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A Wastewater Strength Indicator for Estimating the Energy Performance and Recovery Potential in WWTPs

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Abstract

This study aims to propose a practical indicator that enables quick and reliable evaluation of the relationship between influent characteristics and energy performance and recovery in municipal wastewater treatment plants (WWTPs). A composite Wastewater Strength Indicator (WWSI) was developed, integrating wastewater dilution and pollutant load into a single metric. Theoretical correlations were established through mathematical estimation and verified using case studies of six WWTPs in Bulgaria based on operational data from 2020–2022. WWSI correlates strongly with both specific energy consumption (kWh/kg COD removed) and electrical energy recovery rate. WWTPs with a WWSI below 0.25 perform unsatisfactory, exhibiting specific energy consumption levels above 2.0 kWh/kg removed COD, whereas those with a WWSI above 0.35 demonstrate higher energy efficiency, with specific consumption below 1.0 kWh/kg removed COD. The treatment of low-strength wastewater leads to inherent energy inefficiencies that are difficult to overcome through sludge digestion and cogeneration alone. Despite sludge calorific values ranging from 11.5 to 19.4 MJ/kg, the energy recovery potential in the studied WWTPs remained below 35%, confirming that energy neutrality is challenging for diluted wastewater. A conversion coefficient of 0.039 kWh/MJ was introduced to facilitate rapid estimation of potential electrical recovery from sludge calorific values. The proposed WWSI provides a simple yet effective tool for benchmarking WWTPs and supports future upgrades toward energy-neutral wastewater management.

Keywords: Municipal Wastewater Treatment Plants (WWTPs); Energy Recovery; Wastewater Strength Indicator (WWSI); Low-Strength Wastewater; Sludge Calorific Value; Energy Neutrality; Cogeneration.

1. Introduction

Wastewater treatment plants (WWTPs) have long been recognized as facilities with the potential for energy production. In recent years, the recovery of green energy from WWTPs has gained even greater importance within the context of the circular economy. The need for further investigation into this topic has been underscored by the energy neutrality requirements established in the recent recast of the Urban Wastewater Treatment Directive and in Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources [1, 2]. It is estimated that approximately 70% of the organic matter entering WWTPs is transformed into biomass through conventional biological treatment processes [3]. The energy chemically bound in this biomass can be valorized as biogas. Furthermore, some studies suggest that the energy content of the biomass is roughly twice that required for conventional municipal wastewater treatment at typical organic matter concentrations of 400–500 mg/L of chemical oxygen demand (COD) [4].

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Currently, three main processes are applied for energy recovery from sludge in WWTPs: incineration, anaerobic digestion with methane production, and anaerobic fermentation with hydrogen production. The most common and oldest of these is anaerobic digestion of sludge, despite its sustainability limitations, such as the generation of the greenhouse gas N_2O. More recent technologies aimed at enhancing the utilization of the chemical energy stored in organic matter include thermochemical processes such as pyrolysis, gasification, and hydrothermal treatment [5]. The focus of this paper is on the more widely implemented technologies; thus, the less commonly applied methods mentioned above are not analyzed further.

Although various energy recovery technologies are available, the recovery potential of municipal WWTPs treating wastewater with a low pollutant load ("low-strength wastewater") has not been sufficiently analyzed. The term "low strength" appears in a number of research publications [6–8]. Some studies define specific pollutant concentration ranges, while others use nutrient ratios as references for wastewater strength. For example, Srinivasa Raghavan et al. [9] refer to the NSF Standard 40, which defines residential-strength wastewater as BOD_5 = 100–300 mg/L and TSS = 100–350 mg/L, and high-strength wastewater as that exceeding residential strength. The authors further classify wastewater with COD below 2000 mg/L as low strength and COD above 2000 mg/L as medium to high strength. Rahman et al. [10] categorize "low-strength wastewater" as having total COD of 161 ± 20 mg/L and ammonia nitrogen of 23.1 ± 3.3 mg/L. Park et al. [11] describe "low-strength municipal wastewater" as having COD of 250 mg/L. Sarpong et al. [12] define three COD-based thresholds: low-strength (390 mg/L), medium-strength (720 mg/L), and high-strength (1230 mg/L). Similarly, Zhang et al. [7] propose that a C/N ratio of 3.4 ± 0.5 characterizes low-strength wastewater, which lacks sufficient carbon for simultaneous nitrogen and phosphorus removal. For any wastewater type, Tomei et al. [13] define "low strength" as influent with a biochemical oxygen demand (BOD) below 1000 mg/L, while high-strength wastewater exceeds 4000 mg/L [13].

