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WENEXUS

DELIVERING THE WATER-ENERGY NEXUS FOR ENERGY EFFICIENCY

D2.3 - PORTFOLIO OF EFFICIENCY MEASURES

Final Version (1.0)

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TABLE OF CONTENTS

1. Introduction **4**

1.1. WENexus overview 4

1.2. Scope of the document 5

1.3. Document structure 6

2. Energy in the water sector **7**

2.1. Importance of energy management in the water sector 8

2.2. Energy consumption in the water sector 12

2.3. Energy production in the water sector 15

2.4. General good practices in the water sector 16

2.4.1. Good practices for efficient energy consumption 16

2.4.2. Good practices for maximizing energy production 19

2.5. WENexus role in the water sector 20

3. Energy efficiency proposed measures for the energy transition in the water sector **23**

3.1. Vector 1: Electromechanical equipment efficiency 23

3.1.1. Pumps 24

3.1.2. Electrical Engine 29

3.2. Vector 2: Energy production capacity - photovoltaic panels 34

3.2.1. Photovoltaic Panels Installation 34

3.3. Vector 3: power storage capacity – Batteries installation 36

3.4. Vector 4: energy production capacity – biomethane systems 37

3.5. Other General measures with relevant impact in the water systems 40

3.6. Water losses impact in the energy efficiency of the water supply systems 46

4. Conclusions **48**

5. References **50**

Annex I – Energy Efficiency Measures Assessment .... **A**

LIST OF TABLES

TABLE 2.1 - PERFORMANCE INDICATORS, FORMULATION AND REFERENCE VALUES IN ENERGY CONSUMPTION IN THE WATER SECTOR 14
TABLE 2.2 - PERFORMANCE INDICATORS, FORMULATION AND REFERENCE VALUES IN ENERGY PRODUCTION IN THE WATER SECTOR 16
TABLE 3.1 - MEASURE ASSESSMENT FOR VECTOR 1: PUMPS 28
TABLE 3.2 - MEASURE ASSESSMENT FOR VECTOR 1: ENGINES 34
TABLE 3.3 - MEASURE ASSESSMENT FOR VECTOR 2: PHOTOVOLTAIC 35
TABLE 3.4 - MEASURE ASSESSMENT FOR VECTOR 3: BATTERIES INSTALLATION 37
TABLE 3.5 - MEASURE ASSESSMENT (BIOMETHANE SYSTEMS) 39
TABLE 3.6 - WATER SUPPLY OPERATION'S MEASURES 41
TABLE 3.7 - WASTEWATER OPERATION'S MEASURES 43

LIST OF FIGURES

FIGURE 2.1 - DESCRIPTION OF THE URBAN WATER CYCLE (AND IDENTIFICATION OF ENERGY EFFICIENCY POTENTIAL) 8
FIGURE 2.2 - ENERGY DATA ASSESSMENT FOR AUDIT 10
FIGURE 2.3 - THE STAGES OF A PDCA MANAGEMENT CYCLE 11
FIGURE 2.4 - LEVELS OF WATER SERVICE EVALUATION 11
FIGURE 2.5 - ELECTRICITY CONSUMPTION IN THE WATER SECTOR BY STAGE OF THE URBAN WATER SYSTEM IN THE EU 12
FIGURE 3.1 - DEGRADATION OF PUMPS PERFORMANCE SHOWN BY THE REDUCTION OF HEAD AT A CONSTANT FLOW RATE 25
FIGURE 3.2 - INSTALL ADDITIONAL LOW-CAPACITY PUMPING SYSTEMS IN TOWER TANKS: MEASURE FUNCTION ILLUSTRATION 27
FIGURE 3.3 - IE EFFICIENCY CLASSES FOR 4 POLE MOTORS AT 50HZ 30
FIGURE 3.4 - IE EFFICIENCY CLASSES FOR 4 POLE MOTORS AT 50HZ 31

ACRONYMS

CO_2	Carbon Dioxide
ERSAR	Water and Waste Services Regulatory Authority
GA	Grant Agreement number 101120628 - LIFE22-CET-WENexus - LIFE-2022-CET-PDA - LIFE-PJG CINEA/D/01
GDPR	General Data Protection Regulation - Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of the companies' Data and on the free movement of such Data and repealing Directive 95/46/EC.
H_2S	Hydrogen sulfide
Partners	For the purposes defined in this DMP, the following entities shall be considered as the Consortium Partners: S317 Consulting, Lda. (hereinafter referred to as S317); ENGIDRO Engineering Solutions, Lda. (hereinafter referred to as Engidro); Sérvulo e Associados, Sociedade de Advogados, SP, RL (hereinafter referred to as Sérvulo).
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

1.1. WENexus overview

Under the Grant Agreement[1] (GA), WENexus – *Delivering the Water-Energy nexus for energy efficiency* (hereafter referred to as "WENexus"), is a European project, financed under the LIFE - Clean Energy Transition 2022 Programme, and led by S317 Consulting in a consortium with Engidro Engineering Solutions and Sérvulo e Associados. The project started in September 2023, and it is intended to last 3 years (pilot phase).

The WENexus project aligns seamlessly with the objectives and prerequisites outlined in key documents, including the *Plano Estratégico para o Abastecimento de Água e Gestão de Águas Residuais* (PENSAARP2030), *Plano Nacional de Energía e Clima 2030* (PNEC), the Portuguese Roadmap for Carbon Neutrality 2050, and the United Nations 2030 Agenda for Sustainable Development Goals (SDGs). At its core, the project looks for the adaptation of the water sector by directing the development, implementation, and standardization of innovative tools designed to enhance energy efficiency within the water sector. This endeavor is complemented by the provision of comprehensive technical, financial, and legal support to the organizations responsible for water and wastewater service management and operations, guaranteeing a high degree of replicability and transferability potential within the sector.

WENexus primarily focuses on mobilizing private investment for water infrastructure renovation by creating innovative financial models specifically tailored for energy efficiency investments in water services infrastructures. Additionally, the project aims to contribute to the de-risking of energy efficiency projects in water infrastructures. All things considered, the project's goals are:

1. Contribute to the energy transition and sustainable energy use in the water sector.
2. Leverage investments that promote energy efficiency in water supply and wastewater systems in Portugal.
3. Ensure the replicability and transferability of the projects and good practices identified through the pilots developed.

Hence, WENexus' goals were designed to achieve energy and efficiency improvements specifically through four key vectors:

[1] Grant Agreement number 101120628 - LIFE22-CET-WENexus - LIFE-2022-CET-PDA - LIFE-PJG CINEA/D/01

Vector 1 - acting on the system's electromechanical equipment efficiency, replacing them with more energy-efficient ones, where warranted, or eliminating hydraulic inefficiencies that may exist in the systems; Vector 2 - acting on sustainable energy production capacity by implementing energy production systems generated from photovoltaic panels; Vector 3 - acting on the power storage capacity, foreseeing the installation of storage batteries; Vector 4 - acting on energy production capacity the efficiency of the overall system, introducing systems to produce biomethane.

For the purpose of the present report, the vectors of the project were the baseline for the formulation of the efficiency measures.

1.2. Scope of the document

This Portfolio of Efficiency Measures was developed with the main objective of providing efficiency measures applicable to the Water-Energy nexus that is approached in the scope of the WENexus project. Because of this, it is essential to consider that the project aims to support water and wastewater utilities from the Portuguese water sector, in terms of management measures to increase their return on investment towards their processes. The deliverable is inserted in the Work Package 2, since it already has the purpose of being accessed for consultation of the utilities, providing a set of typified interventions aimed at improving energy performance of the water supply systems, as well as establish key performance indicators for each measure to assess the impact of its efficiency.

The presented measures are inserted in the water and wastewater cycle processes, which can be optimized leading to saving energy in the consumptions, and producing energy more efficiently. The document provides a separation of measures by the four vectors of the WENexus project (presented in 1.1), as well as additional measures that can be useful to water and wastewater utilities, but are not integrated in any of the vectors.

The measures presented in the scope of vector 1 include all practices that can be implemented to reduce energy consumption and, consequently less costs with the utilities' processes. This vector incorporates a wide range of measures, since they are applicable to different stages of the urban water cycle. The most relevant measures in this vector lead to the improvement of pumping systems, which are the biggest cause of intensive energy consumption, throughout the entire cycle. Measures deriving from vector 2 aim to increase the production capacity of utilities, through solar energy, namely the adaptation of current systems to the installation of photovoltaic panels. The measures related to vector 3 intend to decrease production losses, which has to do with the storage practices, regarding the installation of batteries in the utilities' system. Thus, these measures essentially provide guidelines on how to optimize the storage capacity of existing batteries, or how to replace them by more efficient ones.

Finally, the approach of measures towards vector 4 is regarding the optimization of the energy production capacity through biomethane. For this purpose, there are presented biomethane solutions that are explored to provide an innovative support to the current water systems, with a good cost-benefit for the water and wastewater utilities.

1.3. Document structure

The current document is structured in four Sections: Section 1 (Introduction), Section 2 (Energy in the Water Sector), and Section 3 (Efficiency Measures); Section 4 (Conclusions).

Firstly, Section 1 provides the context of the document by showcasing the relevance of the aggregation of efficiency measures in a Portfolio document, for the purpose of WENexus' support to the water and wastewater utilities of Portugal. Secondly, Section 2 provides an explanation of how the Portuguese water sector works, what are the gaps in terms of energy consumption and production throughout the water cycle, and what is being done so far to achieve the European 2030 targets of energy efficiency. Besides, it also provides good management practices and specific implementation practices to apply within the water sector, related to the optimization of systems, that can support utilities in their management. Subsequently, Section 3 presents the specific efficiency measures that utilities can implement, organized according to the four vectors of the WENexus project. Finally, Section 4 presents the main outcomes of the measures presented, in the form of main conclusions.

2. ENERGY IN THE WATER SECTOR

WENexus goes beyond the conventional focus on energy efficiency and self-consumption, by introducing a pioneering approach around the connection between energy and water. This perspective allows to recognize that the sector's activities inherently involve significant energy consumption and, consequently, leads to improvement opportunities in urban water efficiency, to optimize water supply and wastewater systems.

Portugal has set energy and water efficiency targets for 2030 as part of its National Energy and Climate Plan and Green Growth Commitment. In the water sector, Portugal aims to improve water efficiency by reducing unbilled water from 35% in 2012 to a maximum of 20% in 2030.[2]

The International Energy Agency reports that electrical energy consumption of the water sector accounts for 4% of total electricity consumption, worldwide.[3] As for the European scope, the water sector is a significant consumer of energy, with the electricity consumed to collect, pump, and treat water accounting for 2.6% of EU electricity consumption, which represents 30-40% of the total energy consumption in the water sector.[4] The services of water production, distribution, and treatment lead to electricity costs that significantly contribute to increasing the operating costs of urban water and wastewater utilities, which are responsible to manage those services.[5]

In Portugal, the urban water system (UWS) represents 3%–4% of the total national electricity consumption, but it is one of the sectors with the highest number of energy-intensive facilities at a national level, being responsible for a consumption of around 100GWh/year.[6] Today, there are already solutions to reduce energy consumption at all stages of the urban water cycle, allowing it to not only become more efficient, but also become a source of energy production.

