METHODOLOGY FOR EVALUATION OF ENERGY EFFICIENCY IN WATER SUPPLY SYSTEMS

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ABSTRACT

Operating water supply systems demands significant energy, with distribution networks, treatment facilities, and particularly pumps being major consumers of electricity. As environmental concerns grow and sustainable energy practices become essential, improving the energy efficiency of water delivery systems is a critical priority.

For the evaluation of the energy efficiency in water supply systems a dedicated methodology has been developed applicable to both existing and new water supply systems.

This approach breaks down energy consumption across various system elements by comparing actual usage to the theoretical minimum. Two main elements are distinguished: operational and technical energy demand, each of which is further subdivided.

By applying custom-designed key performance indicators (KPIs), the methodology highlights the specific improvement potential of each component, enabling the prioritization of measures that deliver the greatest cost-benefit impact. Additionally, the KPIs enables fair and meaningful comparisons between systems worldwide, considering their specific physical characteristics, such as supply distance and elevation.

A matrix is employed to visualize the results, offering a comprehensive summary that delineates efficient and inefficient segments of energy use.

1.0 Introduction

Water supply systems are among the largest energy consumers within municipal infrastructure. From water extraction and treatment to transport and distribution, each step in the process requires substantial energy input. As global energy costs rise and sustainability becomes a key priority, improving the energy efficiency of these systems is essential not only for environmental protection but also for economic viability and long-term resilience.

An energy-efficient water supply system contributes to:

- Reduced operational costs for municipalities and utility providers
- Lower greenhouse gas emissions, supporting climate goals
- Improved system reliability and performance
- Long-term sustainability of water infrastructure

To address these needs, first priority avoidance of energy consumption and second priority regain of energy should guide the design and operation of modern water supply systems:

By focusing on these two priorities, municipalities and utilities can transform traditional water supply systems into more sustainable, cost-effective, and future-ready infrastructure.

The key lies in thoroughly analysing and understanding the systems to identify where genuine opportunities for optimization exist. The methodology presented in this paper provides a practical and effective toolset for this purpose, enabling a structured approach to analyse, identify, and implement optimization opportunities within complex systems.

2.0 Methodology

Purpose of this methodology for evaluation of energy efficiency in water supply systems is to offer a structured and quantifiable framework for performance evaluation and optimization across different system configurations.

This approach involves a detailed breakdown of energy consumption across the different components of the system, such as water intake, treatment, transport, and distribution, by comparing the actual energy used with the theoretical minimum required for each process. By quantifying the gap between real and ideal energy usage, inefficiencies within individual system elements can be identified, providing a basis for targeted optimization and energy-saving measures.

The foundation of the methodology lies in the application of standardized **Energy Balance Tables** and clearly defined **Key Performance Indicators**.

2.1 Energy Balance Table

To effectively evaluate and communicate the energy efficiency of a water supply system, it is strongly recommended to summarize the findings in the form of an **Energy Balance Table**.

