

Article

Regulatory-Aligned Energy Assessment for Wastewater Collection Networks Under the Scope of the UWWTD 2024/3019

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Abstract

The revised EU Urban Wastewater Treatment Directive (UWWTD, EU 2024/3019) expands the scope of the previous directive (Council Directive 91/271/EEC, 1991) by explicitly including combined sewer systems, stormwater discharges, and overflow events while promoting energy neutrality and reducing greenhouse gas (GHG) emissions across urban wastewater systems. Although the Directive establishes energy accountability at the system level, it does not define how energy performance in wastewater collection networks should be structured, assessed, or benchmarked, resulting in a significant implementation gap. This paper presents a novel, regulatory-aligned, data-driven framework to organise, analyse, and interpret energy-relevant information in support of UWWTD requirements, with specific focus on wastewater collection networks. Using Portuguese regulator datasets, supplemented with published sources, existing metrics are reorganised into energy-significant dimensions that differentiate structural, excess-driven, operational, and renewable-related components of energy use. The preliminary findings show that available datasets already support a screening-level diagnosis of specific energy intensity, pumping-related energy shares, inflow-driven excess volumes, and associated GHG emissions. However, important gaps remain regarding subsystem disaggregation, hydraulic normalisation, and measurement granularity. The study restructures existing information into a novel audit-compatible framework, proposes additional metrics and measurement requirements, and identifies measures to facilitate UWWTD implementation. Although developed for the Portuguese context, the framework offers a scalable pathway for integrating wastewater collection networks into energy neutrality governance across European Member States.

Keywords: energy efficiency; energy neutrality; performance assessment; revised UWWTD; undue inflows; urban wastewater systems; wastewater collection networks

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1. Introduction

Urban wastewater systems are increasingly recognised as energy-intensive infrastructures, contributing substantially to electricity demand and greenhouse gas (GHG) emissions worldwide [1,2]. Over the past two decades, research has progressively expanded beyond hydraulic performance and pollutant removal to address energy efficiency, resource recovery, and climate adaptation [3–6]. Wastewater treatment plants

(WWTPs) typically consume 20–60 kWh per population equivalent per year, whereas collection using pumping systems can account for 30–50% of total system electricity use, particularly under complex topographic conditions or high infiltration rates [7–9].

Despite these advances, methodological development has remained largely focused on treatment processes. Energy benchmarking and audit procedures have concentrated on process-level optimisation within WWTPs [10–14], while wastewater collection networks, whose energy demand is predominantly volume-driven, have received comparatively limited attention.

The regulatory context is now undergoing a significant shift. The revised EU Urban Wastewater Treatment Directive (UWWTD, EU 2024/3019 [15]) extends its scope to combined sewer systems, stormwater discharges, and overflow management and introduces sector-wide targets for energy neutrality and GHG emission reduction. Overflows are widely recognised as environmentally significant sources of pollutant loads to receiving waters, contributing to episodic releases of untreated wastewater and associated ecological pressures. This explains the strengthened regulatory emphasis placed on overflow monitoring and control under the revised Directive. Article 11 establishes mandatory periodic energy audits for urban WWTPs and their connected collecting systems. However, although neutrality targets are expressed through renewable energy equivalence requirements for treatment facilities above defined population thresholds, the Directive does not specify how energy performance in collection networks should be measured or normalised. In the UWWTD, collection systems integrate both collection and transport infrastructure and processes, including pumping. This concept is adopted in this paper.

This creates a non-trivial implementation gap: wastewater networks are explicitly included within audit requirements, yet no structured methodology exists for network-specific energy assessment. Commonly used metrics such as specific energy use (kWh/m³) provide useful benchmarks but can obscure key operational drivers related to undue inflows, such as infiltration and stormwater inflows, and to hydraulic seasonality effects on energy demand and pumping configuration [13,16–18]. These limitations highlight the need for methodologies capable of integrating energy-related metrics into national and local assessment frameworks.

More detailed methodologies, including process-level monitoring, system-wide energy balances, and integration of energy recovery technologies, offer richer insights and support meaningful subsystem disaggregation analysis [12,13,19–21]. A comprehensive Performance Assessment System (PAS) for energy efficiency tailored for wastewater systems was developed and demonstrated, incorporating criteria related to energy consumption, operation and maintenance (O&M) costs, and environmental impacts [19]. Three levels of analysis were proposed to assess the impact of undue inflows in the water–energy–greenhouse gas (W-E-G) emissions nexus: at a national level, the utility level, and at the subsystem level. The results showed the implications of undue inflows on energy and GHG emissions, including the effect of flooding and discharges [20]. These studies highlight that variability in inflows and stormwater contributions can strongly influence both energy use (or energy consumption) and GHG emissions, underscoring the need for accurate characterisation of hydraulic and operational conditions. While these several approaches provide robust technical insights at process and subsystem level, their application within regulatory contexts remains constrained by the structure and granularity of national aggregated reporting datasets, which often aggregate energy use at utility level without distinguishing between structural drivers (e.g., elevation, network layout) from operational ones (e.g., undue inflows, control strategies), constraining their application to meet energy neutrality obligations introduced in the revised UWWTD. Similar limitations have been documented in comparative benchmarking studies and water governance assessments [22–24]. Such aggregation reduces transparency and hinders the distinction

between structurally unavoidable energy and energy that could be reduced through improved hydraulic management or inflows' control.

While structured energy audit procedures are comparatively well developed for WWTPs, emphasising subsystem disaggregation, process normalisation, and differentiation between avoidable and unavoidable energy components, equivalent frameworks for collection networks remain underdeveloped [9,25]. Lessons from treatment-focused energy audits, including systematic disaggregation and performance normalisation, have not yet been consistently transferred to sewer systems.

The emergence of improved digital monitoring tools, including Supervisory Control and Data Acquisition (SCADA) systems, real-time sensors, and data-driven modelling approaches [26], offers new opportunities to improve energy transparency and optimise operational performance [27,28]. Nevertheless, the effectiveness of these tools depends on the availability, granularity, and structure of performance metrics within regulatory reporting schemes.

Against this background, a clear gap persists between the energy neutrality obligations introduced in the revised UWWTD and the current structure of national regulatory datasets used to assess wastewater collection networks. The literature review found no evidence of a framework designed to reorganise regulatory data into energy-significant analytical dimensions, specifically tailored to wastewater collection systems and an energy-neutrality focus.

This study addresses this gap by adapting an existing hierarchical performance assessment system to the requirements of the revised UWWTD, focusing exclusively on wastewater collection networks. Using Portuguese regulator (ERSAR) data as a baseline case, the study (i) analyses currently available datasets in Portugal to extract energy-related insights; (ii) identifies structural and operational energy uses in wastewater collection networks; (iii) proposes additional network-specific metrics and measurement needs to support regulatory alignment; and (iv) proposes a set of steps for an energy audit.

With these objectives, this study aims also to highlight limitations and missing information that constrain energy assessment. Similarities with energy audit approaches established for wastewater treatment are analysed to identify the audit methodological elements and energy efficiency measures that are transferable to wastewater collection from other sectors.

By bridging regulatory requirements, performance assessment practice, and dataset analysis, the proposed framework provides a first neutrality-oriented benchmarking approach for wastewater collection systems. This supports decision-making by utilities and regulators, enabling progress toward enhanced energy efficiency, energy neutrality, and alignment of wastewater service management with wider climate mitigation objectives.

2. Methodology and Data

2.1. Conceptual Framework Basis

The methodological framework proposed in this study builds on a progressive line of research on energy performance in wastewater systems, evolving from structured performance assessment toward system-level integration [19,20].