Multiple factors contribute to the occurrence of low-strength municipal wastewater. The most significant include processes within sewerage systems, such as biodegradation of organic matter, dilution of domestic wastewater by external water sources, stormwater inflow, and sewer exfiltration [14, 15]. To quantify dilution, the term "I/I water" (infiltration/inflow water) is often employed in the literature. For instance, Ohlin Saletti et al. [16] report that a considerable proportion of the total annual wastewater volume entering WWTPs typically consists of infiltration water. The authors conclude that infiltration and inflow are pervasive issues that impose substantial economic costs [16].

Despite these studies, there is still no universally accepted definition of "low-strength wastewater" or established concentration thresholds that would allow reliable classification of municipal influent [9]. Generally, influent exhibiting pollutant concentrations lower than those predicted by engineering design calculations is referred to as "low-strength" or "diluted" wastewater.

Based on this review, it can be concluded that most studies address "low strength" primarily as a hydraulic or concentration issue rather than as a determinant of bioenergy potential. This narrow interpretation limits the integration of wastewater characterization into energy-neutral design frameworks. Hence, a more precise definition is required to enable effective articulation of research findings in the field of water engineering. This paper introduces a composite indicator designed to better characterize wastewater strength and bridge existing research gaps.

Wastewater dilution has been identified as a major factor contributing to higher energy demands in WWTPs [17–19]. Longo et al. [20] reported that Spanish and German WWTPs exhibit notably low dilution factors, making them more energy efficient than comparable facilities in other countries, regardless of the treatment technology employed. Niu et al. [19] suggested that increasing influent COD concentrations to 500 mg/L could reduce the total energy consumption of the wastewater treatment sector by at least 20%. Furthermore, when all other factors were held constant, the electrical energy consumption of fully loaded WWTPs was approximately 12% lower than that of underloaded or overloaded plants [19]. Cardoso et al. [15] found that plant size, load factor (capacity utilization), and dilution factor are among the most significant determinants of WWTP energy performance. Similarly, the results of Sarpong et al. [12] confirm that influent COD concentration and plant capacity have a substantial impact on energy recovery potential.

Although prior research has generally established that low-strength wastewater is associated with higher energy demand and lower energy recovery potential, the literature still lacks a quantitative analysis for clear definition of these correlations. The present study addresses this gap by linking wastewater strength to energy recovery potential using quantitative indicators.

A variety of key performance indicators (KPIs) and methodologies have been employed for assessing and benchmarking energy performance in WWTPs [15, 17, 19, 20]. de Matos et al. [21] identified twenty-one research papers discussing KPIs for evaluating the energy efficiency and eco-efficiency of WWTPs. Despite the abundance of indicators and methods, there is still no widely accepted procedure for evaluating energy performance in municipal wastewater treatment [22, 23]. However, there is a general consensus that no single KPI can universally characterize energy performance [20, 24].

The most commonly used indicators include energy consumption per cubic meter of treated water (kWh/m^3). Longo et al. [20] concluded that this indicator appears in approximately 90% of the reviewed studies, but yields misleading benchmarking results because it ignores the impact of wastewater dilution. The inadequacy of this indicator has been highlighted in several other studies [18, 24, 25]. To address these limitations, some researchers use it only to quantify the energy required for wastewater pumping [24, 26]. Conversely, because the removal of organic matter and nutrients constitutes a major energy-consuming process, reporting energy consumption per unit of pollutant removed has been recognized as more meaningful [18, 20]. For example, some authors normalize energy use per person equivalent (PE) served (kWh PE^{-1} yr^{-1}) or per kilogram of COD removed (kWh kg COD yr^{-1}) [18, 27].

