balance scheme specific for wastewater systems proposed by Jorge *et al.* (2022) was applied herein. Mathematical modelling was used to calculate the different components of the balance, allowing a micro-level energy efficiency assessment. This energy balance allows the identification of the main energy inefficiencies of the wastewater system and the analysis of different measures to reduce water-energy consumption and to recover energy. The proposed balance only focuses on the transport component of wastewater systems, including raising and gravity sewers. WWTP were not included herein, although the methodology can be extended to incorporate other components, such as treatment and heat recovery processes.

The referred energy balance is depicted in Table 4.1 for typical wastewater systems. Figure 4.1 shows the schematic representation of the different inputs and outputs of energy components associated with the energy balance calculation.

Table 4.1 – Energy balance scheme for wastewater systems (Jorge *et al.*, 2022).

<table>
<tr><th></th><th colspan="2">ENERGY INFLOWS</th><th colspan="3">ENERGY OUTFLOWS</th></tr>
<tr><td rowspan="9">Total energy used for system processes (transport and treatment), E_T</td><td rowspan="6">Total inflow intrinsic energy (associated with gravity flow), E_I</td><td rowspan="3">Inflow intrinsic energy associated with authorized or due inflows, E_{IAI}</td><td rowspan="6">Total inflow intrinsic energy, E_I</td><td colspan="2">System downstream energy, E_{IDE}</td></tr>
<tr><td colspan="2">Recovered energy (e.g., micro-hydropower), E_{IRE}</td></tr>
<tr><td rowspan="2">Dissipated energy, E_{ID}</td><td>…due to inefficiencies in energy recovery equipment (e.g., turbines), E_{IDT}</td></tr>
<tr><td rowspan="3">Inflow intrinsic energy associated with undue inflows, E_{IUI}</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{IDL}</td></tr>
<tr><td rowspan="2">Energy associated with exceedance volumes, E_{IEV}</td><td>…not connected to an energy-consuming component, E'_{IEV}</td></tr>
<tr><td>…potentially inflowing to an energy-consuming component, E''_{IEV}</td></tr>
<tr><td rowspan="3">External energy (electrical), E_E</td><td rowspan="2">External energy associated with authorized or due inflows, E_{EAI}</td><td rowspan="3">External energy, E_E</td><td colspan="2">Elevation associated energy, E_{EE}</td></tr>
<tr><td rowspan="2">Dissipated energy, E_{ED}</td><td>…due to inefficiencies in electromechanical equipment (e.g., pumps), E_{EDE}</td></tr>
<tr><td>External energy associated with undue inflows, E_{EUI}</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{EDL}</td></tr>
</table>

The light grey boxes refer to the macro-level components, the dark grey boxes refer to the meso-level additional components to those in macro-level and the micro-level corresponds to all energy balance components (white and grey boxes).

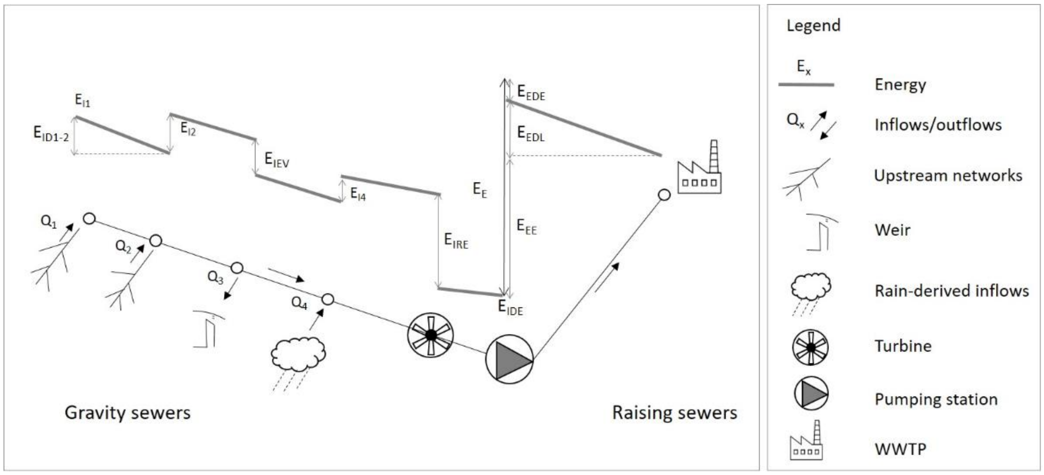


Figure 4.1 – Schematic representation of the energy components in wastewater systems.

The energy balance can be applied at three assessment levels (macro, meso, and micro-level) depending on the available data (network inventory data, flow measurements or energy measurements) and the time horizon (day, month, year). Thus, the energy balance can be calculated by utilities with different maturity levels, systems, layouts, and operation modes.

First, a macro-level assessment provides a global overview of the major components of energy consumption in the system. The external energy and the energy associated with undue inflows and authorized inflows can be estimated annually. This assessment is significant, as it allows for a preliminary evaluation of energy consumption in the system. The macro assessment can also be used when wastewater utilities do not have hydraulic models or have limited data.

Second, a meso-level assessment is an intermediate level that requires additional data and can also be applied by utilities that do not have hydraulic models. The calculations consist of the elevation-associated energy and the dissipated energy components in a disaggregated way, including the pump inefficiencies, friction losses and local head losses. If results from energy audits are available, then the computation of the dissipated energy associated with the pumping equipment will be more accurate. When these results are not available, the estimation of the pumping station efficiency can be carried out in a simplified way.

Finally, the third proposed assessment is the micro-level assessment, which requires a calibrated hydraulic model of the network and provides a detailed assessment of the energy consumption in every component of the energy balance, typically applied at the subsystem level. The adopted level of simplification in the mathematical model depends on several factors, mainly the modelling purpose and scope, the required and available data, and the loading conditions of the system. The simplifications of the data, network and structures of the drainage system must guarantee a reasonable description of the real operational conditions. Data requirements of a mathematical model are significant and should be complemented with fieldwork to define and characterize the magnitude and relevant characteristics of the system (Almeida and Cardoso, 2010). There is a wide variety of software suitable for the mathematical modelling of stormwater drainage systems, such as SWMM, Mike Urban, Mike Flood, Info Sewer and Sewer Cad, among others. Any of these can be used for computing the energy balance components. This approach can only be applied by wastewater utilities with a high maturity level since they need to have hydraulic models already implemented and calibrated. Otherwise, simplified approaches should be preferentially used (Jorge *et al*., 2022).

The results obtained by the micro-level assessment allow the identification of the main inefficiencies of the system and the establishment of improvement measures at the tactical level of planning. The current paper focuses on the micro-level. A detailed description of this assessment is provided in section 4.2.2. Macro- and meso-level assessments, as well as their application results, have been further described by the authors of (Jorge *et al*., 2022).

4.2.2 Micro-level assessment description and formulation

The total energy used in the system for transport and treatment is the sum of the total inflow intrinsic energy and external energy. Total inflow intrinsic energy refers to the energy associated with the free surface flow, which is composed of kinetic and potential energy. External energy refers to the energy supplied by the pumping stations. Both energy components are divided into two parts: the energy associated with authorized or due inflows and the energy associated with undue inflows.

From the perspective of the energy outflows, the total inflow intrinsic energy includes the system downstream energy, the recovered energy, the dissipated energy due to inefficiencies in the energy recovery equipment or pipe friction and local head losses and, finally, the energy associated with exceedance volumes (not connected to energy-consuming component or potentially inflowing to energy-consuming components). The external energy can also be divided into the elevation-associated energy (necessary energy to pump the wastewater volume between the water level in the pumping well and the elevation in the downstream delivery point) and the dissipated energy due to the inefficiencies in electromechanical equipment or due to pipe friction and local head losses. A more detailed description of the energy balance has been provided by Jorge *et al*. (2022). The required data and the formulas for calculating each component of the energy balance are presented in Table 4.2.

Regarding the remaining components of the energy balance presented in Table 4.1, the energy at the final section of the system, E_{IDE} (typically the connection to a WWTP or an interceptor sewer), was calculated by applying equation (4.3) at the final node of the system (kWh), and E_{EDL}, the energy dissipated by friction losses and local head losses, was calculated by applying equation (4.6) to each pumping station. In the micro-level application, the percentage of the energy associated with authorized or due flows, E_{IAI} and E_{EAI}, can be estimated by the hydraulic model considering the dry weather inflow. Similarly, the energy associated with undue inflows, E_{IUI} and E_{EUI}, can be estimated using a proportion of the runoff volume entering the system (wet weather inflow). Concerning the components of the energy associated with exceedance volumes (E'_{IEV} and E''_{IEV}), these can be estimated by considering the discharged and flooded volumes obtained by the model. Detailed procedures to calculate the latter components without the use of a hydraulic model have been described by Jorge *et al*. (2022).

As mentioned, the full application of the micro-level assessment requires a calibrated hydraulic model of the drainage system to allow the reliable simulation of the system behaviour and the calculation of the energy balance components.

Table 4.2 – Equations for calculating the energy balance components.

Hydraulic head	$H = \frac{p}{\gamma} + \frac{v^2}{2g} + z$	(4.1)
Total energy used for system processes	$E_T = E_I + E_E$	(4.2)
Total inflow intrinsic energy	$E_I = \gamma\left(\sum_{j=1}^{T}\sum_{i=1}^{N} Q_{i,j}H_{i,j}\Delta t_j\right).\alpha$	(4.3)
External energy	$E_E = \gamma\left(\sum_{j=1}^{T}\sum_{i=1}^{Np_s} \frac{Q_{p_{s\,i,j}}H_{p_{s\,i,j}}\Delta t_j}{\eta_{p_{s\,i,j}}}\right).\alpha$	(4.4)
Recovered energy	$E_{IRE} = \gamma\left(\sum_{j=1}^{T}\sum_{i=1}^{N_t} \eta_{t_{i,j}}Q_{t_{i,j}}H_{t_{i,j}}\Delta t_j\right).\alpha$	(4.5)
Dissipated energy due to pipe friction and local head losses	$E_{IDL} = \gamma\left(\sum_{j=1}^{T}\sum_{i=1}^{N_p} Q_{i,j}\Delta H_{i,j}\Delta t_j\right).\alpha$	(4.6)
Dissipated energy due to inefficiencies in energy recovery equipment	$E_{IDT} = \gamma\left(\sum_{j=1}^{T}\sum_{i=1}^{N_t}\left(1-\eta_{t_{i,j}}\right)P_{h_{i,j}}\Delta t_j\right).\alpha$	(4.7)
Total dissipated energy associated with inflow intrinsic energy	$E_{ID} = E_{IDL} + E_{IDT}$	(4.8)
Elevation associated energy	$E_{EE} = \gamma\left(\sum_{j=1}^{T}\sum_{i=1}^{Np_s} Q_{p_{s\,i,j}}\Delta z\Delta t_j\right).\alpha$	(4.9)
Dissipated energy due to inefficiencies in electromechanical equipment	$E_{EDE} = \gamma\left[\sum_{j=1}^{T}\sum_{i=1}^{Np_s}\left(1-\frac{1}{\eta_{p_s}}\right)Q_{p_{s\,i,j}}H_{p_{s\,i,j}}\Delta t_j\right].\alpha$	(4.10)
Total dissipated energy associated with external energy	$E_{ED} = E_{EDE} + E_{EDL}$	(4.11)

The parameters presented in the formulas are H = hydraulic head (m); p = the pressure (Pa); γ = the water specific weight (9800 N/m^3); v = mean flow velocity (m/s); g = gravity acceleration (m/s^2); z = the node elevation (m) (z corresponds to the elevation of the level of water with respect to the zero elevation, z_0. The zero elevation, z_0, can typically be assumed as the minimum elevation of the system or the elevation of the delivery point (Mamade *et al.*, 2018; Mamade, 2019). However, a discussion regarding the selection of this reference is presented in section 4.4.2); E_T = total energy used for systems processes; E_I = total inflow intrinsic energy (kWh); E_E = external energy (kWh); $Q_{i,j}$ = flow inflowing to node i and time j (m^3/s); $H_{i,j}$ = hydraulic head of the inflow to the node i and time j (m); Δt_j = time interval j (s); α = unit conversion factor from W.s to kWh, $\alpha = 1/(1000 \times 3600) = 2.78 \times 10^{-7}$; N = number of nodes with inflow; T = number of time intervals; $Q_{p_{s\,i,j}}$ = pumped flow of the pumping station i at time j (m^3/s); $H_{p_{s\,i,j}}$ = manometric head of the pumping station i at time j (m), assuming equal pumps installed in parallel; $\eta_{p_{s\,i,j}}$ = global efficiency of the pumping station i at time j (-); N_{p_s} = number of pumping stations. E_{IRE} = recovered energy (kWh); $\eta_{t_{i,j}}$ = global efficiency of turbine i at time j (-); $Q_{t_{i,j}}$ = flow of the turbine i at time j (m^3/s); $H_{t_{i,j}}$ = net head of the turbine i and time j (m); N_t = number of energy recovery devices; E_{IDL} = energy dissipated in pipe friction and local head losses (kWh); $\Delta H_{i,j}$ = total head loss in pipe i at time j (m); N_p = number of pipes; E_{IDT} = dissipated energy in turbines (kWh); $P_{h_{i,j}}$ is the hydraulic power of the turbine i at time j (kWh); E_{ID} = total dissipated energy (kWh); E_{EE} = elevation associated energy (kWh); Δz = geometric-head difference, between the pumping well and the delivery point (m); E_{EDE} = dissipated energy associated with pumps inefficiency (kWh); E_{ED} = total dissipated energy (kWh).

4.2.3 Energy recovery and economic viability

The application of the micro-level assessment allows the estimation of the potential of energy recovery. For this purpose, the available hydraulic power can be estimated by equation (4.12), and the potential energy recovery by equation (4.13):

$$P_h = \gamma Q H \tag{4.12}$$

$$E = \eta P_h \Delta t \tag{4.13}$$

in which P_h is the available hydraulic power (W), E is the potential energy recovery (kWh) and Δt is the operating time (h) in the period of analysis.

The energy recovery can be carried out by installing turbines adequate for low heads and high flow rates (e.g., water wheels, Archimedes screws). Despite the highly corrosive properties of wastewater and transported solid material, there have been several successful applications in wastewater systems (Berger *et al.*, 2013; Pereira, 2018).

The economic analysis of these projects should be based on the calculation of the annual recovered energy for a defined design flow rate, and the respective costs and benefits during the project lifetime. The capital costs (CC), operation and maintenance (O&M), costs and gross and net revenues are calculated. Several economic indicators can be used to evaluate the feasibility of these projects, such as the net present value (NPV), the payback period (PBP) and the internal rate of return (IRR) (Oliveira *et al*., 2021).

The additional input data to calculate these indicators are the discount rate, t_a; the project lifetime, n (years); the energy cost unit, C_u (€/kWh); and the annual O&M costs, defined as a percentage of the CC. The CC includes the equipment control, management, civil works and turbine generator setup. The CC includes the revenues throughout the analysis, and the referred economic indicators are calculated for each design flow rate and each technological solution (Oliveira *et al*., 2021). An acceptable and feasible solution should fit the highest NPV, with an acceptable IRR (>10%) and an adequate payback period ideally lower than 10 years (Castro, 2018).

4.3 Case study

The application of the micro assessment requires that wastewater utilities have a hydraulic model of the network that is implemented and adequately calibrated. For the current study, a Portuguese wastewater utility provided a calibrated and reliable hydraulic model of a separate drainage subsystem. This subsystem, located in the Lisbon area, is part of a larger system that intercepts urban wastewater collected by the municipal drainage networks. Currently, the entire system serves a population of 800 000 equivalent inhabitants.

The network scheme of the selected subsystem is presented in Figure 4.2. It includes part of the general gravity flow interceptor and two emissaries. The first emissary is gravitationally connected to the general interceptor, and the second emissary has a gravitational part and a pumped part, since it does not have the possibility of a total gravitational connection to the general interceptor. The subsystem has a total network length of 15 km and is composed of 432 conduits, with diameters varying between 200 mm and 2200 mm, elevations between 2 m and 133 m, with one pumping station with a manometric head of 13 m, 92 sub-catchments and two weirs. The hydraulic model of the analysed subsystem is calibrated with the flow rate data for dry and wet weather collected in five udometers.

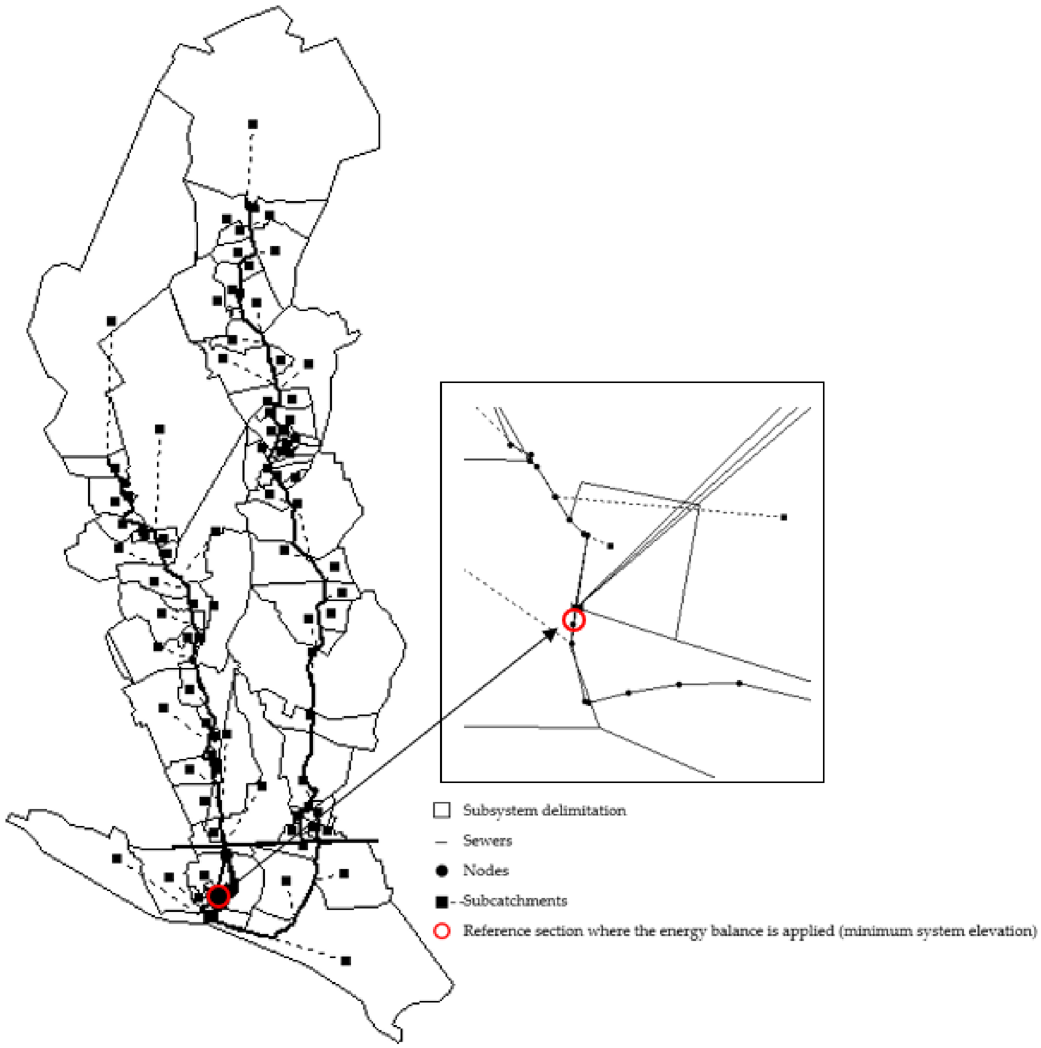


Figure 4.2 – Network scheme of the selected subsystem.

The hydraulic model was built using the commercial software SWMM developed by the U.S. Environmental Protection Agency. Simulations were carried out for two days in the reference period of 2015: one day of June, representing the dry season (reference situation), and one day of January, representing the wet season. The selection of these days was proceeded by an analysis of records for the season, and it was found that these two days are representative of the corresponding average situations. Therefore, the results for the January day were considered representing a maximum energy consumption profile, and the results for the June day were considered to represent a minimum energy consumption profile. Whenever data are available, a complete year should be simulated. Otherwise, simplifications must be assumed. In the current case, the simplification considers the results of the simulations for each day (June or January) as representative of the two seasons of the year (i.e., dry and wet seasons).

4.4 Results and discussion

4.4.1 Energy balance for wastewater systems

The micro-level assessment allows the identification of the main energy inefficiencies in wastewater systems. The most important assumptions for this assessment are: (i) the percentage of the energy associated with authorized or due inflows can be estimated by the hydraulic model considering the dry weather inflow; (ii) the percentage of undue inflows can be estimated using a proportion of the runoff volume entering the system (a percentage of 75% was considered for the present case, based on results of a previous sensitive analysis procedure) (Jorge *et al.,* 2021a); and (iii) the pump efficiency was assumed to be 30% in both cases, since no auditing data were available, and old wastewater pumps usually have very low efficiencies.

The total inflow intrinsic energy is given by equation (4.3). The reference elevation, z_0, corresponds to the lowest elevation point (2.03 m). At the inflowing nodes of the system, the hydraulic head is given by the summation of the potential head and the kinetic head.

The dissipated energy in free surface systems without energy recovery equipment is equal to the difference between the total inflow intrinsic energy and the system downstream energy. The latter was calculated by equation (4.3), considering that the hydraulic head is given only by the kinetic head, since the potential head at the delivery point is 0 m (no drop at the manhole). In the current case, the recovered energy (equation (4.5) and the respective dissipated energy (equation (4.7) are null. Concerning the components of the energy associated with exceedance volumes (E'_{IEV} and E''_{IEV}), it can be estimated considering the discharged and flooded volumes obtained by the hydraulic model.

The results obtained for the energy balance application at a micro-level to the selected case study considering the reference situation (June, dry season) are presented in Appendix A2 (Table A2.1). The results for this typical summer day correspond to a minimum energy consumption profile for the current case study. This case is associated with purely dry weather conditions, so it is assumed that the percentage associated with undue inflows is 0%. The total wastewater collected volume at dry weather is 3 614 230 m^3/year. The total pumped volume is 816 505 m^3/year, and the total external energy consumption is 98 688 kWh/year. Concerning the exceedance volumes, at dry weather conditions, no overflows occur in the system.

The results obtained for the micro-level of the energy balance for a typical day in January (wet season) are presented in the Appendix A2 (Table A2.2). Similar to the previous results, the values for this season correspond to a maximum energy consumption profile for the present case study. For this case, the percentage of undue inflows is 42.6%. The total wastewater collected volume at dry weather is 6 090 268 m^3/year, and the total volume at wet weather is 27 020 098 m^3/year. The total pumped volume is 2 701 973 m^3/year, and the total external energy consumption is 326 578 kWh/year. The exceedance volumes were estimated from the discharged and flooded volumes obtained from the hydraulic model, with a total of 19 931 068 m^3/year.

Figure 4.3 shows the comparison of the energy balance components for both seasons. Components that are zero in both cases (recovered energy and dissipated energy associated with energy recovery equipment) are not depicted.

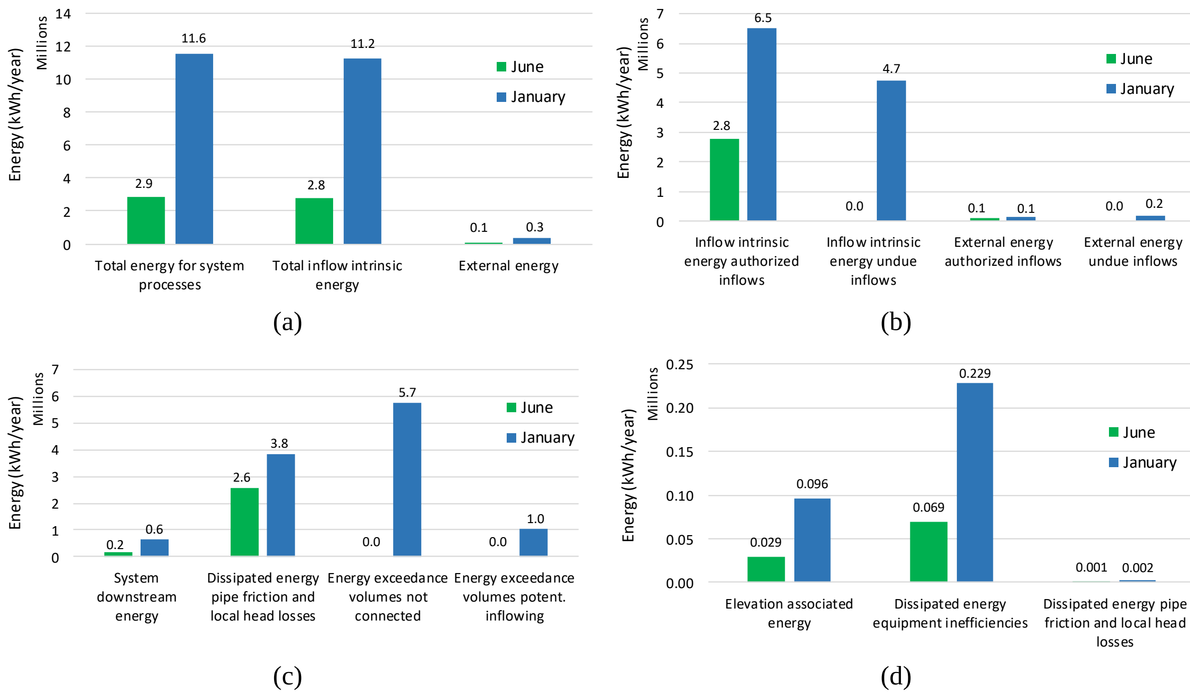


Figure 4.3 – Comparison between the energy balance components for both seasons (June and January): (a) Energy inflows: total energy for system processes, total inflow intrinsic energy and external energy; (b) energy inflows: inflow intrinsic energy and external energy associated with authorized inflows and to undue inflows; (c) energy outflows: system downstream energy, dissipated energy due to pipe friction, and local head losses and exceedance volumes not connected to an energy consuming component and potentially inflowing to an energy-consuming component; (d) energy outflows: elevation associated energy and dissipated energy.

A substantial increase (four-times higher) in the total energy for system processes was observed in the wet season, which is mostly associated with the undue inflows, mainly direct rainfall, and infiltration (Figure 4.3a). The external energy is also higher in the wet season, though with a lower increase (three-times higher), because of the higher occurrence of discharges and floods in this season Figure 4.3a,d).

The component related to the energy associated with exceedance volumes not connected to energy-consuming components only exists in wet season and is derived from undue inflows (Figure 4.3c). This component represents the theoretical energy that would be additionally consumed if the total volume that left the system (because of discharges or floods) was also pumped. Calculating this component is important to show to wastewater utilities the importance of acting in the control of undue inflows to reduce energy consumption. This action, in most cases, will only achieve the expected results when the discharged or flooded volumes are eliminated, and only later will the impact be reflected in the reduction of energy consumption. It also highlights the importance of measuring discharges because of their environmental effect and their impact on energy consumption.

In both cases, the total inflow intrinsic energy has high values (>95% of the total energy) since the system is mainly composed of gravity sewers with only one pumping station (Figure 4.3b). The energy associated with undue inflows considering both seasons is, on average, 21.3%, which is within the estimated range (20–44%) of the macro-level analysis in previous studies (Jorge *et al.*, 2022). These components strongly depend on the length of the gravity sewer and the number of pumping systems. The current case has only one pumping station and 15 km of sewers, with the total inflow intrinsic energy per unit length being 183 946 kWh/km for the first case and 749 282 kWh/km for the second case. This network only represents a small subsystem inside the utility, highlighting that the results could differ depending on the system layout, characteristics, and condition.

The available energy at the downstream end is significantly low (<7%), as the manhole at the reference section has no drop (0 m), and this energy is only associated with the residual velocity component. Therefore, most of the energy associated with the gravity flow is dissipated. Finally, since there is no installed energy recovery equipment, no recovered energy was calculated.

4.4.2 Reference elevation analysis

Several energy balance studies in the urban water cycle have considered the minimum elevation of the system as the reference elevation, z_0 (Cabrera *et al.*, 2010; Souza *et al.*, 2011; Lenzi *et al.*, 2013; Carriço *et al.*, 2014; Feliciano *et al.*, 2014; Mamade *et al.*, 2018; Mamade, 2019). This reference elevation ensures that the energy balance components are always positive, making them easy to understand and compute. However, the reference elevation significantly affects the energy efficiency indices results based on the energy balance, which is important for the diagnosis of the system.

To assess the effect of the reference level on the results, the case study was divided into six smaller subsystems: four gravity sewers, one general interceptor and one elevation conduit. Three different situations were analysed: (i) the subsystems are connected and interdependent, and the reference elevation is the global system minimum elevation (2.03 m); (ii) the subsystems are dependent, but the reference elevation is the system downstream end section (15.00 m); and (iii) the subsystems are independent, and each one has as different reference elevation corresponding to its minimum elevation point. This sensitivity analysis was carried out for the wet season. Two energy efficiency indices, E_{AR_1} and, E_{AR_2}, were calculated. The first energy efficiency index is the energy supplied per unit volume of authorized or due inflows, defined by:

$$E_{AR_1} = \frac{E_S}{V_{AI}} \tag{4.14}$$

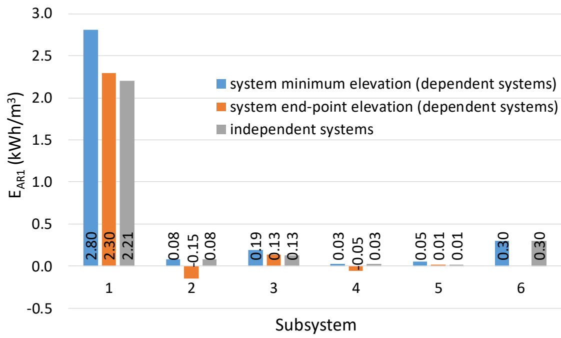
in which E_{AR_1} is the energy supplied per unit of authorised or due inflows (kWh/m^3), E_S is the energy supplied (either inflow intrinsic energy, E_I, or external energy, E_E) to the system (kWh) and V_{AI} is the volume of authorised or due inflows (m^3).

The second energy efficiency index E_{AR_2} represents the energy supplied over the minimum energy required by the system, defined as follows:

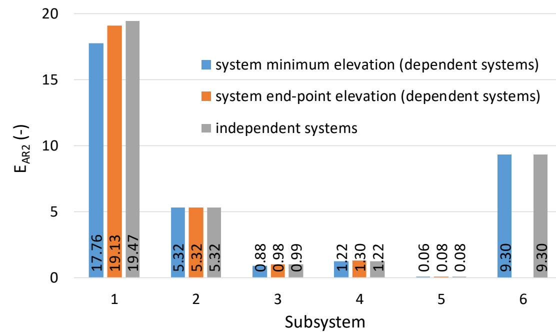
$$E_{AR_2} = \frac{E_{exc}}{E_{min}} \tag{4.15}$$

in which E_{exc} is the energy in excess in the system, typically associated with undue inflows (kWh), and E_{min} is the minimum energy required by the system, associated with the operation at dry weather (kWh).