The first step consisted of developing a comprehensive PAS, tailored to evaluating energy efficiency in wastewater systems [19]. This PAS established a standard Objectives–Criteria–Metrics structure aligned with infrastructure asset management principles and strategic utility planning. Four strategic objectives were defined: (i) energy use efficiency, (ii) carbon neutrality, (iii) energy production and recovery, and (iv) economic and financial sustainability. Importantly, the framework incorporated hydraulic and operational dimensions often overlooked in energy assessments of wastewater networks, including metrics addressing undue inflows and operational practices. The PAS was validated with

Portuguese utilities, demonstrating feasibility, measurability, and coherence with existing regulatory reporting structures.

In a second step, this PAS was expanded [20] to integrate an explicit water–energy–greenhouse gas (W–E–G) nexus perspective, with a particular emphasis on quantifying the effect of undue inflows on the W–E–G nexus (mainly reflected in metrics P7–P10 in Table 1). This work formalised the causal links between undue inflows, energy use, and GHG emissions, introducing performance metrics capable of capturing seasonal variability, rainfall-driven inflows, and subsystem-level hydraulic behaviour. A three-tier analytical structure (national, utility, and subsystem level) was also introduced, demonstrating how data granularity constrains or enhances the robustness of energy and emissions evaluation [20]. The combined PAS is represented in Table 1. The main structure (metrics Mx.x.x) comes from [19] and metrics Px from [20]; metrics P1–P3, P6, and P14 are common to both. ERSAR’s assessment system focuses on the quality of service delivered by Portuguese utilities, namely, regarding service provision, service sustainability, and environmental sustainability. The system is designed to be applied at the utility level. As this PAS proposed in this study has a different scope and purpose, only three metrics reported in Table 1 (M1.1.1, M1.1.3, and M3.1.1) are derived from the Portuguese national regulator’s (ERSAR) existing set of metrics [29,30]. Metric 2.1.1 was introduced into the ERSAR metrics framework following the publication of a new technical guide [31]; however, it remains under testing and has not yet been fully consolidated within the regulatory assessment system. Although ERSAR formally uses the term *indicator*, a specific type of metric, the broader term *metric* is adopted throughout this paper for consistency.

Because of data availability constraints, it was not possible to calculate all PAS metrics; therefore, only some reference values were set. In Table 1, good performance is shown in green, fair performance in yellow, and poor performance in red. Whenever applicable, reference values are differentiated between type A and type B utilities. Type A utilities are responsible for bulk transport and treatment, whereas type B utilities are primarily responsible for collection and transport, although some also operate type A system components. Typically, type B utilities convey wastewater volumes to type A utilities.

Table 1. Complete PAS: objectives, criteria, metrics, and reference values (adapted from [19,20]).

Metric *	Reference Values **
Objective 1 Energy consumption efficiency	
Criterion 1.1: Energy efficiency of wastewater systems	
M1.1.1: Specific energy per total WW volume (kWh/m ³)— <i>metric from [30]</i>	A: [0, 0.5]; [0.5, 0.6]; [0.6, +∞] B: [0, 0.2]; [0.2, 0.3]; [0.3, +∞]
M1.1.2: Specific energy per total pumped volume (kWh/m ³)	A: [0, 0.5]; [0.5, 1.7]; [1.7, +∞] B: [0, 0.09]; [0.09, 0.12]; [0.12, +∞]
M1.1.3: Pumping stations energy efficiency [kWh (m ³ .100 m)]— <i>metric from [29]</i>	[0.27, 0.45]; [0.45, 0.68]; [0.68, 5]
P1 and M1.1.4: Percentage of total energy use for elevation (%)	A: [0, 15]; [15, 30]; [30, 100] B: [0, 5]; [5, 40]; [40, 100]
P2 and M1.1.5: Percentage of total energy use for WW treatment (%)	A: [0, 5]; [5, 50]; [50, 100] B: [0, 5]; [5, 30]; [30, 100]
M1.1.6: Energy consumption for WWTP per population equivalent (kWh/e.p.)— <i>metric adapted from [32]</i>	[0, 20]; [20, 50]; [50, +∞]
M1.1.7: Percentage of pumps with acceptable efficiency (%)	-
Criterion 1.2: Practices of operation, cleaning, and maintenance	
M1.2.1: Energy consumption for sewer network cleaning [tep/(100 km.year)]	-
M1.2.2: Energy consumption for septic tanks cleaning [tep/(km of travel.year)]	-

M1.2.3: Operation practices improvement to lower elevation height (–)	–
Criterion 1.3: Control of undue inflows	
M1.3.1: Quarter energy peak factor (–)	[1.0, 1.25]; [1.25, 1.75]; [1.75, +∞[
P6 and M1.3.2: Energy consumption seasonality (–)	[1.0, 1.75]; [1.75, 2.5]; [2.5, +∞[
M1.3.3: Percentage of energy equivalent to the volume generated in the served area used for elevation (%)	[95, 100]; [80, 95]; [0, 80]
P3 and M1.3.4: Percentage of energy equivalent to the volume generated in the served area used for WW treatment (%)	[95, 100]; [80, 95]; [0, 80]
M1.3.5: Effect of excessive inflows on energy use (%)	[0, 2.0]; [2.0, 5.0]; [5.0, 100]
P4. Inflows seasonality (–)—metric from [33]	[1, 1.25]; [1.25, 2.0]; [2.0, +∞[
P5. Inflows in periods with precipitation (–)—metric from [33]	[1, 1.25]; [1.25, 2.0]; [2.0, +∞[
P7. Energy consumption in periods with precipitation (–)	[1.0, 1.75]; [1.75, 2.5]; [2.5, +∞[
P8. Effect of undue inflows in energy (–)	[0, 2.0]; [2.0, 5.0]; [5.0, +∞[
P9. Effect of infiltration on energy (–)	[0, 2.0]; [2.0, 5.0]; [5.0, +∞[
P10. Effect of rain-derived inflows on energy (–)	[0, 2.0]; [2.0, 5.0]; [5.0, +∞[
Objective 2 Carbon neutrality	
Criterion 2.1: GHG emissions in equipment, processes, and transport	
P11 and M2.1.1: Specific GHG emissions associated with total WW volume (kg CO ₂ eq/m ³)	[0, 0.3]; [0.3, 0.5]; [0.5, +∞[
P12 and M2.1.2: Specific GHG emissions associated with pumped volume (kg CO ₂ eq/m ³)	[0, 0.4]; [0.4, 0.5]; [0.5, +∞[
P13 and M2.1.3: Specific GHG emissions associated with WW-treated volume (kg CO ₂ eq/m ³)	[0, 0.2]; [0.2, 0.4]; [0.4, +∞[
P14 and M2.1.4: Specific GHG emissions associated with the volume generated in the served area (kg CO ₂ eq/m ³)	–
M2.1.5: Specific GHG emissions associated with O&M (kg CO ₂ eq/m ³)	[0, 1 × 10 ^{−4}]; [1 × 10 ^{−4} , 2 × 10 ^{−4}]; [2 × 10 ^{−4} , +∞[
Criterion 2.2: Use of clean energy	
M2.2.1: Percentage of total energy use from clean energy sources (%)	–
Objective 3 Energy production and recovery	
Criterion 3.1: Self-energy production	
M3.1.1: Energy self-production (%)—metric from [30]	[20, 100]; [10, 20]; [0, 10]
Criterion 3.2: Energy recovery	
M3.2.1: Recovered energy (%)	–
Criterion 3.3: Use of purely gravity systems	
M3.3.1: Percentage of sewer network not associated with pumping stations (%)	–
Objective 4 Economic and financial sustainability	
Criterion 4.1: Wastewater system associated costs (except maintenance)	
M4.1.1: Percentage of the cost of total energy equivalent to the volume generated in the served area used for elevation (%)	–
M4.1.2: Percentage of the cost of total energy equivalent to the volume generated in the served area used for WW treatment (%)	–
M4.1.3: Percentage of the cost of total energy use for elevation (%)	–
M4.1.4: Percentage of the cost of total energy use for WW treatment (%)	–
M4.1.5: Cost associated with the quarter energy peak factor (–)	[1, 1.5]; [1.5, 2.5]; [2.5, +∞[
M4.1.6: Cost associated with energy use seasonality (–)	[1, 2]; [2, 3]; [3, +∞[
M4.1.7: Percentage of the cost associated with energy self-production (%)	–
M4.1.8: O&M costs of energy use reduction by control of undue inflows (%)	–
Criterion 4.2: Maintenance costs	