Sabia et al. [23] proposed a composite indicator, the Global Energetic Index (GEI), defined as a weighted sum of three commonly used metrics: energy per cubic meter, energy per PE, and energy per COD removed. Although applied successfully to ten WWTPs, the method's reliance on weighting coefficients represents a limitation. Another composite index, the Water Treatment Energy Index (WTEI), was developed under the ENERWATER project [26, 28, 29] to assess energy efficiency and assign energy labels. While this methodology is comprehensive, it requires extensive data and complex calculations involving numerous assumptions and weighting factors. Moreover, it does not establish a link between wastewater strength and energy recovery potential. Longo et al. [29] provided a comprehensive comparison of the most widely used methodologies and indicators for assessing and benchmarking energy performance. Among the drawbacks identified were the inability of certain indicators to account for exogenous factors beyond WWTP control, the high data requirements, and the computational complexity of some algorithms. They concluded that an indicator is effective only when it aligns with available data, the expertise of evaluators, and the goals of stakeholders interpreting the results.

This paper advances the state of the art by addressing the three research gaps outlined above. A new composite indicator for the evaluation of municipal WWTPs, termed the Wastewater Strength Indicator (WWSI), is introduced. This indicator integrates the two principal adverse effects of sewerage systems - wastewater dilution and pollutant load loss into a single measure. Unlike the traditional "energy per cubic meter" metric, the proposed WWSI accounts for pollutant load, thereby overcoming the limitations of previous approaches. Furthermore, the WWSI is straightforward to calculate, does not require extensive monitoring, and is easily accepted by stakeholders without compromising analytical rigor. The applicability of the proposed WWSI for evaluating energy performance and recovery potential is demonstrated through a case study of six municipal WWTPs.

The paper is organized into four sections, as illustrated in Figure 1.

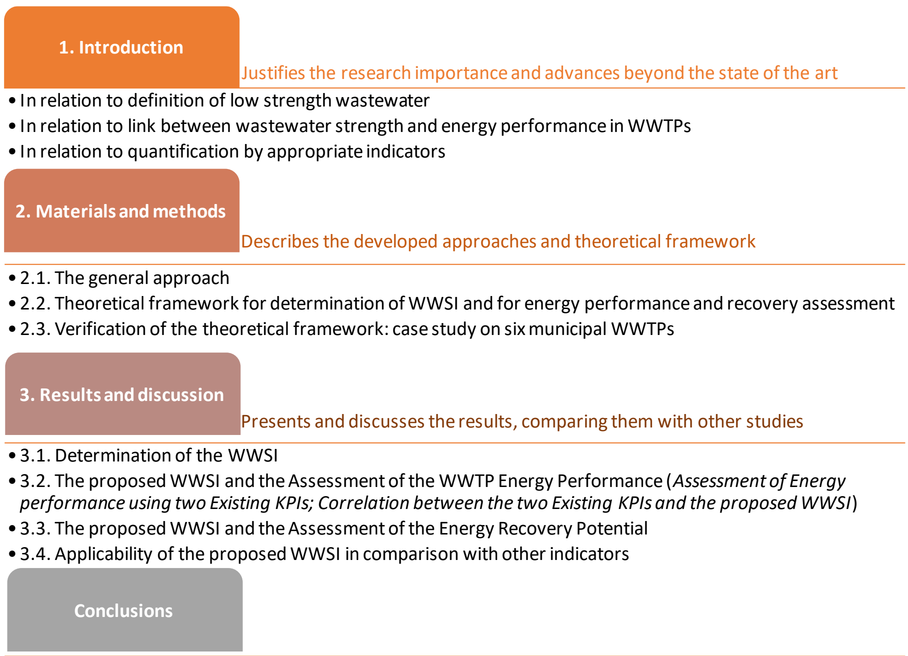

Figure 1. Structure of the study

Following this introduction, the next section (Materials and Methods) presents the developed approach and the methodologies applied for estimating the WWSI, as well as the energy generation and recovery rates. The third section discusses the verification of the proposed methodology, carried out through an investigation of six municipal WWTPs in Bulgaria treating low-strength wastewater. These facilities employ conventional treatment schemes comprising of mechanical pre-treatment, followed by activated sludge processes with biological nitrogen and chemical/biological phosphorus removal. Sludge stabilization is achieved through enclosed anaerobic digestion with methane recovery (methane tanks), open anaerobic digestion, or aerobic stabilization. The final section presents the conclusions and summarizes the main research findings.