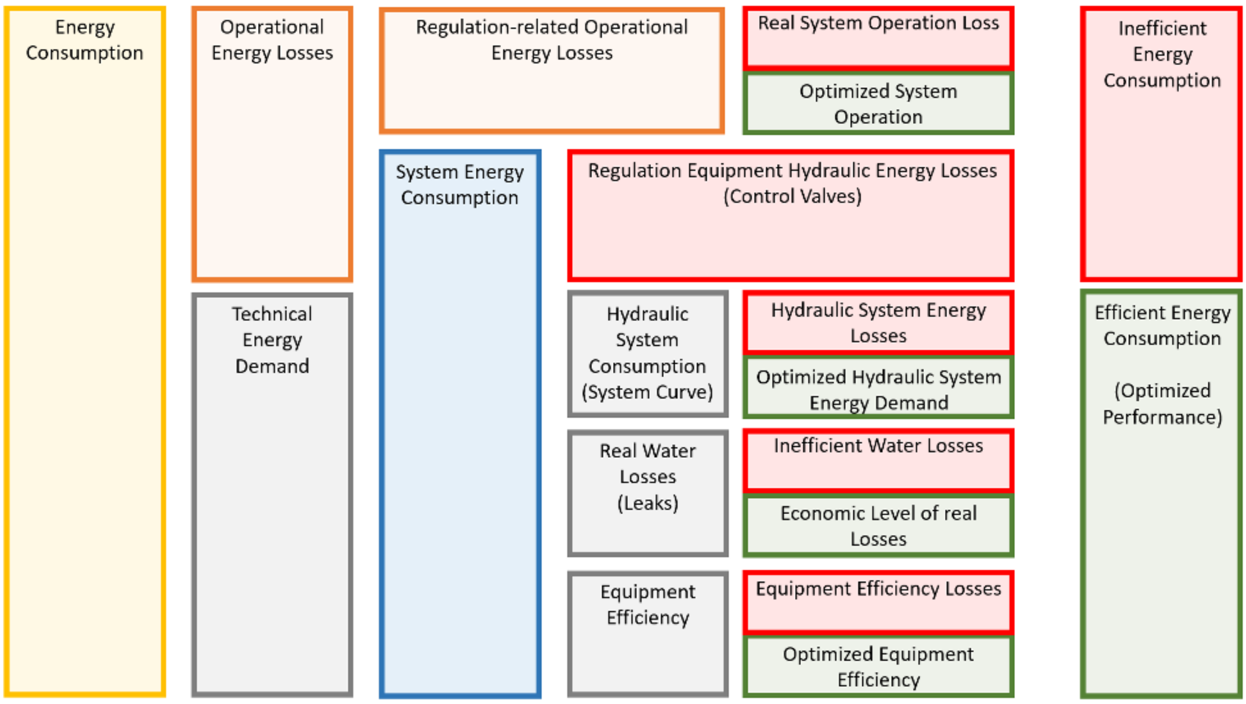
The purpose of the Energy Balance Table is to provide a clear and structured overview of all energy consumers within the water supply system. By presenting energy consumption in a consolidated format, inefficiencies can be clearly identified, enabling the systematic prioritization of improvement measures.

Key benefits of using an Energy Balance Table include:

- Quantification of individual energy consumption across all components of the water supply system (water source, treatment, transportation, distribution).
- Comparison with the theoretical optimum system performance, allowing the identification of deviations and inefficiencies.
- Determination of energy-saving potential for each component or subsystem, highlighting where the greatest opportunities for improvement exist.

In summary, the Energy Balance Table serves as a fundamental tool for transparent energy performance analysis and strategic planning toward a more energy-efficient and sustainable water supply system.

The water balance table can be structured as follows:



While a single water balance table can represent the entire water supply system, greater insight is achieved by developing separate balance tables for the individual component, water **source**, water **treatment**, water **transport** and water **distribution**. This approach improves transparency and facilitates meaningful comparisons, particularly for systems of different water sources and associated treatment processes.

The individual components of the energy balance table are outlined below.

The total **Energy Consumption** of the water supply system component, measured within the specified system boundaries. The energy consumption can broadly be categorized into two main components the operational energy losses and the technical energy demand.

Operational energy losses refer to the portion of energy consumed during regular operation and control of the water supply system that exceeds what is technically necessary. They are defined as the difference between the actual energy demand and the theoretical technical energy demand.

Water supply systems are typically designed to accommodate maximum design flow conditions. However, actual operational scenarios often deviate from these design assumptions. These deviations can have negative effects on overall energy efficiency.

In complex systems, a high degree of operational flexibility exists due to varying hydraulic parameters, like flow rates, hydraulic head or equipment configuration and operating status. By adjusting system operations, such as tank volume management or pump scheduling, toward scenarios with higher energy efficiency, significant energy savings can be achieved.

Furthermore, this category also includes energy losses resulting from flow and pressure control mechanisms, such as pressure-reducing valves or throttling devices. These losses are an inherent aspect of system regulation and are accounted for within the energy balance as part of operational losses. However, they are specified separately under the category of "**Regulation Equipment Hydraulic Energy Losses"**.

By subtracting the "Regulation Equipment Hydraulic Energy Losses" from the total "Operational Energy Losses," the remaining portion represents the general "**Regulation-Related Operational Energy Losses"**.