M4.2.1: Repair or replacement costs of pumping equipment [€/equipment.year]	-
M4.2.2: Cleaning operations costs of energy [€/100 km.year]	-
M4.2.3: Solids removal operations costs of energy [€/kg.year]	-

* Metrics Mx.x.x come from [19] and metrics Px from [20]. ** Results are classified depending on reference values: good performance: green; fair performance: yellow; poor performance: red.

In Table 1, reference values were retrieved from other studies [19,20,30,32,33]. In all these studies, reference values and their classification as good, fair, or poor performance were based on a similar procedure, supported by theoretical concepts, design criteria, and relevant legislation. In some cases, additional benchmarks were drawn from comparable metrics in established PAS and supported by a literature review. In cases where sufficient data were available, statistical analyses were conducted on the results from the calculation of the metrics with utilities' data. Metrics results were then classified into three categories—good, fair, and poor—typically corresponding to the 25th and 75th percentiles, which were further refined and validated through discussions with the utilities.

Although the combined PAS presented in Table 1 provides a comprehensive and technically robust structure for assessing energy performance in wastewater systems, its direct adoption as a regulatory reference under the revised UWWTD requires careful consideration.

The PAS was originally conceived as a strategic and tactical performance assessment tool for utilities, integrating energy, environmental, operational, and financial dimensions in a holistic method. This design is well suited to internal utility management and asset planning contexts. However, its direct transposition to a regulatory context must consider the constraints related to comparability, aggregation level, and reporting harmonisation inherent to national datasets.

Additionally, several PAS metrics require detailed operational and subsystem-level information (e.g., sub-daily flows, disaggregation by pumping station, detailed cost allocation), which is not systematically available in national regulatory datasets. While such metrics remain methodologically sound and highly valuable for utility-level management, their immediate applicability in a regulatory compliance context depends on their alignment with existing reporting practices and data structures.

For this reason, before proposing any regulatory-aligned restructuring, it is essential to examine the baseline currently available. In Portugal, ERSAR provides a structured nationwide dataset that serves as the foundation for regulatory assessment. Understanding the scope, granularity, and limitations of these datasets is a necessary intermediate step in determining which components of the PAS can be operationalised with existing data, where critical gaps persist, and what additional measurement requirements are needed to support future alignment.

Within a regulatory context, metrics can be classified according to their analytical level and data requirements. “Screening” metrics are directly calculable from aggregated annual reporting and support national benchmarking; they can include proxy-based metrics (e.g., seasonality ratios) that highlight potential hydraulic–energy interactions but without enabling causal attribution. “Diagnostic” metrics rely on partial functional disaggregation (e.g., separation of pumping and treatment energy) and allow identification of dominant energy drivers at the utility level, though they remain insufficient for distinguishing structural from avoidable energy components. “Audit-ready” metrics require subsystem-level monitoring, hydraulic normalisation, and temporally resolved energy data; these enable defensible separation of structural, excess-driven, and operational energy components, consistent with established energy audit principles.

Figure 1 schematically illustrates the sequential general steps proposed for developing a regulatory-aligned energy audit for wastewater collection networks under the revised UWWTD.

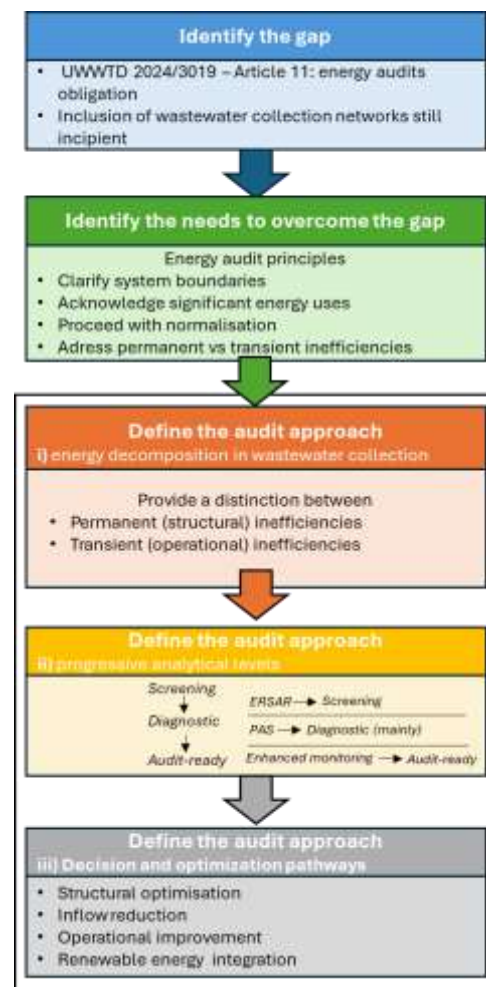


Figure 1. Proposed steps for a regulatory-aligned (revised UWWTD) energy audit for wastewater networks.

The following Section 2.2 examines the current Portuguese regulatory data landscape, identifying both its potential and its constraints as a foundation for UWWTD-oriented energy performance assessment. Only after establishing this baseline can principles for regulatory alignment be systematically derived.

2.2. ERSAR Dataset

2.2.1. Available Portuguese Data from the National Water Regulator

In Portugal, ERSAR maintains a structured and publicly available reporting system for water and wastewater utilities, covering 12 type A wastewater utilities and 213 type B. This system should constitute the primary baseline for any regulatory-oriented performance assessment and, therefore, represents the logical starting point for evaluating the feasibility of UWWTD-aligned energy analysis.

The ERSAR dataset includes annual, utility-level information on [34] several variables (dARxxx):

- Total energy use (dAR071);
- Energy use for elevation and treatment, when reported separately (dAR072 and dAR073);

- Number of pumping stations and treatment plants (dAR038 and dAR039);
- Reported floods and discharge occurrences, with heterogeneous monitoring coverage (dAR045 to dAR050);
- Self-energy production (dAR070);
- Population equivalent served by WWTPs (dAR046);
- Total collected or treated wastewater volumes (dAR056 and dAR060/61);
- Wastewater volumes in the three months with the highest and lowest volumes (dAR067 and dAR068).

From these variables, several energy-related metrics are already included in the ERSAR's assessment or can be calculated at the national scale. These are identified as ARx (under use, wastewater) or PARx (also for wastewater, which are still under testing by ERSAR). These include:

- Specific energy intensity (kWh/m³): can be calculated;
- Pumping stations energy efficiency (kWh/(m³·100 m) (AR16): included;
- Self-energy production (%) (AR19): included;
- Functional energy allocation, e.g., pumping versus treatment share: can be calculated;
- Energy use associated with wastewater treated (kWh/m³) (PAR06): included;
- Energy use for WWTPs per population equivalent (kWh/e.p.): can be calculated;
- Preliminary estimates of indirect GHG emissions, using national emission factors (kg CO₂e/m³) (PAR04): included;
- Undue inflows seasonality (-) (PAR03): included;
- Floods occurrence (n.^o/100 km sewer.year) (AR04): included;
- Control of emergency and storm overflow discharges (%) (AR20): included.