In Figure 2.1 the urban water cycle in Portugal, from the water catchment, treatment and transport (bulk systems) to the water distribution networks for consumer use (retail systems) that then needs to be collected through sewerage, and treated in wastewater treatment plants (bulk systems).[7] Amongst the water cycle, there are specific stages that currently require higher values of energy consumption and, according to data from the Water and Waste Services Regulatory Authority (ERSAR), it is possible to

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[2] National Energy and Climate Plan 2021-2030 (NECP 2030) – Portugal (December 2019)
[3] International Energy Agency (2016)
[4] Water-Energy Nexus in Europe – JRC (Science for Policy Report) – European Commission (2019)
[5] Energy Efficiency Investments in Urban Water and Wastewater Utilities – The World Bank (2019)
[6] Technical Guide: Efficient use of energy in water services – ERSAR (2018)
[7] Energy Efficiency in Water Cycle Management – Veolia Group (2024)

measure the reduction potential of this energy consumption for each of these stages. The reduction estimates are of 20%-40% for water catchment, 5%-25% for water pumping, 20%-40% for water distribution, and 25%-60% for wastewater treatment. The same type of estimate also applies to the increase potential of energy production at the end of the cycle, which is 20%-60%.[6]

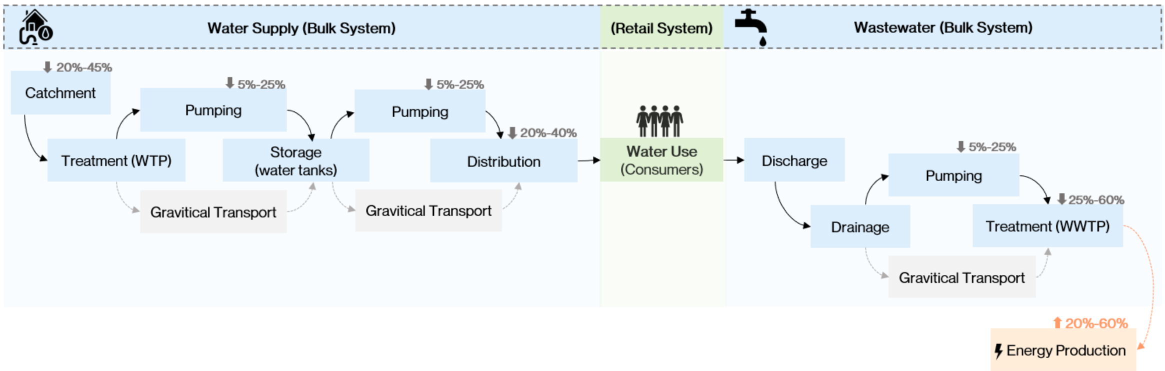

Figure 2.1 - Description of the urban water cycle (and identification of energy efficiency potential)

2.1. Importance of energy management in the water sector

For Portugal's water and wastewater utilities, achieving sustainable energy management systems allows them to achieve a range of benefits for different aspects of their operations. The two main ones are financial sustainability and alignment with the sector targets, at a national and European level.[8]

The implementation of energy efficiency measures, operational optimization of treatment plants, and addressing leakages and losses in the water network are crucial for reducing energy consumption in the water sector. These measures not only contribute to cost savings but also support the EU in meeting its energy efficiency targets for 2030.[2] By aligning with these predefined sectorial targets, water utilities are able to framework strategic plans that have a strong emphasis on the optimization of operating costs, thereby contributing as well to the overall objectives of the Water-Energy Nexus. The most important measures outlined in the strategic reports must emphasize the mitigating of water inefficiencies, particularly reducing physical water losses, which will not only contribute to conserving efforts, but also result in a notable reduction of energy consumption. This dual impact alleviates financial burdens and addresses environmental costs associated with excessive energy use.[9]

There are many reasons for the need of improvement of the hydric efficiency in the Portugal's water sector:

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[8] Reducing the Energy Footprint of the Water Sector – EurEau (2019)
[9] Energy efficiency in the European water industry: learning from best practices (Journal of Water and Climate Change) – Research article (2012)

- It is an environmental duty, since water is a limited resource needed to protect, conserve and manage in order to guarantee the sustainability of the ecosystems and services that they provide to society and ensure the sustainability of other resources associated.
- It is a strategical need, as the increase of water availability and water reservoirs are fundamental for the country.
- Correspond to the economic interest at different levels:
    - **National strategy**: Proper management of the water resources and maintenance of a crucial production factor;
    - **Water utilities sustainability**: Improved processes leading to lower operational costs and increase of the feasibility of their activities;
    - **Consumers' interests**: Lower costs within the water services life-cycle allowing for reduced water tariffs.

The challenges ahead for sustainable water services in Portugal and beyond include economic and financial sustainability, infrastructure sustainability, resource use and recovery, human capital, information management, knowledge, and innovation. These challenges are interconnected and require a comprehensive approach to ensure the effectiveness, efficiency, sustainability, and added value of water services.[10]

Narrowing down to the water management entities, these should address audits at different stages to ensure effective governance. Energetic audits can be wither simple, lasting for one to three days or, on the other hand, they can be complex, lasting for at least five days. The complex audits need to be performed in the scope of the Intensive Energy Consumption Management System (SGCIE), that mandates supervision and audit by specialized energy audits' technicians, in Intensive Energy Consumption (CIE) installations, which are intensive energy consumers that have had a consumption of energy equal or superior to 500 tons equivalent to petrol in the previous civil year.[11]

[10] "Portugal's integrated water sector policy had positive impact on society, economy & environment" – LIS-Water (2022)
[11] The Development of a Framework for Assessing the Energy Efficiency in Urban Water Systems and Its Demonstration in the Portuguese Water Sector – Urban Water Unit, National Civil Engineering Laboratory (2020)

An energy audit comprises three essential stages: Preparation, Fieldwork, and Information Processing. In the context of energy management, water companies are required to provide energy-related information, which is listed in Figure 2.2.

Collection of energy bills and production values for a minimum period of 1 year	Conducting all required measurements
Gathering data on technical characteristics and operating regimes of key equipment	Observing the practices of facility users and identifying anomalous situations
Gathering all necessary elements to perform energy balances for the installation and major consuming equipment	Identifying energy-saving measures that can be implemented

Figure 2.2 - Energy data assessment for audit

After proceeding with the energy assessment, the information is processed in order to draw conclusions and propose improvement measures. Based on these measures, the final output will be the determination of the energy efficiency measures that are more economically viable. Additionally, these measures should be guided by an action plan that formulates how to achieve and monitor the performance of those measures, as well as identifying anomalies or future measures that must be implemented in order to continuously improve the installation's energy performance.[11]

To ensure the efficiency and sustainability of water services, water management entities need to adopt assessment practices and continually improve their performance through PDCA (Plan-Do-Check-Act) cycles. These cycles allow to evaluate the entities' energy performance, support in decision making, and monitor the efficiency measures' impact on the entities' water supply systems and wastewater and rainwater systems. The four stages of a PDCA cycle are depicted in Figure 2.3, along with their respective descriptions.[12]

[12] Avaler+: Assessment of the efficiency and energetic sustainability in the urban water services – Guide for Diagnosis, Prioritization of alternatives, Monitoring and Review of the Action Plan – LNEC (2021). Available at: Guia_avaler_final.pdf

Figure 2.3 - The stages of a PDCA management cycle

In order to ensure that the PDCA cycle approach is implemented successfully, it is highly important to establish energy efficiency Performance Indicators (PI's), and the respective metrics that will measure their effectiveness. For different stages of the UWS, there are different PI's to be considered that, once measured, will define the quality of service of each water utility.

The assessment is based on the definition of bands of reference that reflect the level of satisfaction with the service, according to the PI defined, for the diverse indicators based on pre-defined objectives of the utility. For each PI, ERSAR has defined what values correspond to a 'Good evaluation', an 'Average evaluation' and a 'Unsatisfactory evaluation', each one corresponding to different colors: green, yellow and red, respectively, as demonstrated in Figure 2.4.[13]

Figure 2.4 - Levels of water service evaluation

In Portugal, the performance assessment system is regulated by ERSAR, and is calculated for drinking water systems and for wastewater systems, on an annual basis, by all water utilities. ERSAR has established the following reference values for the standardized energy consumption and the respective efficiencies for drinking water systems:

[13] Guide for Assessing the Quality of Water and Waste Services Provided to Users – ERSAR (2021). Available at: [Guia_Tecnico27.pdf (ersar.pt)]

- ‘Goode evaluation’: [0.27; 0.40] (pump efficiency 68%–100%)
- ‘Average evaluation’:]0.40; 0.54] (pump efficiency 50%–68%).
- ‘Unsatisfactory evaluation’:]0.54; 5] (pump efficiency below 50%)

In total, there are eight energy efficiency PI’s, each with a specific formulation and intervals of values that define their level of evaluation. From these PI’s, there are six related to energy consumption in the water sector (explained in Section 2.2), and two related to energy production in the water sector (explained in Section 2.3).

2.2. Energy consumption in the water sector

The water sector in Portugal is responsible for an electrical energy consumption of more than 1000 GWh/year, a value that corresponds to more than 2% of the country's total electrical consumption. There is an uneven distribution of water consumption amongst different sectors, being agriculture, the one responsible for the majority of the consumption (75%). The second-most relevant is the urban sector, responsible for 20% of the total Portugal’s water consumption, which is the sector analyzed in the scope of the WENexus project, thus, the focus for the development of the present document.[14]

Within the urban water sector, and according to studies conducted by ERSAR, it is estimated that the most important share of energy consumption in the water sector is related to water supply, which is a tendency occurring in Europe, as demonstrated in Figure 2.5.[3] Thus, this stage of the urban water system will be the main source of inputs to improve the current energy consumption values.[6]

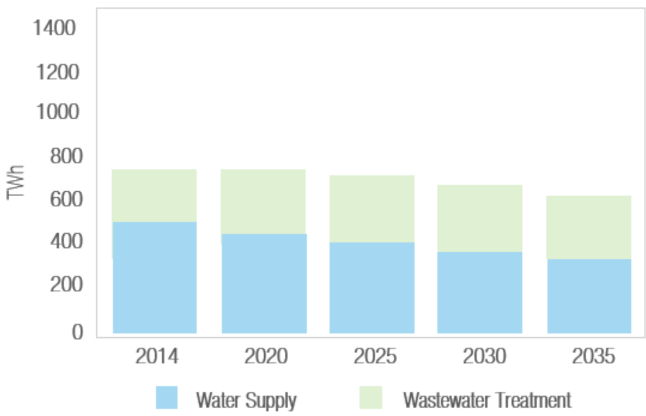

Figure 2.5 - Electricity consumption in the water sector by stage of the urban water system in the EU

[14] National Program for the efficient use of water: Implementation 2012-2020 – PNUEA. Available at: PNUEA_2020_Jun2012.pdf (apambiente.pt)