Figure 4.4 shows the results of the energy indices E_{AR_1} and E_{AR_2} for the six subsystems calculated for the three different reference elevations. The selection of different reference elevation values leads to different results even though the differences do not change the ranking of the subsystems in terms of energy efficiency. System 1 is always the most energy-intensive, and subsystems 3, 4 and 5 are assessed as the less intensive for both indices. When subsystems are considered as a whole and the reference elevation is the downstream end (case ii), the values of E_{AR_1} for subsystems 2 and 4 assume negative values, since these systems are at elevations below the endpoint, while the other subsystems are above the reference elevation. The index E_{AR_2} is always positive because it is the ratio of two negative energy components for subsystems 2 and 4.



(a)



(b)

Figure 4.4 – Performance indices to analyse the system reference elevation: (a) E_{AR_1}, (b) E_{AR_2}.

Based on these results, the recommendation is to use a unique regional reference for elevation in the calculation of the energy balance. This reference elevation should be further analysed with different case studies. However, it should ensure that all values of energy components and the respective energy efficiency indices, E_{AR_1} and E_{AR_2}, are positive and easy to understand, facilitating the analysis of the results.

4.4.3 Energy recovery curves application and economic viability

Preferable locations for installing energy recovery devices are sites with significant elevation drops combined with high flow rates and available physical space. The locations with a higher potential for energy recovery should be identified and analysed. The average head, flow rate and available hydraulic power allow the selection of adequate types of energy recovery equipment (turbines). For instance, the inverted Archimedes screw represents a very cost-effective technological solution for energy recovery in water systems with low available heads and for a wide range of flow rates (Simmons *et al.*, 2021). The solution is adequate for liquids transporting solid material (YoosefDoost and Lubitz, 2020). In the current case study, the selected energy recovery solution is the inverted Archimedes screw turbine.

A preliminary assessment of the energy recovery potential was carried out for the two seasons (wet and dry). This assessment aims to illustrate different scenarios for energy recovery at the last point of the final interceptor, considering that the available head is 3 m at the manhole and that the flow rate is constant in each season (Figure 4.5a). Available average flow rates, available heads and the corresponding hydraulic powers calculated by equation (4.12) are depicted in Figure 4.5b and Table 4.3. Calculated powers correspond to available mechanical powers in the flow, not accounting for the turbine efficiency. The points are marked as “dry season” and “wet season,” referring to each season. Curves are presented on a logarithmic scale.

These results show that the highest potential for energy recovery is in the wet season, with an average available hydraulic power value of 121 kW. In dry season, the average hydraulic power is significantly lower (47 kW). The values show good recovery potential associated with low heads (3 m).

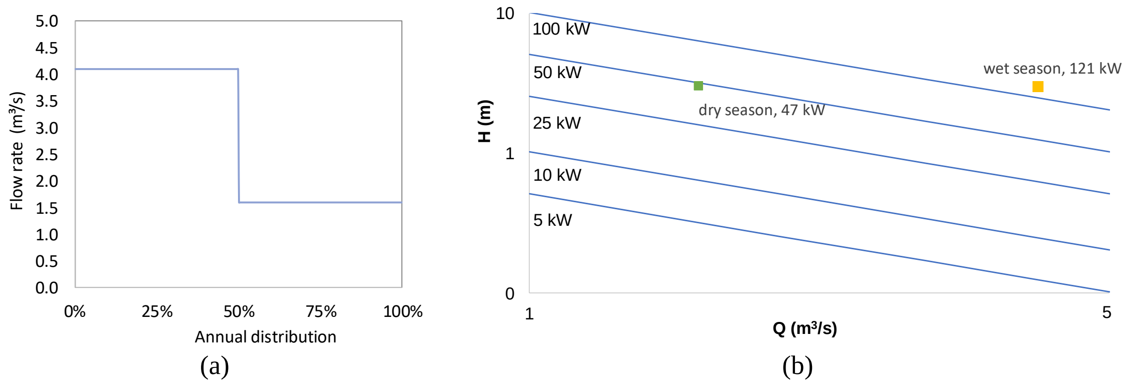


Figure 4.5 – (a) Annual distribution of the flow rate; (b) curves for potential hydraulic power recovering (η = 100%).

Table 4.3 – Head, flow rate and hydraulic power for both seasons of the case study at the reference section.

Head, H (m)	Season	Average Flow Rate, Q (m^3/s)	Hydraulic Power (kW)
3	Dry	1.6	47
	Wet	4.1	121

Figure 4.6 shows the estimated hydraulic power, considering the efficiency of 70% for this equipment (Lashofer *et al.*, 2013). Considering that the inverted Archimedes screw turbine operates with this efficiency for a wide range of flow rates (between 20%–110% of rated conditions), the annual recovered energy and the corresponding installed power were simulated for different design flow rates. The maximum recovered energy (515 MWh/year) was observed for design flow rate of 4.1 m^3/s, with a corresponding installed power of 84 kW (Figure 4.7). Considering the corrosive characteristic of the fluid with solids, the use of these turbines or equivalent equipment in wastewater systems is difficult, and efficiencies can be lower than 70%.

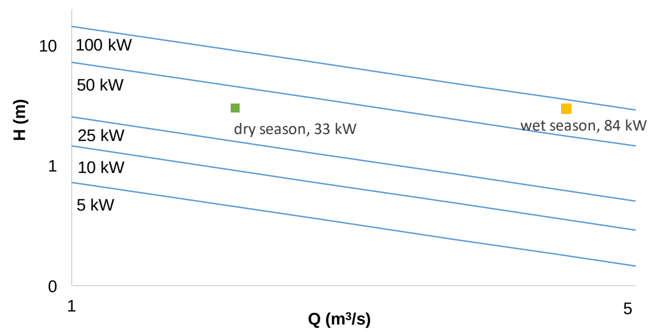


Figure 4.6 – Curves for potential hydraulic power recovering (η = 70%).

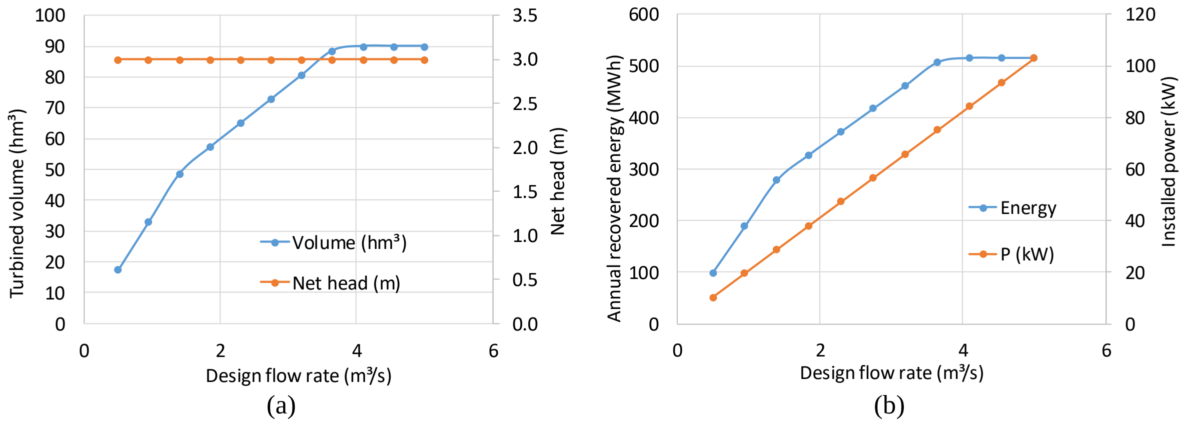


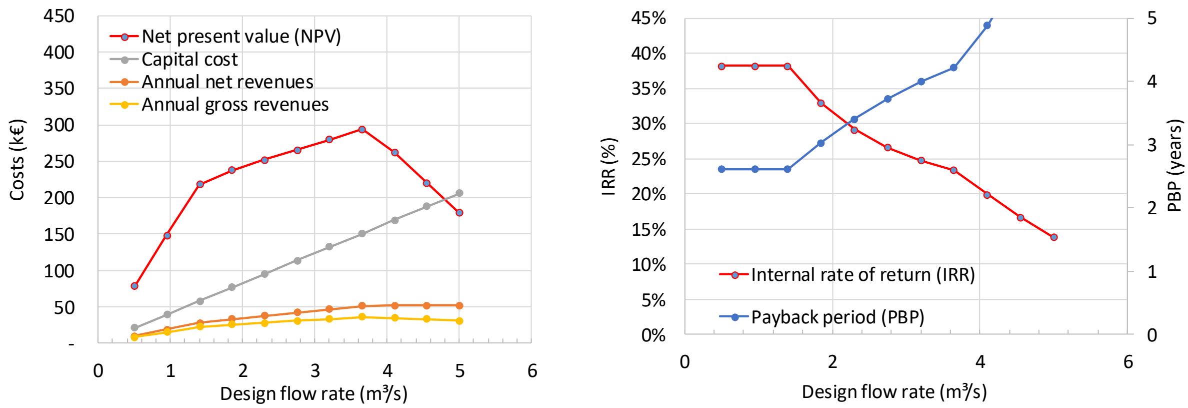
Figure 4.7 – (a) Annual turbined volume and net head; (b) annual recovered energy and installed power for the Archimedes screw.

Economic analysis requires the calculation of the capital cost, O&M costs, gross and net revenues, as well as several economic indicators, such as the NPV, PBP and IRR. The assumptions adopted herein are: (i) discount rate = 5%; (ii) project lifetime = 20 years; (iii) energy unit cost = 0.10€/kWh; (iv) annual O&M = defined as a percentage of the capital cost (5%). The discount rate, project lifetime and unit energy cost are the typical values used by water utilities in Portugal (Oliveira *et al.*, 2021). The unit capital cost for the Archimedes screw turbine is 2 k€/kW.

The results for NPV, capital costs, O&M costs and revenues for the Archimedes screw solution are presented in Figure 4.8a as a function of the design flow rate, and the respective PBP and IRR are presented in Figure 4.8b.

The maximum recovered energy for the flow rate of 4.1 m^3/s (Figure 4.7b), while the maximum economic benefit leading to the maximum NPV (293.7 k€) is for the design flow rate of 3.65 m^3/s (Figure 4.8a). The corresponding installed power is 75 kW, and the annual recovered energy is 507 MWh/year, which corresponds to a specific energy recovery indicator of 0.01 kWh/m^3. For this flow rate, the Archimedes screw turbine has a capital cost of 150.4 k€, O&M costs are 15 k€/year, the gross revenue is 50.7 k€ and the net revenue is 35.7 k€. The PBP is 4 years, and the IRR is 23%.

The potential for energy recovery can also be evaluated in the other sites of the system, such as after discharges with significant flows or in sewer sections with significant head drops. In each case, the potential for energy recovery and the respective economic viability analysis should be carried out.



(a) (b)

Figure 4.8 – Economic analysis of the Archimedes screw installation as a function of the design flow rate: (a) CC, O&M costs, revenues and NPV; (b) PBP and IRR.

4.5 Conclusions

This paper presents a detailed application of a novel energy balance scheme for assessing energy efficiency in wastewater systems, through hydraulic modelling. In the wet season, a substantial increase (four times higher) in the total energy is observed, mainly derived from undue inflows. Also, a major part of the energy consumption is associated with the total inflow intrinsic energy (>95% of the total energy used for system processes), since the system is mainly composed of gravity sewers and only one pumping station. The energy associated with undue inflows considering both seasons is significant, being on average 21.3%. The component related to the energy associated with overflows potentially inflowing to energy-consuming component represents energy that would be consumed additionally if the total volume that left the system was also pumped. Therefore, this component should not be mistreated since it highlights to wastewater utilities that, while they do not reduce these exceedance volumes, the impact of actions in the control of undue inflows to reduce energy consumption is compromised.

Regarding the reference elevation analysis, there is evidence that this parameter significantly affects the energy efficiency indices, and the recommendation is to use a unique regional reference in the calculation of the energy balance.

The potential for energy recovery is also of utmost importance since it enhances the need of considering the energy recovering practice from wastewater systems, which sometimes can be neglected because of recognised limitations. Results in the present paper show a good potential for energy recovery (500 MWh/year) and workable economic viability considering the several indicators presented, namely PBP of 4 years and IRR of 23%. Additionally, this work reinforced the need for wastewater utilities to focus on the several energy balance components to highlight the main inefficiencies, even if it is not possible to calculate all of them, and different solutions with different results can be considered. Also, it is of the utmost importance to align the proposed energy balance with performance metrics that support the diagnosis of energy efficiency in wastewater utilities. The potential for energy recovery should also be analysed in locations with high flow rates and with available heads higher than 2-3 m.

Chapter 5 – Performance assessment system for energy efficiency in wastewater systems

This chapter corresponds to the research paper:

C. Jorge, M.C. Almeida, and D. Covas (2021), *Performance assessment system for energy efficiency in wastewater systems*. Water, 13, 1807. https://doi.org/10.3390/w13131807.

Author contribution: The author co-developed the conceptual idea and the methodology and carried out the data analysis and investigation.

Abstract

Performance assessment is essential to effectively evaluate and monitor the activity of water utilities, support decision making, and encourage continuous improvement. Performance assessment systems (PAS), covering several service objectives and criteria, have been successfully applied in water supply and wastewater systems. Tailored approaches focusing on the assessment of the energy use and efficiency in wastewater systems are still limited. This paper aims at the development and demonstration of a comprehensive 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 greenhouse gases emissions, among others. Management and control of excessive or undue inflows to these systems is specifically addressed by several novel criteria and metrics. The proposed PAS should be adapted by each utility to be aligned with the objectives of the organisation and with the implemented asset management strategy. The proposed approach and the resulting consolidated PAS are thoroughly described. Results from the application of the PAS to several Portuguese utilities are discussed. This PAS aims at contributing to a reliable and replicable process to assess energy efficiency in wastewater systems and to encourage a more rational energy management.

Keywords: energy efficiency, performance assessment systems (PAS), performance metrics, undue inflows, wastewater systems.

5.1 Introduction

Urban water systems performance is of the utmost importance for responding to current and future challenges in urban areas. In the last decade, performance assessment has been a topic of growing attention in the water industry since water utilities are increasingly incorporating sustainability and improvement principles in their practices, with the water services' regulators as an important driving force (Alegre *et al.,* 2011).

Energy efficiency is a fundamental topic for the water sector (Basupi *et al.,* 2014; Twomey Sanders, 2016; Wakeel *et al.,* 2016; Venkatesh *et al.,* 2017) with implications to water utilities, the users, and the society in terms of economic and financial sustainability and environmental performance. Main environmental issues include the rational and efficient use of natural resources and the reduction of emissions contributing to greenhouse gas (GHG) effects (Nair *et al.,* 2014; Singh and Kansal, 2018). According to Directive (EU) 2018/2002, the water and wastewater sectors accounted for 3.5% of electricity use in the EU in 2018, and this share is expected to rise in the short and medium terms. In Portugal, the consumption in the water sector has increased steadily by 10% over the five-year period from 2011 to 2015. Despite water supply having a larger share of this consumption (62% in 2015), wastewater systems have an equally large consumption that cannot be ignored (ERSAR and ADENE, 2018). The referred directive requires the Member States to achieve cumulative end-use energy savings by setting ambitious targets for 2030 and emphasising that "the effective management of water can make a significant contribution to energy savings" (Directive (EU) 2018/2002).

In Portugal, the Technical Guide 24 (GT24), published by ERSAR and ADENE (2018), presents recommendations for efficient energy use in the water sector. The document includes relevant information to the improvement of the energy management of pumping systems and of water and wastewater treatment infrastructures, including recommendations and methodologies for the diagnosis and the monitoring of the energy performance in these assets, among other aspects. The GT24 also introduces the importance of specific water-energy actions, which lead to the improvement of energy efficiency, increase the combined potential of savings, and enhance the competitiveness and resilience of the water-sector systems (ERSAR and ADENE, 2018). This guide and the other mentioned initiatives, together with several water utilities actions that promote energy efficiency in the water sector, also allow contributing to the international commitment of Portugal to reduce GHG emissions (Turner *et al.*, 2015). The goal is for the balance between emissions and removals from the atmosphere to be zero by 2050, that is, to have a zero-carbon footprint in water services, achieving carbon neutrality (RNC, 2050).

Most studies on energy use and management in the urban water cycle that have been published in recent years focus on the water supply subsector, with the development of several approaches to foster energy efficiency in water utilities (Duarte *et al.,* 2008; Cabrera *et al.,* 2010; Mamade *et al.,* 2017; 2018). For the wastewater subsector, existing studies are limited and tend to concentrate on individual assets, such as wastewater treatment facilities (Nowak *et al.,* 2015; Silva *et al.,* 2016) or pumping stations (Hou *et al.,* 2015; Zhang *et al.*, 2016), with very few existing developments centred on the integrated analysis of energy efficiency in the wastewater complete system. A recent study (Loureiro *et al.,* 2020) analysed the energy use and efficiency in this subsector integrated in a broad urban water-cycle analysis. For the few specific studies found, none uses a tailored performance assessment system (PAS) to support energy management. There remains a need to adapt and explore new approaches to wastewater and storm water systems to assess inefficiencies and opportunities for improvement.

Extensive research and practical applications use structured approaches to define performance assessment systems (PAS) to support the objective and robust management of urban water systems (Matos *et al.*, 2003; Cardoso *et al.*, 2004; Cabrera and Pardo, 2008; Cardoso, 2008; Canneva and Guérin-Schneider, 2011; van den Berg and Danilenko, 2011; Vilanova *et al.*, 2015; Alegre *et al.*, 2016). Examples of such systems include those applicable under the regulation activities of water and wastewater services provision and benchmarking activities (ERSAR, 2018).

Water services are complex due to multiple factors (macroeconomic, social, and environmental); therefore, the use of performance assessment systems is very useful to effectively evaluate and monitor the activity of utilities. More specifically, those benefits are as follows: measuring the quality of service and the utility effectiveness and efficiency; supporting the decision-making process; identifying improvement areas; making the comparison between objectives fair and transparent; providing benchmarking with similar utilities in the country or region or with standards of international good practice; supporting results dissemination; and encouraging utilities to continually improve their service (van den Berg and Danilenko, 2011; Vilanova *et al.*, 2015; Alegre *et al.*, 2016). Additionally, the adoption of performance assessment systems can highlight the main inefficiencies in the systems, consequently allowing to set energy efficiency improvement measures (e.g., energy production, energy recovery, single components, and system-wide improvement measures, maintenance measures, among others) that contribute to increase the efficiency of the water-energy infrastructures and its environmental impacts (Liu *et al.*, 2012; Berger *et al.*, 2013; Puleo *et al.*, 2016).

Definition of a PAS is not a trivial task. This definition gains from the alignment with the performance assessment structure proposed by ISO 24510-24512:2007 series for water supply and wastewater systems management. Also, it is of utmost importance to ensure the alignment with PAS for other purposes in the organisations, such as the infrastructure asset management (IAM) methodology proposed by Alegre and Covas (2010) and Almeida and Cardoso (2010). The IAM is an integrated approach aligned with the Plan-Do-Check-Act principles typically used in quality systems standards. The PAS should be aligned with the strategic management planning, the strategic objectives of the organisation, and the adopted methodology for implementing asset management. The PAS should take into consideration the organizational resources for effective implementation of a planning process at the tactical level for energy management along with its application in the short to long term. The PAS structure is centred on the definition of objectives, assessment criteria, and metrics (O-C-M) in addition to which it is necessary to define reference values, to allow robust comparisons, and to define targets for each utility (Alegre and Covas, 2010; Almeida and Cardoso, 2010). The objectives aim to consider the several points of view of the assessed problem, and the criteria allow evaluation of several aspects or principles of these objectives. Metrics are parameters or functions used to assess the criteria. The analysis and interpretation of the performance metrics should take into account the context factors, external or internal, considering the area served by each utility. Reference values are standard values used to classify metrics results. Targets are understood as the values to be achieved for each metric for a set deadline. Often, multi-criteria analysis is used to support the selection and prioritization of decisions (Carriço *et al.*, 2021).

The current paper aims to propose and validate a PAS specifically tailored to assess energy efficiency in wastewater systems, taking into consideration the existing methodologies, the common concerns, the long-term objectives on energy efficiency, and the identified knowledge gaps. The main novelties of the proposed approach are a complete objective, criteria, and metrics structure, considering the specificities of each system and the management objectives, considering the alignment with previous methodologies developed by the wastewater utilities. Thus, the proposed energy assessment PAS for wastewater systems is a novel approach not yet developed nor applied to real-life wastewater systems and, innovatively, adopts a holistic view of the wastewater system and includes metrics to assess the potential inflows to systems often surcharged by undue or excessive inflows.

5.2 Methodology

5.2.1 General approach

A methodology for the construction of an oriented PAS for energy efficiency in wastewater systems is described herein. The PAS in the scope of energy efficiency in wastewater systems should be aligned with the strategic objectives of the wastewater utilities since this alignment is one of the main difficulties of utilities (Almeida *et al.*, 2018). The methodology for the construction of a specific PAS to evaluate energy efficiency in wastewater systems is based on the accepted O-C-M structure of the methodology proposed by Alegre and Covas (2010) and Almeida and Cardoso (2010), framed by the typical strategic objectives of the utilities. The focus is on the wastewater-energy use associated with the collection and transport of wastewater throughout the system and also in the current operation and maintenance activities. The system evaluates the energy consumed in pumping stations, the efficiency in the use of resources, the impact of undue inflows in energy consumption, and the organisational and environmental sustainability.

The first step consists of the definition of the objectives by identifying the relevant points of view to assess the performance of wastewater systems in terms of energy efficiency. Once the objectives are set, the second step focuses on the selection of the criteria allowing the evaluation of each objective. The third step is the identification of a set of metrics to assess each criterion. The last step consists of the definition of the reference values and targets (Figure 5.1). These targets are defined by the wastewater utilities (WU) considering the different planning periods; the definition of targets is out of the scope of the present paper (white box).

The adopted approach to develop the PAS is composed of three main stages: (1) PAS development; (2) PAS validation and consolidation; and (3) reference values establishment. This process is schematically depicted in Figure 5.2, in which grey boxes represent developed tasks and white boxes the results.

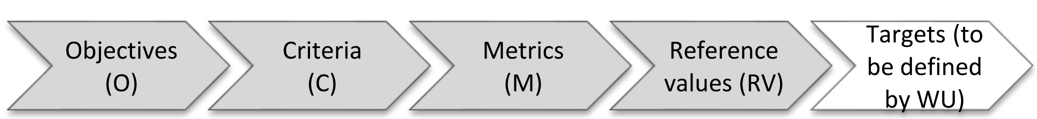


Figure 5.1 – Structure of the PAS.

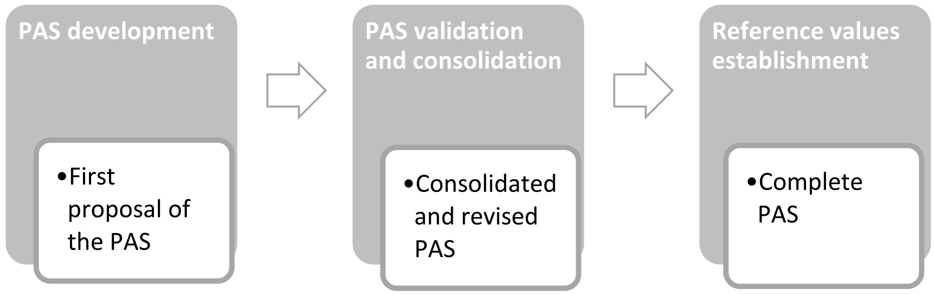


Figure 5.2 – Stages for the construction of the PAS and main results.

The first stage involves the development of a preliminary version of the PAS. The PAS should be as wide as possible to attend to the diversity of wastewater utilities in terms of systems, available data, O&M practices, etc. Therefore, a validation and consolidation process is applied in a second stage to ensure the adequacy and applicability to typical wastewater utilities.

The definition of reference values (third stage) for general use by wastewater utilities benefits from application to several utilities, and thus, it is recommended to carry out this stage after the consolidation of the O-C-M part of the PAS as the last stage. The application of the consolidated PAS to real systems data provides information to decide on reference values for the metrics, setting the rules to proceed with the assessment of results from the application of the O-C-M. Three classes (good, fair, and poor) are defined to classify the values of the metrics, completing the O-C-M structure. The use of common reference values allows a fairer, transparent, and more systematic assessment of the performance of each wastewater utility as well as the comparison between utilities. Details of these stages and the interaction with Portuguese utilities are described in the following sections. The O-C-M structure and its application are presented in section 5.3.

5.2.2 PAS development

The PAS development stage (stage 1) refers to the development of objectives, criteria, and metrics. This is based on a literature review on the performance assessment systems in the scope of the urban water cycle using standardized metric libraries as well as user-developed or customized indicators or indices. Additionally, sessions of brainstorming and debate with wastewater utilities should be promoted together with tailored surveys to their multidisciplinary teams. In the current case, a total of eight wastewater utilities and a total of 21 staff members were invited to the sessions. The face-to-face meetings and brainstorming with the Portuguese wastewater utilities allows ensuring the coherence and feasibility of the methodology as well as the capacity building of the involved utilities. Following this process, research teams from utilities can work together for transferring knowledge, gaining mutual benefits, and enriching the proposed concept.

For the current purpose, the PAS is grounded on the identification of the specific causes and relevance of each identified energy inefficiency for the whole system as well as in sub-catchment areas. The basis for the structure of the approach is the need to ensure the coordination with the existing decision levels and operational areas of the utility as a way to ensure the effectiveness of the actions and a process of continuous improvement, which together with a solutions portfolio, leads to action plans. Utility managers, municipalities, and the local population need to be involved to obtain a broader understanding of problems and to enable the implementation of more effective solutions facilitated by a wider set of actors in what is necessarily a multifaceted problem.

At this level, assuming the utility has adopted a strategy for energy efficiency in wastewater systems, it is necessary to identify the objectives that ensure that the assessment system of the wastewater utility allows to objectively evaluate the magnitude of the problem and the evolution when an action plan is being implemented. Also, current requirements as environmental and utilities sustainability, adaptation, and mitigation to climate change and the strategic objectives of utilities should be considered to identify the most relevant dimensions to be included in the specific PAS objectives.

In the selection of performance metrics, the following requirements need to be assured for each metric: to be relevant for the objectives of the urban water cycle services; to fit in the predefined assessment criteria; to be clearly defined, with a concise meaning; to be reasonably achievable (which mainly depends on the related variables); to be auditable; to be as universal as possible and to provide a measure which is independent of the particular conditions of the utility; to be simple and easy to understand; and to be quantifiable to provide an objective measurement of the service, avoiding any personal or subjective judgement. Collectively, performance metrics should comply with the following requirements: each metric should provide information significantly different from the other metrics; definitions of the metrics should be unequivocal (this requirement is made extensive to its variables); only metrics which are deemed essential for effective performance evaluation should be established (Alegre *et al.*, 2015).

The leading principles of an integrated assessment focusing on energy efficiency in wastewater systems are based on the adoption of a tailored PAS for energy efficiency in wastewater systems considering not the several energy efficiency aspects in wastewater utilities but the specific ones that focus on water-energy nexus, including dimensions of performance, cost, and risk; diagnosis and evaluation of the problem; the comparability and evaluation of performance over time; the identification of opportunities for increased resource-use efficiency (with focus on energy); the internalisation of a structured process to manage energy efficiency in wastewater systems in coordination with other areas of activity in the utility; and other relevant stakeholders in a continuous improvement process (Alegre *et al.*, 2011).

A validation and consolidation process needs to be posteriorly applied to ensure the adequacy and applicability to typical wastewater utilities.

5.2.3 PAS validation and consolation

Stage 2 consists of the PAS validation and consolidation. The first proposal of PAS, including only objectives, criteria, and metrics, needs to be validated and consolidated with the end-users, the wastewater utilities. For this purpose, the proposed PAS should be analysed together with several wastewater utilities managing different systems (treatment, transport, and collection) with different levels of maturity and resources (human, technological, and economical). The objective is to jointly establish and accept a standard assessment regarding the energy efficiency of wastewater systems to allow comparability and performance assessment over time.

The PAS validation by the utilities provides an opportunity to revise and adjust metrics’ definition, to identify relevant sources of information for metrics’ calculation, and to test the assessment approach adequacy to different utilities, with different stages of maturity. The validation of the proposed PAS is carried out both with the Portuguese regulator data (ERSAR, 2018) and for selected wastewater utilities divided into two types: the wastewater bulk transport and treatment utilities (type A) and the collection and transport (sometimes also include treatment) utilities (type B). The Portuguese quality of service assessment system lead by the national regulator is compulsory for all water and waste services providers; therefore, the respective metrics can be calculated, when possible, for all the Portuguese wastewater utilities.

In the current application, eight wastewater utilities representative of the Portuguese reality have supplied additional data for testing the proposed PAS. The followed approach allows ensuring the coherence and feasibility of the methodology as well as capacitating the teams of the involved utilities. This step aims at applying the proposed PAS to each utility reality and consolidating the first version of PAS.

The wastewater utilities (WU) participating in the validation are responsible for urban water systems of different dimensions, with several effective service households between 2 220 and 296 022, network extensions between 32 km and 1539 km, number of pumping stations between 2 and 380, and number of wastewater treatment plants (WWTP) between 0 and 176. Table 5.1 summarizes the global characterization of the utilities. Data were supplied for the reference period of 2015 to 2019, whenever available.

Table 5.1 – Global characterization of the selected wastewater utilities (WU).

WU/Type	Number of Effective Service Households	Network Extension (km)	Number of Pumping Stations	Number of WWTP
WU1/Type A	35 204	32	3	23
WU2/Type A	311 490	447	192	65
WU3/Type B	19 772	546	66	9
WU4/Type A	488 725	1498	380	176
WU5/Type B	55 363	1539	85	16
WU6/Type B	158 303	977	26	16
WU7/Type B	2 220	55	2	0
WU8/Type B	29 722	444	17	1

It should be highlighted that the calculation of metrics requiring more detailed data is globally less feasible in wastewater systems when compared with water-supply systems since the subsector continues to face difficulties regarding information availability and collection. Therefore, only part of the proposed metrics can be currently calculated by most utilities.

5.2.4 Reference values establishment

The last stage (stage 3) is where the reference values are established. The application of PAS to real systems data provides information to decide on reference values for the metrics, thus setting the rules to proceed with the assessment of results from the application of the objectives, criteria, and metrics.