This baseline provides two important advantages. First, it ensures national coverage and comparability across utilities. Second, it allows retrospective assessment over multiple years, enabling trend analysis and cross-sectional benchmarking. When assessed against the expanded requirements of the revised UWWTD, the ERSAR data structure reveals critical analytical constraints.

2.2.2. Structural Limitations of the Current Regulatory Dataset

Although reasonably robust at an aggregated level, the ERSAR dataset presents structural limitations that restrict its suitability for neutrality-oriented or audit-based energy assessment:

- Aggregation bias—energy and volume data are typically reported annually at utility scale, masking intra-annual variability and hydraulic seasonality;
- Limited subsystem disaggregation—energy use is rarely reported at the individual pumping station level or network segments, preventing functional disaggregation comparable to WWTP energy audits;
- Absence of hydraulic normalisation variables—reporting does not systematically include volumes generated within the served area, pumped volumes by elevation range, or dynamic head conditions;
- Insufficient quantification of undue inflows—although floods and overflows are reported, volumetric measurements are inconsistent or unavailable;
- Measurement heterogeneity—monitoring practices vary significantly across utilities, affecting data consistency;
- Limited emissions granularity—GHG emissions are not directly measured and must be estimated from energy use.

These limitations do not undermine the validity or usefulness of the ERSAR dataset itself; rather, they constrain its analytical scope and its capacity to support neutrality-

oriented performance assessment and audit-compatible methodologies in alignment with the revised UWWTD.

2.2.3. Analytical Implications for UWWTD Alignment

The revised UWWTD extends accountability to combined systems, stormwater discharges, overflow events, and energy neutrality targets. Meeting these expanded policy objectives implicitly requires the ability to:

- Link energy use to hydraulic drivers (e.g., rainfall-derived inflows);
- Assess seasonal and event-based variability;
- Evaluate exceedance volumes and their energy implications;
- Quantify system-level GHG impacts;
- Ensure traceable and auditable energy allocation across system components.

At present, the ERSAR data allow for the estimation of national energy intensity and functional energy shares, but they do not support robust causal attribution between hydraulic behaviour and energy performance. In particular, the energy implications of undue inflows, e.g., infiltration, and rainfall-derived flows cannot be directly quantified from annual aggregated datasets. Likewise, the separation of structural (topography-driven) versus operational (potentially avoidable) energy components is not feasible.

Thus, while the ERSAR dataset provides a valuable starting point, it does not constitute a fully adequate assessment structure for meeting the expanded analytical and compliance requirements introduced by the UWWTD. This baseline assessment reinforces the need for a structured regulatory alignment procedure, presented in Section 2.3, that interprets the revised Directive's objectives and implicit requirements and derives an aligned, technically coherent performance assessment structure.

2.3. Regulatory Alignment Procedure

The original PAS framework presented in Section 2.1 was not designed to address the expanded scope introduced in the revised UWWTD. The Directive elevates energy neutrality, stormwater integration, and system-level accountability to formal compliance objectives, thereby requiring a reinterpretation of energy performance assessment principles.

To operationalise the revised Directive within a regulatory context and objectives into measurable assessment dimensions, a structured interpretation of Article 11 was conducted. This analysis identifies four implicit technical requirements for energy performance assessment:

1. System-level energy accountability—the Directive requires wastewater collection networks to be explicitly included in energy audits. Because energy neutrality targets apply at the system level, assessments can no longer focus solely on WWTPs. Instead, the entire system (including collection, transport, and treatment) must be addressed through consistent boundaries and functional energy use disaggregation (e.g., elevation, treatment, auxiliary services).
2. Hydraulic–energy integration—by formally incorporating combined sewer systems, stormwater discharges, and overflow management, the Directive establishes hydraulic behaviour as a determinant of energy performance. Energy consumption must, therefore, be evaluated in relation to flow variability, rainfall influence, and exceedance events. This requires hydraulic normalisation and seasonality-based metrics capable of capturing undue inflows and rainfall-driven variability.
3. Emissions transparency—to support climate objectives, energy use must be systematically translated into GHG emissions. This implies consistent linkage between electricity use and emission factors and, where applicable, differentiation between direct

and indirect emissions. Emissions intensity metrics must, therefore, complement traditional energy intensity metrics.

4. Comparability and scalability across Member States imply that regulatory instruments must be replicable and compatible with aggregated national datasets while allowing progressive refinement where more detailed measurements are available. This ensures both harmonisation and adaptability.

Collectively, these requirements show that regulatory alignment cannot rely solely on aggregated volumetric specific energy use (SEC) metrics. Instead, a structured performance architecture is needed to ensure coherence between hydraulic behaviour, energy use, and emissions.

Alignment with the revised UWWTD does not require adoption of the complete PAS structure developed in Section 2.1. Instead, it requires selective reorganisation of its energy-relevant components within a regulatory-oriented structure that:

- Prioritises energy intensity and functional allocation metrics;
- Incorporates undue inflows and rainfall-driven variability as structural drivers of energy performance;
- Ensures explicit linkage between energy use and GHG emissions;
- Maintains compatibility with existing regulatory reporting datasets and structure (e.g., ERSAR);
- Enables progressive enhancement through additional measurements at the utility or subsystem level.

This resulting structure must be technically robust, operationally feasible, scalable across varying data maturity contexts, and suitable for audit-based verification.

From a methodological perspective, this implies structuring the assessment into four different dimensions:

- Structural energy demand—driven by topography, network configuration, and required elevations;
- Excess-driven energy—associated with undue inflows and rainfall events;
- Operational variability—linked to pump efficiency, control strategies, and operational practices;
- Renewable-related components of energy use.

The present study addresses this regulatory gap by reorganising and selectively operationalising the energy-relevant components of the previously developed PAS structure within a regulatory-alignment perspective. The earlier PAS provides the conceptual and metric support, while the W–E–G nexus extension supplies the hydraulic–energy causal structure.

The proposed framework builds on the hierarchical structure and metric logic embedded in previous work but introduces an explicit regulatory alignment layer.

This reorganisation is specifically designed to operationalise the audit obligations of Article 11 for wastewater collection networks. This regulatory translation constitutes the core methodological innovation of the study and is detailed in Section 3.

2.4. Energy Audit Principles and Their Translation to Wastewater Collection Networks

Energy audits constitute structured and systematic procedures for quantifying energy use, identifying significant energy functions, detecting inefficiencies, and proposing technically and economically viable improvement measures. International standards such as the ISO 50002 [35] define energy audits as a process grounded in clear system boundaries, identification of significant energy uses, performance metrics, data validation, and reporting of improvement opportunities. In the water sector, specialised guidance

documents and professional practice manuals (e.g., [25]) further detail recommended audit procedures for drinking water and wastewater facilities.

Recent analyses within the context of the revised UWWTD highlight that Article 11 requires periodic energy audits for treatment facilities and their connected collecting systems [9]. Article 2(32) of Directive EU/2023/1791 ([36], discussed in [9]) specifies that audits should include quantification of energy use, identification of significant processes, benchmarking, and definition of improvement actions. Importantly, no single prescriptive procedure currently exists for wastewater sector energy audits. Instead, audit practice is built around a set of core principles, including:

- Clear definition of system boundaries;
- Identification of significant energy uses;
- Subsystem-level disaggregation where measurement capabilities allow;
- Normalisation against relevant hydraulic or pollutant loads;
- Distinction between permanent (structural) and transient (operational) inefficiencies;
- Structured audit cycles, including identification and verification of improvement measures.