The Águas de Portugal Group participates in a group of companies that, in partnership with municipalities, provides services to about 80% of the Portuguese population. This group is responsible for water supply and wastewater sanitation, encompassing activities such as water capture, treatment, and transportation to municipal water reservoirs for human consumption or direct distribution to consumers. Additionally, it involves the transportation, treatment, and environmentally safe discharge of urban wastewater into the receiving environment. In its processes, the group consumed over 725 GWh/year in 2019, of which 140 GWh/year is consumed at EPAL. This accounts for 19% of the Group's overall consumption, with EPAL playing a pivotal role as the primary water supplier to the city of Lisbon, serving approximately 3 million residents and thus exhibiting a higher concentration of consumption.[15]

The water-energy nexus in the context of water supply systems means that every drop of water has an embedded potential energy (natural, shaft, or mixed) and, therefore, water losses inevitably mean increased energy consumption. Energy costs are the second highest expenditure of a water utility after personnel. Given the climate change challenges, particularly the increasingly more frequent droughts and floods worldwide, one of the main concerns of water utilities is to reduce water losses.[16] In order to characterize the type of consumption that is affecting energy efficiency, it is important to highlight that the most relevant losses are due to real energy losses in the process (around 37,5%), and volumes of non-revenue water (at least 30%).[6]

It is estimated that a reduction in consumption along the wastewater supply chain by 10% can generate total savings of around 72 million euros, thus recovering 15% of current energy costs. For real energy losses, the most significant stages enabling intensive energy consumption are the ones requiring pumping processes, which occur in pumping facilities (for water pumping). In relative terms, historically the consumption from this source will represent around at least 80% of the total consumption in water supply.[17]

The high consumption values observed are due to the energy performance of pumping facilities in water supply, which has been unsatisfactory or average (median 0.55 to 0.61 kWh/m3/100m), indicating that there is a high improvement potential in energy efficiency.[18]

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[15] Zero Energy Neutrality – Águas de Portugal in Sustainable Development (October 2020). Available at: NEUTRALIDADE ENERGÉTICA ZERO - ÁGUAS DE PORTUGAL NO DESENVOLVIMENTO SUSTENTÁVEL (engenhoearte.info)
[16] Top-Down and Bottom-Up Approaches for Water-Energy Balance in Portuguese Supply Systems (April 2018). Available at: water-10-00577.pdf
[17] Performance Assessment System for Energy Efficiency in Wastewater Systems – Water (2021)
[18] Energy consumption in urban water services in mainland Portugal (Resultados 2004-2017) – LNEC. Available at: Consumo de energia nos serviços urbanos de água em Portugal Continental. Resultados 2004-2017 (lnec.pt)

It is also relevant to analyze the quality of service in the water sector. Over the past decades, Portugal has witnessed substantial improvements in public services related to water supply, urban wastewater sanitation, and waste management. This progress has been driven by significant investments and a consistent public policy, with crucial contributions from EU funds. The coverage of water supply has risen from 80% in the 1990s to 97% in 2021, while sanitation reached 86%, falling short of the 90% target set in 2013. Moreover, water quality has achieved high levels, with nearly 99% of analyses conducted and compliance with around 99% of parameter values, reflecting safety and quality for consumers. In the urban waste sector, there has been a notable shift from landfill disposal to organic and material valorization since 2002, resulting in 100% proper management of urban waste produced.

Water supply and sanitation services have benefited from regional co-financing and investments in multi-municipal systems, while waste management efforts have seen coordinated actions from various entities, particularly management entities. Continuous progress demonstrates Portugal's commitment to enhancing infrastructure and environmental practices, despite persistent challenges in areas such as sanitation adoption and full compliance with established targets.

In the sequence of the service evaluation processes, specifically in terms of energy efficiency, there are six Performance Indicators (PI's) formulated for energy efficiency assessment in what regards to energy consumption. In Table 2.1 are presented these PI's, as well as their formulation and reference values that each of them considered for the evaluation of each process.

Table 2.1 - Performance Indicators, formulation and reference values in energy consumption in the water sector

Performance Indicator	Formulation	Reference Values (example of evaluation)
Standardized energy consumption (kWh/(m3.100 m))	Energy consumption for pumping/Sum of the volume elevated multiplied by the pump head/100	[0.27; 0.40];]0.40; 0.54];]0.54; 5]
Energy consumption per volume treated (kWh/m3)	Energy consumption for treatment/Treated Water	Example for activated sludge treatment: ≤ 0.280 + 1192/TW; > 0.350 + 1490/TW *(*)TW – Treated Wastewater*
Energy consumption per mass removed (kWh/kg)	Energy consumption for treatment/Mass Removed	Example of biochemical oxygen demand mass removed ≤ 2;]2; 10]; > 10
Energy consumption for sewer cleaning (kWh/ton)	Energy consumption for sewer cleaning/Sediments removed	Reference values to be defined during Avaler + project

Energy consumption for wastewater collection from septic tanks (kWh/m3)	Energy consumption for wastewater collection from septic tanks/Wastewater collected from septic tanks	Reference values to be defined during Avaler + project
Energy consumption for sludge disposal (kWh/m3)	Energy consumption for sludge disposal/Treated water	Reference values to be defined during Avaler + project

2.3. Energy production in the water sector

The water sector has significant potential to produce renewable energy, which can replace fossil fuels and help the European Union and Member States to meet their renewable energy targets. In Portugal, the water sector plays a significant role in energy production, showcasing a noteworthy interplay between consumption and generation. According to the International Trade Administration, the installed capacity (MW) for the production of energy in the water sector in Portugal has remained over 8,000 MW, with a modest decrease from 8,141 MW in 2022, to 8,120 MW in 2023.[19]

In 2015, the total energy consumption in the sector reached 1016 GWh, reflecting the diverse activities related to water supply and sanitation. Surprisingly, the energy production in the same year amounted to 35 GWh, indicating a notable degree of self-sufficiency in the sector's energy supply.[20]

It is noteworthy that, in 2015, a substantial portion of managing entities in the water supply subset demonstrated a sustainable initiative by reporting that 21% of them invested in their own energy production. This proactive approach underscores a growing awareness of the importance of energy self-sufficiency in the water sector in Portugal. Additionally, in the wastewater sanitation subset, 15% of managing entities also actively participated in energy generation, signalling a positive trend towards sustainability and efficiency in the treatment of wastewater in the country. These data suggest an ongoing pursuit of greener and more innovative energy solutions in the water sector in Portugal. There is a growing inclination among management entities to engage in energy production. However, based on the 2015 data, only 18% of the total water utilities within the water supply system reported involvement in energy production. In the context of the wastewater system, in 2015, 21% of the managing entities within the water supply subset reported engaging in energy production.[6]

[19] Portugal - Country Commercial Guide (Energy). International Trade Administration (2024)
[20] National Policy Framework for the deployment of alternative fuels infrastructure – DGEG (2017)

In the context of the service evaluation processes for water utilities, specifically in terms of energy efficiency, there are two PI's formulated for energy efficiency assessment in what regards to energy production within the water sector. In Table 2.2 these PI's are presented, as well as their formulation and reference values that each of them considered for the evaluation of each process.

Table 2.2 - Performance Indicators, formulation and reference values in energy production in the water sector

Performance Indicator	Formulation	Reference Values (example of evaluation)
Energy supplied in excess (kWh/m3)	Excess energy supplied / Consumption volume authorized or billed wastewater volume	● [0; 0.40]; ●]0.40; 1.0]; ●]1.0; +∞[
Energy production from biogas (kWh/m3)	Electrical energy produced from biogas/Treated water	● ≥ 0,0009 CBO5; ● [0.0007 CBO5; 0,0009 CBO5[; ● < 0,0007 CBO5 *(*) BOD5= influent BOD5 [mg/L]*

2.4. General good practices in the water sector

In the context of sustainable resource management, Portugal reveals the imperative need of adopting conscientious energy practices within the water sector. According to the legislation, it becomes paramount to explore and implement strategies that not only ensure the efficient utilization of water resources but also minimize the environmental footprint associated with their extraction, treatment, and distribution. This statement deepens the core field of energy best practices within Portugal's water sector, that can either apply to the energy consumption or the energy production within the UWSs. In this Section, both typologies of best practices will be presented and briefly explained.

2.4.1. Good practices for efficient energy consumption

Practices that allow energy savings in the processes of UWSs that require energy consumption. These practices can be divided in three groups, according to the stage of the urban water system:

2.4.1.1. Water supply

- **Reducing energy consumption in water catchment –** the intake structures must be designed and constructed in such a way that, at any time of the year, conditions for easy entry of water are ensured, and to the extent possible, of the best quality found at the source under consideration.
- **Reducing energy consumption in water plants -** there is potential to save energy by reducing the need to treat water treatment residues; some water treatment processes can be optimised by:
    - Replacing inefficient and over dimensioned components;

   - Deactivating parts which are no longer required;
   - Optimizing pumping system operations by:
     - Replacing inefficient pumps;
     - Installing variable frequency drives;
     - Using centrifugal pumps (suction water from the suction well and discharge it to another unit of the system);
     - Improving operational set up of pumping design.
- **Reducing energy consumption in water storage** – sizing of the reservoirs must consider constant flow rate and the manometric height of the conveyance system.
- **Reducing energy consumption in water distribution –** practices to be implemented in the distribution networks:
   - Network pipes should be directed towards areas of highest demand, and the layout should primarily be grid-based;
   - Pipes and collectors should be laid in unbuilt public roads or spaces, preferably installed beneath sidewalks.
- **Reducing energy consumption in drinking water networks** – implementation of water-loss management technologies, such as:
   - Pressure and leakage management (less pressure will use less electricity and less water volume will be lost).
   - Pumping stations (Correct operation and good maintenance of pumping equipment, such as pumps, motors, valves and pipes, as well as technical optimization of the energy required by pumps behind storage tanks, which can be minimised by keeping the level in the storage tank as high as possible).

2.4.1.2. Water use *(outside of the project's scope)*

- **Reducing water consumption per capita** – some good practices for consumers to cut domestic consumption include:
   - Reducing hot water use (accounts for 80% of the overall energy use in homes);

  - Improving energy efficiency of household devices (e.g. dishwashers and washing machines);
  - Reducing leakages inside buildings (immediately repairing dripping taps or faulty toilet flushes);
  - Promoting toilet cisterns instead of flush valves.

2.4.1.2. Water treatment

- **Reducing the amount of water collected by sewer systems** – measures that can save energy through reducing the volume of water entering our wastewater network and treatment plants:
  - Promoting natural water retention systems;
  - Proper disconnection of 'flu clean water' from sewers (groundwater, drainage, sources, brooks, water from heat pump systems, and cooling water);
  - Promoting separate sewer systems when appropriate;
  - Reducing impervious surfaces, enhancing the infiltration of storm water in soils.
- **Reducing the energy consumption in WWTP -** reduce energy consumption through various actions:
  - Improve efficiency of decomposition processes of organic matter (anaerobic digestion and aeration equipment);
  - Use efficient activated sludge processes (e.g. energy-efficient bubble aerators and sludge belt thickeners);
  - Reduce wastewater with reuse and recycling;
  - Regular energy audits (both electricity and heat), possibly accompanied by internal energy saving targets;
  - Preventive maintenance (well-maintained devices keep their energy-efficiency).