In the present study, the reference values are defined considering realistic limits for each metric together with a statistical analysis of the metrics application by the utilities. Three classes representative of the quality of service provided (good, fair, and poor) are proposed to classify the values of the metrics. Typically, values of the percentile 25 and percentile 75 are considered when defining the minimum and maximum values of the performance range, respectively. Additionally, the average and median values are analysed. When metrics are obtained with annual and global values, the set of the Portuguese regulator utilities can be considered, which allows a more robust reference-values definition.

Even when only a limited set of values are available, a detailed analysis of the context of each utility should be carried out considering the area served by each wastewater utility. Reference values should always consider the referred context since the effective operation of systems needs to reflect the proper context and consider adjusted values. Regarding the targets, after analysing their specific PAS with focus on the metrics, each utility has to define, for each metric, reasonable values to be achieved at a different time (short, medium, and long term).

Attending to all the described steps, the resulting consolidated PAS is presented and discussed in the following sections.

5.3 Results and discussion

5.3.1 Consolidated PAS

The energy-efficiency objectives defined in the proposed PAS are presented below. These consider specifically the water-energy nexus dimensions with focus on the functioning of the wastewater systems considering wastewater pumps, undue inflows, untreated discharges, etc. Therefore, the proposed objectives include the energy-use efficiency, carbon neutrality, and environmental and financial impacts as follows:

- Objective 1 – Energy-use efficiency: ensures the efficiency in the use of energy in the operation of the wastewater systems and promote a sustainable use of the resource, targeting the specific inefficiencies of each system. The criteria associated with this objective focus on the adoption of best cleaning, operation, and maintenance practices in the replacement of equipment for more efficient ones or in the implementation of solutions to increase their efficiency and also in the control of undue inflows, among others.
- Objective 2 – Carbon neutrality: promotes mechanisms to control the emission of GHG associated with energy consumption in wastewater systems, reducing the respective impact in climate change. Encourages fast reductions in GHG caused by the several activities associated with system components that require energy supply. The proposed criteria for this objective focus on replacements at the equipment, operation, and maintenance-level actions and promotion of the use of clean energy (such as solar energy, wind energy, and hydropower).
- Objective 3 – Energy production and recovery: promotes the energy recovery practice and energy self-production in wastewater systems. The criteria associated with this objective relies on energy recovery (e.g., by turbines, Archimedes screw) and energy self-production.
- Objective 4 – Economical and financial sustainability: ensures efficiency in the use of economic resources associated with energy (e.g., reduce energy costs, energy recovery, equipment, operation, and maintenance).

Each objective should be assessed from different and relevant points of view (criteria). Figure 5.3 presents the PAS objectives and the corresponding assessment criteria. Each objective has two to three criteria. Specific metrics, preferably quantitative, are defined to obtain an objective assessment of each criterion. The quantitative metrics allow the incorporation and evaluation of objective information, covering a more comprehensive definition of energy efficiency. Metric selection aims to adequately evaluate the proposed criteria, taking into consideration eventual interrelations between metrics.

The proposed PAS includes four objectives, 10 criteria, and 35 metrics, including 31 new metrics, one metric (M1.1.3) of the PAS of the Portuguese regulator (ERSAR, 2018), two metrics (M1.1.1 and M3.1.1) from ERSAR and ADENE (2018) and one metric (M1.1.6) adapted from Matos *et al.* (2003). Metric M1.1.5 has also been proposed by Loureiro *et al.* (2020) but detailing each urban water cycle stage. Objectives, criteria, metrics, and corresponding reference values are presented in Table 5.2. Since it was not possible to calculate all the metrics due to data availability constraints, only some reference values have been proposed except for M1.1.3 (ERSAR, 2018). The establishment of the remaining reference values will be carried out as a future work. Whenever applicable, a distinction is indicated between the reference values for utilities of type A and type B. Good performance is highlighted as green, fair performance as yellow, and poor performance as red.

Due to the high number of proposed metrics, the description and formulation for each one is not detailed herein and are supplied in Appendix A3 (Table A3.1).

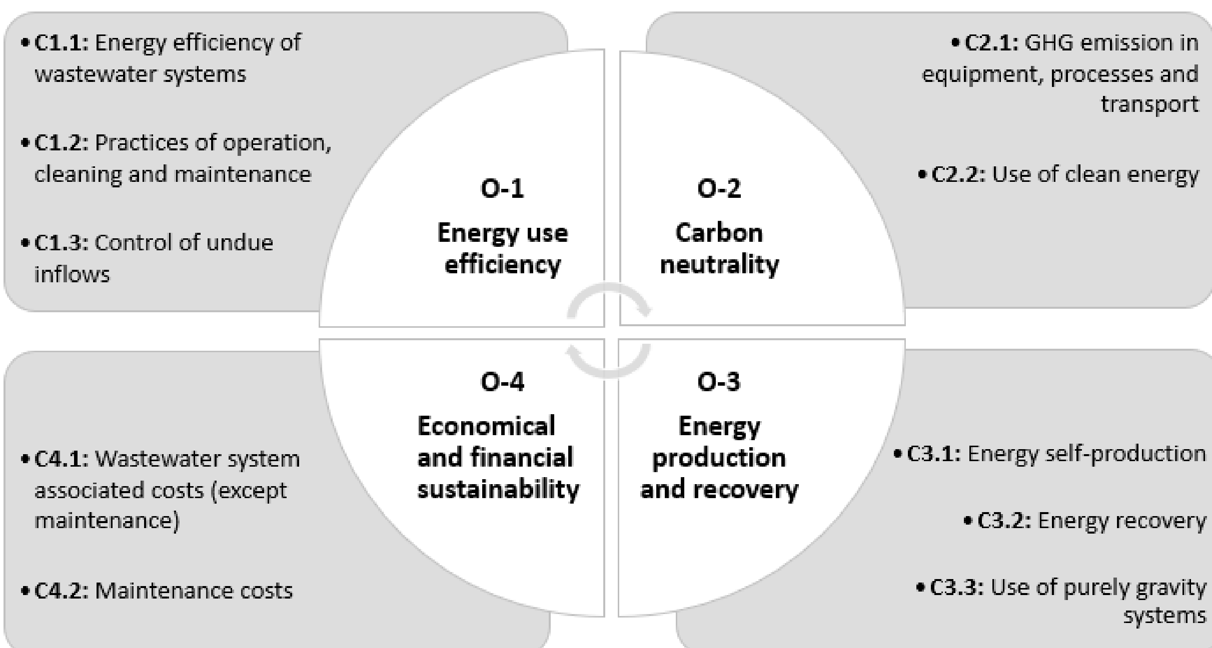


Figure 5.3 – PAS for energy efficiency in wastewater systems objectives and criteria.

Table 5.2 – Complete PAS: objectives, criteria, metrics, and reference values.

Metric	Reference values
Objective 1 | Energy use efficiency	
Criterion 1.1: Energy efficiency of wastewater systems	
M1.1.1: Specific energy per total WW volume (kWh/m^3) – *metric from ERSAR and ADENE (2018)*	A: [0, 0.5];]0.5, 0.6];]0.6, +∞[B: [0, 0.2];]0.2, 0.3];]0.3, +∞[
M1.1.2: Specific energy per total pumped volume (kWh/m^3)	A: [0, 0.5];]0.5, 1.7];]1.7, +∞[B: [0, 0.09];]0.09, 0.12];]0.12, +∞[
M1.1.3: Pumping stations energy efficiency [kWh/(m^3.100m)] – *metric from ERSAR (2018) (AR10)*	[0.27, 0.45];]0.45,0.68];]0.68,5[
M1.1.4: Percentage of total energy consumption used for pumping (%)	A: [0, 15];]15, 30[; [30, 100] B: [0, 5];]5, 40[; [40, 100]
M1.1.5: Percentage of total energy consumption used for WW treatment (%)	A: [0, 5];]5, 50[; [50, 100] B: [0, 5];]5, 30[; [30, 100]
M1.1.6: Energy consumption for WWTP per population equivalent (kWh/e.p.) – *metric adapted from Matos et al. (2003) (wOp18)*	[0, 20];]20, 50[; [50, +∞[
M1.1.7: Percentage of pumps with acceptable efficiency (%)	-
Criterion 1.2: Practices of operation, cleaning, and maintenance	
M1.2.1: Energy consumption for sewer network cleaning [tep/(100km.year)]	-
M1.2.2: Energy consumption for septic tanks cleaning [tep/(km of travel.year)]	-
M1.2.3: Operation practices improvement to lower pump heads (-)	-
Criterion 1.3: Control of undue inflows	
M1.3.1: Quarter energy peak factor (-)	[1.0, 1.25[; [1.25, 1.75[; [1.75, +∞[
M1.3.2: Energy consumption seasonality (-)	[1.0, 1.75[; [1.75, 2.5[; [2.5, +∞[
M1.3.3: Percentage of energy equivalent to the volume generated in the served area used for pumping (%)	[95, 100]; [80, 95[; [0, 80[
M1.3.4: Percentage of energy equivalent to the volume generated in the served area used for WW treatment (%)	[95, 100]; [80, 95[; [0, 80[
M1.3.5: Effect of excessive inflows on energy consumption (%)	[0, 2.0[; [2.0, 5.0[; [5.0, 100]
Objective 2 | Carbon neutrality	
Criterion 2.1: GHG emission in equipment, processes, and transport	
M2.1.1: Specific GHG emissions associated with total WW volume ($kgCO_2eq/m^3$)	[0, 0.3];]0.3, 0.5];]0.5, +∞[
M2.1.2: Specific GHG emissions associated with pumped volume ($kgCO_2eq/m^3$)	[0, 0.4];]0.4, 0.5];]0.5, +∞[

Table 5.2 (cont.) – Complete PAS: objectives, criteria, metrics, and reference values.

Metric	Reference values
M2.1.3: Specific GHG emissions associated with WW treated volume (kgCO2eq/m^3)	[0, 0.2];]0.2, 0.4];]0.4, +∞[
M2.1.4: Specific GHG emissions associated with the volume generated in the served area (kgCO_2eq/m^3)	-
M2.1.5: Specific GHG emissions associated with O&M (kgCO_2eq/m^3)	[0, 1x10^{-4}];]1x10^{-4}, 2x10^{-4}];]2x10^{-4}, +∞[
Criterion 2.2: Use of clean energy	
M2.2.1: Percentage of total energy consumption from clean energy sources (%)	-
Objective 3 | Energy production and recovery	
Criterion 3.1: Energy self-production	
M3.1.1: Energy self-production (%) – *metric from ERSAR and ADENE (2018)*	[20, 100]; [10, 20[; [0, 10[
Criterion 3.2: Energy recovery	
M3.2.1: Recovered energy (%)	-
Criterion 3.3: Use of purely gravity systems	
M3.3.1: Percentage of sewer network not associated with pumping stations (%)	-
Objective 4 | Economical and financial sustainability	
Criterion 4.1: Wastewater system associated costs (except maintenance)	
M4.1.1: Percentage of cost of total energy equivalent to the volume generated in the served area used for pumping (%)	-
M4.1.2: Percentage of cost of total energy equivalent to the volume generated in the served area used for WW treatment (%)	-
M4.1.3: Percentage of the cost of total energy consumption used for pumping (%)	-
M4.1.4: Percentage of the cost of total energy consumption used for WW treatment (%)	-
M4.1.5: Cost associated with the quarter energy peak factor (-)	[1, 1.5]; [1.5, 2.5[; [2.5, +∞[
M4.1.6: Cost associated with energy consumption seasonality (-)	[1, 2]; [2, 3[; [3, +∞[
M4.1.7: Percentage of cost associated with energy self-production (%)	-
M4.1.8: O&M costs of energy consumption reduction by control of undue inflows (%)	-
Criterion 4.2: Maintenance costs	
M4.2.1: Repair or replacement costs of pumping equipment [€/(equipment.year)]	-
M4.2.2: Cleaning operations costs of energy [€/(100km.year)]	-
M4.2.3: Solids removal operations costs of energy [€/(kg.year)]	-

5.3.2 Results from application to wastewater utilities

Selected metrics were calculated considering two different data sets: data from all the 281 utilities reporting to the Portuguese regulator (ERSAR, 2018) and data from eight wastewater utilities directly participating in the application and consolidation of the PAS (Table 5.1). Not all the proposed metrics could be calculated by the wastewater utilities due to the lack of available data. Due to the number of proposed metrics, only the results of a selected number of metrics, the most relevant, will be presented herein. Metrics requiring global and annual data can generally be calculated for all the Portuguese wastewater utilities. The Portuguese regulator data have been used to support the reference values definition. Metrics requiring more detailed data (e.g., monthly, daily data, audits data) are calculated for the eight involved utilities.

The national water assessment system (ERSAR, 2018), although designed to provide a national overview of the water and sanitation sector, can contribute to several areas of study with some metrics or variables to support the energy performance assessment. Consequently, one metric associated with energy issues in wastewater systems was selected (M1.1.3: Pumping stations energy efficiency, ERSAR AR10), and other metrics use variables from the Portuguese regulator assessment system (Table A3.1).

The set of metrics representative of the global energy efficiency assessment in general wastewater systems are selected and presented herein: Objective 1 – metrics 1.1.1, 1.1.3, 1.1.4, 1.3.1, 1.3.2, and 1.3.3; Objectives 2, 3, and 4 – metrics 2.1.1, 3.1.1, and 4.1.5, respectively. Results for the utilities are anonymous and are numerated from 1 to 8. Results for all the Portuguese wastewater utilities – metrics 1.1.1, 1.1.3, 1.1.4, 2.1.1 and 3.1.1 – are marked as ERSAR (orange box and whiskers plot). In all cases, results for the selected utilities are also shown (blue box and whiskers plot). Whenever significant, results are divided between type A and type B utilities. The reference period is 2015 to 2019, whenever data are available. Reference values are highlighted with colour bands: good performance is highlighted as green, fair performance as yellow, and poor performance as red.

Figure 5.4 presents the results obtained for the metric 1.1.3, which is a metric selected from the Portuguese regulator assessment system (ERSAR, 2018). Metric 1.1.3 represents the average amount of energy consumed per cubic meter pumped to a head of 100 m. Reference values range from good performance are marked as green [0.27; 0.45], fair performance marked as yellow]0.45; 0.68], and finally poor performance marked as red]0.68; 5[. The minimum theoretical value corresponds to a 100% motor and pump performance, and it is 0.27 kWh/(m^3.100 m). The Portuguese regulator report (ERSAR, 2018) shows that energy efficiency for wastewater utilities varies between 0.32 and 2.00 kWh/(m^3.100 m). The results show a variation in the quality of service from fair to poor, indicating significant potential for improvement of energy management. For the selected utilities (blue box and whiskers plots), the trend is similar, with an overall performance classified as poor.

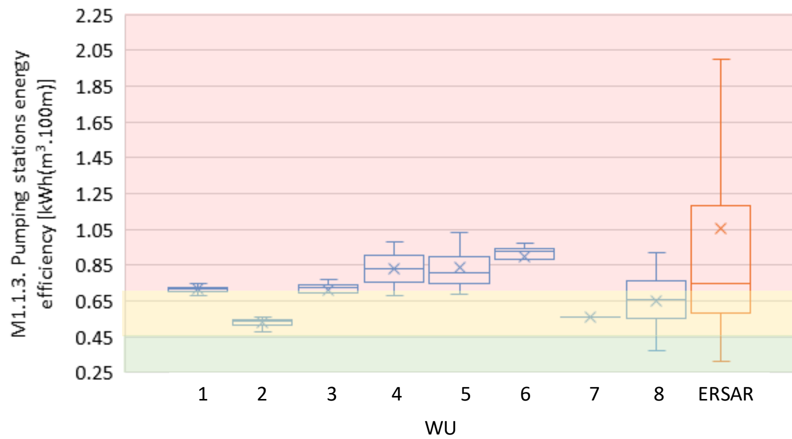


Figure 5.4 – Results for the metric M1.1.3: pumping stations energy efficiency.

Metric 1.1.3 is the only metric focusing on energy performance in wastewater systems considered by the Portuguese regulator. Since this metric is only for pumping stations, it is insufficient to provide guidance regarding the overall energy efficiency of the wastewater systems.

Figure 5.5 presents the results obtained for the remaining selected metrics for Objective 1. Figure 5.5a,b show that the values for metric 1.1.1 (specific energy) vary significantly from type A to type B utilities. Regarding the selected wastewater utilities, the majority of collection and transport (type B) utilities have values for specific energy below 0.20 kWh/m^3 (good performance), whereas type A utilities values vary between 0.40 and 0.80 kWh/m^3 (mainly fair and poor performance).

Concerning the universe of the Portuguese utilities, values from type B utilities are significantly lower. These results show that type A consume significantly more than type B utilities, given the higher number of energy consuming components. Type A utilities typically have a higher number of pumping stations and WWTP; therefore, their energy consumption per cubic meter of collected or treated wastewater tends to be higher.

Regarding the percentage of the total energy used for pumping (metric 1.1.4), Figure 5.5c,d show that type B utilities (Figure 5.5d) have generally higher values since these utilities commonly have a lower number of WWTP, and the major part of the utility energy consumption is consumed by the pumping stations (despite O&M energy consumptions). Overall, WU1 has a better performance comparing the type A wastewater utilities, and WU5 and WU6 also perform better comparing to type B wastewater utilities.

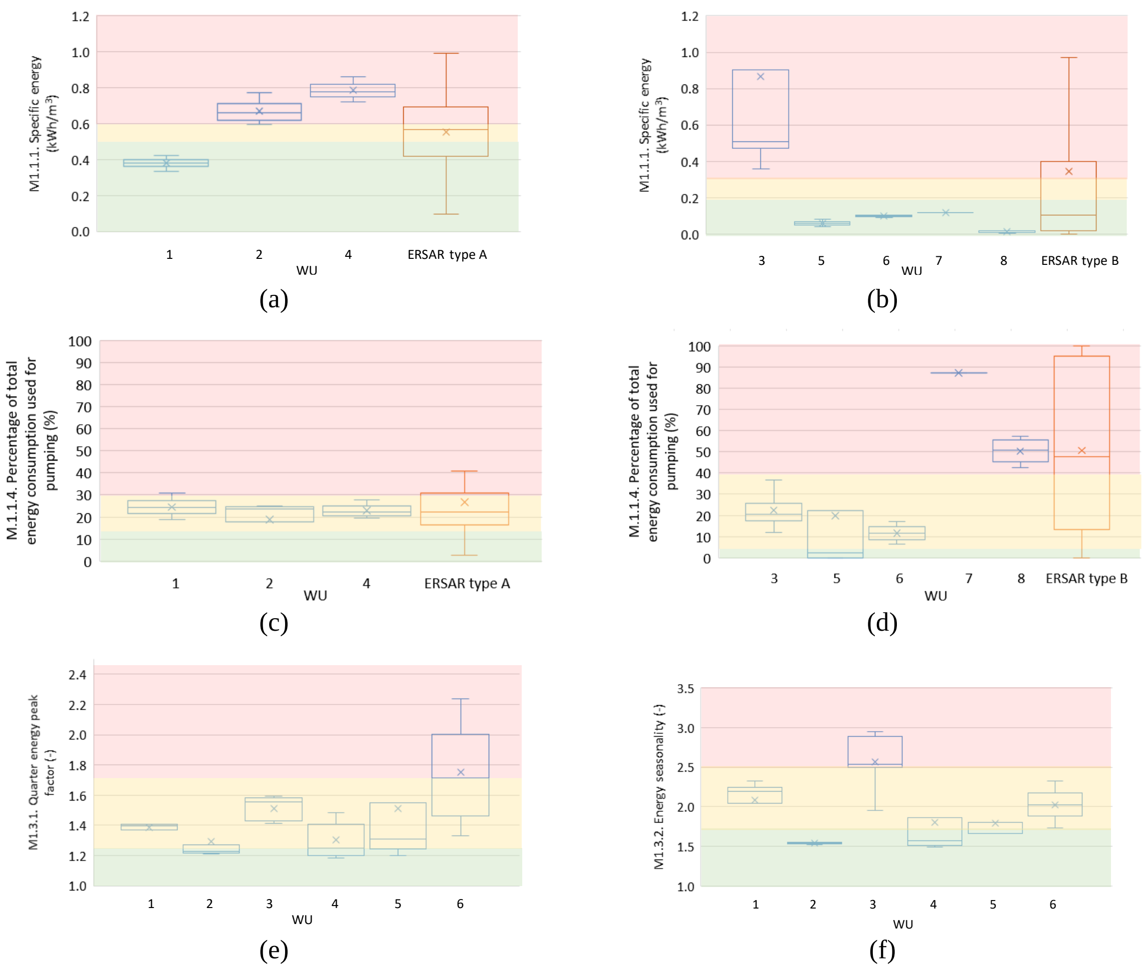


Figure 5.5 – Results for the selected metrics of Objective 1: (a) M1.1.1 Type A WU; (b) M1.1.1 Type B WU; (c) M1.1.4 Type A WU; (d) M1.1.4 Type B WU; (e) M1.3.1; and (f) M1.3.2.

Metrics 1.3.1 and 1.3.2 (Figure 5.5e,f) are included in the control of undue inflows criterion (criterion 1.3), and both allow a diagnosis concerning the presence of these type of flows in the network, specifically their impact on energy consumption. Metric 1.3.1 (quarter energy peak factor) represents the ratio between the average three months of higher energy consumption and the average annual consumption. Results for this metric vary from 1.2 and 2.2 over the years for the several utilities, and average values round 1.5 (fair performance). This result shows that, typically, the energy consumption in that specific three months of the year are one and a half times higher when compared to the average annual consumption. This highlights the importance of raising awareness of wastewater utilities to excessive volumes inflowing to the systems, always considering other variables that influence energy consumption (e.g., population, tourism, water supply consumption). WU4, WU5, and WU6 are the ones that have more variable values for this metric over the years. Metric 1.3.2 (energy seasonality) represents the ratio between the average three months of higher energy consumption and the average three months of lower consumption. For the selected utilities, values vary from 1.5 to 3 and WU3, WU4, and WU6 are the ones with more variability along the reference period.

Finally, metric 1.3.3 (percentage of energy equivalent to the volume generated in the served area used for pumping) was calculated only by one wastewater utility (WU2) since data requirements include water discharges or calibrated hydraulic model. This metric aims to address the concept of equivalent energy as the total energy required to pump the total volume generated in the served area if there were no limitations on the transport capacity of the network upstream as well as in the pumping installation. This variable is included in the PAS to calculate the energy that would be consumed additionally if the total volume that left the system (due to discharges or floods) was also pumped. It also intends to raise awareness of wastewater utilities about the effect of acting in control of undue inflows to reduce energy consumption. Expected reduction of energy consumption will only be achieved when the discharged or flooded volumes are eliminated. It also highlights the importance of measuring discharges not only for the well-known reasons associated with environmental impacts. Values for WU2 vary from 99.90% to 99.99%. Results are not represented in Figure 5.5 due to the narrow variability of the values.

The proposed reference values for this metric (Table 5.2) show that almost all the volume generated in the system is pumped, and thus, the control of undue inflows will generate an effective reduction of energy consumption. In all situations, it is important to highlight that the confidence in the results should be evaluated case by case, as the uncertainty associated with data from energy and volume measurements can introduce significant variations. Figure 5.6 presents the results obtained for the selected metrics for Objectives 2, 3, and 4.

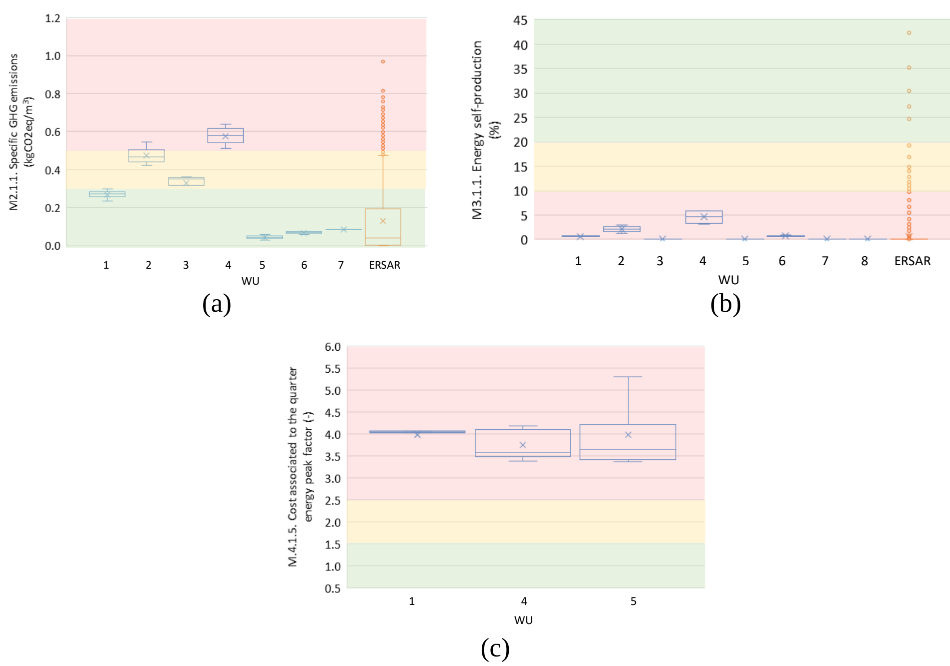


Figure 5.6 – Results for the selected metrics of Objectives 2, 3, and 4: (a) M2.1.1; (b) M3.1.1; and (c) M4.1.5.

Figure 5.6a shows that four of the selected wastewater utilities (WU1, WU2, WU3, and WU4) have higher values for the metric 2.1.1 (specific GHG emissions) when compared to all Portuguese utilities (values located on the top of the orange box and whiskers plot) typically associated with the type A utilities. On the other hand, WU5, WU6, and WU7 have lower values (all type B wastewater utilities). These results, as those for metric 1.1.1., are explained by the fact that type A wastewater utilities transport large volumes of wastewater and typically have a higher number of pumping stations and WWTP, which increases their energy consumption per cubic meter of collected or treated wastewater as well as the specific GHG emissions.

Regarding energy self-production (metric 3.1.1. shown in Figure 5.6b), the values are generally low (for selected WU, all values are above 10%), and there is a great opportunity for improvement in the energy self-production field using several sources (e.g., solar, wind, hydropower energy). The use of clean energies should be preferable (e.g., solar energy).

Finally, metric 4.1.5 (Figure 5.6c) shows the cost associated with the quarter energy peak factor for the utilities that provided costs data for the reference period. This metric is related to metric 1.3.1 (Figure 5.5e) and evidences a very poor performance, with costs associated with the months of higher energy consumption being three or four times higher when compared to the average annual costs.

5.3.3 General recommendations for PAS application

The usage of a PAS allows performance assessment through time in the wastewater utility and can also be used for benchmarking between utilities. Globally, data availability and reliability are low in wastewater systems. This lack of data is specially related to the few energy and flow measurements, gaps in inventory data, and few audits of measurement processes, among others. This conditioned knowledge about the systems functioning directly affects the calculation of metrics and the application of the PAS in a comprehensive manner. However, this should be interpreted as an opportunity for utilities to be aware of the data needs and of how much can be gained with better knowledge of the system performance. Overall, data are essential to improve performance and to take adequate decisions, and wastewater utilities need to make a considerable effort regarding data collection, reliability assessment, and processing. For this reason, it is important to identify the multiple uses for data to be collected to ensure that this effort in gathering data is valuable, as the context of each utility should be considered.

Regarding each objective and criterion, even if all are significant, when it comes to calculating metrics, each utility should establish priorities and select those that are relevant. The utility can benefit from comparing the results with other similar utilities.

Concerning some general priorities for action that can be applicable to a global set of utilities, there is evidence that Objective 1 is more comprehensive and can easily illustrate the overall performance of the systems. For example, if a utility has a high specific energy (M1.1.1), the percentage of pumps with acceptable efficiency (M1.1.7) should be analysed, and the audits process can be promoted. Also, in this case, it is important to analyse the results of the metrics related to the control of undue inflows (metrics from criterion 1.3).

On the other hand, if a utility is investing in energy self-production (M3.1.1), it is important to analyse the recovered energy (M3.2.1) and the percentage of total energy consumption from clean energy sources (M2.2.1). The latter also affects the metrics of Objective 2 and Criterion 2.1, which are important due to the international agenda and sustainability problems related to GHG emissions and carbon neutrality. Metrics from Objective 4 can be associated with a fourth priority, as this objective does not affect the main energy efficiency issue although it is extremely important in the assessment of the use of economic resources associated with energy. However, each wastewater utility should make this analysis considering their own context.

Finally, the analysis of energy efficiency in wastewater systems using a tailored PAS allows utilities to have a more holistic view of their systems' performance without being conditioned by the regulator performance assessment system, which is intended to be general and to use a limited number of metrics.

5.4 Conclusions

This paper presents a novel performance assessment system for energy efficiency in wastewater systems as well as the results from the validation and application of the PAS involving several Portuguese wastewater utilities willing to tackle this issue.

The main results for some selected metrics allowed assessing performance trends within the utilities and to compare with others. One of the main conclusions is that there is a global deficit of available and reliable data that significantly condition the PAS metrics calculations. However, each utility should consider their own scope and limitations to plan investments in data collection to gather necessary data to enable a proper diagnosis of the energy use. The confidence in the results should always be evaluated case by case to avoid the propagation of errors and reduce the associated uncertainty.

The tailored PAS focuses on the overall energy performance of hydraulic systems, allowing to assess the impact of undue inflows on the energy consumption and efficiency of wastewater systems as well as the opportunities to improve practices in operation and maintenance and GHG emissions, among other dimensions.

The application of the methodology was well received by the participating wastewater utilities, and the alignment with the other utilities methodologies was perceived as a significant benefit and presented good results in terms of testing and validation. As future work, it is of utmost importance to apply the proposed methodology to more case studies to proceed with reference-values fine tuning and to propose the remaining reference values. The application of the proposed PAS can be further explored for the selection of energy-efficiency solutions. Finally, it is of the utmost importance to ally the proposed PAS with specific energy balances that support the diagnosis of energy efficiency in wastewater utilities.

Chapter 6 – Water, energy, and emissions nexus in wastewater systems

This chapter corresponds to the research paper:

C. Jorge, M.C. Almeida, R.S. Brito and D. Covas (2022), *Water, energy, and emissions nexus: effect of inflows in urban drainage systems*. Water, 14(6), 868. https://doi.org/10.3390/w14060868.

Author contribution: The author co-developed the conceptual idea and the methodology and carried out the data analysis and investigation.