In WWTPs, audit applications commonly involve subsystem disaggregation (e.g., aeration, sludge treatment, pumping), hydraulic and pollutant loads normalisation, and diagnostics distinguishing between structural versus operational energy drivers [9,25]. These applications need to be supported by relatively mature monitoring systems that enable detailed energy and process analysis. These principles can be translated to wastewater collection systems, as presented in Figure 2.

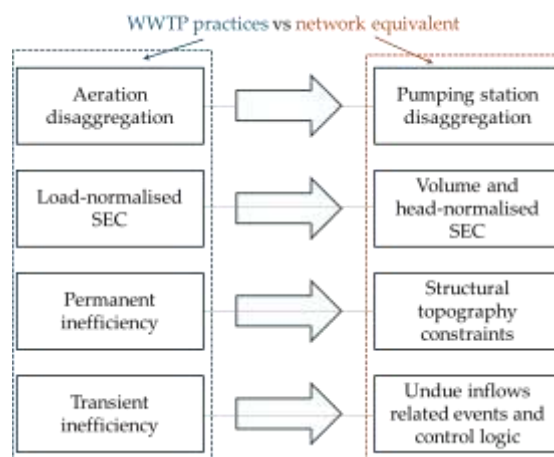


Figure 2. WWTP audit practices vs. network equivalent.

Wastewater collection networks differ structurally from treatment facilities. In the first case, energy demand is predominantly associated with sewers' layout, flow variations, and pumping systems [7,20]. In the second case, in WWTPs, permanent inefficiencies are often associated with structural or design-related constraints, such as oversized equipment, suboptimal aeration systems, or outdated process configurations [9,25]. Transient inefficiencies, in contrast, are mainly linked to operational control strategies, load variability, or temporary deviations from optimal setpoints [17,18].

In wastewater collection networks, inefficiencies can also be distinguished between permanent and transient. Permanent inefficiencies are largely associated with structural energy demand, driven by topography, elevation needs, network layout, and long-term infrastructure characteristics [7]. By contrast, transient inefficiencies are primarily linked to undue inflows, rainfall-induced variability, and the operational control of pumping systems, all of which can increase energy use beyond structurally necessary levels [18,20].

Measurement granularity in collection networks is typically lower than in WWTPs, limiting direct subsystem-level attribution. While WWTPs often benefit from detailed, process-level monitoring that enables subsystem disaggregation and load normalisation [7,13], collection networks are often monitored only at the aggregated utility level, especially within regulatory reporting schemes [23,24]. This constrains immediate causal attribution, but the fundamental energy audit principles remain applicable to collection systems when supported by progressive enhancement of monitoring practices [9,25].

Based on these principles and in alignment with the regulatory requirements of Article 11, the present study structures network-level energy assessment around the four dimensions previously presented (structural energy demand, excess-driven energy, operational variability, and renewable-related components of energy use).

These dimensions form a conceptual bridge between established audit practices and the specific operational logic of wastewater collection networks. They do not presume full subsystem modelling but define a progressive pathway from screening-level metrics toward audit-ready attribution.

The primary limiting factor remains measurement granularity, which is considerably lower in networks than in WWTPs, and thus requires progressive improvement of monitoring capabilities.

Nevertheless, the comparison demonstrates that extending energy audit logic to wastewater collection systems is both feasible and methodologically coherent—if monitoring practices evolve to support greater transparency and subsystem-level insight.

3. Results

3.1. National Baseline: Energy Performance Assessment from Regulator Data

The ERSAR dataset [34,37] provides sufficient information to support a first-level national assessment of energy performance in wastewater collection networks. Before analysing the dispersion of the results, it is essential to clarify which metrics can be consistently derived from the available regulator data. Table 2 summarises the main metrics obtained from the ERSAR database and their corresponding analytical level.

As previously defined, metrics are classified within a regulatory context as “Screening”, “Diagnostic,” or “Audit-ready” metrics. In the present case, all metrics included in the ERSAR assessment framework fall into the screening-level category.

Using annual, utility-level reporting, several of the screening-level metrics listed in Table 2 can be systematically calculated, forming the basis for national-scale benchmarking and initial identification of energy-performance patterns.

Table 2. Energy-related metrics from the ERSAR data [34].

Metric	Units	Formulation	Reference Values
AR16: Pumping stations' energy efficiency ⁽¹⁾	kWh/(m ³ .100 m)	Energy consumption for elevation/standardisation factor Note—Standardisation factor: m ³ /(year.100 m)	[0.27; 0.54]; [0.54; 0.90]; [0.90; 5.00]
AR19: Self-energy production	%	Energy consumption from self-production/total energy use × 100	A: [0, 5]; [5, 50]; [50, 100] B: [0, 5]; [5, 30]; [30, 100]
PAR06: Energy consumption for treated wastewater	kWh/m ³	Energy consumption for treatment/total wastewater treated volume	-
PAR04: Specific GHG emissions ⁽²⁾	kg CO ₂ eq/m ³	Total energy use × IF ⁽³⁾ /total volume of wastewater collected or treated × 1000	[0, 0.2]; [0.2, 0.34]; [0.34, +∞] ⁽⁴⁾

PAR03: Undue inflows seasonality	-	Wastewater volumes in the three months with the highest volumes/wastewater volumes in the three months with the lowest volumes	-
AR04: Flood occurrence	n. ^o /100 km sewer.year (type A) or n. ^o /1000 connections.year (type B)	Number of flooding occurrences in public areas and/or properties originating from the public wastewater sewer network/100 km of sewer (type A) or/1000 connections (type B)	A: [0.0; 0.5]; [0.5; 2.0]; [2.0; +∞] B: [0.0; 0.25]; [0.25; 1.0]; [1.0; +∞]
AR20: Control of emergency and storm overflow discharges	%	Emergency and storm overflow structures with direct discharge to the receiving environment that are monitored and operating satisfactorily/total number of these structures	[90, 100]; [80, 90]; [0, 80]

⁽¹⁾ Equivalent to M113 in Table 1; ⁽²⁾ equivalent to M211 in Table 1; ⁽³⁾ considering an impact factor (IF) associated with electric consumption of 0.47 kg CO₂ eq/kWh according to Decree law 71/2008 [38] for the Portuguese scope; ⁽⁴⁾ defined in [20].

Table 3 summarises the main energy-related metrics from the ERSAR data for wastewater systems for type B utilities and Table 4 for type A, including sample size and national dispersion statistics. The results were considered for the years 2022 and 2023 [34,37] after the last revision of the national performance assessment guide [31]. The national dispersion of ERSAR energy-related metrics reveals distinct structural patterns between type B (collection and transport, sometimes including treatment) and type A (bulk transport and treatment) utilities while also highlighting significant variability and data heterogeneity.

For type B utilities (Table 3), the pumping stations' energy efficiency metric (AR16) shows a median of 0.90 kWh/(m³·100 m), with 50% of utilities falling between 0.66 and 1.19 kWh/(m³·100 m). According to the reference values in Table 2 ([0.27–0.54] good; [0.54–0.90] fair; [0.90–5.00] poor), the median lies at the boundary between fair and poor performance. The upper dispersion (max = 3.51) suggests the presence of hydraulically inefficient or structurally constrained systems. This dispersion indicates that, for collection-dominated utilities, energy performance is strongly influenced by network layout, pumping head, pumping efficiency, and potentially suboptimal operational practices.