2.4.1.4. Good practices transversal to the water cycle:

- **Maximising gravity to collect water and wastewater** – preference for utilizing gravity-fed systems, according to the local topography and the natural landscape formation, instead of primarily choosing pumping systems.

- **Utilization of refrigeration compressors** – it is more efficient to use a refrigeration compressor at its maximum power for a short period of time and store a certain amount of cold, rather than continuously using it with the system at reduced load demand.
- **Replacement of key energy-consuming process equipment** – replace equipment used in the water and wastewater treatment, such as electric motors, lighting systems, and compressed air systems, by more efficient ones.
- **Operation and Maintenance of facilities** - in either a supply or sanitation project, the operation and maintenance of treatment processes and associated infrastructure should be ensured over time.
- **New technologies in the water sector –** these can be applied either in water or wastewater systems:
    - **Implement supervisory control and data acquisition (SCADA) systems –** computed-based program that allows efficient system monitoring, problem detection, energy savings, and improved security in water and wastewater management systems; the program allows gathering and analysing data, monitoring energy use, and controlling various processes within water and wastewater treatment plants; it provides real-time information to operators, enabling them to make informed decisions.
    - **Install smart pumps** - equipped with IoT technology, smart pumps are revolutionizing water treatment systems by providing real-time monitoring and data analytics; they can interpret and visualize data, monitor performance, and provide information on various factors such as water quality, pressure, temperature, and velocity; they contribute to significant energy savings of up to 70% compared to conventional pumps.

2.4.2. Good practices for maximizing energy production

The practices of UWSs treatment that allow a more efficient production of renewable energy, are listed below:

- **Power production from turbines** - raw water or drinking water may flow down a slope before reaching the treatment plant or the end user, and this mechanical energy can be transformed into power by installing turbines along the way;

  - Applicable to water catchment (underground and superficial), water adduction, and distribution.[6]

- **Biogas production from sewage sludge** - the performance of digesters and associated biogas production can be increased by pre-treatment of the sludge with advanced processes such as Cambi thermal hydrolysis, ultrasonic disintegration or electroporation, or by applying co-digestion with organic waste if allowed;
  - Applicable in sludge processing (thickening and dewatering).[6]
- **Solar energy** - photovoltaic systems are a good electrical source, since the price of the solar panels is already competitive and payback times are reasonable;
  - Applicable to water catchment (underground and superficial), water pumping, storage, buildings, support infrastructures and exterior spaces.[6]
- **Thermal energy recovery from the whole water cycle** - the temperature of sewage remains relatively stable throughout the year, thus this heat can be recovered in the sewer networks by heat pumps providing renewable heating to buildings and other facilities;[7]
- **Heat recovery from sewage sludge incineration** - the high potential of energy recovery from sludge can be accessed by way of its dewatering and drying; [7]
- **Other methods that improve sustainable energy production** – listed below are other methods that are considered good practices in terms of increasing the energy production levels in the water and wastewater treatment processes: [21]
  - Cogeneration;
  - Microturbines on the grid;
  - (Co)digestion and hydraulic energy generation from micro-turbines.

2.5. WENexus role in the water sector

Based on the context provided along Section 2, it was possible to identify the process stages, within the sector, with higher potential for energy efficiency increases and improvements - water catchment, pumping, and distribution (within the water supply system), wastewater treatment (process that occurs

[21] Energy efficiency in the European water industry: learning from best practices | Journal of Water and Climate Change

in wastewater treatment plants (WWTP)), and energy production. Additionally, it was also possible to identify good management practices and the Performance Indicators that measure energy efficiency in both energy consumption and production, in the urban water sector. In that sequence, it was presented a list of good practices for the Water-Energy Nexus in the Portuguese water sector, that can guide the management of water utilities in their path towards the 2030 (and subsequent) energy efficiency targets.

The mode of operation within systems and processes controlled by Utilities, aiming at their optimization concurrently with the enhancement of energy efficiency, can be achieved through various means. Regardless of the strategies employed (focused on the equipment retrofit, hydric efficiency improvements on the overall system or renewable energy production) it is always relevant to assess the cost-effectiveness relationship (in terms of impacts reflected in consumption and energy costs).

It is important to notice that the scope of WENexus project is entirely focused on energy efficiency and, therefore, the portfolio of efficiency measures is limited to actions directed to equipment with representative consumptions – pumping groups replacement - and the production of renewable energy – installation of photovoltaic panels (PV) and biomethane. These measures represent a good ratio in terms of cost-benefit, compared to other measures suitable to the sector (which are outside the scope of the program that covers WENexus).

The sector typically addresses energy issues in a fragmented and case-by-case way, without an integrated approach. This is a barrier to de-risking projects and a wider implementation of innovative tools. WENexus will build on existing projects and past experiences to develop an integrated approach by bundling investments and driving stakeholders' engagement to create scale[1].

The project will integrate three components - technical, financial, and legal – on its overall strategy and approach with the Entities, aiming to aggregate and bundle defined measures, define specific financial models and transaction costs and procurement strategies[1].

The technical approach developed by WENexus will be based on a methodology based on three key functionalities relating to the water infrastructures and its technical systems[1]:

- The ability to maintain energy performance and operation of the infrastructure through the adaptation of energy consumption, for example through use of energy from renewable sources;
- The capability to adapt the operation mode in response to the needs of the system while paying due attention to the quality of service and the quality of the product (water).

- The flexibility of the infrastructure's overall energy demand side management, in relation to the grid, for example through flexibility and load shifting capacities.

Regarding the financial approach, traditional models for increasing energy efficiency in water sectors will be revised to introduce innovation to project financing, procurement, and implementation. WENexus will support the de-risking of the investments through project aggregation, standardisation, and harmonisation of tools.

Taking all into consideration, it is now possible to define a set of specific technical measures and actions directed to the energy efficiency, representing this portfolio, within the direct scope of WENexus project (Section 3).

3. ENERGY EFFICIENCY PROPOSED MEASURES FOR THE ENERGY TRANSITION IN THE WATER SECTOR

It is essential for the water services sector to tackle the challenges of energy transition and climate change.. It is clear that there is a high need to support water and wastewater utilities in making sustainable energy investments. The integrated approach of WENexus requires the involvement and research of engineering (financial and juridical topics outside the scope of this report) standardized solutions.

Energy audits will be evaluated, developed (when needed) and standardised to obtain all relevant data on water infrastructures, energy performance, energy consumption, costs of electricity, power regulation systems and exact saving potential. The action plans consider the data obtained in the energy audits, to plan the size of the investment, applicability, and to identify the best financing option (models and sources), timeline for implementation, stakeholders, KPIs and all other concerned parameters. The action plan will also explore and build from similar financing experiences from past projects[1].

Guaranteeing the appropriate evaluation of the technical solutions to be implemented, ensuring they can deliver energy efficiency savings is a key topic to achieve the success of the pilot projects developed with the entities and, as a result, of WENexus. In order to achieve that, a set of typified interventions aiming the energy performance improvement of the water supply systems will be presented in the present section together with the key performance indicators to assess the impact of its efficiency - *"Implementation Difficulty", "Energy Efficiency Impact" and "Need for Investment"* – evaluated on a qualitative basis under a three level scale (*"Low", "Medium", "High"*) according with the team expertise and literature information (when available) .

However, it is emphasized that the conducted evaluation will need to undergo a more detailed analysis in the following phase of implementation of the pilot projects in order to obtain a more tangible assessment of each measure. **ANNEX I** presents the evaluation matrix for all measures addressed in this Section.

3.1. Vector 1: Electromechanical equipment efficiency

Acting on system's electromechanical equipment, replacing them with more efficient ones, where warranted, or eliminating hydraulic inefficiencies that may exist in the systems is one of the prior goal of WENexus. [1]

Pumping units are devices whose purpose is to move fluids through the energy they add to the fluid, by transforming mechanical energy (pump shaft) into hydraulic energy (fluid). This equipment consumes a significant amount of energy, which is directly related to the flow rate of the pump and the pressure differential (or head) it adds to the fluid[6].

These units include a variety of equipment and components (pumps, engines, piping and valves, control panels, sensors, etc.) that together ensure the proper functions and purpose. There is thus a significant potential for reducing energy consumption in pumping units and systems as a consequence of the equipment's inefficiencies once it is expected, during the years of operation, a performance decrease due to the usage, wear of its components, cavitation and corrosion.

3.1.1. Pumps

3.1.1.1. Pumps Replacement

The replacement of pumps in water supply and wastewater systems is of paramount importance for the continuous and reliable operation of these critical infrastructures. Over time, pump components can experience wear and tear, leading to reduced efficiency and potential breakdowns. Regularly upgrading and replacing pumps not only ensures optimal performance but also contributes to the overall efficiency of water management.

Efficient pumps are crucial for maintaining adequate water pressure, preventing system failures, and minimizing energy consumption. Moreover, advancements in pump technology often result in more energy-efficient and environmentally friendly options, aligning with the growing emphasis on sustainability in water infrastructure.

The real impact of this measure needs to be evaluated for each specific in each case, since it depends on the pumping system operating conditions, the installed equipment's characteristics and the available pumps in the market. There are several aspects that can influence the measure impact, namely:

- The suitability of the pumps installed (for example, if they are oversized, they could be replaced with a group with less power and lower consumption, partly resulting of the reducing head losses in the system);
- Years and condition of the installed pumps (over the years is normal that the pumps performance decrease, reducing its efficiency);
- The availability on the market of pumps with better performance rates for the required operating points.

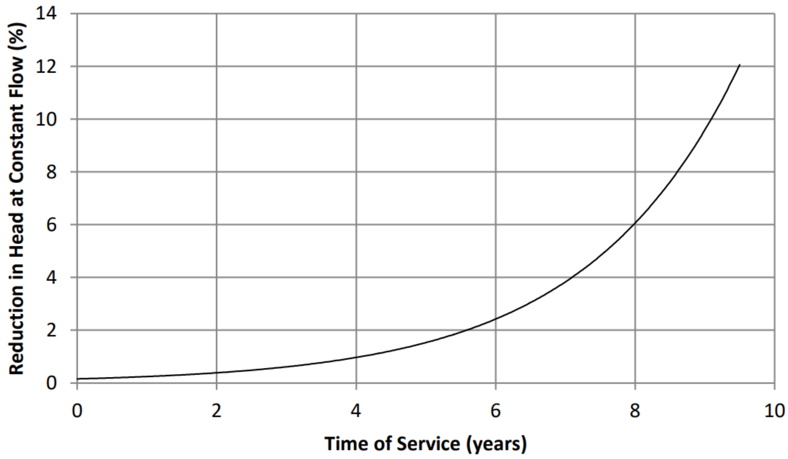

Figure 3.1 - Degradation of pumps performance shown by the reduction of head at a constant flow rate

Source: On the Performance Degradation of Centrifugal Pumps, A. Eaton, F. D'Alessandro, W. Ahmed, M. Hassan, 2018

The impact achieved through the implementation of this measure should be evaluated through:

- Pumps overall efficiency [ŋ]
- Consumption differential between the existing equipment and the equipment under evaluation
- Savings [€/year] = Current Pump Consumption Cost [€/year] – Proposal Pump Consumption Costs [€/year]

  Energy consumption cost of each pump: Consumption Cost [€/year] = P x N x CE, where:

  N – number of operating hours per year [hour/year]

  CE – Energy cost [€/kWh]

  P - Rated power of the pump [kW]

  Rated power of the pumps: P [kW] = 9.8 x H x F / η, where:

  H – Head [mWG]

  F – Flowrate (m^3/s)

  ŋ - Pumps overall efficiency [-]

- Return on investment: ROI [years] = $\frac{EC}{Savings}$, where:

  EC – Equipment cost [€]

Note: in addition to a reduction in consumption charges (kWh), in some cases there may also be a reduction in costs associated with the contracted power.