Abstract

The urban water sector significantly contributes to energy consumption and greenhouse gas (GHG) emissions. Detailed assessment of the wastewater system input provides opportunities for improving the water, energy, and emissions nexus. The inflow of water not requiring treatment into wastewater systems is acknowledged worldwide. These undue inflows can increase the footprint of these systems. Together with flooding and discharges, monitoring of undue inflows is not a common practice in wastewater utilities. Three levels of analysis are proposed to assess the magnitude of the impact of undue inflows in the water-energy-greenhouse gas (W-E-G) emissions nexus: at a national level, calculation of performance metrics using yearly data; at the utility level, performance metrics calculations using yearly, monthly, and sub-daily data; at the subsystem level, calculations using mathematical modelling. Results show the implications of undue inflows on energy and GHG emissions, including the effect of flooding and discharges. The importance of undue inflows in the W-E-G nexus is sustained by the results of three case studies in Portugal. Each level of analysis is tailored to the information available, allowing a step-by-step understanding of the relationship between water, energy consumption, and emissions of the urban drainage inflows.

Keywords: drainage systems, energy consumption, performance assessment, undue inflows, wastewater, water-energy-greenhouse gas emissions nexus.

6.1 Introduction

The relevance of the interdependence between water, energy, and greenhouse gas (GHG) emissions is widely acknowledged (Nair *et al.*, 2014; Chhipi-Shrestha *et al.*, 2017; Lee *et al.*, 2017; Singh and Kansal, 2018). An effective reduction in GHG emissions in all anthropogenic activities requires global and urgent action, as clearly stated in the latest IPCC report (IPCC, 2021). The environmental and societal burden of high energy consumption, heavily based on fossil fuels and increasing costs to consumers, is problematic in all sectors, the water sector not being an exception (Eurostat, 2021). Significant efforts are pursued to increase the use of non-fossil energy sources. Even so, the primary energy consumption (i.e., the total energy demand of a country) from fossil fuels in the world, North America, and Europe still correspond to a share of 84.3%, 81.7%, and 73.6%, respectively, values for 2019 (Our World in Data, 2021).

Many studies can be found on the water–energy nexus for water to energy production, but few exist on the energy for the water sector (Rothausen and Conway, 2011; Nair *et al.*, 2014). The latter often comprises the energy used for water heating having a relevant share (Rothausen and Conway, 2011; Plappally and Lienhard, 2012; IEA, 2016). The urban water sector has a substantial contribution to energy consumption and the production of GHG emissions. Opportunities to reduce the footprint on this nexus are also recognized, including the change in energy sources, the reduction in the specific energy consumption, the energy recovery, and emissions reduction (Environmental Agency, 2009; Rothausen and Conway, 2011; Loubet *et al.*, 2013; Elías-Maxil *et al.*, 2014; Nair *et al.*, 2014; Ballard *et al.*, 2018; Lam and van der Hoek, 2020). Global statistics, for the urban water sectors, are not readily available, given the sector ill-defined boundaries, a high number of actors involved, and intertwined issues (Rothausen and Conway, 2011; Nair *et al.*, 2014; Ananda, 2018). Broad information on the energy consumption share for the water sector is not currently available nor easy to find (IEA, 2016; Zib *et al.*, 2021).

The energy consumption for water has links to many areas in our society. Studies using life cycle assessment (LCA) provide a comprehensive picture of the water, energy, and GHG emissions nexus and are of value to support decision making accounting for their interdependencies (Rothausen and Conway, 2011; Loubet *et al.*, 2013; Nair *et al.*, 2014; Chhipi-Shrestha *et al.*, 2017; Singh and Kansal, 2018; Xue *et al.*, 2019). Challenges in these approaches are the scale of the studies, detail of the individual processes, and data reliability and compatibility (Loubet *et al.*, 2013; Chini *et al.*, 2018; Zib *et al.*, 2021). Figure 6.1 identifies the water sector processes, showing those managed by service providers in urban areas. Utilities managing drinking water (grey shade) and wastewater (blue shade) are not involved in the energy consumption related to all uses, for instance, uses inside the household (e.g., energy used for residential water heating has typically a high value (Plappally and Lienhard, 2012)). On the other hand, electricity distribution utilities do not have the means to separate the energy consumption fraction linked to water at end-users. Therefore, bridging the global versus processes assessments are essential to consolidate and clarify the context and scope of the different studies and promote a common language and approach.

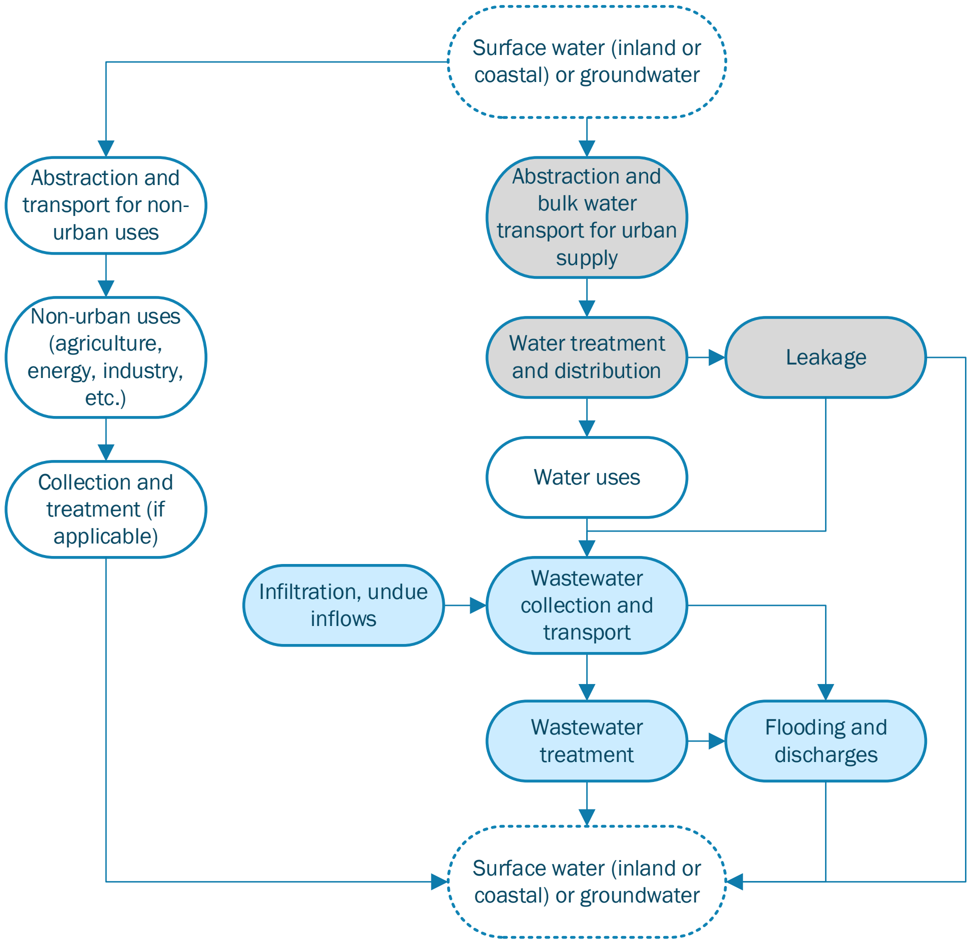


Figure 6.1 – Water sector processes managed by service providers in urban areas (shaded boxes).

The water supply and wastewater sectors, represented with grey and blue shaded boxes in Figure 6.1, respectively, have a significant energy footprint. These sectors are typically managed by water utilities (water supply and wastewater systems). Water losses and undue inflows have a direct influence on the system performance, including impacts on system processes' efficiency, total energy consumption, and associated costs (among other variables).

An estimate of energy consumption in this sector is presented by IEA (2016), based on average energy intensities by region for each process. The results provide a worldwide estimate of 120 Mtoe (million tonnes of oil equivalent) of energy (2014), of which 60% is consumed as electricity. This electricity consumption is equivalent to 4% of worldwide energy consumption. The remaining 40% are as fuel and natural gas. According to this publication, the energy associated with water losses or leakage is significant. The estimate for wastewater systems corresponds to 1% of worldwide energy consumption. Factors influencing the energy consumption are "the share of wastewater collected and treated, the groundwater infiltration and rainfall into the sewage system, the treatment level, the contamination level and the energy efficiency of operations". The reduction in inflows not requiring treatment is considered a way to reduce consumption. As an example, reported by IEA (2016), in Germany, wastewater, strictly defined, accounts for only 50% of the water treated in wastewater treatment plants (WWTP), the remaining 50% being undue inflows (UI).

Scenarios for energy consumption by the water supply and wastewater sector are of steady growth, even considering measures to reduce energy consumption in individual processes (Plappally and Lienhard, 2012; IEA, 2016). The deterioration over time of system components (e.g., pipes, manholes) contributes to the increase in inflows not requiring treatment.

Causes of these UI into wastewater systems are associated with groundwater infiltration, rain-derived inflows, among others (Jorge *et al.*, 2021c; 2022). Average values of undue inflows into wastewater systems reported for Norway, Denmark, Finland, and Sweden are between 30% and 80% (Jenssen Sola *et al.*, 2018), values estimated considering average dry weather flows and these authors discuss the uncertainty related to the methods used, also resulting from calculations using time-aggregated volumes, yearly.

The GHG emissions associated with energy consumption in the wastewater sector are substantial. Direct and indirect GHG emissions integrate CO_2 emissions related to energy consumption and others not linked to energy consumption, such as methane (CH4) and nitrous oxide (N_2O) emissions, mainly in wastewater systems (Rothausen and Conway, 2011; Lam and van der Hoek, 2020; Vasilaki *et al.*, 2020; Water UK, 2020). Specific data on the water, energy, and emissions nexus in the sector, reported for individual regions or countries, can be found in the literature (e.g., Rothausen and Conway, 2011; Nair *et al.*, 2014; IEA, 2016; Water UK, 2020; Zib *et al.*, 2021).

Within the urban water cycle, the water, energy, and emissions nexus has been analysed for the drinking water and wastewater sector, including embedded energy associated with leakage in water supply systems and UI (including groundwater infiltration and rain-derived inflows) in wastewater systems (Chhipi-Shrestha *et al.*, 2017; Singh and Kansal 2018). However, few detailed studies incorporating this issue were found (Chhipi-Shrestha *et al.*, 2017; Jenssen Sola *et al.*, 2018; Vasilaki *et al.*, 2020).

A knowledge gap is identified on the consideration of the UI and overflows, the latter either at overflow structures or flooding not returning to the system. It was found by Chhipi-Shrestha *et al.* (2017) that the infiltration and inflow to the sewer network are major contributors to the water footprint but did not account for overflows. The quantification of these undue inflows is complex and not carried out systematically. Few studies consider the implications of UI in the water, energy, and emissions nexus; when included, the issue is not approached comprehensively, and the relevance and uncertainties of UI are not recognized.

Previous studies on strategic and tactical assessments of wastewater utilities provide the background for proceeding with this analysis, looking at the water, energy, and emissions nexus (Almeida *et al.*, 2021a; Jorge *et al.*, 2021b). Results showed that service provision objectives are compromised by overflow discharges and surface flooding, even if not regularly quantified. A major cause for these events is the large volume of UI; the quantification of these volumes remains a challenge because of the limited measurements available in drainage systems. These studies addressed this issue, and metrics are proposed for direct and indirect estimation of the magnitude of UI. The latter includes assessing volumes' seasonality, confirmed by correlation with rainfall and allowed for some quantification of the magnitude of the problem. Seasonality of inflows to WWTP and seasonality related to rainfall confirmed the significance of UI volumes. The direct assessment was carried out for sub-catchments with continuous monitoring, allowing a better estimate of UI. Results regarding specific energy consumption, energy consumption per population equivalent, and specific GHG emissions (associated with total wastewater volume) ranged from poor to good performance, depending on the utility.

This paper analyses and discusses the use of energy by wastewater utilities and the respective GHG emissions, focusing on the effect of UI. A three-level approach for assessing the use of energy, based on data collection and analysis and performance assessment metrics calculation is proposed and applied to case studies. The assessment levels are specified depending on data availability and to allow applications accordingly. A detailed assessment is presented, providing a deeper insight into the water, energy, and greenhouse gas (W-E-G) components at the utility level. The effectiveness of measures to reduce UI and the associated energy consumption and emissions are discussed. Results show the implications of UI on energy consumption and GHG emissions, including the effect of flooding and discharges.

The paper presents the following novel contributions: (i) the discussion of the importance of UI volumes in treated wastewater, often overlooked, on the W-E-G nexus; (ii) the integration of overflows in the analysis; and (iii) the assessment of the magnitude of the problem using performance metrics including overflows, tailored to the information available.

6.2 Methodology

6.2.1 Context, scope and data

This paper focuses on energy for water, concentrating on the operation of the drainage subsector in urban, peri-urban, and rural agglomerations. This approach includes the blue shadowed components in Figure 6.1 (not accounting for the needs for construction or rehabilitation of new assets). End-use energy consumption is also excluded (e.g., residential pumping) since it is out of the direct control of the wastewater utility. WWTP were not included herein, although the methodology can be extended to incorporate other components, such as treatment processes.

For the emissions, only indirect CO_2 emissions related to energy consumption are included, since non-CO_2 emissions' broad estimations require data not available on a wider scale. The wastewater processes' non-CO_2 emissions are assumed to have minor variation associated with UI when compared to a situation with only wastewater inflows requiring treatment.

The CO_2 emissions associated with the energy consumed by the wastewater utility for the system operation are given by:

$$CO_{2\ emissions} = \sum_{i=1}^{n} E_i \times F_i \tag{6.1}$$

where E_i is the energy consumption associated with the type of energy i (kWh/year), F_i is the emission factor of the type of energy i (kgCO_2 eq/kWh), and n is the number of energy types. For Portugal, the emission factor used is 0.47 kgCO_2 eq/kWh according to legislation (Decree-law 71/2008).

The proposed approach to assess the impact of undue inflows on the W-E-G nexus is organized in three levels of analysis. The first is a national level assessment, using yearly public data. The second is a utility level assessment using available data from a subset of nine utilities, with a more detailed approach for yearly data, monthly data, and sub-daily measurements from sub-catchments. The third is the subsystem level assessment, using detailed calculations, including discharges and flooding, based on mathematical modelling.

The comprehensive assessment of energy consumption, emissions, and effect of UI for wastewater systems requires an integrated perspective considering the boundaries of the system and its components capacity (e.g., WWTP or pumping stations, PS) (Figure 6.2). This is especially relevant when estimating potential reductions impacting the W-E-G nexus. Even if measures to reduce UI are applied, these might not have an immediate impact on energy and emissions reduction. A reduction in energy consumption and GHG emissions can only be achieved when inflows are equal to or lower than the components' maximum capacity.

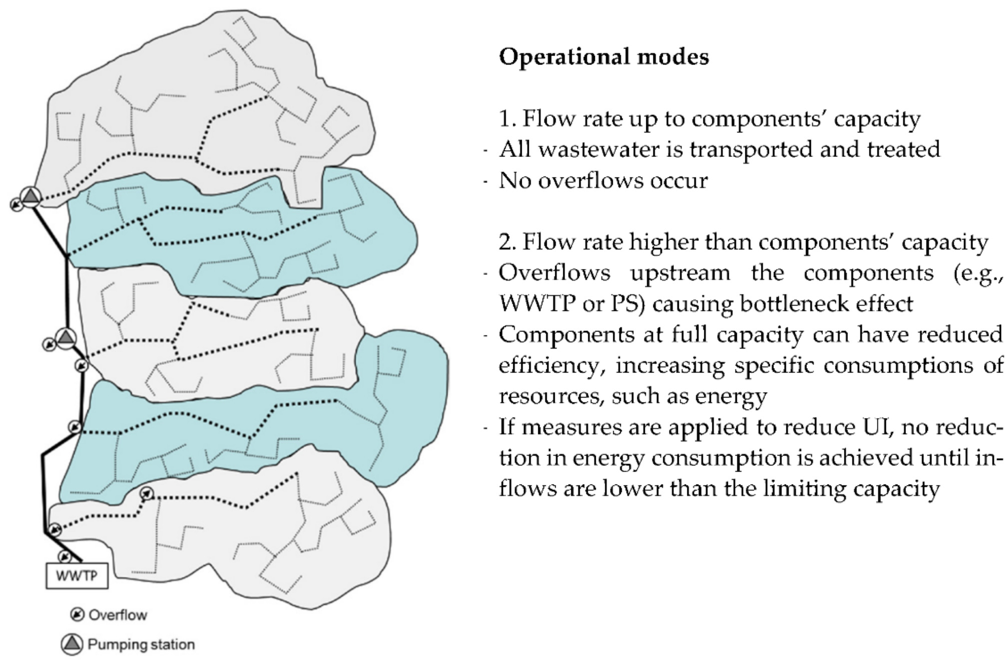


Figure 6.2 – Integrated view of the system.

6.2.2 Evaluation of the effect of UI on the W-E-G nexus

Specific and quantitative performance assessment metrics were proposed to obtain an evaluation of the W-E-G nexus that is essential to carry out a proper diagnosis and to support the application of improvement measures. These metrics were used for the three levels of analysis, as indicated in Table 6.1. Performance metrics (Pi) regard energy consumption (P1–P3), seasonality (P4–P7), effects of UI (P8–P10), and GHG emissions (P11–P14).

The selection of the reference values for P14 will be carried out in future work. Different reference values are used for type A (wastewater bulk transport and treatment) and type B utilities (collection and transport, sometimes including treatment) when justified. Good performance values are presented in green, fair performance in yellow, and poor performance in red in both Table 6.1 and the presentation of results. The description and formulation of the novel metrics proposed are detailed in Appendix A4 (Table A4.1).

Table 6.1 – Performance metrics to support evaluation of W-E-G components.

Performance Metric (Pi)	Description	Reference Values (**Good**; **Fair**; **Poor**)	Assessment Level
P1 Percentage of total energy consumption used for pumping (%) [1]	Energy consumption for pumping in relation to the total energy consumption	A: [0, 15];]15, 30[; [30, 100] B: [0, 5];]5, 40[; [40, 100]	National
P2 Percentage of total energy consumption used for WW treatment (%) [1]	Energy consumption for treatment in relation to the total energy consumption	A: [0, 5];]5, 50[; [50, 100] B: [0, 5];]5, 30[; [30, 100]	Utility
P3 Percentage of energy equivalent to the volume generated in the served area used for pumping (%) [1]	Total energy used to pump the total volume from the served area if there were no limitations on the transport capacity of the network upstream of the pumping installation	[95, 100]; [80, 95[; [0, 80[	Subsystem
P4 Inflows seasonality (−) [2]	Ratio between inflows in the 3 months with the highest volumes and those in the 3 months with the lowest volumes	[1, 1.25[; [1.25, 2.0[; [2.0, +∞[	Utility
P5 Inflows in periods with precipitation (−) [2]	Ratio between inflows in the 3 months with the highest rainfall and those in the 3 months with the lowest rainfall	[0, 2.0[; [2.0, 5.0[; [5.0, +∞[	Utility
P6 Energy consumption seasonality (−) [1]	Ratio between energy consumption in the 3 months of highest consumption and that in the 3 months of lowest consumption	[1.0, 1.75[; [1.75, 2.5[; [2.5, +∞[	Utility
P7 Energy consumption in periods with precipitation (−)	Ratio between energy consumption in the 3 months with the highest rainfall and that in the 3 months with the lowest rainfall	[1.0, 1.75[; [1.75, 2.5[; [2.5, +∞[	Utility
P8 Effect of UI in energy (−)	Ratio between energy consumption related with UI and with dry weather	[0, 2.0[; [2.0, 5.0[; [5.0, +∞[	Utility
P9 Effect of infiltration in energy (−)	Ratio between energy consumption related with infiltration and with dry weather	[0, 2.0[; [2.0, 5.0[; [5.0, +∞[	Utility
P10 Effect of rain-derived inflows in energy (−)	Ratio between energy consumption related with rain-derived inflows and with dry weather	[0, 2.0[; [2.0, 5.0[; [5.0, +∞[	Utility
P11 Specific GHG emissions associated with total WW volume ($kgCO_2\,eq/m^3$) [3]	Ratio between GHG emissions associated with the total energy consumption and the volume of wastewater collected or treated	[0, 0.2];]0.2, 0.34];]0.34, +∞[	National
P12 Specific GHG emissions associated with pumped volume ($kg\,CO_2\,eq/m^3$) [3]	Ratio between GHG emissions associated with the energy consumption for pumping and the pumped volume	[0, 0.27];]0.27, 0.34];]0.34, +∞[	Utility Subsystem
P13 Specific GHG emissions associated with wastewater treated volume ($kgCO_2\,eq/m^3$) [3]	Ratio between GHG emissions associated with the energy consumption for treatment and the volume of wastewater collected or treated	[0, 0.13];]0.13, 0.27];]0.27, +∞[	Utility
P14 Specific GHG emissions associated with volume generated in the served area ($kgCO_2\,eq/m^3$) [1]	Ratio between GHG emissions associated with the energy consumption associated with the total volume generated in the served area and the volume of wastewater collected or treated	-	Subsystem

[1] As proposed in Jorge *et al.* (2021b); [2] as proposed in Almeida *et al.* (2021a); [3] adapted from Jorge *et al.* (2021b) (the reference values were adapted to the current study, in P11-P13, considering an impact factor associated with the electric consumption of 0.47 $kgCO_2\,eq/kWh$ according to Decree-law 71/2008, for the Portuguese scope)

6.2.3 Assessment at a national level

At a national level, only annual and aggregated data are normally available. Two performance metrics were proposed at the national level (see P1 and P11 in Table 6.1).

Additionally, at this level, it is of utmost importance to analyse the reported energy consumption and volumes of wastewater collected or treated, as well as data from floods and discharges, even though these data are few and typically qualitative. All these variables were analysed graphically together with the annual rainfall data to assess the magnitude of the problem and to compute the correlation between variables.

6.2.4 Assessment at the utility level

At the utility level, a set of performance metrics was proposed in Table 6.1 to deepen the assessment concerning the impact of UI on energy. At this level, besides yearly data, monthly data is frequently available, allowing for the evaluation of seasonal variations, quite relevant in wastewater systems. However, monthly data can still dampen the analysis of the phenomena behind wastewater flows. Groundwater inflow, rain-derived surface flow and sanitary discharges, among others, show rapid sub-hourly variations, making it relevant to investigate sub-hourly data to quantify the undue inflow volumes and assess their impact on energy consumption and emissions. Besides infiltration and rain-derived inflows, several other UI (e.g., saline waters) can occur. If so, the corresponding metrics can be included, such as P9 and P10 in Table 6.1.

Among the metrics applicable at the utility level, four (P4–P7) use monthly wastewater volumes, energy consumption or precipitation data and can be applied to utilities that already monitor monthly volumes downstream from the entire system or sectorial drainage basins. Whenever detailed monitoring is available, upstream of a PS or a WWTP, the complementary three metrics (P8–P10) can be calculated, using sub-daily flow and precipitation data. For metric P9, sub-daily data on dry and wet weather seasons is required. For metric P10, detailed data on several precipitation events is required.

To calculate the global volume of undue inflows, it is necessary to process the daily flow patterns from the hourly flow and precipitation data. Calculation of the specific undue inflows (infiltration and rain-derived inflows) requires 15 min interval (or less) data on flow and precipitation, as in Almeida *et al.* (2021b).

Metrics P3 and P14 use measurements of the discharges and overflows that occur in the system, allowing a comprehensive assessment of the actual volumes that are, at some point, transported in the sewers. Since discharged and overflow volumes are often unavailable for the complete system operated by the utility, a more detailed assessment is not proposed, but can be included whenever such data are attainable. Such detailed assessment is proposed at the subsystem level.

6.2.5 Assessment at subsystem level

At a subsystem level, the identification of the impact of UI in energy consumption at PS or WWTP is very important and benefits from adopting an integrated analysis, including processes, such as flooding and discharges. The integrated analysis is essential to assess the advantages of acting in UI to reduce energy consumption and GHG emissions. For this purpose, the total equivalent energy associated with the drainage basin upstream of a PS can be calculated. This energy is the total energy needed to pump the entire volume generated in the region if there were no limitations in the network transport capacity upstream of the PS. It corresponds to an estimate of the energy consumed if no discharges and floods occur and the entire volume generated is pumped (Jorge *et al.*, 2021a; Jorge *et al.*, 2021c; 2022).

Specific energy associated with UI suggests a substantial energy-saving potential by improving and investing in the control of UI, particularly in these systems located upstream of PS and WWTP. This study intends to raise awareness of wastewater utilities about the energy savings potential from reducing UI, being fully effective only when exceedance volumes are negligible, as referred to in Figure 6.2.

This approach looks at the entire system upstream to assess the effect of UI on a PS and allows a better interpretation of the benefits associated with inflows reduction. It also highlights the importance of measuring flows at discharge structures because of their environmental effect and impact on energy consumption and emissions.

To estimate the energy consumption associated with the exceedance volumes (discharges and floods), a simplification based on an average unit energy consumption was adopted. Thus, the total equivalent energy consumption, E_{Teq}, is given by:

$$E_{Teq} = V_{Tb} \times E_U \tag{6.2}$$

where V_{Tb} is the volume generated in the PS served area in the period of analysis (m^3), and E_U is the unit average energy consumption per unit of volume (kWh/m^3). The calculation of E_U is based on the actual energy intensity, i.e., the consumption per pumped volume. As a simplification, the PS efficiency is assumed to be constant.

The method for UI impact assessment in the energy consumption of PS is composed of four steps (Jorge *et al.*, 2021a):

(i) Characterization of the reference situation, i.e., system behaviour for dry weather.
(ii) Analysis of the effect of an energy-saving measure focusing on the control of undue inflows, namely the reduction in undue rain-derived inflows to separative wastewater system considering scenarios of 100%, 75%, 50%, 25%, and 10% reduction.
(iii) Analysis of the effect of an energy-saving measure focusing on the control of undue inflows, namely the reduction in groundwater inflows infiltration considering infiltration rates of 100%, 75%, 50%, 25%, and 10% of the daily dry weather volume, uniformly distributed by the total sewer extension.
(iv) Performance assessment based on selected metrics to support evaluation of W-E-G components by the utility as presented in Table 6.1: P3, P12, and P14.

This procedure can be used for any installation (WWTP, PS, or other energy-consuming assets) using flow measurement data or mathematical modelling, as in the present study. Alternative simplified approaches can be used (Jorge *et al.*, 2021a).

6.3 Case studies

At a national level, the analysis of the data reported by the wastewater utilities to the Portuguese regulator (ERSAR, 2016; 2017; 2018; 2019; 2020) was analysed. This Portuguese regulatory system for services assessment is compulsory for all water, wastewater, and waste services providers and annual data is publicly available.

In the Portuguese wastewater sector, the same utilities handle wastewater bulk transport and treatment (type A utilities) and others the collection and transport, sometimes including treatment (type B utilities). There are 12 type A and 269 type B Portuguese wastewater utilities. The analysis for all the 281 utilities was carried out yearly for the 5-year period 2015–2019. For this level, rainfall data used to characterize dry and wet weather were provided by the Portuguese meteorological institute (IPMA, 2021).

At the utility level, the approach was applied using data provided by nine utilities (Almeida *et al.*, 2021b) representative of the Portuguese wastewater sector. Wastewater systems present different dimensions and contexts, as in Table 6.2. Characteristics of the systems were provided for context purposes. The type of system is frequently used to compare utilities.

Table 6.2 – Characteristics of systems used in evaluation at utility level.

Utility	Served Area and Type of System	Sewer Length (km)	PS (n.)	WWTP (n.)
1	Mostly rural, A	32	3	23
2	Mostly rural, A	447	192	65
3	Mostly rural, B	546	66	9
4	Mostly rural, A	1498	380	176
5	Averagely urban, B	1539	85	16
6	Mostly urban, B	977	26	16
7	Mostly urban, B	55	2	0
8	Averagely urban, B	444	17	1
9	Mostly urban, B	619	0	0

Three utilities are type A and six are type B utilities. Provided information includes monthly data from 2015 to 2019 and detailed sub-hourly data from measurement campaigns during 2020. These data were previously processed, dry weather flow patterns were determined, and undue inflows were characterized (Brito *et al.*, 2022). For this level, rainfall data used to characterize dry and wet weather were collected by the utility's rainfall meters.

At the subsystem level, this approach was applied to a case study based on an actual wastewater separate system at Venteira, Amadora, Portugal. Mathematical modelling of scenarios used the SWMM software (version 5.1, USEPA). Venteira is a real system and the model used was built using real inventory data, measured flows, and precipitation data, both in dry and wet weather. A pumping station, Ps, was included at the downstream end of the system, ensuring that downstream conditions would not influence the upstream operation.

The model of the case study was calibrated and validated in a previous study (Cardoso *et al.*, 2016) and adapted to the present application. As input data for characterization of the reference situation, a dimensionless dry weather flow pattern and the average sanitary flow volume corresponding to the population in the basin were used. For the simulation of rainfall scenarios, a precipitation event was used

(Figure 6.3b). For the simulation of infiltration scenarios, total dry weather daily volume was used (Figure 6.3a) as a reference and a uniform distribution of the corresponding infiltration throughout the sewer network was considered, as previously described. The downstream pumping station, Ps, has a manometric head of 3.00 m and an associated weir.

The sewer length is 2.6 km, sewer diameters vary between 200 and 500 mm, and the PS is at the system downstream end. The model includes seven sub-catchments, with a total area of 0.25 km^2. The total daily dry weather volume is 2 380 m^3 and the unit infiltration volume varies from 0.089 to 0.893 m^3/m for the simulated scenarios (Jorge *et al.*, 2021a). The network scheme of Venteira is presented in Figure 6.3c.