Self-energy production (AR19) is negligible for most type B utilities, remaining below the lower performance threshold defined in Table 2. Only a small subset of utilities report non-zero values, with a maximum of 54%, confirming that renewable self-production is not yet structurally embedded in these systems.

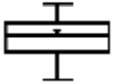
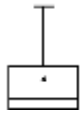
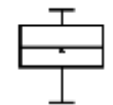
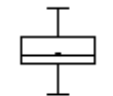
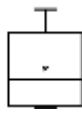
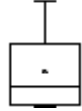
Energy consumption associated with treated wastewater (PAR06) has a median of 0.58 kWh/m³ (P25–P75: 0.32–1.08 kWh/m³), with values ranging from 0 to 6.85 kWh/m³. The broad dispersion reflects the heterogeneity of treatment responsibilities among type B utilities. Zero or near-zero values correspond to utilities without direct treatment functions, whereas higher values likely reflect small-scale or decentralised treatment facilities, which typically operate with reduced economies of scale and higher unit energy intensities.

Table 3. National energy-related metrics from the ERSAR dataset for type B utilities (for years 2022 and 2023).

Metric	n	Min	P25	Average	Median	P75	Max	Boxplot ⁽¹⁾
AR16: Pumping stations' energy efficiency [kWh/(m ³ .100 m)]	160	0.38	0.66	1.02	0.90	1.19	3.51	
AR19: Self-energy production (%)	314	0.00	0.00	1.37	0.00	0.00	54.00	
PAR06: Energy consumption associated with wastewater treated (kWh/m ³)	223	0.00	0.32	0.97	0.58	1.08	6.85	
PAR04: Specific GHG emissions (kg CO ₂ eq/m ³)	300	0.00	0.00	0.05	0.02	0.07	0.54	
PAR03: Undue inflows seasonality (-)	142	1.00	2.00	148.65	118.00	201.75	2680.00	
AR04: Flood occurrence (n. ^o /1000 drains.year)	361	0.00	0.00	3.90	0.75	3.93	52.19	
AR20: Control of emergency and storm overflow discharges (%)	247	0.00	0.00	27.29	0.00	54.00	100.00	

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

Table 4. National energy-related metrics from the ERSAR dataset for type A utilities (for years 2022 and 2023).

Metric	n	Min	P25	Average	Median	P75	Max	Boxplot ⁽¹⁾
AR16: Pumping stations’ en- ergy efficiency [kWh/(m ³ .100 m)]	24	0.3	0.50	0.59	0.58	0.63	0.92	
AR19: Self-energy produc- tion (%)	24	0.00	0.00	6.38	2.00	9.25	25	
PAR06: Energy consump- tion associated with wastewater treated (kWh/m ³)	24	0.15	0.33	0.41	0.43	0.54	0.61	
PAR04: Specific GHG emis- sions (kg CO ₂ eq/m ³)	24	0.03	0.08	0.091	0.09	0.11	0.15	
PAR03: Undue inflows sea- sonality (-)	24	1.00	2.00	79.29	57.50	151.75	201.00	
AR04: Flood occurrence (n. ^o /100 km sewer.year)	24	0.00	0.30	50.33	3.55	10.13	610.70	
AR20: Control of emergency and storm overflow dis- charges (%)	24	0.00	0.75	20.75	11.50	37.00	62.00	

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

Specific GHG emissions (PAR04) show a median of 0.02 kg CO₂e/m³, within the “good” performance range ([0–0.2]). However, the upper range (max = 0.54) exceeds the upper reference threshold (0.34), suggesting that some utilities operate with comparatively carbon-intensive electricity profiles or elevated specific pumping energy.

The highest dispersion occurs in the undue inflows seasonality metric (PAR03). Although the first quartile equals 2.00, the median reaches 118, and the maximum is 2680. These extreme values are physically implausible if interpreted strictly as hydraulic seasonality. They most likely reflect inconsistencies in reporting, data aggregation, or highly uneven quarterly data inputs. This illustrates both the analytical potential and fragility of proxy-based metrics derived from aggregated regulatory datasets. From a regulatory-alignment perspective, it reinforces the need for data validation and clearer interpretation rules before such metrics can support audit-level assessments.

Flood occurrence (AR04) and storm overflow control (AR20) also show wide dispersion for type B utilities, with median overflow control remaining at 0%, explained by limited monitoring or reporting coverage despite regulatory requirements.

For type A utilities (Table 4), dispersion patterns differ substantially. Pumping stations’ energy efficiency (AR16) shows a median of 0.58 kWh/(m³·100 m), within the fair performance range and with a much narrower dispersion (P25–P75: 0.50–0.63). This reflects the greater structural homogeneity of bulk transport and treatment systems.

Self-energy production (AR19) exhibits a higher central tendency (median = 2.0%) compared to type B utilities, although it is still within the lower performance band. The upper quartile (9.25%) suggests that some type A utilities have begun to integrate renewable energy generation, consistent with treatment-centred neutrality pathways.

Energy consumption associated with treated wastewater (PAR06) shows a median of 0.43 kWh/m³ (P25–P75: 0.33–0.54 kWh/m³), with limited dispersion (maximum 0.61 kWh/m³). As this metric is still under testing and lacks defined regulatory reference values, the results remain exploratory. Nevertheless, the narrow interquartile range suggests relatively homogeneous treatment energy intensity among type A utilities, consistent with medium- to large-scale treatment processes operating under more standardised conditions.

Specific GHG emissions (PAR04) exhibit a median of 0.09 kg CO₂e/m³, within the “good” reference band, with moderate dispersion (max = 0.15), suggesting greater operational stability compared to type B systems.

As with type B utilities, the undue inflows seasonality proxy (PAR03) shows significant dispersion (median = 57.50; max = 201). Although in type A systems the values are less extreme than in type B systems, these values still suggest reporting inconsistencies or limitations intrinsic to aggregated quarterly ratios. Without hydraulic normalisation or event-based validation, PAR03 cannot be interpreted as a direct measure of physical inflow seasonality.

Overall, the regulator dataset supports screening-level benchmarking of energy performance across utility types and allows the identification of structural differences between utility types. However, the magnitude of dispersion (particularly for seasonality and overflow-related metrics) reveals that aggregated annual reporting can amplify inconsistencies and mask causal drivers. As a result, aggregated annual data do not allow causal attribution of energy use.

Energy audit logic, as applied in WWTPs, extends beyond benchmarking; it benefits from decomposing total energy demand into structurally required and potentially avoidable components. Translating this logic to wastewater collection networks requires a structured but realistic regulatory-aligned framework, relying on existing datasets while defining a feasible pathway toward audit-ready energy accountability.

3.2. Regulatory-Aligned Audit Framework for Wastewater Collection Networks

3.2.1. Decomposition of Network Energy Demand

This section and Section 3.2.2 present both the application of the analysis and the operationalisation of the proposed framework, including the categorisation of energy dimensions and associated formulations. In line with the audit principles discussed in Section 2.4, neutrality-oriented assessment of wastewater collection networks benefits from a structured decomposition of total energy demand.

At the conceptual level, the total annual electricity consumption of a wastewater collection system (E_{total}) can be expressed by Equation (1):

$$E_{total} = E_{structural} + E_{excess} + E_{operational} \quad (1)$$

where:

- $E_{structural}$ represents structurally required energy associated with topography, elevation, and network configuration;
- E_{excess} corresponds to energy induced by undue inflows, rainfall-driven variability, and excess conveyed volumes;
- $E_{operational}$ reflects deviations linked to pump efficiency, control logic, and operational practices.