3.1.1.2. Install additional low-capacity pumping systems in tower tanks

In pumping stations associated to tower water tanks, one possible solution to improve the energy efficiency is the installation of a new pumping system in addition to the existing pumps. This possible new system should been design for situations when the downstream water demand is low. If the pumping station have installed energy production (PVs), this measure can have major impact since for several hours of the day the system could be running using only the energy produced in the site. Otherwise, usually the pumps already installed (design for peak flows) have high power and cannot be supplied exclusively by the PVs.

Summarizing and according to Figure 3.2 below, the measure corresponds to:

- **Equipment to be installed:**
  Installation of a pumping system (number and characteristics of the pumps to be defined on a case-by-case basis). These new pumps will be connected to the suction and compression pipes of the existing pumping system, requiring a set of check valves downstream of the pumps and sets of gate valves upstream and downstream the connections;
- **Operating mode**
  - To avoid constraints and malfunctions in operation and allow a simpler installation, it is suggested that pumping systems operate alternately;
  - As long as the water levels in the tower tank are high, will work the new lower capacity pumping system;
  - When the water level drops below a certain value (to be defined on a case-by-case basis) the existing higher capacity pumping system comes into operation;
- **Summarising**
  - During high demand periods (peak hours) the existing high-capacity pumping system will operate, partly using the energy produced by the PVs (if available), but is also expected that require significantly energy consumption from the public grid;
  - During the remaining hours, the new lower capacity pumping system will operate, which will minimise the use of energy from the public grid, since whenever there is energy available in the PVs, this will be the used source.

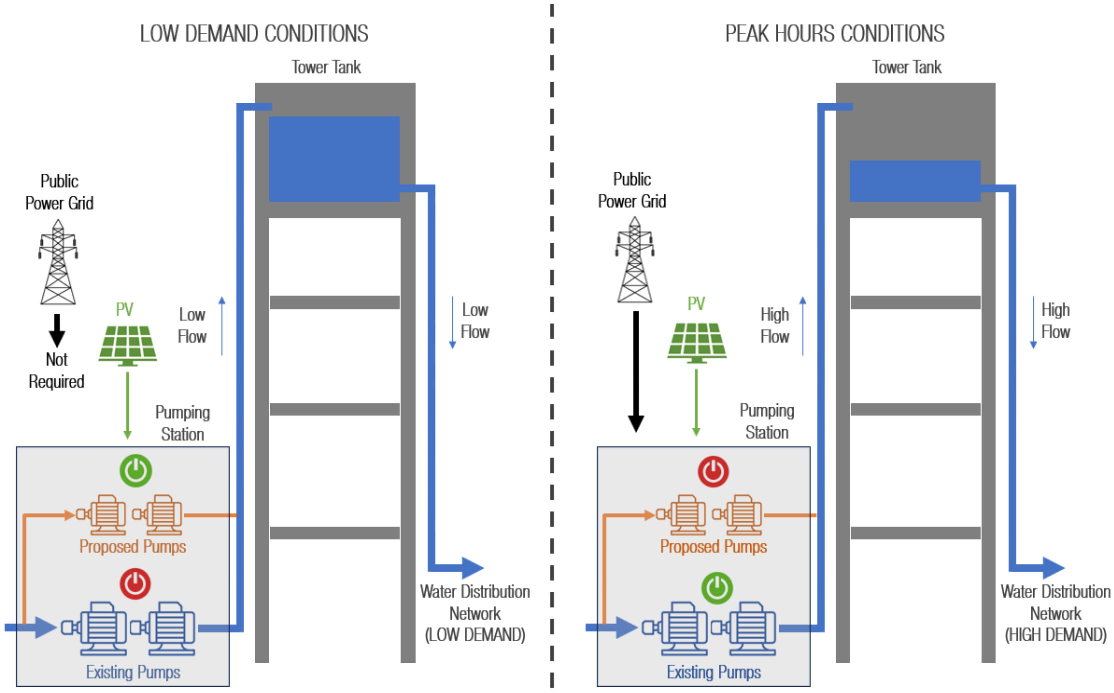

Figure 3.2 - Install additional low-capacity pumping systems in tower tanks: Measure function illustration

The impact of this measure depends on several aspects as for example the PV capacity installed in the site, so, the impact estimate needs to be analysed case by case. However, the benefit of this measure results mainly by the reduction of energy consumed from the public grid.

To increase this measure impact, new available pumps on the market show defined specifications that allow them to be directly connected to the energy generation system (PVs). In these cases, there is also an improvement in efficiency, since the inverter is a component that may incur some small losses in the overall performance of the system.

3.1.1.3. Operational correction for optimal operating performance

This strategic measure involves a meticulous assessment and adjustment of operational parameters to ensure that the systems function at their optimal performance levels. By fine-tuning the operational parameters, such as flow rates, pressure, and distribution patterns (optimize delivery points) the water supply and sanitation systems can effectively meet the demands of their respective communities while minimizing energy consumption and operational costs. Furthermore, this proactive approach contributes to the longevity of the infrastructure and ensures the reliable delivery of the service.

Identifying and correcting operational inefficiencies can lead to a more efficient use of energy resources, resulting in both economic and environmental benefits through the reduction on the overall consumption of the equipment or group pf equipment. For instance, reducing overflows in service tanks reduces both water losses and energy consumption as less water needs to be treated and pumped (in the case of rising or mixed systems)[6].

The optimization of the system can be achieved through various means, including:

- Replacement of pumps that are over or undersized;
- Substitution of pumps operating far from the optimal operating point (inefficient);
- Adjustment of the operational strategy, favouring the simultaneous operation of a greater number of pumps at lower speeds for the same flow rate;
- Operation management adapted to consumption patterns and aiming to decrease the overall energy consumption.

In order to trace and identify the improvements in the overall efficiency of the system, the implementation impacts of this action can be measured through a specific analysis to the system, reviewed on a case-by-ca basis. Mapping energy consumption through an energy-balance scheme for the water supply systems is useful to identify critical components requiring action and to plan intervention for improved energy efficiency[6].

Table 3.1 - Measure assessment for vector 1: Pumps

Measure	Implementation Difficulty	Energy efficiency impact	Need for investment
Pumps replacement	Medium	Medium	Medium
Install additional low-capacity pumping systems in tower tanks	Low	Medium	Medium
Operational correction for optimal operating performance	Medium	Medium	Low

**Qualitative analysis through experts' team knowledge and based on some literature references. A case-by-case detailed analysis should be carried during implementation phase with the entities.*

Low
Medium
High

3.1.2. Electrical Engine

3.1.2.1. Engine replacement

Electrical motors coupled to the electric pump groups and units are vital to their performance and are responsible for a large percentage of the total consumption. Investing in high-efficiency motors[22] is one of the solutions to reduce energy costs once a high-efficiency motor exhibits superior performance, leading to a reduction in electrical energy consumption and a decrease in energy losses. The reduction in losses enables these types of motors to operate at lower temperatures, thereby contributing to an increase in their lifetime[6].

The replacement with higher-class motors will enable an optimization of their efficiency (increased power factor) by enhancing their performance, consequently resulting in reduced energy consumption and diminished energy losses. Additionally, noteworthy benefits include an extended lifetime (due to lower operating temperatures), increased reliability, and reduced noise levels (attributed to lower ventilation power)[23].

According to the current international standard, there are five classes of efficiency[24]:

- IE1: Standard efficiency
- IE2: High efficiency
- IE3: Premium efficiency
- IE4: Super premium efficiency
- IE5: Ultra premium efficiency

[22] According to the directives already approved *(COMMISSION REGULATION (EU) 2019/1781)*, motors placed on the European market from 7.5 to 375 kW starting in 2015 and from 0.75 to 375 kW starting in 2017 must have a minimum efficiency class of IE3 or IE2 when equipped with electronic speed controllers.

[23]Energy Efficiency Guide: Good practice manual – ERSE (2013)

[24] Percentage of motors of high yield in the costs of companies. EDP (2024)

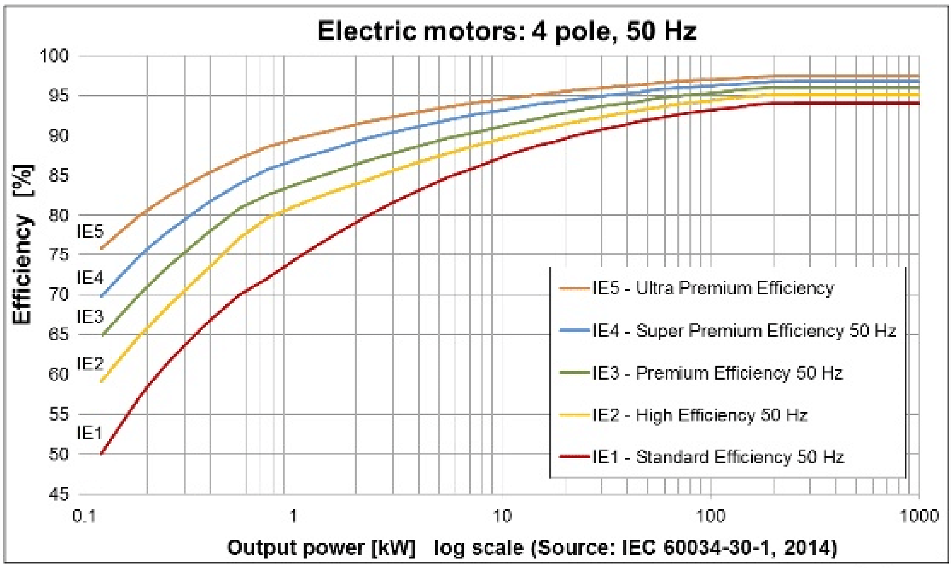

Figure 3.3 - IE efficiency classes for 4 pole motors at 50Hz

Source: Energy Efficiency in Variable Speed Centrifugal Chiller Systems Driven by Synchronous Reluctance Motors[Error! Bookmark not defined.]