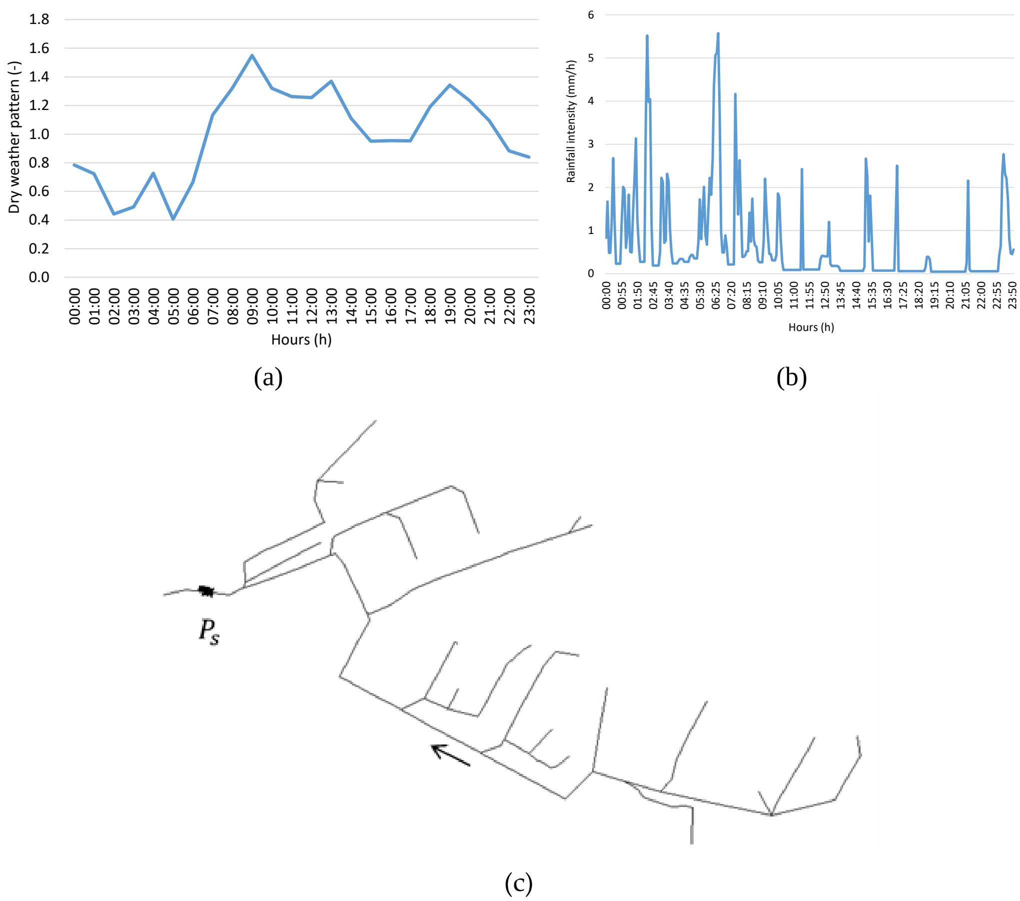


Figure 6.3 – Venteira case study: (a) daily dry weather pattern, (b) rainfall event, and (c) network scheme.

6.4 Results and discussion

6.4.1 W-E-G nexus at national level: the case of continental Portugal

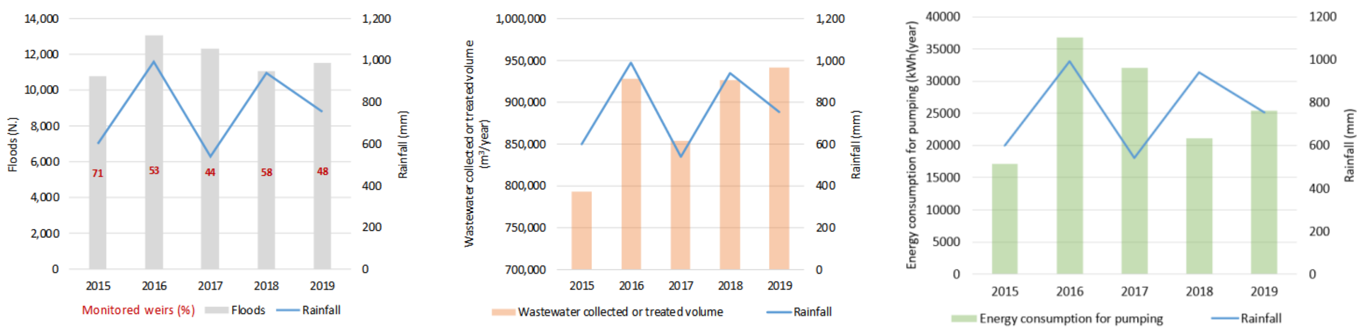
Results for the assessment of the W-E-G nexus at the national level are presented in Figure 6.4 and Figure 6.5, respectively, for the analysis of the Portuguese regulator data and the performance metrics. These data have associated quality assurance procedures. In the last decade, the Portuguese regulator ERSAR has carried out the application of the quality of the service evaluation accompanied by audits to all water utilities. This yearly procedure feeds an information system publicly available including several measured operating quantities. These data have adequate reliability to be used for the national assessment level proposed in the methodology.

Detailed information is in Appendix A4 (Tables A4.2–A4.6). Both Figure 6.4 and Tables A4.2–A4.6 results are for 5 years (2015–2019) and for 12 type A and 269 type B Portuguese wastewater utilities. Values shown are the medians of the 281 wastewater utilities.

The combined analysis of the yearly data on wastewater collected or treated volumes, energy consumption, rainfall, discharges, and floods allow to identify evidence of inflows associated with the occurrence of precipitation and their impact on energy consumption. Results of this analysis show, for all years, that the increase in energy consumption, collected or treated wastewater volumes, and the number of floods, are aligned with the variation in precipitation (Figure 6.4a–c). Although with limitations in the reliability of this raw information, the impact of undue inflows on these variables is significant even with this aggregation of data.

The implications of UI are important in terms of untreated discharges and floods, as well as in the overall high volume of wastewater, with a direct impact on energy consumption. The wastewater collected or treated volume has a strong correlation with rainfall (Pearson coefficient $r = 0.76$), especially considering that a part of the rain-derived inflows does not reach the outlet of the system, being discharged during transport or upstream of measurement devices. This observation also applies to the correlation of the monitored weirs with floods, which have a significant negative correlation (Pearson coefficient $r = -0.64$). The latter implies that the occurrence of discharges and floods should also be evaluated jointly because floods can result from the non-existence of an emergency weir, for example, at pumping stations. Depending on the system and available monitoring data, this causal relationship between the occurrence of discharges, floods, and precipitation can be challenging to characterize. The absence of monitoring on discharge structures, as shown by the percentage of unmonitored structures (Figure 6.4a), implies an underestimation of the occurrences. In this context, it is strongly advisable to improve the monitoring at discharge structures and to upgrade the system maintenance and rehabilitation to reduce overall effects and data reliability.

At national and utility assessment levels, some wastewater utilities have older parts of the systems as combined, but in these cases, interceptors divert wastewater flows for the WWTP. The values used for calculations relate to the wastewater part of the system and corresponding overflows of untreated water. Flows not diverted to the WWTP are directly discharged to receiving waters or stored and treated later. In this way, evaluation of the impact on the wastewater systems is carried out even when a part of the system is combined. Furthermore, given the obligation of treating wastewater flows, in combined systems, this approach is important to evaluate the impact of excessive inflows reaching the WWTP both in dry weather and wet weather. It is important to emphasize that, because of the occurrence of overflow upstream energy consuming components, these volumes are not accounted for in wastewater collected or treated volumes. The methodology generally applies to free surface sewers. In Portugal, most wastewater systems are free surface sewers. Pressure conduits are limited to pumping systems and vacuum systems are only used in small systems not being representative of the country-wide reality. Pressure and vacuum sewers might exist, but in these cases, the vulnerability to rain-derived and infiltration inflows is considerably low. In sewers with free surface flow, although there is some capacity to accommodate part of the UI when these are high, they can cause overflows in manholes, which can cause floods. With PS and WWTP, the capacity to accommodate undue inflows is usually lower. These components are normally equipped with emergency weirs to prevent flooding of the facilities and to protect electromechanical equipment and treatment processes, when volumes are excessive, or to use temporarily, in case of repair or maintenance activities.



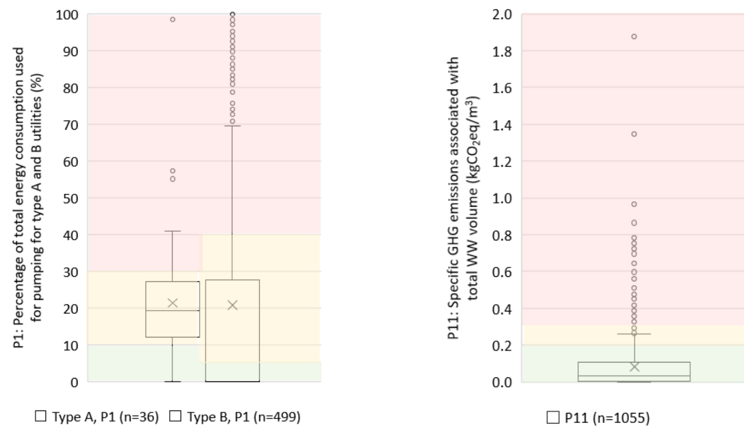
(a) (b) (c)

Figure 6.4 – National characterization for the evaluation of the W-E-G nexus: (a) floods, monitored weirs vs. rainfall, (b) wastewater collected or treated volume vs. rainfall, and (c) energy consumption for pumping vs. rainfall.

Results for the metrics P1 and P11 are presented in Figure 6.5. The background colours derive from the classification according to the proposed reference values. Green stands for good performance, yellow for fair performance, and red for poor performance.

Wastewater bulk transport and treatment systems (type A) consume significantly more energy than collection and transport systems (type B), given the higher number of PS and WWTP. These characteristics increase their energy consumption per cubic meter of collected or treated wastewater, as well as of specific GHG emissions. Additionally, type A utilities are frequently more penalized because of the high UI received from type B utilities. Therefore, it is expected that the proportion of the pumped volume is higher in type A utilities and reference values are more restricted (Figure 6.5a). In terms of performance, at a national level, both types of utilities have balanced performance, as both average and median results for P1 achieve a fair performance.

Regarding P11 (Figure 6.5b), performance is better, with average and median values of specific CO_2 emissions achieving good performance. However, as explained before, it is important to highlight that the total wastewater volume does not account for overflows, and both energy consumption and wastewater volume are biased by this phenomenon.



(a) (b)

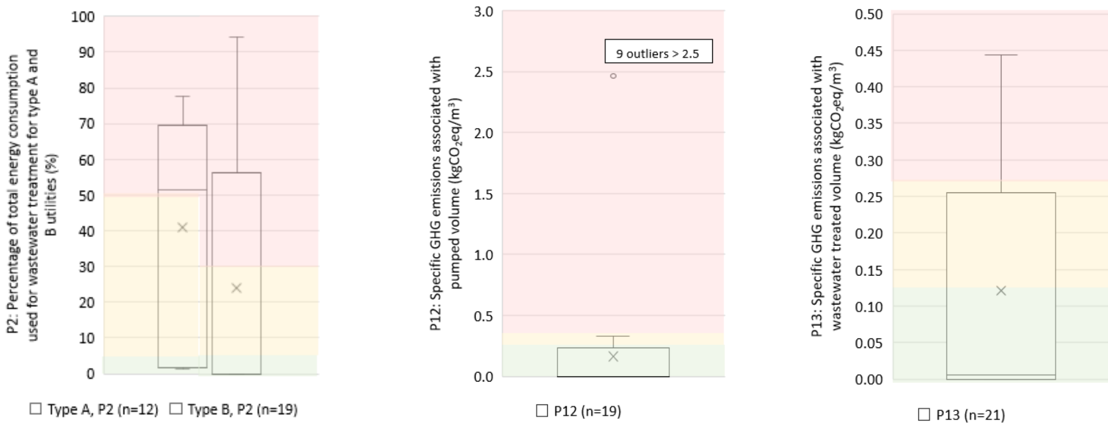
Figure 6.5 – Results of evaluation at national level for (a) percentage of total energy consumption used for pumping (P1) for type A utilities (left) and type B utilities (right) and (b) specific GHG emissions associated with wastewater treated volume (P11).

6.4.2 W-E-G nexus at utility level: the case of nine Portuguese utilities

The metrics were calculated using the data from the utilities. At the utility level, the results presented originate from measurement locations that were audited by the research team using European standards, to have a measure of the reliability of the data used.

Results for metrics P2, P12, and P13 are presented in Figure 6.6 for the five years. A graph for each type of utility is presented for metric P2 because reference values are different for type A and type B utilities.

Metric P2 results show that a fair percentage of energy is consumed in WWTP processes. GHG emissions are higher in wastewater treatment (P13) than in wastewater pumping (P12). If a comparison with annual volumes can be made, utilities can carry out a preliminary assessment using only yearly data, even if more disaggregated information is unavailable.

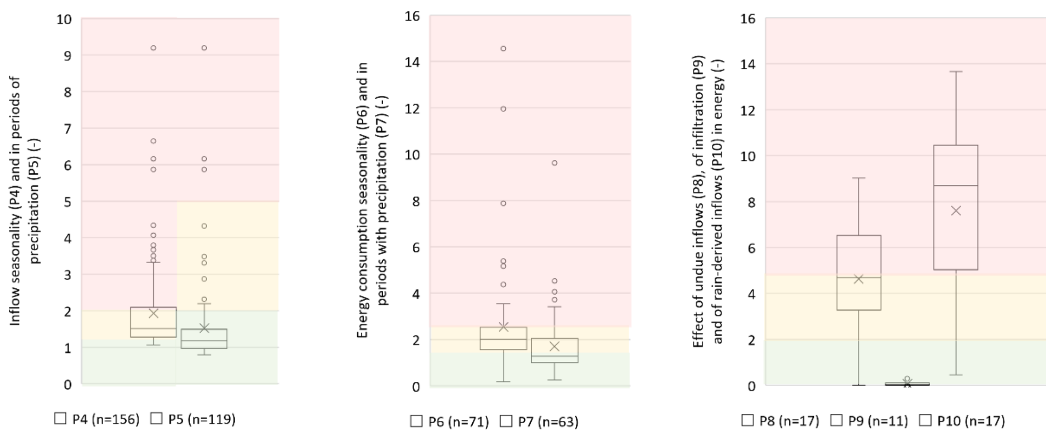


(a) (b) (c)

Figure 6.6 – Results of evaluation at utility level for (a) percentage of total energy consumption used for WW treatment (P2) for type A (left) and type B utilities (right), (b) specific GHG emissions associated with pumped volume (P12), and (c) specific GHG emissions associated with wastewater treated volume (P13).

Metrics P4-P7 were calculated for many sub-systems, defined by a downstream boundary (PS or WWTP). Data simultaneity is also a constraint, such as for metric P8, for which monthly precipitation and energy data must be available for the entire year to enable metric calculation. Metrics P4-P7 were calculated for 63 up to 156 locations (n in Figure 6.7a,b). For metrics P8-P10, since they require very detailed information (data acquisition with less than 1 hour time steps, and sometimes, simultaneous rainfall records), it is only possible to apply the calculation procedure to the locations where the utilities installed rain gauges, collected a representative data sample, and proceeded with adequate and comprehensive data processing (according to Brito *et al.*, 2022). It is important to highlight that the confidence in the results depends on the uncertainties of various sources, namely the data acquisition and processing system (Brito *et al.*, 2022). Furthermore, including broader approaches, requiring less detailed data, is very important to allow utilities with fewer resources to carry out the diagnosis, leveraging the implementation of a continuous improvement process.

Data between 11 and 17 measurement locations are available for this set of metrics (Figure 6.7c). Box and whisker plots present the statistics of the results in Figure 6.7.



(a) (b) (c)

Figure 6.7 – Results of evaluation at utility level for (a) inflow seasonality (P4) and inflows in periods with precipitation (P5), (b) energy consumption seasonality (P6) in periods with precipitation (P7), and (c) effect of undue inflows (P8), of infiltration (P9), and of rain-derived inflows (P10) in energy.

Seasonality refers to the variations along the different seasons or times of the year, being a very important dimension to understand the impact of rain-derived inflows in wastewater systems. Inflow seasonality is confirmed by the P4 results and, even though in most cases performance is fair, most seasonality can be explained by rain-derived inflows (P5). Energy consumption also presents a marked seasonality (P6), and it looks as if consumption in periods with precipitation (P7) relate closer to overall seasonality. These results suggest undue inflows can be strongly related to yearly variations in energy consumption.

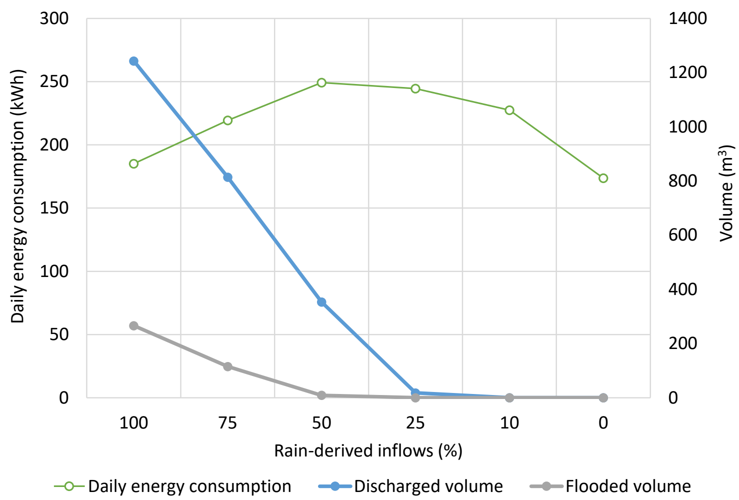
When the basis is sub-hourly data, it is possible to observe that undue inflows have a marked influence on energy consumption, increasing from 4 to 7 times the consumption associated with wastewater (P8). Infiltration seems to have a lower influence (P9) than rainfall (P10). Rain-derived inflows increase from 5 to 10 times the energy consumption associated with wastewater during rain events in most locations. Conclusions regarding the contribution to GHG emissions (P9 and P10) have the same trend.

6.4.3 W-E-G nexus at subsystem level: the Venteira case study

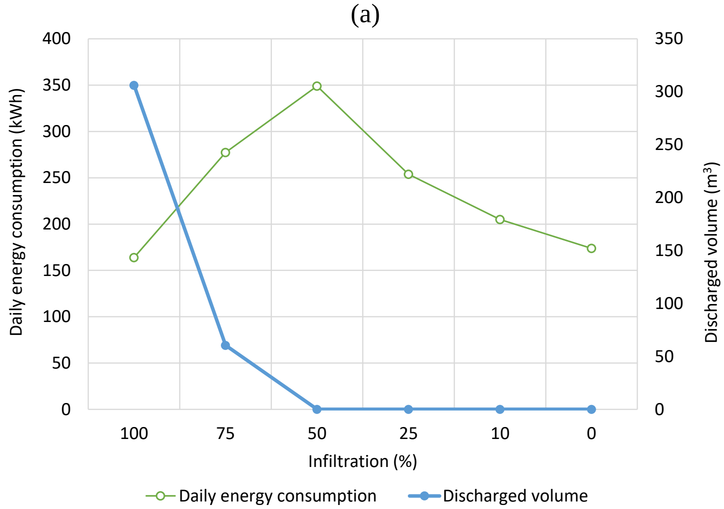
At the subsystem level, the analysis of the UI impact in the system is carried out by observing the evolution of the relevant variables, such as the energy consumption in the PS and volumes discharged and flooded upstream of the PS, as shown in Figure 6.8. Figure 6.8a,b shows that the daily energy consumption increases with rain-derived inflows and infiltration up to a certain point (i.e., 50%), and then, decreases. This decrease follows the start of a discharge because of the capacity limitation of the PS and it becomes more explicit when flooding begins. This phenomenon demonstrates that what is really reducing is the volume that leaves the system due to the systems' limiting capacity (as overflows). Only after these overflows are eliminated, will the reduction in undue inflows impact the energy consumption.

The initial increase in energy consumption is related to the overall pump operation (e.g., pump operating time and number of start-ups), which does not depend only on the inflow volume. It was assumed that these overflows do not re-enter the system.

This analysis shows that the assessment of the UI impact on energy performance is biased by other performance problems (i.e., discharges and floods) in the system and, if they are not included, it leads to an incomplete assessment of the problem. Therefore, energy-saving measures focusing on the reduction in UI considering only measured volumes (a realistic situation, since there are few flow measurements or mathematical models for this type of system) are insufficient, being difficult to have a noticeable impact of UI reduction in energy consumption or emissions. Measures implemented will first impact the reduction in overflows until the transport capacity of the critical components is reached (because of capacity exceedance), and only after additional reductions in UI will the effect on energy consumption and emissions be achieved.



(a)



(b)

Figure 6.8 – Impact of UI in energy consumption and in discharged and flooded volumes associated with (a) rain-derived inflows and (b) infiltration (no flooding occurrence).

This method also contributes to determining, for each specific case, the minimum reduction in UI from which an impact on energy consumption and emissions can be observable. In the present case study, the analysis of the results in Figure 6.8a shows that, for rain-derived inflow, starting from a situation where 100% of the area is contributing, it would be necessary to reduce by 25% the area connected to the wastewater separative system to have a significant impact on energy consumption and emissions. For infiltration, a minimum reduction of at least 50% of the average daily dry weather volume would be necessary (Figure 6.8b). It should be noticed that infiltration rate was considered constant for the present case study as a necessary modelling simplification; for longer time periods and when the main objective is to quantify these inflows, infiltration should be characterized over time.

Figure 6.9 shows the results for the total equivalent energy consumption, for the rain-derived inflows and infiltration scenarios and the comparison with the dry weather reference situation. These results reinforce the need to consider the volume generated (wastewater and overflows) upstream of the PS, clarifying that the impact of reducing UI on energy consumption will only be effective for reductions higher than those typically perceived (because usually volumes are measured in the PS and not further upstream). For the scenario of 100% contribution of rain-derived inflows, the calculation of the equivalent energy showed that energy consumed increases to more than double when compared with the dry weather situation. The same trend is observed in the infiltration scenario.

The results confirm the growth of energy consumption with increasing UI volume, the relevance of an integrated analysis of the effect of these inflows for different systems and the importance of assessing the potential impact of UI control measures in energy-saving and emissions.

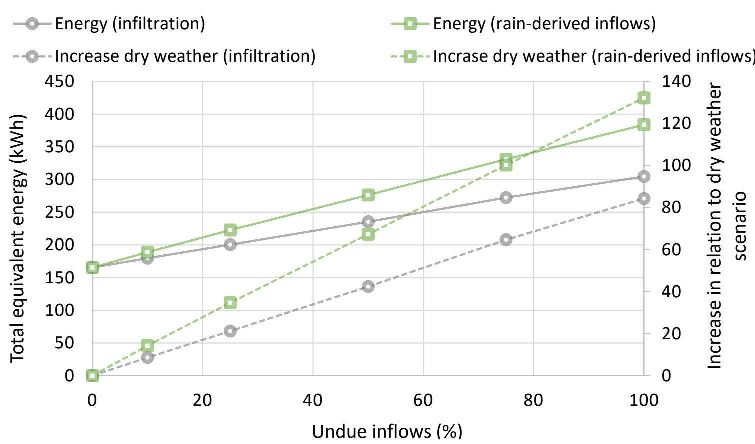


Figure 6.9 – Total equivalent energy consumption for the different UI scenarios.

To sum up, it is possible to assess more robustly the impact that UI have on the energy consumption and on GHG emissions of the systems, showing opportunities for actions in this area.

As previously presented, a set of performance metrics is proposed, to detail this assessment at the subsystem level (Table 6.1). For the present case study, three performance metrics were applied, namely: P3 – percentage of energy equivalent to the volume generated in the served area used for pumping (%); P12 – specific GHG emissions associated with pumped volume ($kgCO_2$ eq/m^3); P14 – specific GHG emissions associated with volume generated in the served area ($kgCO_2$ eq/m^3). Results are presented in

Table 6.3 for both analyses (rain-derived inflows and infiltration) for the several scenarios (corresponding to 100%, 75%, 50%, 25%, and 10% of reduction). Results for the reference situation (dry weather) are also presented. Good performance values are presented in green, fair performance in yellow, and poor performance in red.

Table 6.3 – Results for P3, P12, and P14 performance metrics for the subsystem level.

Scenario/Performance Metric	**P3 (%)**	**P12 (kg CO_2 eq/m^3)**	**P14 (kg CO_2 eq/m^3)**
Rain-derived inflows (% of inflowing)			
100%	61 🔴	0.022 🟢	0.036
75%	75 🔴	0.027 🟢	0.036
50%	90 🟡	0.033 🟢	0.037
25%	99 🟢	0.036 🟢	0.037
10%	100 🟢	0.040 🟢	0.040
0% (dry weather)	100 🟢	0.035 🟢	0.035
Infiltration (% of daily dry weather volume)			
100%	86 🟡	0.019 🟢	0.022
75%	98 🟢	0.034 🟢	0.035
50%	100 🟢	0.049 🟢	0.049
25%	100 🟢	0.042 🟢	0.042
10%	100 🟢	0.038 🟢	0.038
0% (dry weather)	100 🟢	0.035 🟢	0.035

In the scenario of rain-derived inflows, P3 shows good performance only when implementing energy-saving measures leading to 25% of rain-derived inflows. For rain-derived higher than 25%, the volume of the overflows is higher, creating a discrepancy between the energy consumption for pumping and the energy consumption associated with the total volume generated in the served area. For the scenario of infiltration, the effect is smoother, being necessary to implement measures leading only to 75% of infiltration to achieve good performance.

Regarding P12 and P14, there is no strong trend observed since the decrease in the energy consumption and in the volumes are not proportional. For P12, values show good performance, but the reality at the subsystem level significantly differs from a broader level in which the reference values were established. P14 has no judgment about performance since few studies exist to set reference values.

6.5 Conclusions

The importance of the UI volumes of treated wastewater for the W-E-G nexus, often overlooked, was made clearer. Rain-derived inflows and groundwater infiltration from cracks or joints result in a flow rate increase in the wastewater separative system, reducing the available capacity and increasing transport, pumping and treatment costs. The relevance and implications for energy consumption and GHG emissions were shown in the three levels of analysis. Even at an aggregated level, the combined analysis of the yearly data on wastewater volumes, energy consumption and rainfall showed the relation between rain-derived inflows and energy consumption.

The need to integrate the systems' exceedance in the analysis, resulting in discharges and flooding, was emphasized. The importance of having a three independent levels approach was demonstrated, allowing utilities with scarce data to tackle this issue and have an available approach to make some progress. This kind of approaches are truly relevant, since the wastewater subsector still faces a significant problem related to data availability and feasibility (e.g., installing data collection equipment as well as implementing robust and calibrated hydraulic models). At a national and utility level, the relation between flooding and discharge occurrences and higher rain-derived inflows was not always obvious, because of insufficient monitoring of overflows. However, at a utility level, it was possible to cascade down the analysis with more detailed data, and a strong relation between seasonal undue inflows and energy demands was found and quantified. An increase of four to seven times in energy consumption and GHG emissions because of overall undue inflows was observed. This increases to 5–10 times during rain events because of rain-derived inflows. In the case study utilities, infiltration has lower influence.

At a subsystem level, it was possible to quantify the impact of reducing UI, making clearer the benefits on energy consumption and GHG emissions, with a due quantification of flooding and discharges. Additionally, a way to select a target for UI reduction was presented. In the case study, energy consumption and GHG emissions would reduce when rain-derived inflow is cut down to 25% or when infiltration is cut down to 50%.

Interconnections between urban drainage systems and poor assets condition, together with low maintenance, are bound to be the origin of undue inflows and of the undesirable flooding and discharges upstream of PS and WWTP, with consequences on public health, safety, the environment, economic performance, and quality of service. Acting on the causes of UI, including the improvement of asset condition, is a labour and resource-intensive task, and utilities need to understand the medium-term benefits of such investments. Acting in UI control only envisaging reduced energy consumption might not lead to the expected result. Initially, there will be a decrease in discharged or flooded volume and only later will the impact be reflected in the reduction in high volumes and, consequently, in the associated energy consumption.

Globally, data availability and reliability are low in wastewater systems. The conditioned knowledge directly affects the calculation of performance metrics, so these metrics should be adapted to the existing data. The proposed methods to assess the magnitude of the problem are suited to different maturity levels of the utilities and are applied to the entire system, including overflows. The simplifications presented in the assessment levels are based on reasonable assumptions and practical experience of working with wastewater utilities. The methodology provides a way to quantify the actual performance and to assess the potential and effectiveness of measures thus positively contributing to decision making.

Results show an additional opportunity for utilities to get return from investments on monitoring. Overall, data are essential to support management decisions and to improve system performance. Further research should focus on adapting and extending the proposed methodology to different case studies and to the reality of other countries. The application of the most detailed parts of the methodology requires having reliable data with less uncertainty and collected with shorter acquisition time by monitoring systems, allowing to reduce the results uncertainty.

Chapter 7 – From assessment to a decision: a global framework to manage energy use in wastewater systems

This chapter corresponds to the research paper:

C. Jorge, M.C. Almeida and D. Covas (2022), *From assessment to a decision: a global framework to manage energy use in wastewater systems*. Submitted to International Journal of Environmental Science and Technology in September 2022.

Author contribution: The author co-developed the conceptual idea and the methodology and carried out the data analysis and investigation.

Abstract

This paper presents a global framework to assess the energy use and efficiency in wastewater systems, 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 the analysis of the portfolio of measures were carried out according to the following steps: (i) an extensive review and compilation of existing energy use improvement measures on the urban water cycle, (ii) a tailored survey addressed to multidisciplinary 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 improvement measures. Results from the survey for the different assessed dimensions (e.g., priority, importance, applicability, and implementation) of each measure are presented as well as a specific analysis of wastewater utilities real cases. The final portfolio of measures is instrumental for wastewater utilities to select the measures, to decide which are the priority ones and to prepare an implementation plan.

Keywords: energy efficiency, energy use, improvement measures, portfolio, wastewater systems.

7.1 Introduction

Nowadays, the management of energy use is essential in urban water systems, as the efficient use of energy is associated with the environmental and economic sustainability of these systems (Bylka and Mroz, 2019). The International Energy Agency (IEA) reports that 4% of the worldwide energy is used by the water sector and 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 water sector (UN, 2014; IEA, 2019). Therefore, reducing energy use is a priority in the management of urban water systems (Gómez *et al.*, 2018).

The need to increase the use of energy efficiency measures is of the utmost importance to achieve a consistent reduction of energy consumption and greenhouse gas (GHG) emissions. A clear understanding of such energy efficiency 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). Thus, energy solutions, 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 (Martin and Grossmann, 2015; Nazemi *et al.*, 2015; Antonello *et al.*, 2016; Pérez-Sánchez *et al.*, 2017; Ananda, 2019; 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). Replacing existing with more efficient pumping systems can save about 20% of energy (Greenberg, 2011). Improving pumping systems 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 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% to 20% energy savings (EPRI, 2009). The installation of variable frequency drives to control the pump speed also allows for improving the energy performance of the system (Nogueira Vilanova and Perrella 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 (Trianni *et al.*, 2014). The use of renewable energy sources, (e.g., solar and wind energy) significantly improves the performance of urban water systems (Trianni *et al.*, 2014).

In general, there is a lack of a systematic understanding of the relationship between the energy efficiency diagnosis and assessment and the identification of energy solutions, especially for the wastewater subsector, where limited data exist. To bridge this gap, previous studies (Jorge *et al.*, 2021b; 2022) were developed to allow the identification of the main energy inefficiencies in wastewater systems. A novel energy balance was proposed, tailored to transport processes and types of flows of wastewater systems as well as 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, taking into consideration the existing methodologies, the long-term objectives for energy efficiency, and the identified knowledge gaps (Jorge *et al.*, 2021b).

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

The present paper aims at proposing a portfolio of measures to improve energy use tailored to wastewater systems, considering the 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 the tailored portfolio of energy use improvement measurements for wastewater systems and the integration of this portfolio in a comprehensive energy efficiency framework, innovatively adopting a holistic view of the energy efficiency in wastewater systems.