2. Material and Methods

To achieve the research objectives, the general methodological framework illustrated in Figure 2 was adopted. Part 1 of the approach establishes the theoretical framework. Specifically, it presents the developed methodology for defining the Wastewater Strength Indicator (WWSI), the procedure for rapid estimation of energy recovery through cogeneration, and the final calculation of the overall energy recovery potential. Part 2 of the approach describes the verification of the theoretical framework using a case study of six WWTPs. The proposed WWSI is calculated, and its relevance for estimating energy performance and recovery potential is analyzed.

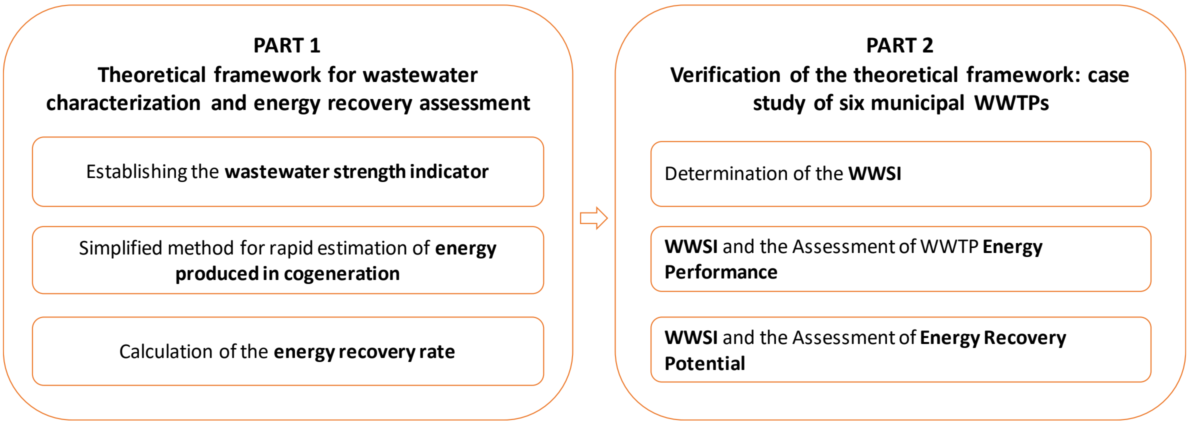

Figure 2. The general approach

2.1. Theoretical Framework for Determining the WWSI and Assessing Energy Performance and Recovery

2.1.1. Establishment of the Wastewater Strength Indicator (WWSI)

The strength of wastewater can be attributed to several factors, two of which are of particular significance:

- ***Dilution of wastewater with extraneous water and rainwater inputs***

The sources of extraneous water typically include infiltration and inflow, collectively referred to as "I/I water" [16]. In combined sewer systems, the inflow of rainwater further increases the total volume entering the WWTP. The fraction of actual wastewater (WW fraction) in the mixed influent at the WWTP inlet can be expressed as:

$$WW\ fraction = \frac{Volume\ of\ the\ wastewater\ (domestic,industrial,etc.)}{Total\ volume\ at\ WWTP\ inlet} \tag{1}$$

According to national design standards [30], the volume of wastewater is estimated as 90% of the invoiced water supplied. A higher *WW fraction* indicates more concentrated (stronger) wastewater, whereas a lower value corresponds to more diluted wastewater.

- ***Loss of pollution load in the sewerage system (load factor)***

The second major factor that significantly reduces the pollutant load and, consequently, the wastewater strength is the degradation of organic matter occurring within the sewerage system. The magnitude of this loss can be estimated by calculating the ratio between the measured and theoretical loads at the WWTP inlet. It is important to note that the term load factor (LF) is used by other authors to denote the ratio between the served population equivalent (PE) and the design population equivalent [15, 20]. The same meaning is adopted in the present study:

$$Load\ factor\ (LF) = \frac{Measured\ BOD\ load\ at\ WWTP\ inlet}{Theoretical\ BOD\ load\ at\ WWTP\ inlet} \tag{2}$$

A higher LF value indicates more concentrated (stronger) wastewater and, correspondingly, a lower loss of pollutant load. The measured pollutant load is calculated by multiplying the measured concentration by the measured flow rate. The theoretical pollutant load is calculated by multiplying the specific load per person by the number of customers. The value of the specific load per person (60 g BOD_5 /cap·d) is adopted from the German standard ATV-DVWK-A 131, which is also applied in the Bulgarian normative documents [31].