The consideration and feasibility of implementing this measure will always depend on the cost of equipment replacement and the energy savings achieved through it. In order to assess that a detailed analysis, on a case-by-case basis, should be taken. The impact achieved through the implementation of this measure should be evaluated through [6]:

- Motor efficiency [η_{motor}]
- Consumption differential between the existing equipment and the equipment under evaluation
- Savings [€/year] = $\sum_i^n \frac{P_{iNA}\times FC_{iA}}{\eta_{iA}} - \frac{P_{iNB}\times FC_{iB}}{\eta_{iB}} \times CE_I \times N_I$, where:

i – Operating period

PNA – Rated power of the equipment under evaluation [KW]

PNB – Rated power of the existing equipment [KW]

FCA – Load factor of the equipment under evaluation for the period i

FCB – Load factor of the existing equipment for the period i

Carga = Supplied power (or energy) / nominal power (or energy)

CE – Energy cost [€/KWh]

N – number of operating hours per year [hour/year]

- Return on investment: ROI [year] = $\frac{CT_B - CT_A}{Savings}$, where:

CT – Equipment cost [€]

3.1.2.2. Variable Frequency Drives (VEV) installation

In terms of electrical power consumption and overall performance, it can be advantageous to adjust the engine speed according to the loads or process requirements. To control the speed of engines without relying on external mechanical devices, it is necessary to vary the frequency of the supply voltage.

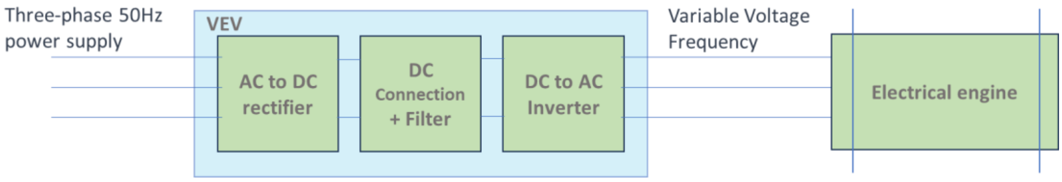

Figure 3.4 - IE efficiency classes for 4 pole motors at 50Hz
Source: Technical Guide: Efficient use of energy in water services – Ersar (2018)6

Overall, the implementation of Variable Frequency Drives (VEV) is recommended for electric motors operating under a variable load at less than 50% capacity for at least 20% of their operating time, and preferably for a minimum of 2000 hours per year. In summary, the main advantages resulting from the application of VEV to electric motors are:

- Energy savings up to 50% or more, with an average value of 20–25%;
- Reduction of power peaks during motor start-up and shutdown;
- Increased motor longevity;
- Improved power factor;
- Possibility of bypass;
- Wide ranges of speed, torque, and power.

The profitability of VEV depends on the engine power to be controlled and the type of application. However, there are other important factors such as the number of annual operating hours and the engine's load profile. Regarding the final factor, the more variable the load profile, the greater the potential for energy savings.

The impact achieved through the implementation of this measure should be evaluated through an energy audit and:

- Motor/VEV efficiency peak/average

- Effective engine power (output)
- Consumption differential between the existing equipment and the equipment under evaluation
- Savings [€/year] = $\sum_{i}^{n} \frac{P_{iNA} \times FC_{iA}}{\eta_{iA}} - \frac{P_{iNB} \times FC_{iB}}{\eta_{iB}} \times CE_I \times N_I$, where:

  i – Operating period

  PNA – Rated power of the equipment under evaluation [KW]

  PNB – Rated power of the existing equipment [KW]

  FCA – Load factor of the equipment under evaluation for the period i

  FCB – Load factor of the existing equipment for the period i

  Load = Supplied power (or energy) / nominal power (or energy)

  CE – Energy cost [€/KWh]

  N – number of operating hours per year [hour/year]

- Return on investment: ROI [year] = $\frac{CT_B - CT_A}{Savings}$, onde:

  CT – Equipment cost [€]

3.1.2.3. Usage of soft starters

Engines often require large amounts of energy when quickly accelerating to full speed. Soft starters (also when combined with VEV) can be used to reduce inrush currents and limit torque—protecting the equipment and extending its life by reducing engine heating caused by frequent starts and stops[25].

A soft starter, also known as reduced voltage starters (RVSS) is a solid-state device that protects AC electric motors from damage caused by sudden influxes of power by limiting the large initial inrush of current associated with motor startup. They provide a gentle ramp up to full speed and are used only at startup (and stop, if equipped)[25].

Soft starts not only help to reduce component stresses on an electrical motor but may also contribute to saving electrical energy. Energy savings may be further increased by using intelligent soft starts, which

[25] How to choose between a soft starter and a variable frequency drive – EATON: Powering Business Worldwide (2024).

adapt their supply of current and voltage in real time to what is being demanded by the engine under load.

Today's RVSS are light, compact and can be fully integrated into an automated system. They incorporate monitoring and feedback functions which can be remotely accessed and can also be programmed with adaptive control profiles which set acceleration and deceleration rates. "In some cases, energy-saving soft starts have demonstrated 25-50% savings on the energy normally consumed by a standard electric motor"[26]. Once all these predictions are made on theorical terms, the real total amount of potential savings is dependent on the system characteristics and gear load and operation of each application and should be evaluated case by case.

The impact achieved through the implementation of this measure should be evaluated through an energy audit and:

- Motor/Pump/RVSS efficiency peak/average
- Consumption differential between the existing equipment and the equipment under evaluation
- Savings [€/year] = $(EC_i - EC_f) \times CE \times N$, where:

  EC_i – Initial energy consumption

  EC_f – Final energy consumption

  CE – Energy cost [€/KWh]

  N – number of operating hours per year [hour/year]

- Return on investment: ROI [year] = $\frac{CT_B - CT_A}{Savings}$, where:

  CT – Equipment cost [€]

[26] How To Save Energy Using Soft Starts – RAOSE Automation (2022)

Table 3.2 - Measure assessment for vector 1: Engines

Measure	Implementation Difficulty	Energy efficiency impact	Need for investment
Electrical engine substitution	Low	Medium	Medium
Variable Frequency Drives (VEV) installation	Low	Medium	Low
Usage of soft starters	Low	Low	Low

**Qualitative analysis through experts knowledge and based on some literature references. A case-by-case detailed analysis should be carried during implementation phase with the entities.*

Low
Medium
High

3.2. Vector 2: Energy production capacity - photovoltaic panels

In addition to energy-consuming processes and equipment, there are also technologies that promote local energy production, resulting in energy savings and, consequently, economic gains.

Solar photovoltaic technologies have the ability to convert solar radiation into electrical energy through their photovoltaic cells. A solar photovoltaic system, essentially composed of a solar collector and an inverter, plays a crucial role in generating direct current electricity. The electricity generated, as it passes through the inverter, is converted into alternating current that can be applied to various uses.

The installation of photovoltaic panels in the infrastructures of water supply and sanitation systems, such as WTPs, WWTPs, water's tanks, and pumping stations, provides the opportunity to use the generated energy in pumping systems, water treatment, and other operations related to these services, associated with equipment that involves significant electrical energy expenses.

3.2.1. Photovoltaic Panels Installation

The installation of photovoltaic panels requires a rigorous technical study for precise dimensioning. Beginning with a complete data collection related with site assessment, factors such as solar irradiance, shading analysis, and orientation. The dimensioning process involves careful consideration of the electrical load requirements, ensuring that the installed capacity matches the energy needs. Accurate calculations for the size and capacity of inverters, as well as the appropriate wiring and interconnection components, are crucial for achieving optimal system performance.

The impact achieved through the implementation of photovoltaic panel systems should be evaluated through this calculation and continuous monitoring of energy balance:

- Evaluation of consumption and load curves
- Nominal Capacity (Nominal Power) of the Solar Panel (kW)
- Peak Sunshine hours (h/year)
- Installation capacity requirement [KW] $= \frac{Electrical\ energy\ consumption\ (kWh/year)}{Peak\ sunshine\ Hours\ (h/year)}$
- Savings [€/year] = $\left(EC_i - EC_f\right) \times CE \times N$, where:

  EC_i – Initial energy consumption

  EC_f – Final energy consumption

  CE – Energy cost [€/KWh]

  N – number of operating hours per year [hour/year]
- Return on investment: ROI [year] = $\frac{C_{PP}}{Savings}$, where:

  C_{PP} – Photovoltaic Panel cost [€]

Table 3.3 - Measure assessment for vector 2: Photovoltaic

Measure	Implementation Difficulty	Energy efficiency impact	Need for investment
Photovoltaic panels	Medium	High	High

**Qualitative analysis through experts knowledge and based on some literature references. A case-by-case detailed analysis should be carried during implementation phase with the entities.*

Low
Medium
High

The integration of energy storage batteries can further optimize consumption and store excess energy for later use. This measure is addressed in Vector 3 : Power Storage Capacity – Batteries Installation).

3.3. Vector 3: power storage capacity – Batteries installation

The implementation of energy storage batteries in water supply and sanitation systems represents a significant evolution in the energy management of constituent infrastructures.

In the context of water supply systems, energy storage batteries play a crucial role in maximizing the efficiency of the water transportation and distribution process for human consumption, particularly in locations where water needs to be lifted (pump stations) to ensure a continuous flow in the network. Theoretically, these batteries enable the accumulation of energy generated during periods of high production surplus. In this way, in addition to ensuring continuous service functioning and, consequently, service quality, and by enabling the strategic use of this energy when demand is higher or during periods of low production, they contribute to the energy efficiency of the system and the reduction of energy costs.

For the specific case of sanitation, the combination of anaerobic sludge digestion, photovoltaic sources, and storage batteries in WWTP not only generates renewable energy but also enhances operational efficiency, reduces costs, and contributes to sustainable practices.

To properly understand how the energy management should be set, an analysis on how the different components of the installation (PV system, batteries, grid and consumer) interact will be conducted to better define the correct installation approach.