7.2 Background and proposed framework

The focus of the paper is 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, such as infrastructure asset management (IAM) (Alegre and Covas, 2010; Almeida and Cardoso, 2010) and ISO 5000x standards (IPQ 2012; ISO 2014a; 2014b; 2014c). 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 infrastructure asset management, adaptation to climate change, control of water losses, control of undue inflows, or energy management. This type of planning path was initially proposed to provide water utilities with the know-how and tools needed for efficient decision-making in infrastructure asset management of urban water services (Alegre and Covas, 2010; Almeida and Cardoso, 2010).

Typically, water utilities should carry out the steps presented in Figure 7.1a in any planning process. In Portugal, the legislation requires (Decree-law 194/2009) utilities serving over 30 000 inhabitants to produce an IAM plan. At each level, a diagnosis based on a pre-defined performance assessment system, using available information, 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.*, 2021a).

A global framework for assessing energy use and efficiency in wastewater systems is proposed and schematically presented in Figure 7.1b, aligned with the planning process (Figure 7.1a). 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 performance assessment system. These two tools support the selection of measures to improve energy use, attending to the specificities of each system and the overall management objectives, 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 perform a structured assessment for long-term time horizons. The novel contributions of this paper are highlighted in bold in Figure 7.1b.

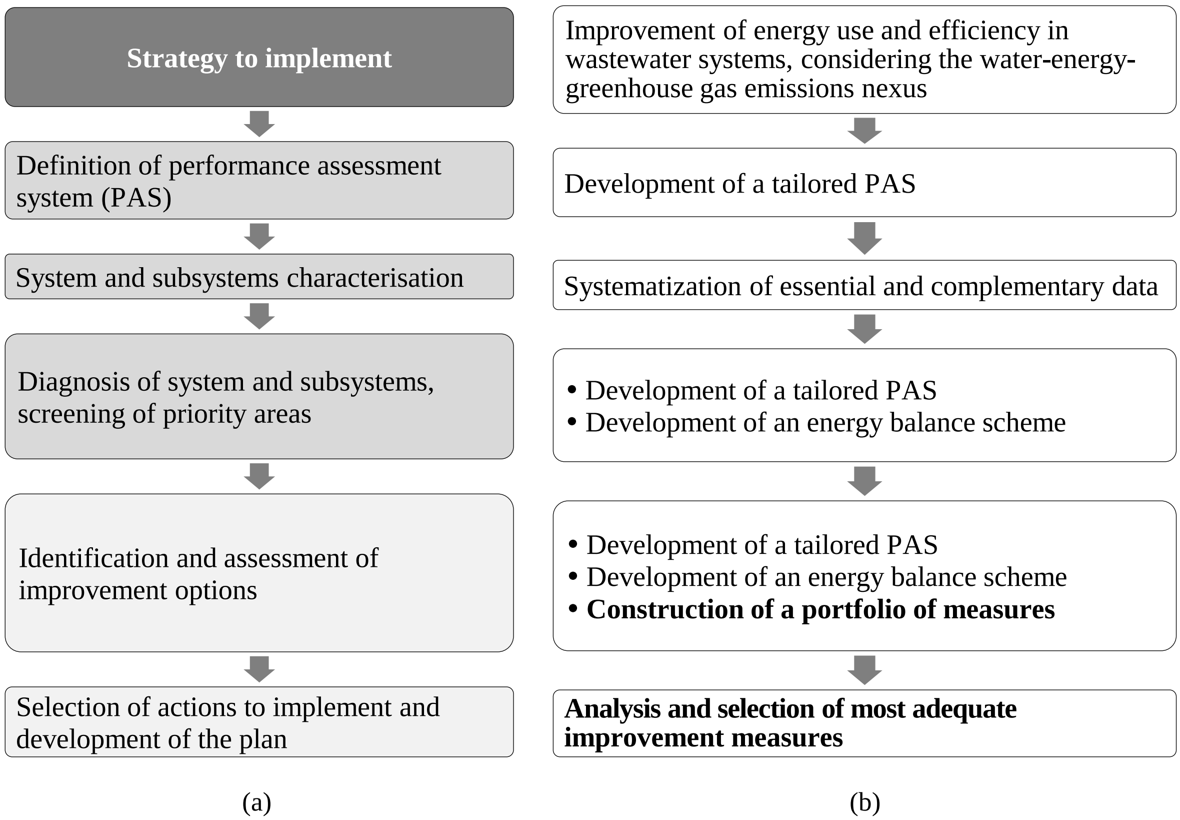


Figure 7.1 – Global framework to assess energy use and efficiency in wastewater systems: (a) Planning steps (Almeida and Cardoso, 2010); and (b) Use of methods and tools developed in the proposed framework.

The energy balance described by Jorge *et al.* (2022) aims at calculating the amount of energy supplied to a system, consumed by electromechanical equipment, and dissipated during wastewater transport. This balance does not focus only on energy-consuming components, as traditional energy audits; 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, wastewater outflowing the system because of capacity exceedance, among others. The energy balance is presented in Table 7.1.

Table 7.1 – Energy balance scheme for wastewater systems (Jorge *et al.*, 2022).

<table>
<tr><th colspan="3">ENERGY INFLOWS</th><th colspan="3">ENERGY OUTFLOWS</th></tr>
<tr><td rowspan="9">Total energy used for system processes (transport and treatment), E_T</td><td rowspan="6">Total inflow intrinsic energy (associated with gravity flow), E_I</td><td rowspan="3">Inflow intrinsic energy associated with authorized or due inflows, E_{IAI}</td><td rowspan="6">Total inflow intrinsic energy, E_I</td><td colspan="2">System downstream energy, E_{IDE}</td></tr>
<tr><td colspan="2">Recovered energy (e.g., micro-hydropower), E_{IRE}</td></tr>
<tr><td rowspan="2">Dissipated energy, E_{ID}</td><td>…due to inefficiencies in energy recovery equipment (e.g., turbines), E_{IDT}</td></tr>
<tr><td rowspan="3">Inflow intrinsic energy associated with undue inflows, E_{IUI}</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{IDL}</td></tr>
<tr><td rowspan="2">Energy associated with exceedance volumes, E_{IEV}</td><td>…not connected to an energy-consuming component, E'_{IEV}</td></tr>
<tr><td>…potentially inflowing to an energy-consuming component, E''_{IEV}</td></tr>
<tr><td rowspan="3">External energy (electrical), E_E</td><td rowspan="2">External energy associated with authorized or due inflows, E_{EAI}</td><td rowspan="3">External energy, E_E</td><td colspan="2">Elevation associated energy, E_{EE}</td></tr>
<tr><td rowspan="2">Dissipated energy, E_{ED}</td><td>…due to inefficiencies in electromechanical equipment (e.g., pumps), E_{EDE}</td></tr>
<tr><td>External energy associated with undue inflows, E_{EUI}</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{EDL}</td></tr>
</table>

The light grey boxes refer to the macro-level components, the dark grey boxes refer to the meso-level additional components to those in macro-level and the micro-level corresponds to all energy balance components (white and grey boxes).

The energy balance can be applied in different assessment levels depending on available and reliable data and on the existence of mathematical models. Three assessment levels are proposed (macro, meso and micro-level). At each assessment level, different data are needed. In short, if a utility only has global data, it can only apply the analysis at the macro-level, focusing on the external energy calculation; if the utility has detailed data on the pumping systems, the meso-level assessment applies, allowing the estimation of different energy components of the external energy; the micro-level assessment can be applied when the pumping systems and the gravity networks are well known and detailed measurement data and mathematical modelling are available, allowing the calculation of all energy balance components (Jorge *et al.*, 2022).

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. Thus, it is of utmost importance to align and complement the proposed energy balance with performance metrics that support the diagnosis of energy efficiency in wastewater utilities and the development of energy efficiency improvement measures.

Jorge *et al.* (2021b) developed a performance assessment system (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 greenhouse gases (GHG) emissions, among others.

The PAS comprises a complete objective, criteria, and metrics structure, considering the specificities of each system and the management objectives, considering the alignment with previous methodologies developed by the wastewater utilities. It adopts a holistic view of the wastewater system to assess the potential inflows to systems often surcharged by undue or excessive inflows. The structure of the PAS is composed of four objectives, 10 criteria and 35 metrics (Jorge *et al.*, 2021b). The objectives and criteria of the PAS are presented in Figure 7.2; the metrics are in Appendix A3 (Table A3.1).

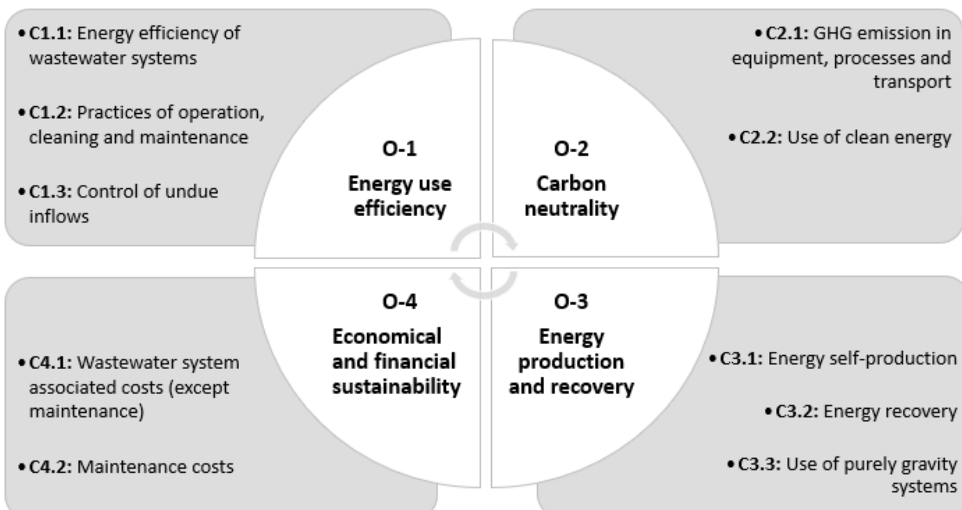


Figure 7.2 – PAS for energy efficiency in wastewater systems objectives and criteria (Jorge *et al.*, 2021b).

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. This step requires an analysis of options for pre-defined scenarios to consider the external context uncertainties. Examples of relevant scenarios to consider are climate change (e.g., increase in rainfall intensity), demographic changes, seasonality, energy costs and energy availability (Alegre and Covas, 2010; Almeida and Cardoso, 2010).

The results allow wastewater utilities to plan the implementation of selected measures and to estimate the impact on the performance. After implementation, utilities should revise the energy balance calculation and the PAS application to reinforce the systems' diagnosis. This process should be periodically reviewed to ensure continuous improvement.

In section 7.3, the methods and data for building a portfolio of energy measures to improve energy use in wastewater systems are presented. The relation of each measure with the respective PAS criteria and with the energy balance components is depicted in section 7.4.1 (Table 7.3).

7.3 Methods and data

7.3.1 General approach

A method for developing and characterizing a portfolio of energy use improvement measures tailored to wastewater systems 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 method is based on identifying and analysing measures leading to potential savings of energy in wastewater systems, following a procedure of "think globally, act locally" (Cabrera *et al.*, 2017).

The development and the analysis of the portfolio of energy solutions 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 multidisciplinary 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 improvement measures. These steps are presented in detail in the following sections.

7.3.2 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. In this study, the online databases Web of Science, Google Scholar and ScienceDirect were used to search and select 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, 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. An initial portfolio was developed.

7.3.3 Energy use improvement measures survey to wastewater utilities

In a second step, a survey was designed and sent to wastewater utilities to validate the initial portfolio. The involvement of utilities allowed a broader understanding of problems and the verification of 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 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 of the measures is related to the reality of the wastewater utility. Importance refers to the measure in global terms and not specifically in the utility. The applicability of the measures is understood in this context as the feasibility of that measure in absolute terms, regardless of whether it is considered a good or bad option in the respective wastewater utility. The implementation only applies to cases where the measure was considered applicable in the wastewater utility, as well as the quantification of benefits and existence of data and the possibility of providing data. 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 case study: 1 – yes; 2 – no; 3 – don't know/no information available.

Twenty-six wastewater utilities (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 types of functions. Fifteen wastewater utilities replied to the survey inquiry. The dimension and context information of these wastewater systems is shown in Table 7.2.

Table 7.2 – Characteristics of the selected WU (ERSAR, 2020).

WU	Served area, type of system	Effective service households (n.)	Sewer length (km)	Energy consumption (kWh/year)	PS(*) (n.)	WWTP(*) (n.)
1	Mostly urban, B	79 377	1024	7 160 177	38	15
2	Mostly rural, A	35 204	31	1 630 246	2	23
3	Averagely urban, B	74 161	897	182 998	40	1
4	Mostly urban, B	62 830	562	2 786 863	24	5
5	Averagely urban, A	324 135	481	33 171 174	192	76
6	Mostly urban, B	125 063	559	16 316 158	21	2
7	Mostly urban, B	58 443	469	4 289 387	28	4
8	Averagely urban, B	2 224	54	48 359	5	0
9	Averagely urban, B	13 444	124	55 459	13	0
10	Mostly rural, B	19 879	548	1 291 497	65	9
11	Mostly urban, B	157 533	854	70 210	10	0
12	Averagely urban, B	28 476	424	359 250	26	0
13	Mostly urban, B	93 213	611	5 453 812	13	4
14	Mostly urban, B	168 635	1022	3 025 661	26	17
15	Averagely urban, A	145 493	126	24 872 555	1	5

(*) PS: Pumping stations; WWTP: Wastewater treatment plants.

7.3.4 Portfolio consolidation with the identification of measures benefits and drawbacks

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 literature review and wastewater utilities practice and testimonies. This analysis is presented in section 7.4.3.

7.3.5 Discussion of the application of selected energy use improvement measures

Four real cases were selected to carry out a quantitative analysis of different energy use improvement measures (i.e., total and partial equipment replacement, solar energy systems, energy recovery). The first three cases were provided by the wastewater utilities answering the survey with positive answers in the fields 'possible quantification of benefits', 'data that allows benefits quantification' and 'possible to provide information as a case study' and with reliable data; the latter real case was taken from the literature. The results are presented in section 7.4.4.

7.4 Results and discussion

7.4.1 Consolidated portfolio of energy use improvement measures for wastewater systems

The consolidated portfolio includes 17 energy use improvement measures for wastewater systems, identified in the literature and complemented with others based on the survey carried out to wastewater utilities (Table 7.3). These 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. Relevant bibliographic references are also included in Table 7.3.

Specific actions needed for the effective implementation of these measures are grouped into the following types (Almeida *et al.*, 2016):

- Construction, rehabilitation, replacement, adaptation. This type of action refers to physical implementation actions in a broader sense. For example, the construction of a storage tank, the rehabilitation of a pipeline or the replacement or adaptation of devices.
- Monitoring and control. These specific actions are important to get basic system information which is relevant for the diagnosis, performance assessment and control and detection of anomalous events. To be effective, it is essential to ensure the collection, storage, and processing of data and the automatic or manual procedures for maintenance and anomalies alert.
- Awareness and information. Awareness and information actions to be developed internally for the organization's employees should be defined as an integral part of implementing an action plan for energy efficiency, desirably as part of the communication and continuous training programme. These actions should focus on the importance and benefits of enhancing energy efficiency and on the role of each in the fulfilment of this objective. Target audiences include utility employees, service providers and customers.
- Training, technical support and documentation. These actions are of great value for introducing and changing procedures. Some subjects that can be considered in this type of action include (i) the description and means of selection of the best techniques, equipment, and devices available in terms of energy efficiency; (ii) methods for carrying out audits of energy use; (iii) operation and maintenance procedures. Depending on the identified needs, the training actions should be

given to technicians or employees at different levels. The preparation and dissemination of supporting documents are also essential, as these materials can describe how to implement specific measures, including appropriate procedures for energy efficiency.

- Standards, regulations, and codes of good practice. An effective way of promoting measures for energy efficiency is the adoption of codes of good practice, which can also be compiled to consider the specificities of this sector, from the conception to the operation of projects, for example, through the requirements by the water utility to service providers or incorporated in technical specifications of tender documents. Using national, European, or international standards is key for ensuring the implementation of good practices.

The implementation actions on “awareness and information”, “training, technical support, and documentation” and “standards, regulations and codes of good practice” are transversal to the six categories of energy use improvement measures. The need for “construction, rehabilitation, replacement, adaptation” and “monitoring and control” are only required in specific situations, as pointed out in Table 7.3. Each identified measure specifically affects the described energy balance components and the PAS calculation. The contributions of each measure to the energy balance components (EB) and the PAS criteria (PAS-C) are also included in Table 7.3.

Other important contextual information needs to be gathered and improved when assessing energy efficiency. For instance, inventory and system components data (e.g., increase data quality and reliability regarding inventory data, pumping stations, mathematical modelling), data on inflows and consumed energy (e.g., flow measurements inflowing to pumping systems, measurements on critical overflow devices like emergency and storm weirs, surface flooding and energy measurements) and data from energy audits.

Table 7.3 – Portfolio of energy use improvement measures (EIM) for wastewater systems.

EIM		Description	References	EB [(a)]	PAS-C [(b)]
1. Equipment					
EIM1.1	Rehabilitation or replacement of electromechanical equipment: 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 (2010), 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).	Walski (2001;2003), Brandt *et al.* (2012), US EPA (2013), Cabrera *et al.* (2017), Menke (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), Baptista (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).	Baptista (2020)	E_{EDL}, E_{IDL}	C1.1, C1.2, C4.2
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), Sola *et al.* (2018)	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).			

Table 7.3 (cont.) – Portfolio of energy use improvement measures (EIM) for wastewater systems.

EIM		Description	References	EB [(a)]	PAS-C [(b)]
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), Jung *et al.* (2014), Coelho (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.* (2014; 2017), Chae *et al.* (2015), Nowak *et al.* (2015), Garcia *et al.* (2021), Llácer-Iglesias *et al.* (2021), Mitrovic *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)		
6. Reduction of GHG emissions					
EIM6.1	Installation of solar energy systems [(*), (**)]	Installation of solar energy systems (e.g., photovoltaic panels).	Lisk *et al.* (2012), Kusakana (2016), DESL (2017), EPA (2018), Bailey *et al.* (2021), Covas *et al.* (2022), 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).	Lisk *et al.* (2012), Kusakana (2016), DESL (2017), EPA (2018)		
EIM6.3	Use of other energy sources [(*), (**)]	Use of other energy self-production sources (e.g., biogas).	Vakilifard *et al.* (2018), Limaye and Welsien (2019), Bailey *et al.* (2021)		

Notes: [(*)] requires actions of "construction, rehabilitation, replacement, adaptation"; [(**)] recommended actions of "monitoring and control"; [(a)] presented in Table 7.1 ; [(b)] presented in Figure 7.2.

7.4.2 Energy use measures survey

The results of the survey for the 15 wastewater utilities are presented in Figure 7.3 for the classification of measures by priority (high, medium, and non-priority) and importance (not important to extremely important). From the 17 analysed energy use improvement measures, the three are considered a priority (i.e., high priority) for a high percentage of wastewater utilities, namely:

- EIM3.1. Reduction of undue inflows: undue connections (87%);
- EIM3.2. Reduction of undue inflows: infiltration in sewer systems' components (80%);
- EIM4.3. Improvement of pumping station maintenance procedures (67%).

Conversely, three measures were considered not a priority by a significant part of the utilities: EIM2.3. Increase of the storage volume of pumping wells (73%); EIM2.2. Continuous or local head losses reduction in pumping systems (67%); and EIM6.2. Installation of wind energy systems (60%).

Regarding the importance, the measures considered the most important by the 15 wastewater utilities are:

- EIM3.1. Reduction of undue inflows: undue connections (47% considered extremely important);
- EIM3.2. Reduction of undue inflows: infiltration in sewer systems' components (33% considered extremely important);
- EIM1.2. Rehabilitation or replacement of components of electromechanical equipment (53% found it very important);
- EIM4.3. Improvement of pumping station maintenance procedures (33% considered very important);
- EIM4.1. Programming the operating mode of pumping systems (67% considered important).

The measures considered the least important for most utilities are: EIM2.3. Increase of the storage volume of pumping wells (30%); and EIM6.2. Installation of wind energy systems (30%).

Results for applicability and implementation are presented in Figure 7.4. For applicability, the measures that are considered more feasible to apply by wastewater utilities are:

- EIM4.3. Improvement of pumping station maintenance procedures (93%);
- EIM3.1. Reduction of undue inflows: undue connections (87%);
- EIM1.2. Rehabilitation or replacement of components of electromechanical equipment (80%);
- EIM3.2. Reduction of undue inflows: infiltration in sewer systems' components (80%).

The measures that are mostly considered as not applicable to wastewater utilities are: EIM2.3. Increase of the storage volume of pumping wells (53%); and EIM5.2. Installation of energy recovery equipment at locations throughout the system (47%).

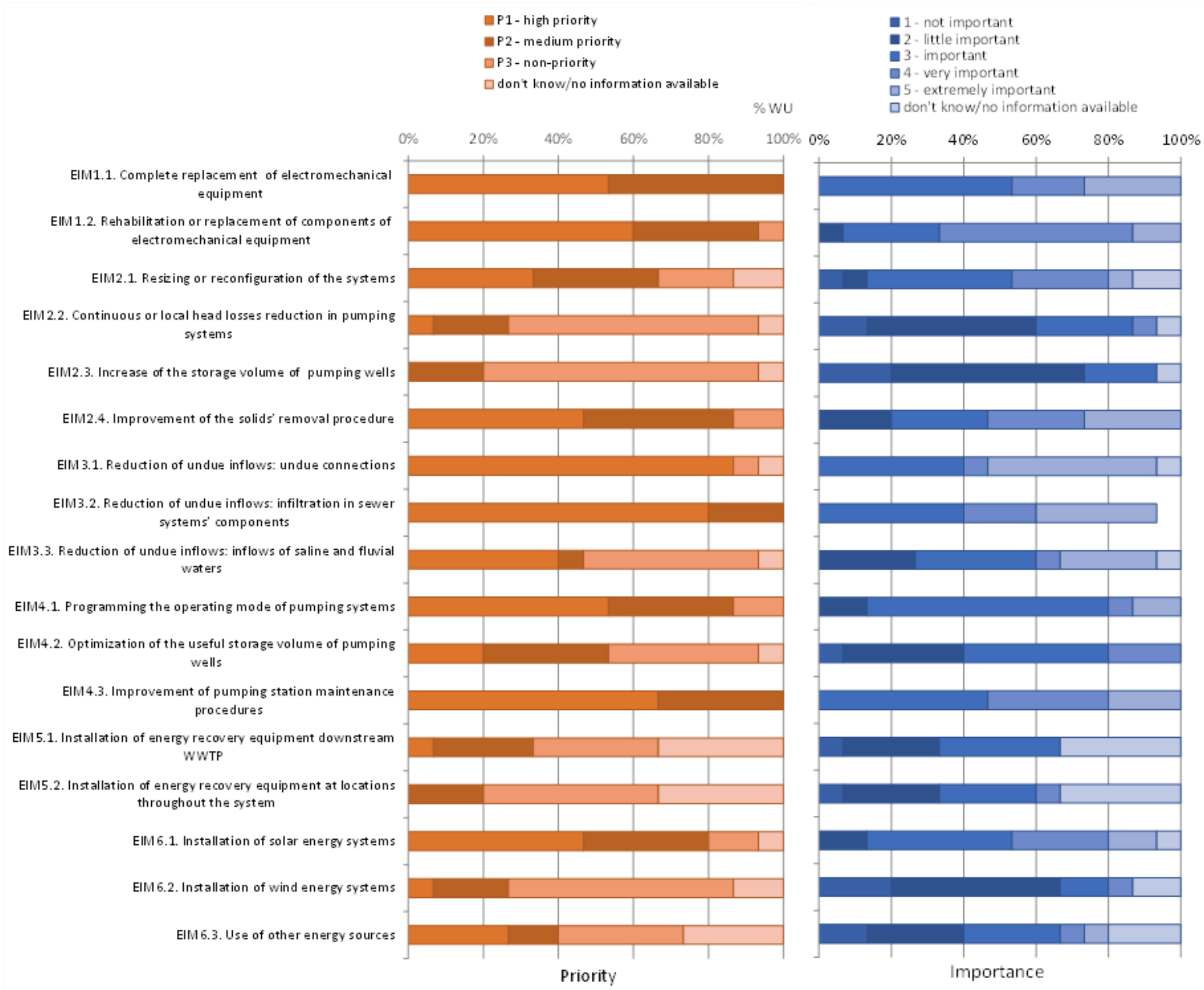


Figure 7.3 – Results of the survey: priority and importance.

Concerning the level of implementation of these measures, the energy use measures more widely implemented in wastewater systems are:

- EIM1.2. Rehabilitation or replacement of components of electromechanical equipment (73%);
- EIM1.1. Rehabilitation or replacement of electromechanical equipment: complete replacement (60%).

The measures mostly planned to be implemented in the short to medium term by wastewater utilities are EIM4.3. Improvement of pumping station maintenance procedures (40%); EIM3.2. Reduction of undue inflows: infiltration in sewer systems' components (40%); and EIM2.4. Improvement of the solids' removal procedure (40%).

Finally, measures mostly not planned to be implemented in the medium term by wastewater utilities are EIM6.2. Installation of wind energy systems (73%); and EIM2.3. Increase of the storage volume of pumping wells (67%).

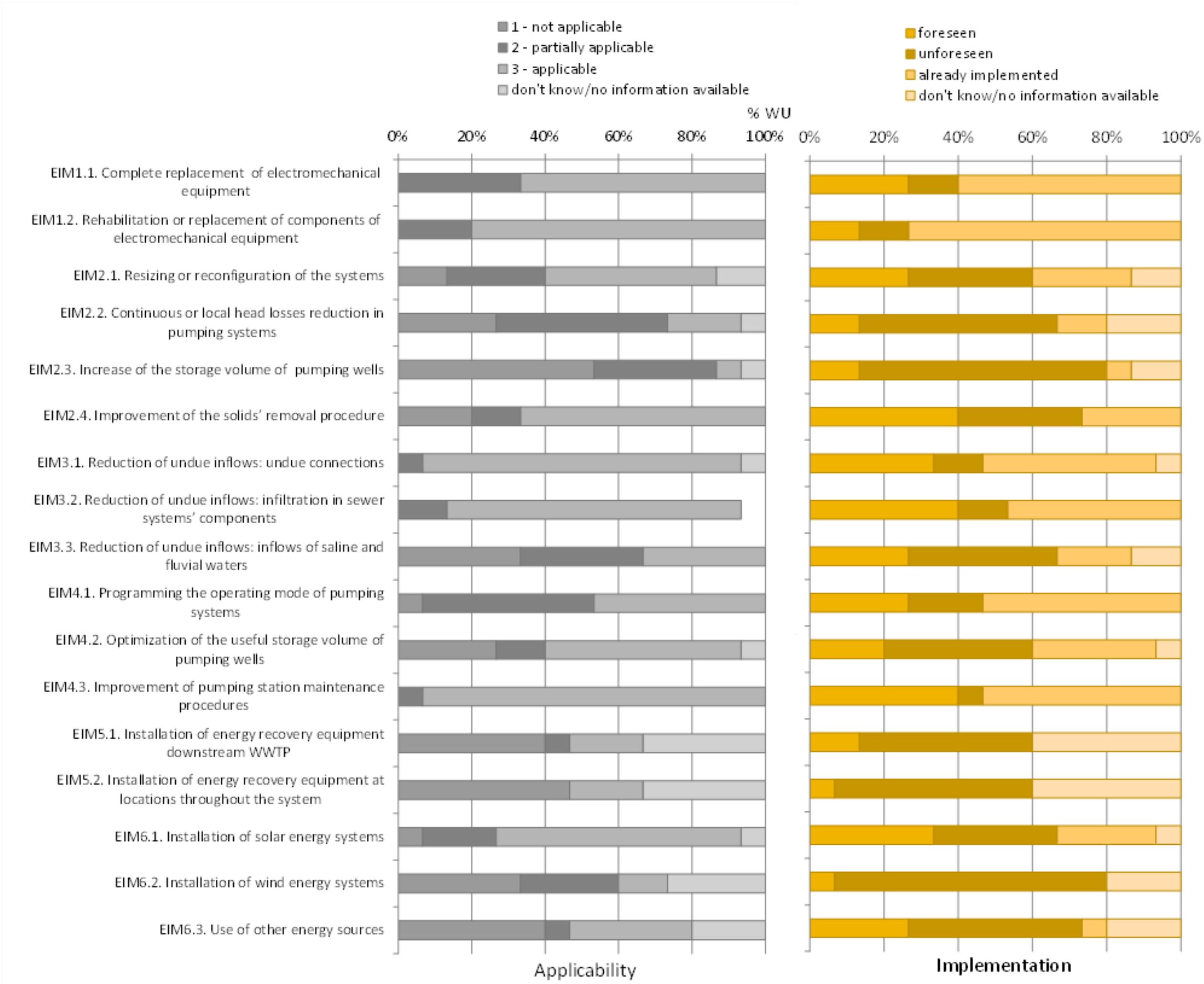


Figure 7.4 – Results of the survey: applicability and implementation.

To summarize, the wastewater utilities that have taken part in the survey are aware of the problem of undue inflows, which is 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). Wastewater utilities implement more often energy improvement measures focusing on individual components (e.g., pumps, valves, 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 did not have data for the measures EIM2.2. Continuous or local head losses reduction in pumping systems, EIM5.2. Installation of energy recovery equipment at locations throughout the system, EIM6.2. Installation of wind energy systems and EIM6.3. Use of other energy sources. Most utilities had data regarding equipment-related measures (EIM1.1. and EIM1.2.), reduction of undue inflows (EIM3.1) and improvement of pumping stations maintenance procedures (EIM4.3).

7.4.3 Benefits and drawbacks of the portfolio of energy use improvement measures

The major benefits and drawbacks of implementing each energy use improvement measure have been 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 water discharges and GHG emissions). Major drawbacks correspond to high financial efforts in terms of capital cost, 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 7.4.

Table 7.4 – 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)

Table 7.4 (cont.) – Main identified benefits and drawbacks of EIM in wastewater systems.

EIM		Benefits	Drawbacks
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
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

Table 7.4 (cont.) – Main identified benefits and drawbacks of EIM in wastewater systems.

EIM		Benefits	Drawbacks
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

7.4.4 Application of selected energy use improvement measures

7.4.4.1 Introduction

Four real-life cases were selected based on existing publications and on available and reliable data provided by wastewater utilities (WU) to illustrate the implementation of energy use improvement measures. These cases show the application of two measures of the equipment category (EIM1.1 Rehabilitation or replacement of electromechanical equipment: complete replacement and EIM1.2 Rehabilitation or replacement of components of electromechanical equipment), one of the reductions of GHG emissions category (EIM6.1 Installation of solar energy systems) and the fourth on energy recovery category (EIM5.1 Installation of energy recovery equipment downstream WWTP). The latter is a reliability study of an energy recovery solution installed at downstream of a WWTP in a Portuguese water utility (Covas *et al.*, 2022; Capelo, 2022).