The industrial contribution to the total load is estimated on the assumption that the industrial flow rate represents 1% of the total accounted water, which is typical for most Bulgarian settlements. It is further assumed that, prior to discharge into the sewer system, the pollutant concentrations of industrial wastewater are reduced to levels equivalent to those of domestic wastewater, as required by national standards [32]. These assumptions are necessary due to limitations in the databases of water operators, which do not always distinguish industrial consumers clearly. Finally, the proposed WWSI is determined by:

$$WWSI = WW\ fraction \times Load\ factor \tag{3}$$

The proposed indicator accounts for the combined effect of the two principal factors influencing wastewater strength—dilution and pollutant load loss. The higher the value of this indicator, the stronger the wastewater (Figure 3).

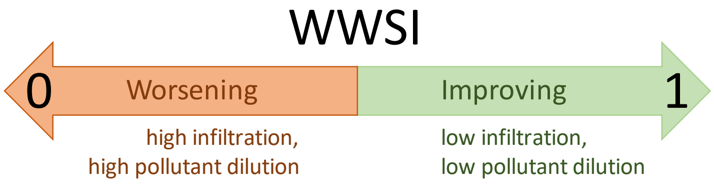

Figure 3. Interpretation of the values of the proposed WWSI

When the WWSI approaches 0, it indicates a deterioration of the conditions, as one or both parameters fall below 1 (due to either high infiltration or high load dilution).

When the WWSI approaches 1, it indicates improvement in the conditions, as one or both parameters approach 1 (due to either reduced infiltration or lower load dilution).

2.1.2. Simplified Method for Rapid Estimation of Energy Recovered in Cogeneration

A number of studies have estimated the potential for energy recovery from cogeneration process, which is recognized as one of the most widely spread approaches for energy recovery in WWTPs [33-39]. The recovery method selection is dependent on the specific conditions of the study. Considering the currently available data set, a simplified method has been developed for the current study as follows:

- ***Estimation of VSS that will be degraded in the digestion tank***

Two of the studied WWTPs have anaerobic digestion tanks with methane recovery. The degradation rates of volatile suspended solids (VSS) in the tanks are 48% in WWTP3 and 51% in WWTP1. Based on these results and general knowledge, a degradation rate of 50% of the VSS in the digestion tank is assumed for the calculations for the other WWTPs.

$$VSS_{degraded} = 0.5 \times VSS \quad [t] \tag{4}$$

where, VSS is the mass of the organic matter in the inlet of the digester tank in metric tonnes.

- ***Converting degraded VSS to COD***

$$COD_{degraded} = 1.42 \times VSS_{degraded} \quad [t] \tag{5}$$

where 1.42 is the conversion coefficient from biomass to COD [40].

- ***Calculation of methane (CH4) produced per unit of $COD_{degraded}$:***

$$CH_{4,produced}[m^3] = 0.35 \times COD_{degraded}\ [kg] \tag{6}$$

where 0.35 is the coefficient for the production of CH4 per unit of COD degraded [41].

- Calculation of the energy bound in the methane (E_{bound}):

$$E_{bound}\ [kWh] = 9.94 \times CH_4\ [m^3] \tag{7}$$

where 9.94 kWh/m3=35,800 kJ/m^3 is the specific energy of methane [42].

- ***Calculation of the energy produced by cogeneration ($E_{produced}$):***

$$E_{produced} = 0.7 \times E_{bound} \tag{8}$$

$$E_{produced,electrical} = E_{produced,heat} = 0.5 \times E_{produced} \tag{9}$$

where 0.7 is a coefficient reflecting the efficiency of the cogeneration process, which consists of 0.35 for heat energy and 0.35 for electrical energy production [42].

Finally, by applying all of the equations presented above, the electrical energy that can be produced through cogeneration is calculated using the following expression, which demonstrates the direct dependence on the volatile suspended solids (VSS)"

$$E_{produced,electrical} = 0.5 \times E_{produced} = 0.5 \times 0.7 \times\ 9.94 \times 0.35 \times 1.42 \times 0.5 \times VSS = 0.8645\ \times VSS \tag{10}$$

Equation 10 illustrates the relationship between the proposed parameter, the WWSI, and the potential for energy production. The VSS generated in WWTPs result from processes occurring in both the primary clarifier and the secondary treatment stage. The VSS produced in the primary clarifier depend on the total suspended solids (TSS) entering the WWTP, which, in turn, are influenced by the degree of wastewater dilution that is, by the first component of the WWSI, the WW fraction (Equation 1). The VSS generated in the secondary clarifier depends on the quantity of excess sludge produced in the biological treatment process, which is influenced by the influent BOD concentration - the second component of the WWSI, the Load Factor (Equation 2).