This average regulation-related operational energy losses can be further differentiated into two components:

- Energy consumption under "**Optimized System Operation**" – representing the theoretical most efficient achievable operating condition within system constraints.
- Additional energy loss under "**Real System Operation Loss**" – accounting for inefficiencies due to deviations from the optimal case, such as suboptimal pump schedules, tank level management, or pressure zoning.

Technical Energy Demand is the energy required by motorized equipment to deliver water under the system's hydraulic conditions, overcoming physical and mechanical constraints. This category reflects the technical energy needed, excluding losses from inefficient control or operation.

The Technical Energy Demand can be further broken down into three key components:

1) Hydraulic System Consumption (System Curve): This includes the energy needed to overcome friction losses in pipelines, valves, and fittings, as well as to provide the necessary static head (elevation gain) across the distribution system. It reflects the baseline hydraulic resistance of the system.
2) Real Water Losses (Leaks): Energy used to pump water that is ultimately lost through leaks in the network. Although the water never reaches the consumer, energy is still consumed to extract, treat, and transport it. This component can be significant, especially in aging or poorly maintained infrastructure.

3) Equipment Efficiency Losses: Energy used to pump water lost through leaks, despite never reaching consumers, still covers extraction, treatment, and transport. These losses can be significant in aging or poorly maintained systems.

System Energy Consumption is a key component of the energy balance and represents the sum of two elements:

- Technical Energy Consumption
- Regulation Equipment Hydraulic Losses

This combined value reflects the total energy required to overcome system-related hydraulic head losses and the energy demand of system-regulating equipment.

Due to its comprehensive nature, System Energy Consumption serves as one of the most informative Key Performance Indicators EC_{WTS} and EC_{SWRO}.

This Key Performance Indicators enables meaningful benchmarking of system efficiency by linking energy use directly to hydraulic performance and water output.

Hydraulic System Energy Consumption refers to the energy required to overcome hydraulic head losses that occur within transport pipelines and intermediate hydraulic components (such as fittings, valves, and bends) throughout the water supply system.

This energy demand is directly related to the system's hydraulic resistance and is influenced by factors flow velocity, pipe roughness, and the configuration of the network.

Hydraulic System Energy Consumption can be divided into two components:

- Optimized Hydraulic System Energy Demand: This represents the energy required under ideal conditions—assuming a system design and operation that follows an optimized system curve with minimal hydraulic resistance.
- Hydraulic System Energy Losses: These are additional energy demands resulting from inefficiencies in the system, such as suboptimal pipe design, excessive friction losses, poorly dimensioned components, or aging infrastructure.

Real Water Losses refer to physical water losses in the distribution system caused by leaks, bursts, and overflows. These losses represent a direct form of energy waste, as energy has already been consumed for the extraction, treatment, and transportation of water that ultimately does not reach the end user.

Real Water Losses can be further classified into two categories:

- Economic Level of Real Water Losses (ELWL): This represents the optimum level of leakage from an economic perspective, balancing the cost of leak reduction measures with the value of water and energy saved. It is generally accepted that eliminating all leaks might economically not be justified.
- Inefficient Water Losses: Any water loss beyond the economic level is considered inefficient. These losses represent avoidable energy consumption, and their reduction offers clear potential for energy and cost savings.

Equipment Efficiency refers to the performance of all hydraulic and associated electrical equipment within the water supply system, such as pumps, motors, and variable frequency drives (VFDs). These components inherently generate energy losses due to their operational efficiency being less than 100%.

In the context of the energy balance, the Equipment Efficiency component can be divided into two parts:

- Optimized Equipment Efficiency: This reflects the energy demand based on the use of theoretically best-performing equipment operating at optimal conditions—typically the manufacturer's rated efficiency at best efficiency point (BEP).

- Equipment Efficiency Losses: These are the avoidable energy losses resulting from the use of outdated, poorly maintained, oversized, or inefficient equipment. They represent the gap between actual performance and the achievable optimized efficiency.

Efficient Energy Consumption refers to the amount of energy required to operate the water supply system under theoretical best-case conditions—assuming optimal hydraulic performance, minimal losses, and the use of high-efficiency equipment operated under ideal control strategies. It represents the benchmark for the system's energy-efficient operation.