7.4.4.2 Complete replacement of electromechanical equipment (EIM1.1)

The wastewater utility 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 total energy consumption of the wastewater utility, the associated costs, as well as the total energy consumption for pumping and the total pumped volume in this pump and the associated costs were provided for 2018 (before the pump replacement) and for the period of 2019-2021 (Table 7.5). For 2019, monthly data were also provided and were analysed to better understand the impact of the pump replacement (Table 7.6). The year/month of the pump replacement (April 2019) is highlighted in both tables.

Two performance assessment metrics are calculated to quantify energy efficiency improvements, namely: M1.1.2. Specific energy per total pumped volume (kWh/m^3) and M4.1.3. Percentage of the cost of total energy consumption used for pumping (%) from the PAS (Table A3.1). These metrics and the respective reference values are also presented in Table 7.5. Performance is classified using a three colour-grid in good (green), fair (yellow) and poor (red), to better interpret the results.

Table 7.5 – Annual data from EIM1.1 application in PS1 of WU2.

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 (%)
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
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 7.6 – Monthly data from EIM1.1 application in PS1 of WU2.

2019	Total energy consumption for pumping (kWh/month)	Total pumped volume (m^3/month)	Total energy costs for pumping (€/month)	M1.1.2 (kWh/m^3) (*)
Jan	15 325	29 126	2 107	0.53 🟡
Fev	13 103	29 078	1 792	0.45 🟢
Mar	11 780	30 629	1 618	0.38 🟢
Apr	10 428	35 348	1 442	0.30 🟢
Mai	7 288	30 240	1 043	0.24 🟢
Jun	6 476	25 866	951	0.25 🟢
Jul	5 669	23 437	881	0.24 🟢
Aug	3 995	16 256	637	0.25 🟢
Sep	5 467	18 439	825	0.30 🟢
Oct	8 019	21 719	1 178	0.37 🟢
Nov	12 641	37 362	1 807	0.34 🟢
Dec	17 288	49 806	2 426	0.35 🟢

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

Results from metrics M1.1.2 and M4.1.3 have improved after the pump replacement, although mostly showing good performance. It is important to highlight that there are other factors influencing energy consumption in pumping station PS1, such as seasonality and undue and excessive inflows (e.g., rainfall). Therefore, it is recommended to also analyse these variables when a diagnosis of energy efficiency of a wastewater pumping station is carried out. Conversely, the replacement of pump groups for other reasons 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 also influence the energy balance calculation, namely the external energy (E_E) and the respective sub-components. However, these components could not be calculated because of the lack of sufficient data.

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

The wastewater utility WU2 also provided data regarding the energy measure EIM1.2. The total energy consumption, the respective costs, the total energy consumption for pumping and the total pumped volume and the associated costs were provided from January 2016 to May 2022 (Table 7.7). During this period, several pump components were replaced and repaired in pumping station PS2, namely: pump impellers, bearings, rectified shafts, bushings, rubbers, sealing rings, brakes, and rewinds. Data were provided for the complete pumping station, since no data were available per pump (the pumping system was composed of three pumps installed in parallel, one group a reserve pump). Replacements and repairs were carried out in the three pump groups for several months along the six-year period (i.e., April 2016, June and October 2017, December 2018, February, July and October 2019, June 2020, April and July 2021 and June 2022).

The same two energy efficiency metrics (Metrics M1.1.2. Specific energy per total pumped volume (kWh/m^3) and M4.1.3. Percentage of the cost of total energy consumption used for pumping (%) from the PAS, see Table A3.1) are calculated and presented in Table 7.7.

Table 7.7 – Annual data from EIM1.2 application in PS2 of WU2.

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, +∞[●

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. Since pump components replacement and repairs were 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. Once again, the pumping station has not performed poorly during this period of analysis. Thus, it is recommended to analyse these results together with others that influence energy consumption (e.g., undue inflows volumes, seasonality). It is also important that energy measurements are carried out for each pump to better understand the effect of implementing energy use improvement measures.

The application of measure EIM1.2 will also influence the energy balance calculation, namely in the external energy (E_E) and the respective sub-components. However, these components could not be calculated because of the lack of sufficient data.

7.4.4.4 Installation of photovoltaic panels (EIM6.1)

This section refers to the implementation EIM6.1, including two cases. The first is from wastewater utility WU2, which installed photovoltaic panels in two WWTPs (WWTP1 and WWTP2) in 2016. For WWTP1, the capital cost involved was 22 337€. The second is from wastewater utility WU14, which has also installed photovoltaic panels in four WWTPs (WWTP1 to WWTP4), in one water supply pumping station (PSWS1), in one water treatment plant (WTP1) and on the roof of the mechanic's workshop (workshop1). The latter has an installed power of 60 kW, is composed of 224 photovoltaic modules and was installed in 2019.

The results of the implementation of measure EIM6.1 are assessed based on data provided by utilities WU2 and WU14, as presented in Table 7.8 and Table 7.9, for the respective years and facilities. One metric – Metric M.3.2.1. Energy self-production (%) from the PAS (Table A3.1) – was calculated, being reference values also presented in the referred tables.

Results of metric M3.2.1 for WU2 mainly highlight a fair performance (Table 7.8), especially regarding WWTP1, which shows that it can become energy self-sustained in the future, allowing quick recovery of the investment made on the equipment (further cost data are not available). Variations in annual data result from gaps in data series due to equipment breakdowns and several other factors, such as equipment location and the number of cloudy days. However, the current values highlight the effort of the wastewater utility to invest in solar energy production.

Table 7.8 – Results of the application of energy measure EIM6.1 for WU2.

Year	Solar energy production (kWh/year)	Energy consumption (kWh/year)	Metric M.3.2.1 (%) (*)
WWTP1			
2016	3123	24 074	13.0 🟡
2017	4 567	24 423	19.0 🟡
2018 (**)	2 414	27 618	9.0 🔴
2019 (**)	2 887	25 993	11.0 🟡
2020 (**)	3 325	18 876	18.0 🟡
2021	4 322	24 775	17.0 🟡
WWTP2			
2016 (**)	3 818	44 599	9.0 🔴
2017 (**)	3 437	33896	10.0 🟡
2018	3 551	39 839	9.0 🔴
2019 (**)	3 118	40 885	8.0 🔴
2020 (**)	4 056	41 213	10.0 🟡
2021 (**)	3 055	43 460	7.0 🔴

(*) –Reference values: [20, 100] 🟢; [10, 20[🟡; [0, 10[🔴 ; (**) – gaps on some monthly data mainly due to equipment breakdowns.

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 7.9), highlighting the effort of the wastewater utility to invest in solar energy production. This performance increase is mainly due to the installation in 2019 of the solar energy recovery equipment at workshop1, as shown by WU14. WWTP2 and WWTP4 are already evidencing values of fair and even good performance, which indicates that the utility can become energy self-sustained in the future. Variation in annual values result from several factors (e.g., cloudy days, equipment breakdowns).

The existence of this renewable energy source also contributes to increase the energy recovered component (E_{IRE}) on the energy balance calculation, thus influencing energy inefficiencies diagnosis and reducing GHG emissions.

Table 7.9 – Results of the application of energy measure EIM6.1 for WU14.

Facility	Solar energy production (kWh/year)	Energy consumption (kWh/year)	Metric M.3.2.1 (%) (*)
	2019		
WWTP1	6 282	290 391	2.2 🔴
WWTP2	4 646	25 549	18.2 🟡
WWTP3	3 629	208 387	2.9 🔴
WWTP4	2 762	19 246	18.9 🟡
PSWS1	6 242	-	-
WTP1	6 078	-	-
Workshop1	37 819	-	-
WU total	67 458	3 041 443	2.2 🔴
	2020		
WWTP1	6 023	3 025 661	2.6 🔴
WWTP2	3 951	229 836	17.6 🟡
WWTP3	6 228	22 466	3.3 🔴
WWTP4	1 369	188 650	7.2 🔴
PSWS1	6 272	-	-
WTP1	6 202	-	-
Workshop1	79 472	-	-
WU total	109 517	3 025 661	3.6 🔴
	2021		
WWTP1	6 077	275 088	2.2 🔴
WWTP2	4 175	23 314	17.9 🟡
WWTP3	6 791	380 437	1.8 🔴
WWTP4	2 865	17 307	33.9 🟢
PSWS1	5 954	-	-
WTP1	5 864	-	-
Workshop1	89 424	-	-
WU total	121 150	3 150 292	3.8 🔴

(*) – Reference values: [20, 100] 🟢; [10, 20[🟡; [0, 10[🔴 **;** WWTP: Wastewater treatment plant; PSWS: Pumping station water supply; WTP: Water treatment plant.

7.4.4.5 Hydro-energy recovery (EIM5.1)

Regarding the implementation of measure EIM5.1, Capelo (2022) analysed the installation of energy recovery equipment downstream of a WWTP (furthermore referred to as WWTP A) from a Portuguese wastewater utility. The inverted Archimedes screw was selected as the most cost-effective technological solution for energy recovery in systems with low available heads and operating for a wide range of flow rates. Additionally, this equipment has a long service life due to the low rotation speed which causes minimal wear during operation, low maintenance costs, high efficiencies (>70%), and allows the passage of large solids without compromising the screw physical integrity and efficiency (Capelo, 2022).

The inverted Archimedes screw was located downstream of the WWTP A, in a bypass channel connecting to a manhole, being the available head 1.5 m (Figure 7.5).

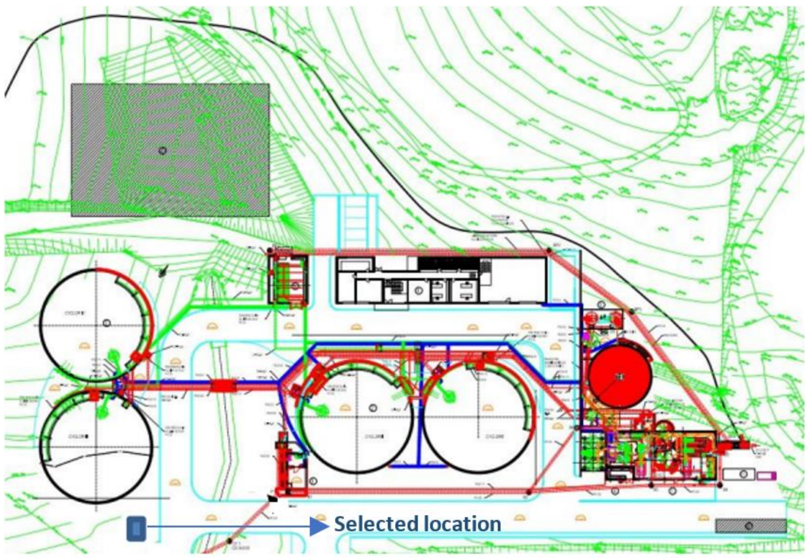
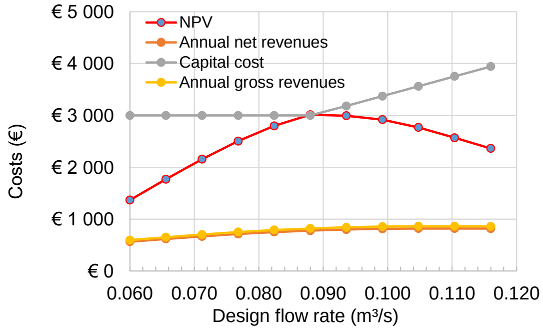


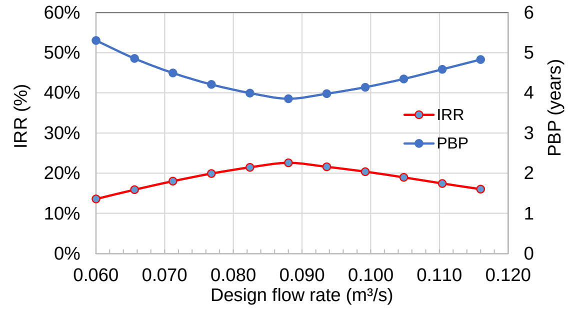
Figure 7.5 – WWTP A scheme with the selected possible location for energy recovery in the WWTP downstream channel (adapted from Covas *et al.*, 2022).

A preliminary assessment of the energy recovery potential was carried out. The Archimedes screw can work for a range of flow rates between 10% and 110% of the 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), while the recovered energy varies between 6.0 and 8.6 MWh/ year. The device operates for the whole year.

An economic analysis was carried out considering several economic indicators, namely the net present value (NPV), the payback period (PBP) and the internal rate of return (IRR). The main assumptions were that prices remained constant over the project lifetime; the discount rate was 5%; project lifetime was 10 years; energy unit cost was 0.10€/kWh; unit capital cost for the Archimedes screw turbine was 3 000 €/kWh; the annual O&M cost was 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 Figure 7.6.



(a)



(b)

Figure 7.6 – Economic analysis as a function of the design flow rate: (a) NPV, investment and accumulated revenues, (b): IRR and PBP.

The design flow rate leading to the maximum NPV value is 0.088 m^3/s, corresponding to an installed power of 1.0 kW and the respective economic indicators: investment = 3 000€, NPV = 3 014€, PBP = 4 years and IRR = 23%. The IRR is higher than the selected discount rate, therefore the investment is profitable. This energy recovery solution has shown to be cost-effective, being the starting point for future energy recovery projects in the WWTPs of Portuguese utilities.

The existence of this energy source also contributes to increase the energy recovered component (E_{IRE}) on the energy balance calculation, thus influencing energy inefficiencies diagnosis.

7.5 Conclusions

This paper presents a portfolio of energy use improvement measures specifically tailored to wastewater systems, as part of a global 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 (e.g., photovoltaic panels, turbines).

The portfolio of energy use improvement measures was developed based on an extensive literature review on the subject area and on the experience of the authors in previously developed methods and tools (i.e., energy balance and PAS). This portfolio was further consolidated based on fruitful discussions with specialists and on a survey carried out with the wastewater utilities. The portfolio has 17 energy use improvement measures, organized into six categories. The main benefits and drawbacks of the measures were identified and analysed. Four real-life cases were presented to illustrate the positive effect of the implementation of these measures. Impacts on energy efficiency and consumption are not always clear with the application of only one specific improvement measure since some other factors can be influencing energy efficiency and consumption. There is a global deficit of available and reliable data that limits the assessment of the actual effects of the implementation of energy use improvement measures as well as the application of the general energy improvement framework. However, this framework constitutes an utmost important tool for wastewater utilities to enable a proper diagnosis of energy efficiency in their systems, considering their own context and limitations. The confidence in the results should always be evaluated case by case to avoid the propagation of errors and to reduce the associated uncertainty.

The current research is a step forward in contributing for increasing energy efficiency in wastewater systems by providing a framework to support further developments. As future work, it is of utmost importance to apply the proposed framework and the portfolio of energy use improvement measures to more case studies to proceed with the further assessment and quantification of the attained improvements.

Chapter 8 – Conclusions and future research

8.1 Research overview

Energy efficiency in wastewater systems has been studied, following a systemic and objective-oriented approach. A comprehensive state-of-the-art review is presented in Chapter 2, highlighting the need for the development of a specific approach for energy efficiency assessment in wastewater systems and of energy balance formulations adapted to wastewater sector data constraints but providing a robust diagnosis of the main energy inefficiencies in any type of system. A novel energy balance specific for wastewater systems, with three different assessment levels (macro, meso, and micro-level) has been developed and applied to a set of wastewater utilities in Chapter 3. A detailed application of the energy balance using mathematical modelling with an energy recovery case application is presented in Chapter 4. A tailored objective-oriented performance assessment system (PAS) with specific and novel energy efficiency metrics (31 new metrics in total) is developed and applied in a large set of wastewater systems in Chapter 5. The magnitude of the impact of undue inflows in the water-energy-greenhouse gas (W-E-G) emissions nexus using three levels of analysis (national, utility and subsystem level) and performance assessment metrics is demonstrated in Chapter 6. Finally, in Chapter 7, a portfolio of measures to improve energy use in wastewater systems is presented and validated by wastewater utilities together with use case applications.

The present research is oriented to the development and application of energy balances and energy efficiency metrics supporting the identification and testing of energy use improvement solutions within a continuous improvement approach.

8.2 Thesis results and conclusions

In the present thesis, several steps were carried out to develop, apply and consolidate a comprehensive framework for assessing energy use and efficiency in wastewater systems, aligned with the asset management methodologies (Almeida and Cardoso, 2010) and with the ISO 5000x standards. This framework differs from existing wastewater-energy management practices, since it focuses on the system as a whole and not on single components, it is objective-oriented and it refers not only to short, but also medium and long-term time horizons. The framework is composed of three main tools: a specific energy balance for wastewater systems, applicable in three different assessment levels (macro, meso and micro-level), a tailored PAS incorporating the several aspects influencing energy efficiency in wastewater systems and the W-E-G nexus, and a portfolio of energy use improvement measures, aligned and tested with wastewater utilities, experts, and specialists within the sector. Proposed tools and methods (e.g., energy balance, PAS, energy improvement measures) can also be easily extended and applied to stormwater systems considering their specificities (e.g., stormwater systems are less energy demanding and have different magnitude and typology of undue inflows inflowing to the networks).

The proposed energy balance has a new structure tailored to wastewater systems having several new components, but aligned, as much as possible, with those proposed for water supply systems (Mamade *et al.*, 2017; 2019) and irrigation systems (Fernandes, 2020) to facilitate a broader analysis of the water cycle. Main differences derive from the hydraulics of wastewater systems, where free surface flows predominate, and from data availability constraints faced by the wastewater sector. Data are globally less reliable in wastewater systems (compared to water supply systems) because this sector continues to face difficulties regarding information collection and reliability.

Despite the referred limitations, the energy balance was successfully applied to different case studies, illustrating the potential use for responding to current challenges of wastewater utilities, even when data are scarce. In the macro-level assessment, the external energy and the energy associated with undue and authorised inflows can be estimated annually. This assessment is significant at the strategic management planning, as it allows a preliminary evaluation of the energy consumption in the system. Macro and meso-level assessment results allowed to conclude that the energy associated with undue inflows can be quite significant, representing 20% to 44% of the total energy consumption in analysed wastewater utilities and the pumping systems' efficiency is generally lower (34% on average, with percentiles 25 and 75 corresponding to 21% and 42%, respectively) than those of the water supply sector. The percentage of undue inflows was found to have an increasing trend with the local annual rainfall. This trend strongly depends on the quality of the data, on the integrity of the infrastructure and on the transport system capacity. It was also evidenced that the dissipated energy associated with undue inflows and pumping stations can be quite significant and the importance of energy improvement measures focusing both on the control of undue inflows and on the replacement and maintenance of existing pumps was highlighted.

Micro-level assessment application had successfully illustrated the potential of the proposed methodology for calculating all energy balance components. In the wet season, a substantial increase (four times higher) in the total energy was observed, mainly derived from undue inflows. The energy associated with undue inflows considering both seasons was found significant, being on average 21.3%. Overflows not returning to the system (e.g., discharges and floods) were pointed as one of the main issues in wastewater systems. The component related to the energy associated with overflows potentially inflowing to energy-consuming components represents energy that would be consumed additionally, if the total volume that left the system was also pumped. Therefore, this component should not be mistreated, since it highlights that, while wastewater utilities do not reduce these exceedance volumes, the impact of actions in the control of undue inflows to reduce energy consumption is compromised. Initially, there will be a decrease in discharged or flooded volumes and only later will the impact be reflected in the reduction in high volumes and, consequently, in the associated energy consumption. The potential for energy recovery was also demonstrated and enhanced the need of considering the energy recovering practice in wastewater systems, which is often mistreated due to recognised limitations. Results showed a good potential for energy recovery (500 MWh/year) and a good economic viability considering the several indicators presented, namely PBP of 4 years and IRR of 23%.

This energy balance can be applied at three assessment levels, aiming to overcome the limitations related to the poor knowledge of the networks and processes, information gaps in inventory data and flow measurements. The limitations derived from conditioned data on wastewater flows imply the use of estimates in many situations, even acknowledging the implications of this procedure. However, this research work reinforced the need for wastewater utilities to focus on the several energy balance components to identify the main system inefficiencies, even though not all components can be calculated.

The energy balance is essential to support the calculation of performance metrics and the comparison of the effects of the implementation of several energy efficiency measures.

A tailored PAS composed of four objectives, 10 criteria and 35 metrics focused on the overall energy performance of hydraulic systems was proposed, allowing to assess the impact of undue inflows on the energy consumption and efficiency of wastewater systems as well as to identify and compare opportunities to improve current in operation and maintenance practices and GHG emissions, among others. The application of the PAS was well received by the participating utilities and presented good testing and validation results. The alignment with the other utilities' methodologies was perceived as a significant benefit. The testing and validation with nationwide data involving several utilities, allowed for a scrutinized and robust PAS, endorsed by participating specialists. One of the main conclusions relied, once again, on a global deficit of available and reliable data that significantly conditioned the PAS metrics calculations. Therefore, not all the proposed metrics could be currently calculated by the wastewater utilities and some reference values were not defined. A PAS that uses available data for most utilities is preferable; but it is important to keep in mind that although using the best available data is advantageous and reasonable for any wastewater utility, metrics requiring either qualitative or more detailed data should be included in the PAS to encourage the gradual improvement in data collection. Assessment of the metadata on data quality and reliability is a good practice for informed decision making and to improve data collection and processing activities. The current PAS proposal already incorporates developments that are expected in the future, namely, desired and unavoidable improvements in flows and precipitation monitoring. These factors allow to act in face of information scarcity or with low reliability and is compatible with increasing levels of available data, in a continuous improvement process. However, each utility should consider its own scope and limitations to plan investments to collect and process necessary data to enable a proper diagnosis of the energy use.

The importance of the undue inflow volumes for the W-E-G nexus, often overlooked, was made clearer. The relevance and implications for energy consumption and GHG emissions were shown in the three levels of analysis (national, utility and system level). Even at an aggregated level, the combined analysis of the yearly data on wastewater volumes, energy consumption and rainfall showed the relation between rain-derived inflows and energy consumption. The need to integrate the systems' exceedance in the analysis, resulting in discharges and flooding, was emphasized. The importance of having a three independent assessment levels was demonstrated, allowing utilities with scarce data to tackle this issue, since the wastewater sector still faces a significant problem related with the installation of data collection equipment as well as with the implementation of robust and calibrated hydraulic models. Results showed an additional opportunity for utilities to get return from investments on flows monitoring. At a national and utility level, the relation between flooding and discharge occurrences and higher rain-derived inflows was not always obvious, because of insufficient monitoring of overflows. However, at a utility level, it was possible to cascade down the analysis with more detailed data, and a strong relation between seasonal undue inflows and energy demands was found and quantified. An increase of 4 to 7 times in energy consumption and GHG emissions was observed because of overall undue inflows. This energy consumption increased 5 to 10 times during rain events due to rain-derived inflows. Acting on the causes of undue inflows, including the improvement of asset condition, is a labour and resource-intensive task, and utilities need to understand the medium-term benefits of such investments.

To proceed with the identification and the assessment of energy efficiency solutions, a portfolio of energy use improvement measures was developed. For this purpose, an extensive literature review was carried out based on scientific publications and on the experience in previously developed methods and tools (e.g., energy balance and PAS), followed by a survey of wastewater utilities and specialists on the subject. The survey allowed the validation of the set of measures to include in the resulting portfolio and to collect further information to characterise them. The portfolio is composed of 17 energy use improvement measures and is organized in six categories: equipment, systems optimization, reduction of inflows to pumping systems, operation and maintenance, energy recovery and reduction in GHG emissions. 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. Four real-life cases were presented to illustrate the positive effect of the implementation of these measures. Impacts on energy efficiency and consumption were not always clear with the application of only one specific improvement measure since some other factors influencing energy efficiency and consumption. Once more, the global deficit of available and reliable data limited the assessment of the actual effects of the implementation of energy use improvement measures as well as the application of the general energy improvement framework. The limited available data directly affected the application of the proposed methods, so the methods should be adapted to the existing data. However, it should be reinforced that the simplifications presented in this research work were based on reasonable assumptions and practical experience of working with wastewater utilities. All information of each selected case study was explored to maximize its use, to overcome the several data constraints.

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. The same procedure is applicable in the plan revision cycle, ensuring continuous improvement, and the diagnosis should be updated accordingly. However, this ideal situation is still hardly achieved in the wastewater sector due to the lack of data, widely mentioned throughout this research. Therefore, it is of utmost importance to incorporate procedures to collect and process necessary data (e.g., flow rate measurements, inventory data improvement and completion, modelling tools) in the management plans.

Overall, data are essential to support decisions to improve systems performance. Important contextual information needs to be gathered and improved when assessing energy efficiency. Quality of inventory and system components data is essential (e.g., increase data quality and reliability regarding inventory data, pumping stations, mathematical modelling), as well as more data on inflows and consumed energy (e.g., flow measurements inflowing to pumping systems, measurements on critical overflow devices like emergency and storm weirs, surface flooding and energy measurements) and data from energy audits.

Utilities' staff can benefit from specific training in hydraulics and metrology, including knowledge of the limitations of each technology. Capacity building in utilities and training of personnel on issues related to measurements quality is a step forward towards enhancing data reliability in the water sector (Brito *et al.*, 2022). The application of detailed parts of the methodology requires reliable data and shorter acquisition times by monitoring systems, to reduce the results uncertainty. For this purpose, utilities need to invest in reliable measurement systems. It is recognised that the selection of the appropriate location and the adequate equipment for monitoring are some of the most challenging issues in the field. The need to improve data traceability in utilities is also clear (Brito *et al.*, 2022). Regular collection of information on hydraulics, hydrology and water quality allows understanding systems' functioning, assessing performance and supporting the setting of management targets, responding to regulatory requirements, and enables the identification of inefficiencies and opportunities for improvement.

In wastewater and stormwater systems, flows are mostly under free surface; pressure flows occur at pressure pipes downstream of pumping stations since pressurised systems are not commonly used. When sewers capacity is exceeded transition to pressure flow can occur for limited, for instance because of high intensity rainfall. Variables of interest include flow rate, water level (for instance, in weirs), flow velocity, water pressure and water quality parameters. In parallel, it is recommended to measure rainfall. Typical measurement sites are system downstream locations (e.g., at entrance of pumping stations or WWTPs), in main sectors of the network and at system boundaries. Despite the costs, it is highly recommended to wastewater utilities to monitor untreated discharges from the systems, such as emergency bypasses and combined sewer overflows (Almeida *et al.,* 2022; Brito *et al.,* 2022). A preliminary definition of a monitoring programme should be the foundation of good measurement practices in urban water systems, considering (Almeida *et al.*, 2022): (i) objectives and intended uses of data (define monitoring objectives and the intended uses of data, e.g., mathematical modelling, detection of undue inflows), human resources (ensure skills and competences); (ii) influencing conditions (register context and pre-campaign information); (iii) methods (identify the methods to determine derived variables, specify a methodology for data processing, define and register equipment installation conditions, define maintenance actions for the equipment); (iv) and sampling (characterization of the phenomenon under study, identification of the sampling interval and verification of whether it is appropriate to the objectives, verification of the equipment's clock punctuality). The ISO 17025:2017 standard has a robust structure to deal with both technical and management aspects, to ensure the overall data quality and common sources of uncertainty. The overall confidence in the results should always be evaluated case by case to avoid propagation of errors and to reduce the associated uncertainty.

To summarize, despite the described limitations and challenges, the proposed framework constitutes an important tool for wastewater utilities to enable a proper diagnosis of energy efficiency in their systems, considering their own context and limitations, and the identification of measures for the continuous improvement of the O&M practices and of the diagnosis. This is also a contribution to support the sector action towards energy efficiency and GHG emissions reduction.

8.3 Main scientific contributions

The thesis has four central scientific outcomes described in the following paragraphs.

An **objective-oriented systemic and integrated framework** for enhancing energy efficiency tailored to wastewater systems aligned with continuous improvement principles and allowing the identification of energy efficiency solutions is presented (Chapters 1 & 7).

A **novel energy balance** specifically tailored for wastewater systems is proposed (Chapters 3 & 4). The key innovative features of this energy balance include the systemic diagnosis of the wastewater systems with three different assessment levels that intend to overcome wastewater sector data limitations as well as to be applied by wastewater utilities with different maturities levels. The energy balance is applied to wastewater systems allowing wastewater utilities to identify the main energy inefficiencies of the transport system, supporting the calculation of performance metrics and the comparison of the effects of the implementation of several energy efficiency measures.

A **performance assessment system** (PAS), complementary to the energy balance and also tailored for wastewater systems, is developed based on an accepted objective-criteria-metrics (O-C-M) structure and aligned with infrastructure asset management (IAM) methodologies (Chapter 5). Novel metrics have been proposed focusing on the overall energy performance of hydraulic systems, allowing to assess the impact of undue inflows on the energy consumption and efficiency of wastewater systems as well as the opportunities to improve practices in operation and maintenance and greenhouse gas (GHG) emissions, among other dimensions. The PAS is tested and validated by several Portuguese wastewater utilities willing to tackle this issue. The importance of the undue inflows' volumes of treated wastewater for the water-energy-greenhouse gas (W-E-G) emissions nexus, often overlooked, is demonstrated in actual use case (Chapter 6).

A **portfolio of energy use improvement measures for wastewater systems** is proposed based on a literature review and on a survey of wastewater utilities and specialists on the subject area (Chapter 7). The survey allows the validation of the set of measures to include in the resulting portfolio and to collect further information to characterise them. The final portfolio of measures is instrumental for wastewater utilities to select the measures, to decide which are the priority ones and to prepare an implementation plan.

8.4 Recommendations for future research

Four recommendations for the industry and for future research are proposed in the following paragraphs.

The first recommendation is to further test the energy framework, in wastewater utilities with different maturity levels and data constraints, and to explicitly include typical scenarios as part of the analysis (e.g., climate change, demographic changes, seasonality, energy costs). This knowledge could be used to develop an energy certificate for wastewater utilities. This instrument could play an important role in the access to funding, complementing energy audits in pumping stations and boosting the relationship between the water and energy sectors while motivating the search for solutions aligned with the W-E-G nexus.

The second is to develop a software package integrating the developed methods and tools, complemented with the options for improving energy efficiency and calculating cost-benefit analyses, to promote the application of this framework and to facilitate the respective application by utilities. This could be carried out by adding rehabilitation costs of pipes, valves, and pumps, among other equipment. The software package could be used by ERSAR to audit energy balances and energy efficiency metrics in the Portuguese wastewater utilities.