Renewable self-production does not constitute an additive energy demand component but acts as an offset mechanism, as expressed by Equation (2):

$$E_{net} = E_{total} - E_{renewable} \quad (2)$$

In wastewater collection networks, renewable generation potential is typically limited due to the spatial dispersion of assets and the relatively small-scale individual pumping loads. Consequently, neutrality strategies in these systems depend primarily on demand reduction and optimisation of structural and operational drivers rather than on direct renewable substitution as commonly observed in WWTPs.

This decomposition is consistent with the permanent–transient inefficiency distinction established in Section 2.4. Permanent inefficiencies correspond mainly to structural energy demand, while transient inefficiencies are expressed in excess-driven and operational components.

3.2.2. Progressive Metrics Structure and Alignment

To operationalise the conceptual framework within regulatory constraints, a progressive metric structure is proposed. It does not replace formal audit procedures but defines the minimum performance structure required to make energy audits in wastewater collection networks technically meaningful and comparable. The framework integrates:

- Aggregated regulatory metrics currently available or obtainable through ERSAR (Table 2);
- Energy-relevant components derived from the previously developed Performance Assessment System (PAS) (Table 1);
- Additional network-specific metrics required to achieve audit-ready attribution. Three output analytical levels are defined:
 - Screening level—aggregated metrics enabling benchmarking;
 - Diagnostic level—partial functional disaggregation allowing preliminary identification of dominant drivers;
 - Audit-ready level—subsystem-based metrics permitting defensible attribution of structural versus avoidable energy components.

This progression acknowledges the current limitations of regulatory datasets and defines a trajectory toward enhanced monitoring consistent with Article 11 audit requirements.

At the screening level, metrics such as specific energy use (kWh/m³), pumping energy share, energy per population equivalent, and indirect electricity-related emissions provide national benchmarking capacity. These metrics are suitable for detecting dispersion patterns and identifying systems with potentially excessive energy intensity, but they do not allow causal separation between structural and avoidable components.

At the diagnostic level, partial functional disaggregation becomes possible where utilities complement annual reporting with additional operational data (e.g., pumped volumes, pumped flows, or rainfall-influenced inflows).

At the audit-ready level, defensible separation of structural and operational components requires minimum additional measurements, including pumping station-level energy metering, pumped flow data, hydraulic head data, and pump performance curves. These elements enable estimation of energy per static head, pump efficiency deviation indices, and wet-weather energy amplification factors. Although such granularity is not yet available in national reporting schemes, it aligns with energy audit practice.

It is important to highlight that all energy-based metrics can be consistently translated into indirect GHG emissions using national emission factors.

The resulting framework reorganises energy assessment around four audit-consistent dimensions: structural energy demand; excess-driven energy; operational variability; and renewable-related components. These dimensions define the structure of the regulatory-aligned metric structure presented in Table 5.

Table 5 consolidates the regulatory-aligned audit structure by explicitly distinguishing between existing regulatory metrics (ERSAR), metrics previously developed within the PAS framework, and newly proposed audit-oriented extensions. This clarification ensures methodological transparency and highlights the progressive nature of the framework, moving from readily available screening metrics toward audit-ready attribution supported by deeper subsystem monitoring.

Importantly, the framework does not assume immediate availability of subsystem-level data across all utilities. Instead, it establishes a scalable approach: screening metrics are immediately applicable using existing regulatory datasets, diagnostic metrics become feasible with moderate data enhancement, and audit-ready metrics represent the target level for full compliance with neutrality-oriented audit logic.

Table 5. Proposed UWWTD-aligned assessment framework for energy audit of wastewater collection networks.

Assessment Dimension	Metric	Formulation	Primary Data Source	Analytical Level	Additional Data Required
Structural energy demand	Specific Energy consumption (SEC) (kWh/m ³) ⁽¹⁾	Total annual electricity consumption/total collected wastewater volume	ERSAR (dAR071/dAR056) and PAS (M1.1.1) data	Screening	No additional data required for the annual total energy and collected volume
	Energy per population equivalent (kWh/e.p.·year)	Total annual electricity consumption/population equivalent served	ERSAR (dAR071/dAR046) and PAS (M1.1.6) data	Screening	Consistent and validated reporting at the utility level
	Energy per static head (kWh/m ³ ·m)	Electricity consumption normalised by conveyed volume and static elevation head	PAS adaptation for audit (utility data) ⁽²⁾	Audit-ready	Measurement of static or total dynamic head at pumping stations
Excess-driven energy	Excess volume ratio (–)	Difference between collected and billed wastewater volumes/by collected volume	New. ERSAR (dAR056–dAR062)/dAR56 data	Screening	Reliable billing data and validation of the collected volume measurement
	Seasonality proxy (–)	Ratio between the maximum and minimum quarterly collected volumes within the same year	ERSAR (PAR03)	Screening	Quarterly or monthly disaggregation of collected volume
	Rainfall-adjusted SEC (kWh/m ³)	Difference between specific energy use under wet-weather and dry-weather conditions	New (utility+rainfall data)	Diagnostic	Energy data for wet and dry weather periods based on rainfall or flow data
	Wet-weather energy factor (–)	Ratio between electricity consumption during wet-weather and dry-weather periods	New (utility data)	Audit-ready	Temporal energy use data and hydraulic classification of wet-weather events
Operational variability	Pumping energy share (–)	Electricity consumption associated with pumping/total electricity consumption	ERSAR (dAR072/dAR071) and PAS (M1.1.4, P1) data	Screening	Functional allocation of energy between pumping and other uses
	Specific pumping energy (kWh/m ³)	Electricity consumption associated with pumping/total pumped wastewater volume	PAS (M1.1.2)	Diagnostic	Pumping-station-level energy metering and pumped volume measurement
	Pump efficiency deviation index (–)	Deviation between actual pumping performance and theoretical pump curve efficiency	New (utility data)	Audit-ready	Pump-level flow, total dynamic head, and power data compared to operating points with manufacturer pump curves
Renewable-related component	Self-production ratio (–)	Electricity generated internally from renewable sources divided by total electricity consumption	ERSAR (AR19) and PAS (M3.1.1)	Screening	Separate accounting of internally generated renewable energy
	Net energy balance (kWh/year)	Difference between total electricity consumption and renewable electricity produced	New. ERSAR (dAR071–dAR070) data	Screening	Annual accounting of total consumption and renewable self-production

⁽¹⁾ Metrics such as SEC are not exclusive to a single assessment dimension. The classification within the structural dimension herein reflects the absence of subsystem disaggregation at this stage; ⁽²⁾ this metric is conceptually equivalent to ERSAR AR16 but expressed per unit of elevation head to facilitate interpretation within energy audit frameworks.

3.3. From Assessment to Energy-Oriented Decision Pathways

Energy audits require identification, prioritisation, and monitoring of improvement measures. Established audit practice in the water sector emphasises the translation of diagnostic findings into technically and economically viable interventions [9,25]. Building on the assessment-to-decision framework previously developed in [39], the present study extends this logic to wastewater collection networks within a regulatory context.

The four assessment dimensions directly align with optimisation measures, as presented in Table 6. This table outlines the proposed optimisation measures and is intended to operationalise the assessment-to-decision step by linking each assessment dimension to corresponding optimisation measures.

Table 6. Energy optimisation measures aligned with audit assessment dimensions (adapted from [39]).