The assessment of the feasibility and impact associated with the implementation of this measure should be analysed on a case-by-case basis, considering:

- Diferencial entre excedente de produção renovável e injeção na rede;
- Assessment of surplus sales contracts (electricity price versus costs of energy injection into the grid);
- Savings [€/year] = E_{stored} * CE

  E_{stored} – Stored energy = Surplus – Grid injection [KWh/year]

  CE – Energy cost [€/KWh]
- Return on investment: ROI [year] = $\frac{CB}{Savings}$, where:

  CB – Batteries cost [€]

Table 3.4 - Measure assessment for vector 3: Batteries installation

Measure	Implementation Difficulty	Energy efficiency impact	Need for investment
Batteries installation	High	Medium	High

**Qualitative analysis through experts knowledge and based on some literature references. A case-by-case detailed analysis should be carried during implementation phase with the entities.*

Low
Medium
High

3.4. Vector 4: energy production capacity – biomethane systems

The Biogas, produced through the anaerobic degradation of organic matter such as animal manure, sewage sludge, food, and agricultural waste, is primarily composed of methane (50–75%) and carbon dioxide (25–50%), with smaller amounts of other gases like nitrogen, oxygen, carbon monoxide, and hydrogen sulfide [27]. This renewable fuel is recognized as a promising source of energy, emphasizing its potential utilization derived from the degradation of organic residues. Despite its lower calorific value compared to natural gas, biogas stands as a viable alternative to reduce dependence on fossil fuels, contributing significantly to the goal of achieving energy sustainability.[28]

In WWTPs, biogas is an essential by-product of sludge treatment, mandated by regulations in most EU countries that prohibit the disposal of untreated sludge in soils. Specific treatments, such as chemical and biological stabilization, can be applied. Sludge stabilization, particularly through anaerobic digestion, plays a crucial role in transforming organic matter, preventing unpleasant odors, and controlling biogas emissions.[29]

Most of the produced biogas is used in Combined Heat and Power systems, incorporating various technologies such as heat engines and fuel cells. [30] The electrical efficiency of these units, critical for WWTPs autonomy, varies between 25% and 45%, underscoring the significance of these systems. [31]

[27] Plugge, C. M. (2017) - Biogas. Microbial Biotechnology, 10(5), 1128-1130 (https://doi.org/10.1111/1751-7915.12854)
[28] Hosseini, S. E., & Wahid, M. A. (2014) - Development of biogas combustion in combined heat and power generation. Renewable and Sustainable Energy Reviews, 40, 868-875 (https://doi.org/https://doi.org/10.1016/j.rser.2014.07.204)
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The injection of biogas into the natural gas network requires compliance with specific standards, varying among European countries.[32] Parameters such as CO_2 content, H_2S concentration, and Wobbe Index play crucial roles, with specific regulations for Portugal, outlining the scenario for the efficient integration of biogas into the energy matrix.[29]

The upgrading of biogas to biomethane, known as Power-to-Methane, stands out as a promising method to enhance its quality, contributing to decarbonization goals. The production of biomethane rich in methane offers a sustainable and effective solution. To optimize biogas implementation in WWTPs, measures like co-digestion of organic waste are crucial. The application of advanced monitoring and control technologies, essential for real-time adjustments, proves to be an effective approach to optimize system performance in WWTPs. [29]

However, the production of biogas in a WWTP depends on various factors, such as the flow rate of sludge to be digested (dependent on the organic load in the WWTP), retention time, process temperature, and proper mixing, among others. It is noteworthy that biological sludge from secondary treatment has a lower potential for biogas production compared to primary sludge.

To estimate biogas production, it is considered that, under normal pressure and temperature conditions - 1 atm and 0ºC, pure methane has a Lower Heating Value (LHV) of 9.44 kWh/m³. In the case of biogas with methane content between 50% and 80%, LHV varies between 4.72 kWh/m³ and 7.55 kWh/m³.

The methane production rate at 35ºC can be estimated using the following formulas (Metcalf & Eddy, 2003):

$$V = 0{,}40 \times [\ (S0 - S) \times Q \times (103\ g/kg)\ -1 - 1{,}42 \times PX\ ]$$

Where:

$$Px = \frac{Y \times Q \times (S0-S) \times (10^3\ g/kg)^{-1}}{1 + kd \times SRT}$$

V - daily volume of biogas produced (m³/d);

0.40 - theoretical conversion factor of the amount of methane produced from the degradation of 1 kg COD, at 35ºC;

[32] Bidlingmaier, W., & Springer, C. (2017) - Wobbe-Index.

$S0 - S$ – substrate reduction (COD mg/L);

Q – effluent flow (m^3/d);

Px - quantity of biomass produced (kg/d);

Y - biomass yield (g VSS/g COD); typical values range between 0.05 and 0.10;

kd - decay coefficient (d^{-1}); typical values range between 0.02 and 0.04;

SRT – sludge retention time (d)

After the estimate of the volume of biogas produced, the energy produced can be calculated as follows:

$$\text{Energy (kWh)} = V\ (m^3) \times BCV\ (kWh/m^3) \times \eta$$

Where:

BCV – Biogas calorific value. A common value is around 6 kWh/m^3 for biogas with a high methane content

η - Efficiency of the conversion system [-], which depends on the type of technology used.

Table 3.5 - Measure assessment (biomethane systems)

Measure	Implementation Difficulty	Energy efficiency impact	Need for investment
Biomethane Systems	High	High	High

**Qualitative analysis through experts knowledge and based on some literature references. A case-by-case detailed analysis should be carried during implementation phase with the entities.*

Low
Medium
High

The consideration of key performance indicators at WWTPs, such as the rate of conversion of waste into biogas and the efficiency of anaerobic digestion, provides valuable information for continuous improvements. These metrics not only assess the success of biogas implementation but also indicate areas for adjustments and process improvements.

3.5. Other General measures with relevant impact in the water systems

In addition to the actions previously presented and with a direct alignment to the WENexus' goals it is possible to highlight a set of critical measures with direct impact on sustainable resource management and cost-effectiveness with an interlink to energy.

In this context, can be made a distinction between the transversal measures aiming to promote energy efficiency increases.[33] However, for the proper identification and implementation of these measures, it's necessary to have improving monitoring systems (e.g., measuring energy consumption or variables that determine/affect it) and information (such as telemetry and cadastre systems). Mapping energy consumption through an energy-balance scheme for the water supply and wastewater systems is useful to identify critical components requiring action and to plan intervention for improved energy efficiency.[13]

- **Water Supply Operation's measures**
    - Construction or rehabilitation interventions, such as resizing or rehabilitating network assets, aiming to optimize the network and minimize water losses (e.g, rehabilitation or replacement of pipelines, water tanks);
    - Network zoning (in areas with identical pressure requirements);
    - Minimization of continuous pressure losses or locations (operational actions to ensure a more uniform flow distribution in the supply network);
    - Bypass to network elements causing localized pressure losses and requiring new water pumping downstream to ensure service (e.g., intermediate tanks);
    - Leak detection and water loss monitoring in the network;
    - Direct supply to network zones without the need for central reservoirs located at higher pumping;
    - Improvement of the monitoring and recording system (e.g., energy, flow, pressure);

[33] Avaler+: Guide for diagnosis, prioritization of alternatives, monitoring and review of the action plan (2021)

- Adjusting the pump operation to operate within a range of flows close to the optimum point;
- Changing water supply sources (when possible without compromising the quality of raw water) to reduce supplied energy;
- Direct supply to network zones without the need for central reservoirs located at higher pumping;
- Energy recovery in pressure reducing valves (e.g.: with the installation of mini turbines on the valves);
- Reduction of the number of operational lines in the WTP;
- Installation or complete replacement of monitoring systems (probes and accessories) for dynamic adjustment of reagent dosing.

Another measure with a relevant impact on the energy efficiency of water supply systems, but beyond the scope of this project, is the use of hydraulic turbines in water conveyance systems, specifically in water supply to populations (catchment, distribution). In hydraulic turbines, water is employed as a source of energy (production of energy). When a pump imparts energy to a flow, it is necessary for that energy to facilitate fluid pumping, which in some cases may not occur, leading to a reverse rotation of the wheel and consequently altering the direction of the flow. This situation of reverse operation of a pump is referred to as PAT (Pump as Turbine), meaning a pump functioning as a turbine. If the energy, in this case, expressed as pressure, is sufficient to overcome the torque of the wheel and shaft, then this torque can be used as a generator, transmitting the moment to the shaft. The water's energy is transferred to the turbine rotor, which, through the shaft, transmits it to the generator, which in turn converts it into electrical energy.[34]

Table 3.6 - Water Supply Operation's measures

Measure	Infraestrutural measures	Non -Infraestrutural measures
Rehabilitation or replacement of water tanks	x	
Rehabilitation or replacement of pipelines	x	

[34] Hydrogeneration - Energy production in water supply systems (Pinto, 2018).

Measure	Infraestrutural measures	Non -Infraestrutural measures
Network zoning (in areas with identical pressure requirements)	x	
Minimization of continuous pressure losses or locations (operational actions to ensure a more uniform flow distribution in the supply network)	x	
Bypass to network elements causing localized pressure losses and requiring new water pumping downstream to ensure service (e.g., intermediate tanks)	x	
Direct supply to network zones without the need for central reservoirs located at higher pumpings	x	
Leak detection and water loss monitoring in the network		x
Improvement of the monitoring and recording system (e.g., energy balance, flow, pressure)		x
Altering the pump operation to operate within a range of flows close to the optimum point		x
Changing water supply sources (when possible without compromising the quality of raw water) to reduce supplied energy	x	
Direct supply to network zones without the need for central reservoirs located at higher pumping	x	x
Energy recovery in pressure reducing valves (e.g.: with the installation of mini turbines on the valves)	x	
Reduction of the number of operational lines in the WTP		x
Installation or complete replacement of monitoring systems (probes and accessories) for dynamic adjustment of reagent dosing	x	x

Measure	Infraestrutural measures	Non -Infraestrutural measures
Installation of hydraulic turbines on water's catchments	x	

- **Wastewater Operation's measures**
    - Construction or rehabilitation interventions, such as resizing or rehabilitating network assets, aiming to optimize the sanitation network (e.g rehabilitation or replacement of pipelines, aerators, compressors, etc.);
    - Replacement of static tube diffusers with flexible fine bubble membrane diffusers;
    - Improvement of the monitoring and recording system (e.g., energy, flow, pressure);
    - Increase in the diameter or number of diffusers to improve oxygen transfer efficiency;
    - Installation or complete replacement of monitoring systems (probes and accessories) for dynamic adjustment of aeration and/or reagent dosing
    - Reduction of the number of operational lines in the WWTP;
    - Adjustment of dissolved oxygen setpoints;
    - Adjustment of the operating mode of mechanical aerators/agitators (submersion, rotation speed, operating time);
    - Ensure complete mixing in the reactor(s);
    - Increase in sludge age at the WWTP;
    - Cleaning of diffusers (injection of formic acid into the air piping);
    - Adjustment of disinfection operating conditions (UV radiation dose) according to the quality of the final effluent.

Table 3.7 - Wastewater Operation's measures

Measure	Infraestrutural measures	Non -Infraestrutural measures
Rehabilitation or replacement of wastewater's pipelines	x	
Replacement of static tube diffusers with flexible fine bubble membrane diffusers	x	

Measure	Infraestrutural measures	Non -Infraestrutural measures
Rehabilitation or replacement of aerators	x	
Rehabilitation or replacement of compressors	x	
Replacement of static tube diffusers with flexible fine bubble membrane diffusers	x	
Improvement of the monitoring and recording system (e.g., energy balance, flow, pressure)		x
Increase in the diameter or number of diffusers to improve oxygen transfer efficiency	x	
Installation or complete replacement of monitoring systems (probes and accessories) for dynamic adjustment of aeration and/or reagent dosing	x	x
Reduction of the number of operational lines in the WWTP		x
Adjustment of dissolved oxygen setpoints		x
Adjustment of the operating mode of mechanical aerators/agitators (submersion, rotation speed, operating time)		x
Ensure complete mixing in the reactor(s)		x
Increase in sludge age at the WWTP		x
Cleaning of diffusers (injection of formic acid into the air piping)		x
Adjustment of disinfection operating conditions (UV radiation dose) according to the quality of the final effluent	x	x

In addition to the previous measures, there is also a set of cross-cutting measures for water supply and wastewater services that contribute to the improvement of the energy efficiency of the systems. It is possible to delineate a set of straightforward measures that directly target areas of consumption, offering opportunities for improvement and reduction within the support infrastructures for administrative and technical purposes. These measures have a more moderate impact on the final energy balance.