Referring to above water balance table it is the sum of green marked optimized energy demands Optimized System Operation, Optimized Hydraulic System Energy Demand, Economic Level of real Losses, Optimized Equipment Efficiency

Inefficient Energy Consumption is defined as the additional energy used beyond the level of efficient energy consumption. This excess energy demand arises from suboptimal system design, operation, equipment inefficiencies, and avoidable losses.

Referring to above water balance table it is the sum of red marked energy losses Real System Operation Loss, Regulation Equipment Hydraulic Energy Losses (Control Valves), Hydraulic System Energy Losses, Inefficient Water Losses, Equipment Efficiency Losses

In principle, this portion of energy use could be avoided through the implementation of a theoretically optimized water supply system, incorporating best-practice engineering, high-efficiency technologies, and smart operational strategies.

2.2 Key Performance Indicators:

The core of the methodology lies in a comparative analysis between a theoretically ideal system and the current system—whether it is an existing, operational one or a newly designed concept. However, such a direct comparison alone is not sufficiently meaningful, as significant differences between the systems may exist in terms of boundary conditions, architecture, and scale.

To account for these complexities, **Key Performance Indicators (KPIs)** are introduced as standardized evaluation metrics. These KPIs enable a more nuanced and system-independent assessment by quantifying the performance of different systems relative to ideal benchmarks.

For instance, one KPI may evaluate the transport distance required within the system and normalize this in relation to the total energy input or logistical efficiency. By doing so, the KPIs make it possible to directly compare systems with fundamentally different architectures or scales. This approach highlights relative performance and identifies optimization potential more transparently and quickly.

One of the most informative and relevant KPI for assessing water transmission systems is the relative energy consumption per cubic meter of delivered water in context of system length and geodetic height difference.

$$EC_{WTS} = \frac{EC[kWh]}{V_{Water}[m^3] * L[km] * H[m]}$$

With:

$EC_{WTS} =$ Relative Energy Consumption Water Transmission System

$EC =$ Relative Energy Consumption Water Transmission System

$V_{Water} =$ Volume of delivered water

$L =$ $Length\ of\ Water\ Transmission\ System$

$H =$ $Elevation\ difference\ that\ a\ water\ transport\ system\ must\ overcome$

For water treatment systems involving seawater desalination, the following KPI can be used to evaluate the relative energy consumption per cubic meter of treated water in context of its salinity:

$$EC_{SWRO} = \frac{EC[kWh]}{V_{Water}[m^3] * S[\%]}$$

With:

$EC_{SWRO} =$ Relative Energy Consumption Sea Water Reverse Osmosis

$S =$ $Salinity$

Different water distribution systems can be evaluated and compared using KPIs that relate the relative energy consumption per cubic meter of distributed water to factors such as the total length of the distribution network or the number of consumers served.

$$EC_{DN} = \frac{EC[kWh]}{V_{Water}[m^3]*L[km]} \quad \text{or} \quad EC_{DN} = \frac{EC[kWh]}{V_{Water}[m^3]*NC[-]}$$

With:

$EC_{DN} =$ Relative Energy Consumption Distribution Network

$L =$ $Network\ length$

$NC =$ $Number\ of\ Customer$

3.0 Conclusion

This methodology for assessing energy efficiency in water supply systems is a newly developed tool, and as such, there is currently no extensive database available for comparison. At present, qualitative evaluation of systems must therefore be carried out in collaboration with experienced engineering firms.

However, if applied consistently, the methodology provides a solid foundation for the rapid and straightforward analysis of energy efficiency, enabling independent assessments based on data from reference systems. Consequently, building and maintaining a comprehensive reference database is essential for unlocking the full potential of this approach.

By applying the Energy Balance Table and the defined KPIs, the methodology enables:

- Objective benchmarking of real-world systems against a technical ideal.
- Cross-comparison between systems of varying design, scale, and context.
- Identification of systemic inefficiencies and potential areas for improvement, regardless of the system type.
- Prioritization of energy-saving measures based on a cost-benefit analysis, enabling decision-makers to focus on actions that offer the best return on investment.

In a subsequent step, key intervention points with the highest optimization potential are identified. This allows for a targeted prioritization of measures based on their cost-benefit ratio. The cost-benefit analysis considers capital investment in relation to potential operational cost savings. The result is a clearly structured action plan with prioritized, high-impact measures.

4.0 Acknowledgements

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