Assessment Dimension	Objective	Typical Measures	Decision Horizon	Audit Relevance
Structural energy demand	Reduce intrinsically required elevation needs and hydraulic constraints	Increased gravitational transport through network reconfiguration Reduction in unnecessary elevation needs Decentralised/modular treatment integration Infrastructure retrofitting to reduce pumping dependence	Medium to long term	Addresses permanent inefficiencies
Excess-driven energy	Reduce avoidable energy associated with undue inflows and rainfall variability	Rehabilitation of sewers Stormwater separation Inflow detection and targeted repair Wet-weather monitoring and flow classification	Medium term	Targets transient, hydraulically driven inefficiencies
Operational variability	Improve pumping performance and control efficiency	Pump resizing and efficiency optimisation Pump speed control (e.g., variable frequency drives) and optimisation of pumping operation (e.g., start/stop levels and control logic) Predictive SCADA-based operation	Short to medium term	Addresses operational inefficiencies identified in audits
Renewable-related component	Offset residual energy demand after demand-side optimisation	Distributed renewable generation (e.g., photovoltaic systems at pumping stations) Utility-level renewable energy supply (e.g., green electricity or centralised photovoltaic systems)	Medium term	Complements efficiency but does not replace demand reduction

Integration of renewable energy should be treated as complementary, rather than a substitute for demand reduction. Where structural and avoidable energy components are not clearly separated, reliance on renewable offsets can delay corrective actions targeting hydraulically or operationally driven inefficiencies.

The transition from energy assessment to decision-making requires structured prioritisation. As demonstrated [39], effective energy management in wastewater systems depends on linking performance metrics to investment planning, operational control, and cost-effectiveness evaluation.

Within the proposed framework, screening metrics trigger diagnostic investigation, diagnostic findings identify dominant drivers, and audit-ready metrics support prioritised intervention planning. This structured pathway ensures that regulatory compliance under Article 11 is not limited to reporting obligations but contributes to measurable energy performance improvement.

By integrating audit principles, regulatory datasets, and decision support logic, the framework establishes a coherent bridge between neutrality-oriented governance and practical utility management.

4. Discussion

The revised UWWTD marks a governance shift by formally integrating wastewater collection networks into energy audit obligations. However, operationalising these obligations requires translating high-level neutrality targets into measurable and hydraulically coherent performance structures.

Energy neutrality obligations inherently require explicit consideration of wastewater collection networks. Aggregated system-level metrics, although useful for benchmarking, are insufficient for neutrality-oriented assessment. Audit-based accountability demands the ability to distinguish between structurally unavoidable energy use (driven by topography, elevation requirements, and network configuration) and potentially avoidable energy associated with undue inflows, rainfall-derived variability, or operational inefficiencies.

This paper demonstrates that existing national water regulator data can enable first-generation energy benchmarking. Metrics such as pumping stations' energy efficiency, self-energy production, and indirect GHG emissions provide screening tools and support national benchmarking. On the other hand, the empirical dispersion observed for the undue inflow seasonality proxy illustrates the fragility of aggregated metrics when interpreted without hydraulic validation. Extreme ratios and wide interquartile ranges confirm that proxy-based metrics derived from annual reporting can amplify inconsistencies rather than clarify energy drivers. This reinforces the need for structured decomposition and minimum measurement requirements as proposed in the present framework.

Audit-level compliance benefits from the attribution of energy demand to structural, excess-driven, and operational drivers. Without such differentiation, neutrality-oriented benchmarking risks remaining descriptive rather than helpful.

Despite the robustness of the proposed framework, several limitations should be acknowledged. First, the analysis relies predominantly on indirect electricity-related emissions, as direct GHG emissions associated with wastewater collection networks (e.g., methane emissions from sewers) are not systematically monitored within current regulatory datasets. Although the conceptual framework recognises the importance of separating direct and indirect emission components, the operationalisation of direct GHG emissions quantification remains a priority for future research. Second, the feasibility of diagnostic and audit-ready metrics depends on progressive enhancement of subsystem-level monitoring, which can require investment and institutional adaptation across utilities. Third, although the original PAS integrates economic and financial sustainability dimensions, the present regulatory-aligned structure focuses primarily on energy and emissions dimensions. A systematic integration of cost-efficiency metrics and cost-benefit evaluation within neutrality-oriented audits is relevant for future development. Finally, while the framework is conceptually transferable, its practical applicability across Member States will depend on national data maturity, reporting harmonisation, and implementation strategies under Article 11.

Also, unlike WWTPs, where renewable production through biogas recovery or large-scale photovoltaic systems can directly meet treatment energy demand, wastewater collection networks are characterised by spatially distributed and relatively small-scale pumping energy requirements. This structural dispersion limits the feasibility of on-site renewable generation. Consequently, the separation of structural versus avoidable energy components becomes even more critical in these systems, ensuring that renewable offset strategies do not mask hydraulically avoidable inefficiencies.

Thus, the framework also incorporates renewable self-production metrics, enabling linkage between consumption reduction and neutrality strategies.

The comparison with treatment-focused audit methodologies is instructive. In WWTPs, energy disaggregation (e.g., aeration, sludge processing), load normalisation, and identification of transient inefficiencies are well established. These principles are conceptually transferable to wastewater collection networks. However, their practical implementation in networks is constrained by limited subsystem-level monitoring, particularly regarding pumping station energy use, pumped volumes, and hydraulic head data.

The regulatory-aligned framework proposed in this study addresses this gap by re-organising existing PAS dimensions into an audit-compatible structure and by identifying minimum additional measurement requirements. Importantly, the framework is scalable: it enables immediate use of aggregated regulatory data for screening while defining a progressive pathway toward enhanced monitoring compatible with audit verification.

From a governance perspective, this approach contributes to translating high-level neutrality obligations into operational performance assessment tools. Rather than requiring complete restructuring of national regulatory systems, it is grounded in existing datasets and performance frameworks, progressively enhancing measurement granularity and analytical depth.

Although applied to the ERSAR context, the methodological gap identified herein is not country-specific. Many Member States rely on aggregated annual regulatory reporting structures like the ERSAR. Therefore, the proposed regulatory-aligned audit structure provides a transferable tool for operationalising UWWTD Article 11 across European contexts.

5. Conclusions

This study presents a novel regulatory-aligned audit structure specifically designed for wastewater collection networks under Article 11 of the revised UWWTD. Rather than proposing an entirely new assessment framework, the work formalises the methodological steps required to translate neutrality-oriented governance into operational and measurable dimensions for wastewater collection networks. This regulatory translation constitutes the core contribution of the study, providing a technically grounded and actionable starting point for Member States seeking to integrate wastewater collection networks into broader energy transition strategies within the urban water sector.

This study demonstrates that wastewater collection networks can, and should, be systematically incorporated into the energy neutrality objectives of the revised UWWTD. By restructuring existing regulatory information into a coherent, audit-compatible structure, the work shows that current datasets already allow meaningful screening of specific energy intensity, pumping-related energy shares, excess volume drivers, and associated GHG emissions. At the same time, the analysis highlights critical data and methodological gaps, particularly in subsystem disaggregation, hydraulic normalisation, and measurement granularity, which must be addressed to enable robust benchmarking and compliance assessments.

The proposed framework provides a practical pathway and scalable pathway for utilities and regulators to structure, evaluate, and enhance energy-relevant information. It also provides a replicable basis for future development across Member States. Ultimately, improving the energy performance of wastewater collection networks will be essential to achieving system-level energy neutrality, improving operational efficiency, and supporting a fair and effective implementation of the UWWTD across Europe.

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Abbreviations

ERSAR	Portuguese water and waste service's national regulator (acronym in Portuguese)
EU	European Union
GHG	Greenhouse gas
O&M	Operation and Maintenance
PAS	Performance Assessment System
SCADA	Supervisory Control and Data Acquisition
SEC	Specific Energy Consumption
tep	Tonne of oil equivalent
UWWTD	EU Urban Wastewater Treatment Directive
W-E-G	Water–Energy–Greenhouse gas emissions
WW	Wastewater
WWTP	Wastewater treatment plant

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