The third recommendation is to carry out additional sensitivity analyses to evaluate the proposed reference elevation for the energy balance calculation and the proposed reference values for performance metrics in the PAS. The impact of energy efficiency solutions should also be further analysed.

The fourth is to extend the W-E-G nexus analysis to include emissions of other greenhouse gases (e.g., methane) and other sources of energy apart from electrical energy (e.g., diesel, labour, and biogas).

Finally, it is relevant to emphasize the several limitations that the wastewater sector is still facing concerning available and reliable data (e.g., inventory data and reliable measurements); the poor knowledge of networks and processes restricts the application to the full extent of the developed methods and tools. However, further developments are encouraged to help to continue overcoming these problems.

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Appendices

Appendix A1: Chapter 3 – Energy balance for wastewater systems

Appendix A2: Chapter 4 – Micro-level application of the energy balance with energy recovery

Appendix A3: Chapter 5 – Performance assessment system for energy efficiency in wastewater systems and Chapter 7 – From assessment to a decision: a global framework to manage energy use in wastewater systems

Appendix A4: Chapter 6 – Water, energy, and emissions nexus in wastewater systems

Appendix A1: Chapter 3 – Energy balance for wastewater systems

Table A1.1 – Energy balance: meso-level application for the wastewater utility WU2.

WU/PS	**Energy component**	**2015**	**2016**	**2017**	**2018**	**Avg.**
WU2/PS1	Elevation energy, E_{EE} (%)	21	28	17	21	**22**
	Dissipated energy pump inefficiency (%), E_{EDE}	78	70	82	78	**77**
	Dissipated energy friction losses (%), E_{EDL}	1	1	1	1	**1**
	External energy (kWh/m^3), E_E	0.111	0.084	0.135	0.110	**0.110**
	Manometric head (m)	9				
	Global efficiency (%)	22	29	18	23	**23**
WU2/PS2	Elevation energy, E_{EE} (%)	88	86	85	82	**85**
	Dissipated energy pump inefficiency (%), E_{EDE}	8	9	10	13	**10**
	Dissipated energy friction losses (%), E_{EDL}	5	5	4	4	**5**
	External energy (kWh/m^3), E_E	0.127	0.129	0.130	0.135	**0.130**
	Manometric head (m)	43				
	Global efficiency (%)	92	91	90	87	**90**
WU2/PS3	Elevation energy, E_{EE} (%)	38	37	41	49	**41**
	Dissipated energy pump inefficiency (%), E_{EDE}	60	61	57	48	**57**
	Dissipated energy friction losses (%), E_{EDL}	2	2	2	3	**2**
	External energy (kWh/m^3), E_E	0.391	0.404	0.359	0.304	**0.365**
	Manometric head (m)	58				
	Global efficiency (%)	40	39	44	51	**44**

Table A1.2 – Energy balance: meso-level application for the wastewater utility WU3.

WU/PS	**Energy component**	**2016**	**2017**	**2018**	**2019**	**Avg.**
WU3/PS1	Elevation energy, E_{EE} (%)	31	35	30	22	**30**
	Dissipated energy pump inefficiency (%), E_{EDE}	67	63	68	77	**69**
	Dissipated energy friction losses (%), E_{EDL}	2	2	2	1	**2**
	External energy (kWh/m^3), E_E	0.330	0.293	0.341	0.479	**0.361**
	Manometric head (m)	40				
	Global efficiency (%)	33	37	32	23	**31**

Table A1.3 – Energy balance: meso-level application for the wastewater utility WU5.

WU/PS	Energy component	2016	2017	2018	2019	Avg.
WU5/PS1	Elevation energy, E_{EE} (%)	78	38	39	39	**48**
	Dissipated energy pump inefficiency (%), E_{EDE}	18	60	60	60	**49**
	Dissipated energy friction losses (%), E_{EDL}	4	2	2	2	**3**
	External energy (kWh/m^3), E_E	0.106	0.217	0.214	0.215	**0.188**
	Manometric head (m)	32				
	Global efficiency (%)	82	40	41	41	**51**
WU5/PS2	Elevation energy, E_{EE} (%)	26	39	38	-	**34**
	Dissipated energy pump inefficiency (%), E_{EDE}	72	58	60	-	**64**
	Dissipated energy friction losses (%), E_{EDL}	1	2	2	-	**2**
	External energy (kWh/m^3), E_E	0.186	0.125	0.129	-	**0.147**
	Manometric head (m)	19				
	Global efficiency (%)	28	41	40	-	**36**
WU5/PS3	Elevation energy, E_{EE} (%)	24	34	35	35	**31**
	Dissipated energy pump inefficiency (%), E_{EDE}	74	64	64	64	**67**
	Dissipated energy friction losses (%), E_{EDL}	1	2	2	2	**2**
	External energy (kWh/m^3), E_E	0.339	0.243	0.238	0.238	**0.265**
	Manometric head (m)	32				
	Global efficiency (%)	26	36	37	37	**34**
WU5/PS4	Elevation energy, E_{EE} (%)	30	45	38	38	**37**
	Dissipated energy pump inefficiency (%), E_{EDE}	69	53	60	60	**61**
	Dissipated energy friction losses (%), E_{EDL}	2	2	2	2	**2**
	External energy (kWh/m^3), E_E	0.079	0.052	0.061	0.061	**0.063**
	Manometric head (m)	9				
	Global efficiency (%)	31	47	40	40	**40**

Table A1.4 – Energy balance: meso-level application for the wastewater utility WU6.

WU/PS	Energy component	2015	2016	2017	2018	Avg.
WU6/PS1	Elevation energy, E_{EE} (%)	10	18	-	-	**14**
	Dissipated energy pump inefficiency (%), E_{EDE}	91	82	-	-	**87**
	Dissipated energy friction losses (%), E_{EDL}	0,5	1	-	-	**1**
	External energy (kWh/m^3), E_E	0.581	0.313	-	-	**0.447**
	Manometric head (m)			**21**		
	Global efficiency (%)	10	18	-	-	**14**
WU6/PS2	Elevation energy, E_{EE} (%)	14	17	20	19	**18**
	Dissipated energy pump inefficiency (%), E_{EDE}	87	83	80	82	**83**
	Dissipated energy friction losses (%), E_{EDL}	1	1	1	1	**1**
	External energy (kWh/m^3), E_E	0.196	0.156	0.139	0.144	**0.159**
	Manometric head (m)			10		
	Global efficiency (%)	14	17	20	19	**18**
WU6/PS3	Elevation energy, E_{EE} (%)	-	-	-	25	**25**
	Dissipated energy pump inefficiency (%), E_{EDE}	-	-	-	75	**75**
	Dissipated energy friction losses (%), E_{EDL}	-	-	-	1	**1**
	External energy (kWh/m^3), E_E	-	-	-	0.492	**0.492**
	Manometric head (m)			**45**		
	Global efficiency (%)	-	-	-	25	**25**
WU6/PS4	Elevation energy, E_{EE} (%)	11	12	12	22	**14**
	Dissipated energy pump inefficiency (%), E_{EDE}	89	88	88	78	**86**
	Dissipated energy friction losses (%), E_{EDL}	1	1	1	1	**1**
	External energy (kWh/m^3), E_E	0.736	0.672	0.686	0.372	**0.617**
	Manometric head (m)			**30**		
	Global efficiency (%)	11	12	12	22	**14**
WU6/PS5	Elevation energy, E_{EE} (%)	7	14	9	13	**11**
	Dissipated energy pump inefficiency (%), E_{EDE}	93	86	92	87	**90**
	Dissipated energy friction losses (%), E_{EDL}	0,5	1	0,5	1	**1**
	External energy (kWh/m^3), E_E	0.558	0.271	0.423	0.298	**0.387**
	Manometric head (m)			**14**		
	Global efficiency (%)	7	14	9	13	**11**

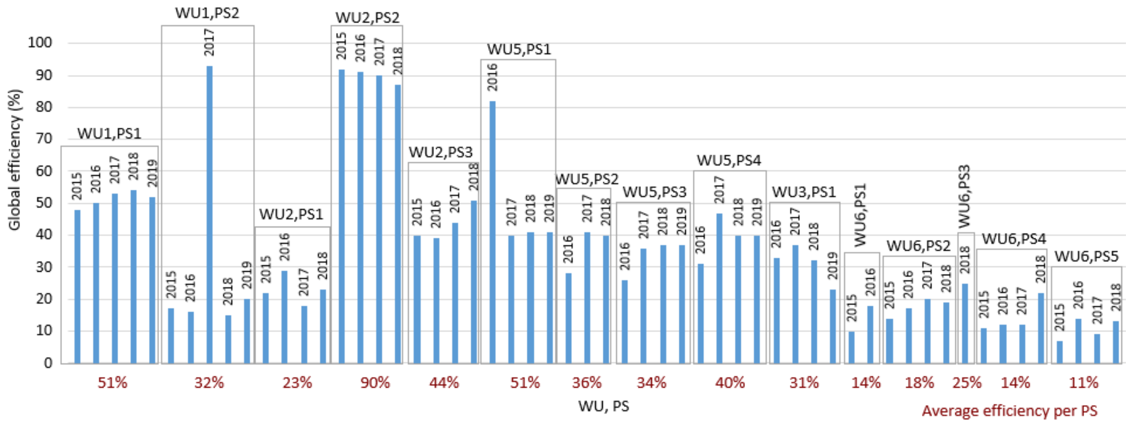


Figure A1.1 – Energy balance: meso-level global efficiency results for each WU and PS.

Appendix A2: Chapter 4 – Micro-level application of the energy balance with energy recovery

Table A2.1 – Results for energy balance application in June: dry season (MWh, % of E_T).

<table>
<tr><th></th><th colspan="2">ENERGY INFLOWS</th><th colspan="3">ENERGY OUTFLOWS</th></tr>
<tr><td rowspan="9">Total energy used for system processes (transport and treatment), E_T = 2 857 MWh (100%)</td><td rowspan="6">Total inflow intrinsic energy, E_I = 2 759 MWh (96.5%)</td><td rowspan="3">Inflow intrinsic energy associated with authorized or due inflows, E_{IAI} = 2 759 MWh (96.5%)</td><td rowspan="6">Total inflow intrinsic energy, E_I = 2 759 184 MWh (96.5%)</td><td colspan="2">System downstream energy, E_{IDE} = 184 MWh (6.4%)</td></tr>
<tr><td colspan="2">Recovered energy (micro hydropower), E_{IRE} = 0 (0%)</td></tr>
<tr><td rowspan="2">Dissipated energy, E_{ID} = 2 574 MWh (90.1%)</td><td>…due to inefficiencies in energy recovery equipment (e.g., turbines), E_{IDT} = 0 (0%)</td></tr>
<tr><td rowspan="3">Inflow intrinsic energy associated with undue inflows, E_{IUI} = 0 (0%)</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{IDL} = 2 575 MWh (90.1%)</td></tr>
<tr><td rowspan="2">Energy associated with exceedance volumes, E_{IEV} = 0 (0%)</td><td>…not connected to an energy consuming component, E'_{IEV} = 0 (0%)</td></tr>
<tr><td>…potentially inflowing to an energy consuming component, E''_{IEV} = 0 (0%)</td></tr>
<tr><td rowspan="3">External energy (electrical), E_E = 99 MWh (3.5%)</td><td rowspan="2">External energy associated with authorized or due inflows, E_{EAI} = 99 MWh (3.5%)</td><td rowspan="3">External energy, E_E = 99 MWh (3.5%)</td><td colspan="2">Elevation associated energy, E_{EE} = 29 MWh (1.0%)</td></tr>
<tr><td rowspan="2">Dissipated energy, E_{ED} = 70 MWh (2.5%)</td><td>…due to inefficiencies (in electromechanical equipment, e.g., pumps), E_{EDE} = 69.5 MWh (2.47%)</td></tr>
<tr><td>External energy associated with undue inflows, E_{EUI} = 0 (0%)</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens), E_{EDL} = 0.5 MWh (0.03%)</td></tr>
</table>

Table A2.2 – Results for energy balance application in January: wet season (MWh, % of E_T).

<table>
<tr><th></th><th colspan="2">ENERGY INFLOWS</th><th colspan="3">ENERGY OUTFLOWS</th></tr>
<tr><td rowspan="9">Total energy used for system processes (transport and treatment), E_T = 11 566 MWh (100%)</td><td rowspan="6">Total inflow intrinsic energy, E_I = 11 239 MWh (97.2%)</td><td rowspan="4">Inflow intrinsic energy associated with authorized or due inflows,
E_{IAI} = 6 504 MWh (56.2%)</td><td rowspan="6">Total inflow intrinsic energy, E_I =
11 239 224 MWh (97.2%)</td><td colspan="2">System downstream energy, E_{IDE} =
645 MWh (5.6%)</td></tr>
<tr><td colspan="2">Recovered energy (micro hydropower),
E_{IRE} = 0 (0%)</td></tr>
<tr><td rowspan="2">Dissipated energy,
E_{ID} =
3 828 MWh (33.1%)</td><td>…due to inefficiencies in energy recovery equipment (e.g., turbines),
E_{IDT} = 0 (0%)</td></tr>
<tr><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens),
E_{IDL} = 3 828 MWh (33.1%)</td></tr>
<tr><td rowspan="2">Inflow intrinsic energy associated with undue inflows,
E_{IUI} = 4 735 MWh (40.9%)</td><td rowspan="2">Energy associated with exceedance volumes,
E_{IEV} =
6 766 MWh (58.5%)</td><td>…not connected to an energy consuming component,
E'_{IEV} = 5 736 MWh (49.6%)</td></tr>
<tr><td>…potentially inflowing to an energy consuming component,
E''_{IEV} = 1 030 MWh (8.9%)</td></tr>
<tr><td rowspan="3">External energy (electrical), E_E = 327 MWh (2.8%)</td><td rowspan="2">External energy associated with authorized or due inflows, E_{EAI} = 133 MWh (1.1%)</td><td rowspan="3">External energy, E_E =
327 MWh (2.8%)</td><td colspan="2">Elevation associated energy,
E_{EE} = 96 MWh (0.8%)</td></tr>
<tr><td rowspan="2">Dissipated energy,
E_{ED} =
231 MWh (2.0%)</td><td>…due to inefficiencies (in electromechanical equipment, e.g., pumps),
E_{EDE} = 229 MWh (1.98%)</td></tr>
<tr><td>External energy associated with undue inflows,
E_{EUI} = 194 MWh (1.7%)</td><td>…due to pipe friction and local head losses (e.g., junctions, bends, valves, screens),
E_{EDL} = 2 MWh (0.02%)</td></tr>
</table>

Appendix A3: Chapter 5 – Performance assessment system for energy efficiency in wastewater systems and Chapter 7 – From assessment to a decision: a global framework to manage energy use in wastewater systems

Table A3.1 – Complete metrics description and formulation: Objective 1.

Metric	Description	Formulation
Objective 1 | Energy-use efficiency		
Criterion 1.1: Energy efficiency of wastewater systems		
M1.1.1: Specific energy per total WW volume (kWh/m^3) (ERSAR and ADENE, 2018)	Energy consumption per unit volume of collected or treated wastewater.	Total annual energy consumption/total annual collected or treated wastewater volume. Note: Variables are included in the Portuguese regulator annual report.
M1.1.2: Specific energy per total pumped volume (kWh/m^3)	Energy consumption per unit volume of pumped wastewater.	Total annual energy consumption for pumping/total annual pumped wastewater volume. Note: Energy consumption for pumping included in the Portuguese regulator annual report. Total annual pumped volume should be obtained from measurements.
M1.1.3: Pumping stations energy efficiency [kWh/(m^3.100 m)] (ERSAR, 2018)	Average pumping energy consumption in the system per 1 m^3 at 100 m of head.	Energy consumption for pumping/standardization factor. Note: Standardization factor: m^3/(year.100 m).
M1.1.4: Percentage of total energy consumption used for pumping (%)	Energy consumption for pumping in relation to the total energy consumption.	Energy consumption for pumping/total energy consumption × 100.
M1.1.5: Percentage of total energy consumption used for WW treatment (%)	Energy consumption for treatment in relation to the total energy consumption.	Energy consumption for treatment/total energy consumption × 100. Note: Energy consumption for treatment should be obtained from measurements.
M1.1.6: Energy consumption for WWTP per population equivalent (kWh/e.p.) *(adapted from Matos et al., 2003)*	Energy consumption for treatment per equivalent of population.	Energy consumption for treatment/population equivalent.
M1.1.7: Percentage of pumps with acceptable efficiency (%)	Percentage of pumps with efficiency losses below 25% of their nominal value.	N. of pumps with efficiency losses below 25% of their nominal value/total n. of pumps × 100. Note: Requires audits data.
Criterion 1.2: Practices of operation, cleaning, and maintenance		
M1.2.1: Energy consumption for sewer network cleaning [tep/(100 km.year)]	Annual energy consumption used to clean each 100 km of the sewer network.	Energy consumption for sewer network cleaning/number of sewer km. Note: Energy consumption for sewer network cleaning should be obtained from measurements.
M1.2.2: Energy consumption for septic tanks cleaning [tep/(km of travel.year)]	Annual energy consumption used for trucks per km travelled to empty septic tanks.	Energy consumption of trucks/total km travelled.
M1.2.3: Operation practices improvement to lower pump head (-)	Practices implemented at the wastewater utility to decrease the energy used for pumping (e.g., pumping operation levels adjustment).	-

Table A3.1 (cont.) – Complete metrics description and formulation: Objective 1.

Metric	Description	Formulation
Objective 1 | Energy-use efficiency		
Criterion 1.3: Control of undue inflows		
M1.3.1: Quarter energy peak factor (-)	Ratio between the average monthly consumption in the three months of highest consumption and the average monthly consumption.	Average energy consumption in the three months of highest consumption/average monthly energy consumption in the year. Note: Requires monthly energy consumption measurements.
M1.3.2: Energy consumption seasonality (-)	Ratio between the average monthly consumption in the three months of highest consumption and the three months of lower consumption.	Average energy consumption in the three months of highest consumption/Average energy consumption in the three months of lowest consumption. Note: Requires monthly energy consumption measurements.
M1.3.3: Percentage of energy equivalent to the volume generated in the served area used for pumping (%)	Total energy required to pump the total volume generated in the served area if there were no limitations on the transport capacity of the network upstream of the pumping installation.	Energy consumption for pumping/energy consumption associated with the total volume generated in the served area × 100. Note: To obtain the energy consumption associated with the total volume generated in the served area it is necessary to measure the volume discharged or to have hydraulic models available.
M1.3.4: Percentage of energy equivalent to the volume generated in the served area used for WW treatment (%)	Total energy used to treat the total volume from the served area if there were no limitations on the transport capacity of the network upstream of the pumping installation.	Energy consumption for treatment/energy consumption associated with the total volume generated in the served area × 100.
M1.3.5: Effect of excessive inflows on energy consumption (%)	Percentage of energy consumption associated with undue inflows.	(Energy associated with the process/total volume of wastewater collected or treated) × (volume of excessive inflows of the dry weather pattern/total volume of wastewater collected or treated) × 100. Note: To obtain the volume of excessive inflows it is necessary to have daily flow patterns available.

Table A3.1 (cont.) – Complete metrics description and formulation: Objectives 2 and 3.

Metric	Description	Formulation
Objective 2 | Carbon neutrality		
Criterion 2.1: GHG emission in equipment, processes, and transport		
M2.1.1: Specific GHG emissions associated with total WW volume (kg CO_2 eq/m^3)	Ratio between greenhouse gas emissions associated with the total energy consumption and the volume of wastewater collected or treated.	Total energy consumption × 7.04 × 10^{-4} (*)/total volume of wastewater collected or treated × 1000. Note: (*) Conversion factor: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (accessed on 12 January 2021).
M2.1.2: Specific GHG emissions associated with pumped volume (kg CO_2 eq/m^3)	Ratio between greenhouse gas emissions associated with the energy consumption for pumping and the pumped volume.	Energy consumption for pumping × 7.04 × 10^{-4} (*)/pumped volume × 1000.
M2.1.3: Specific GHG emissions associated with WW treated volume (kg CO_2 eq/m^3)	Ratio between greenhouse gas emissions associated with the energy consumption for treatment and the volume of wastewater collected or treated.	Energy consumption for treatment × 7.04 × 10^{-4} (*)/total volume of wastewater collected or treated × 1000.
M2.1.4: Specific GHG emissions associated with volume generated in the served area (kg CO_2 eq/m^3)	Ratio between greenhouse gas emissions associated with the energy consumption associated with the total volume generated in the served area and the volume of wastewater collected or treated.	Energy consumption associated with the total volume generated in the served area × 7.04 × 10^{-4} (*)/total volume of wastewater collected or treated × 1000.
M2.1.5: Specific GHG emissions associated with O&M (kg CO_2 eq/m^3)	Ratio between greenhouse gas emissions associated with the energy consumption for operation and maintenance and the volume of wastewater collected or treated.	Energy consumption for operation and maintenance × 7.04 × 10^{-4} (*)/total volume of wastewater collected or treated × 1000.
Criterion 2.2: Use of clean energy		
M2.2.1: Percentage of total energy consumption from clean energy sources (%)	Percentage of total energy consumption that is associated with clean sources (e.g., solar, wind).	Energy consumption from clean sources/total energy consumption × 100. Note: Energy consumption from clean sources should be obtained from measurements.
Objective 3 | Energy production and recovery		
Criterion 3.1: Energy self- production		
M3.1.1: Energy self-production (%) (ERSAR and ADENE, 2018)	Percentage of total energy consumption associated with self-production (e.g., biogas, solar).	Energy consumption from self-production/total energy consumption × 100. Note: Energy consumption for self-production should be obtained from measurements.
Criterion 3.2: Energy recovery		
M3.2.1: Recovered energy (%)	Percentage of the total energy that is recovered by the wastewater utility.	Energy recovered/total energy consumption × 100. Note: Energy recovered should be obtained from measurements.
Criterion 3.3: Use of purely gravity systems		
M3.3.1: Percentage of sewer network not associated with pumping stations (%)	Percentage of the total sewer network that is purely gravity.	Km of purely gravity network/total km of network.

Table A3.1 (cont.) – Complete metrics description and formulation: Objective 4.

Metric	Description	Formulation
Objective 4 | Economical and financial sustainability		
Criterion 4.1: Wastewater system associated costs (except maintenance)		
M4.1.1: Percentage of cost of total energy equivalent to the volume generated in the served area used for pumping (%)	Cost of total energy required to pump the total volume generated in the served area if there were no limitations on the transport capacity of the network upstream of the pumping installation.	Costs of energy consumption for pumping / costs of energy consumption associated with the total volume generated in the served area × 100.
M4.1.2: Percentage of cost of total energy equivalent to the volume generated in the served area used for WW treatment (%)	Cost of total energy required to treat the total volume generated in the served area if there were no limitations on the transport capacity of the network upstream of the pumping installation.	Costs of energy consumption for treatment / costs of energy consumption associated with the total volume generated in the served area × 100.
M4.1.3: Percentage of the cost of total energy consumption used for pumping (%)	Cost of energy consumption for pumping in relation to the total energy consumption.	Costs of total energy consumption for pumping / total energy costs × 100.
M4.1.4: Percentage of the cost of total energy consumption used for WW treatment (%)	Cost of energy consumption for treatment in relation to the total energy consumption.	Costs of total energy consumption for treatment / total energy costs × 100.
M4.1.5: Cost associated with the quarter energy peak factor (-)	Ratio of costs with the average monthly consumption in the three months of highest consumption and the average monthly consumption in the year.	Costs of the average energy consumption in the three months of highest consumption / costs of the average monthly energy consumption in the year.
M4.1.6: Cost associated with energy consumption seasonality (-)	Ratio of costs with the average monthly consumption in the three months of highest consumption and the three months of lower consumption.	Costs of the average energy consumption in the three months of highest consumption / costs of the average energy consumption in the three months of lowest consumption.
M4.1.7: Percentage of cost associated with energy self-production (%)	Percentage of total energy costs associated with self-production (e.g., biogas, solar).	Costs of energy consumption from self-production/total energy costs × 100.
M4.1.8: O&M costs of energy consumption reduction by control of undue inflows (%)	Energy costs of operating and maintenance practices regarding the control of undue inflows to foster the reduction of energy consumption.	Energy costs of operating and maintenance practices regarding the control of undue inflows/total energy costs × 100. Note: Energy consumption associated with operating and maintenance practices regarding the control of undue inflows should be obtained from measurements.

Table A3.1 (cont.) – Complete metrics description and formulation: Objective 4.

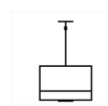
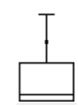
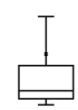
Metric	Description	Formulation
Objective 4 | Economical and financial sustainability		
Criterion 4.2: Maintenance costs		
M4.2.1: Repair or replacement costs of pumping equipment [€/(equipment .year)]	Annual costs associated with the repair or replacement of pumps and/or pump components.	Costs associated with the repair or replacement of pumping equipment/total number of repaired equipment.
M4.2.2: Cleaning operations costs of energy [€/(100 km.year)]	Annual costs associated with cleaning practices in the sewer network.	Costs of energy associated with cleaning practices in the sewer network/number of sewer km. Note: Energy consumption associated with cleaning practices should be obtained from measurements.
M4.2.3: Solids removal operations costs of energy [€/(kg.year)]	Annual costs associated with operations regarding the removal of solids in the sewer network.	Costs of energy associated with solids removal operations/kg of solids removed. Note: Energy consumption associated with solids removal operations should be obtained from measurements.

Appendix A4: Chapter 6 – Water, energy, and emissions nexus in wastewater systems

Table A4.1 – Complete P7–P10 metrics formulation.

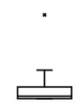
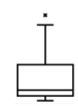
Metric	Description	Formulation
P7 Energy consumption in periods with precipitation (−)	Ratio between energy consumption in the 3 months with the highest rainfall and in the 3 months with lowest rainfall	$\frac{\sum Energy\ consumption\ in\ the\ 3\ months\ with\ the\ highest\ rainfall}{\sum Energy\ consumption\ in\ the\ 3\ months\ with\ the\ lowest\ rainfall}$
P8 Effect of UI in energy (−)	Ratio between energy consumption associated with UI and with dry weather	$\frac{Energy\ consumption\ associated\ with\ undue\ inflows}{Energy\ consumption\ associated\ with\ wastewater\ volume}$
P9 Effect of infiltration in energy (−)	Ratio between energy consumption associated with infiltration and with dry weather	$\frac{Energy\ consumption\ associated\ with\ infiltration}{Energy\ consumption\ associated\ with\ wastewater\ volume}$
P10 Effect of rain-derived inflows in energy (−)	Ratio between energy consumption associated with rain-derived inflows and with dry weather	$\frac{Energy\ consumption\ associated\ with\ rain\ derived\ inflows}{Energy\ consumption\ associated\ with\ wastewater\ volume}$

Table A4.2 – National characterization for the evaluation of the W-E-G nexus for 2015.

Variable/Year	**Annual Rainfall (mm)**	**N. º PS**	**N. º WWTP**	**N. º Weirs**	**Monitored Weirs (%)**	**N. º Floods**	**Min**	**P25**	**Median**	**Average**	**P75**	**Max**	**Boxplot** (1)
2015	599.6	5 375	2 673	6 851	71	10772							
Total energy consumption (kWh/year)							0	13 420	66 301	1 571 982	220 882	1.18×10^8	
Energy consumption for pumping (kWh/year)							0	461	17 156	326 984	80 332	1.94×10^7	
Collected/treated wastewater volume (m^3/year)							93 792	379 491	793 060	6 324 712	2 637 812	4.84×10^8	

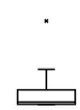
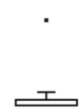
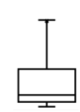
(1) Some outliers were removed to facilitate the graphical reading.

Table A4.3 – National characterization for the evaluation of the W-E-G nexus for 2016.

Variable/Year	Annual Rainfall (mm)	N. º PS	N. º WWTP	N. º Weirs	Monitored Weirs (%)	N. º Floods	Min	P25	Median	Average	P75	Max	Boxplot (1)
2016	991.6	5641	2743	2071	53	13041							
Total energy consumption (kWh/year)							0	18 328	71 572	1 699 059	287 192	1.22×10^8	
Energy consumption for pumping (kWh/year)							0	1 716	36 792	748 795	169 448	2.05×10^7	
Collected/treated wastewater volume (m^3/year)							56 040	431 593	928 722	7 458 093	311 580	5.68×10^8	

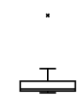
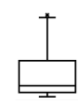
(1) Some outliers were removed to facilitate the graphical reading.

Table A4.4 – National characterization for the evaluation of the W-E-G nexus for 2017.

Variable/Year	Annual Rainfall (mm)	N. º PS	N. º WWTP	N. º Weirs	Monitored Weirs (%)	N. º Floods	Min	P25	Median	Average	P75	Max	Boxplot (1)
2017	541.3	5668	2708	1157	44	12308							
Total energy consumption (kWh/year)							0	16 731	70 881	1 683 566	328 151	8.77×10^7	
Energy consumption for pumping (kWh/year)							0	5 743	32 096	595 261	156 615	1.60×10^7	
Collected/treated wastewater volume (m^3/year)							63 268	348 086	853 829	6 064 429	2 689 580	3.69×10^8	

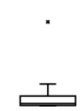
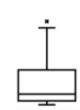
(1) Some outliers were removed to facilitate the graphical reading.

Table A4.5 – National characterization for the evaluation of the W-E-G nexus for 2018.

Variable/Year	Annual Rainfall (mm)	N. º PS	N. º WWTP	N. º Weirs	Monitored Weirs (%)	N. º Floods	Min	P25	Median	Average	P75	Max	Boxplot (1)
2018	939.9	5821	2715	1097	58	11079							
Total energy consumption (kWh/year)							0	17 458	62 756	1 742 734	274 542	9.22×10^7	
Energy consumption for pumping (kWh/year)							0	2 071	21 154	558 493	170 931	1.52×10^7	
Collected/treated wastewater volume (m^3/year)							58 521	373 923	926 211	6 672 083	3 005 179	3.92×10^8	

(1) Some outliers were removed to facilitate the graphical reading.

Table A4.6 – National characterization for the evaluation of the W-E-G nexus for 2019.

Variable/Year	Annual Rainfall (mm)	N. º PS	N. º WWTP	N. º Weirs	Monitored Weirs (%)	N. º Floods	Min	P25	Median	Average	P75	Max	Boxplot (1)
2019	755.6	5983	2724	1549	48	11517							
Total energy consumption (kWh/year)							0	17 063	73 024	1 885 040	277 509	8.77×10^7	
Energy consumption for pumping (kWh/year)							0	1 420	25 423	538 217	159 647	1.52×10^7	
Collected/treated wastewater volume (m^3/year)							65 648	381 769	941 341	6 920 595	2 935 901	3.74×10^8	

(1) Some outliers were removed to facilitate the graphical reading.