- **Lighting retrofit**

The execution of lighting retrofit, particularly the transition to LED illumination holds a significant importance in commercial or services buildings. The primary benefit of LED retrofitting is the drastically lowered energy consumption compared to traditional and fluorescent lighting, resulting in as much as an 80% reduction in energy costs over a year. This measure enhances energy efficiency, reducing overall operational costs while simultaneously contributing to environmental sustainability. LED lighting not only consumes less energy but also show off a longer duration, reducing maintenance requirements and promoting a more economically viable and environmentally responsible lighting solution.

- **Lighting Control Systems**

Control systems are a crucial component of any lighting installation, and regardless of the method employed, the objective is to ensure the lighting functions when required and in accordance with specified requirements. Control and regulation integration systems for lighting vary the light intensity of the installation by switching on/off or regulating its luminous flux, enabling a reduction in energy consumption of up to 70%.[18] Fundamental methods for lightning control:

  - Time-based control (integrated/non-integrated timing);
  - Brightness control (intensity);
  - Occupancy control (presence detection with/without LDR4);
  - User interfaces such as push buttons, touch controls, localized switches, etc.

Automating lighting (also applicable to temperature and blinds control) in a services building enables significant energy savings while ensuring flexibility for easy system expansion without the need for additional wiring. Adjusting or turning off lighting when natural light is sufficient or when the room is unoccupied ensures energy efficiency. Automation ensures even greater energy savings and enhances comfort.[18]

- **Electrical facilities**

The replacement of electronic equipment, such as computers, instrumentation, and control systems, also enables a significant contribution to greater energy efficiency. Older equipment often consumes more energy, being less efficient compared to newer versions that incorporate more advanced technologies. In the case of computers, these advancements allow for reduced consumption during periods of inactivity, thus contributing to the overall efficiency of energy consumption in the facilities.

Regarding of instrumentation and control equipment, the adoption of more efficient electronic devices can result in more streamlined operational processes, leading to more precise measurements, a lower failure rate, and a reduction in energy wastage. Advanced control systems can dynamically adjust energy consumption based on operational demands, ensuring that only the necessary amount of energy is used at any given moment. The replacement or installation equipment more efficient (electromechanical, computer, instrumentation and control, etc.).

3.6. Water losses impact in the energy efficiency of the water supply systems

As previous mentioned, reducing physical water losses results in a significant reduction in energy consumption, in addition to all the other economic and environmental benefits. This is indeed the measure with more importance and relevance in the Portuguese water supply sector. For example, the water lost in the distribution networks or in the domestic connections, have impact in the operation costs off all the water supply system components. These volumes of water are abstracted, treated, pumped, and, at the end are lost and not used by the costumers (the operation costs inherent to these water volumes, including the energy costs, can be saved with the reduction of physical water losses). The impact of the physical water losses occurs in several infrastructures along the water supply cycle and sometimes in more than one Management Utility (for example, water lost in the retail systems have also impact in the energy consumptions of the bulk systems).

According the RASARP 2022[35] in mainland Portugal, the following indicators were recorded in 2021:

- **Water Bulk systems:**
  - Water entering the system: 634 000 000 m^3/year;
  - Total energy consumption: 412 000 000 kW.h/year;

    (based on the previous parameters is considered an energy consumption of 0.65 kW.h per 1 m3 of water)
  - Real water losses: 23 000 000 m^3/year.
- **Water Retail systems:**
  - Water entering the system: 634 000 000 m^3/year;

[35] Water and Waste Services Characterisation Annual Report, ERSAR 2022

- Total energy consumption: 412 000 000 kW.h/year;

  (based on the previous parameters is considered an energy consumption of 0.65 kW.h per 1 m^3 of water)

- Real water losses: 23 000 000 m^3/year.

Based on the mentioned data, it can be estimated that real water losses correspond into increased energy consumption of around 148 million kWh, the emission of an extra 22 thousand tonnes of CO2[36] and an annual extra cost of around 21 million €.[37]

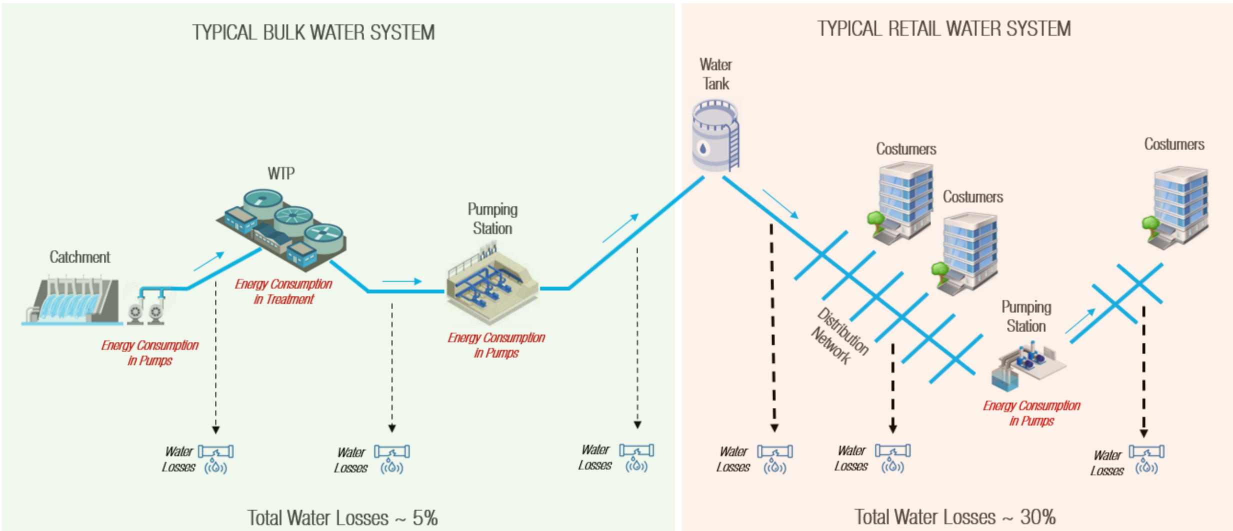

Figure 3.5. *Scheme of the water losses impact*

[36] Considering 151 kgCO2/MWh – 2021. Source: Fator de Emissão da Eletricidade, 2023 Portugal, APA – Agência Portuguesa de Ambiente, 2023
[37] Considering 0,14 euro/kWh in 2021 for Industrial Clients - Band IC (500 MWh < consumption < 2 000 MWh). Source: Energia em Números, 2022, Observatório da Energia

4. CONCLUSIONS

Efficient management of resources related to energy consumption in water and sanitation services is a real need, given the importance of these services for public health, economic activities, and the sustainable development of society. In order to ensure all processes involved in the water sector, energy management plays a crucial role.

The scarcity of natural resources, climate change, and increased demand for water and sanitation services underscore the importance of adopting practices that reduce energy consumption in these services and systems. More efficient resource management is essential to ensure the continuous availability of these services in both quality and quantity, and to mitigate associated environmental impacts.

Given the specific scope of the WENexus project, it is possible to promote the energy efficiency of water supply and sanitation systems through a set of measures classified based on their defined operational objectives. In this way, four major vectors of measures with distinct nature and operational objectives can be identified – promotion of the reduction of energy consumption in the system (vector 1), production of renewable energy (vectors 2 and 4), and energy storage (vector 3) - targeted at different types of equipment and components.

Since there is a significant energy consumption throughout the water cycle, especially in pumping and treating water for consumption and wastewater - WTPs and WWTPs - the importance of adapting and replacing pumps, motors, and auxiliary equipment (VEV and soft starters) with more efficient equipment is emphasized. Additionally, operational changes also contribute to improving the energy efficiency of the involved systems, such as operational correction for optimal operating performance.

Integrating renewable energy sources into water and sanitation processes, such as installing photovoltaic panels in WTPs, WWTPs, water tanks, pump stations, and producing biogas in WWTPs, can be used to meet part of the energy demand of these systems, reducing dependence on non-renewable sources. Although these measures require higher initial investment, considering the fluctuations and perspectives of energy costs, these actions prove to be quite attractive with a good cost-benefit ratio that can be easily demonstrated through low Return on Investment (ROI) values.

Investing in decentralized treatment systems, enabling biogas production at the waste generation site, stands out as an effective measure to enhance operational efficiency. The adoption of these measures not only promote renewable energy production but also aligns the water sector with the principles of circular economy, transforming waste into valuable resources. This approach not only optimizes the operational efficiency of WWTPs but also positions the sector as a key player in the transition to a greener and more efficient infrastructure.

The installation of batteries in the water sector is starting to represent a higher significance as it contributes to enhancing operational resilience and efficiency. The incorporation of battery storage systems provides an emerging solution to address the intermittency inherent to renewable energy sources, ensuring a continuous and reliable power supply for essential water and sanitation infrastructure. This technological advancement enables utilities to mitigate the impact of power disruptions, optimize energy consumption patterns, and reinforce overall system reliability. While the initial investment for battery installation may seem significant, the long-term cost savings are substantial and should be carefully evaluated. Reduced reliance on expensive peak-hour electricity, minimized downtime, and extended equipment lifespan contribute to overall financial benefits.

Overall, for the generality of the measures presented along this document, a careful assessment should be carried in order to monitor and evaluate the real impact on the equipment performance and on total energy balance of the systems. Those analysis can be carried out through energy audits or through control and monitoring components.

Although outside the scope of the project, there are also measures with high positive impacts that can be adopted in operating systems and support infrastructures (e.g., adoption of more efficient lighting and climate control systems).

Knowing that the improvement on water losses is also a crucial factor for the energy and operational efficiency of the systems, accurate measures on this should conducted. Even though this topic is outside the scope of the project, it is relevant to highlight the importance of the topic for the sector as shown in Section 3.6.

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Annex I – Energy Efficiency Measures Assessment

Scale

Low	
Medium	
High	

Definition		Score		
Measure	Vector/area of intervention	Implementation difficulty	Energy efficiency impact	Need for investment
Pumps replacement	Vector 1	Medium	Medium	Medium
Install additional low-capacity pumping systems in tower tanks	Vector 1	Low	Medium	Medium
Operational correction for optimal operating performance	Vector 1	Medium	Medium	Low
Electrical engine substitution	Vector 1	Low	Medium	Medium
Variable Frequency Drives (VEV) installation	Vector 1	Low	Medium	Low
Usage of soft starters	Vector 1	Low	Low	Low
Photovoltaic Panels Installation	Vector 2	Medium	High	High
Batteries installation	Vector 3	High	Medium	High
Biomethane systems	Vector 4	High	High	High

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