Therefore, it is expected that the proposed WWSI can serve as an indicator for estimating the potential for energy generation through cogeneration. This hypothesis is verified using six municipal WWTPs as a case study.

2.1.3. Calculation of Electrical Energy Recovery Rate

The energy recovery rate depends on two main factors: the total energy consumed by the WWTP and the energy that can be produced, as expressed in Equation 11:

$$E_{recovered\ rate} = \frac{E_{produced,electrical}}{E_{used}} \times 100, \qquad [\%] \tag{11}$$

Equation 11 shows that the recovered energy is strongly influenced by the WWSI, since both the numerator and the denominator are dependent on it. The relationship between the WWSI and energy recovery efficiency is examined and verified using data from the six WWTPs included in this study.

2.2. Verification of the Theoretical Framework: Case Study on Six Municipal WWTPs

2.2.1. Main Characteristics of the WWTPs

Six municipal WWTPs in Bulgaria are included in the study. The identification of these WWTPs is by number, as some water operators (WOs) are reluctant to disclose certain data and information. The WWTPs are briefly presented in Table 1

Table 1. General information for the studied WWTPs (as of 2022)

WWTP	Connected people	Generated sludge	Primary clarifiers	Nitrogen removal	Phosphorus removal	Sludge stabilization	Dewatering	Current sludge utilization
	Number	t DM/year						
WWTP1	1 126 694	16 005	yes	DN	$FeCl_3$+Bio	MT	Belt press	Agriculture
WWTP2	131 769	526	yes	DN	FeCl3	OD	Centrifuge	Recultivation
WWTP3	112 415	1264	yes	DN	$FeCl_3$+Bio	MT	Belt press	Agriculture
WWTP4	48 578	154	yes	DN	$FeCl_3$+Bio	AS	Screw press	Kept on site
WWTP5	36 633	193	yes	DN	$FeCl_3$	AS	Centrifuge	Kept on site
WWTP6	5 413	95	no	DN	$FeCl_3$	AS	Centrifuge	No data

Abbreviations used in the table: DM - dry mass; DN - Denitrification/Nitrification; Bio - biological phosphorus removal; MT - methane tank; OD - open digester; AS - aerobic stabilization

All of the WWTPs included in the case study utilize biological nitrogen removal by denitrification/nitrification process and chemical phosphorus removal (except WWTP1, which combines biological and chemical phosphorus removal). This ensures a good starting point for their comparison regarding their energy performance.

2.2.2. Data Collected from the Operation of the WWTPs

The analysis presented in this study is based on two distinct types of data: 1) data provided by the WOs, and 2) chemical analysis of sludge samples for specific parameters conducted at our research centre. The first set of data is presented in Table 2. The second set of data is subsequently discussed in the following section.

Table 2. Level of aggregation of data provided by the WOs

WWTP number	Invoiced water volumes	Flow rates at WWTP inlet	Water quality at WWTP inlet	Generated sludge	Consumed energy
WWTP 1	Yearly	Daily	2 values per week	Yearly	Yearly
WWTP 2	Yearly	Yearly	Yearly	Yearly	Yearly
WWTP 3	Yearly	Daily	Weekly	Monthly	Yearly
WWTP 4	Yearly	Monthly	Weekly	Monthly	Yearly
WWTP 5	Yearly	Daily	Working Days	Yearly	Yearly
WWTP 6	Yearly	Daily	Weekly	Monthly	Yearly

2.2.3. Chemical Analysis for Additional Sludge Characterization

- ***Sludge calorific value***

The WO database has been expanded with additional measurements required for this study. Sludge samples were taken three times at four locations in each WWTP - before and after the digestion unit, after the dewatering facility and from the sludge drying beds (where available).

The sludge samples were analysed for calorific value. The gross calorific value of the non-stabilized and stabilized sludge was determined according to BS EN 15170 standardized method. IKA C-6000 calorimetric system was used for the analysis [43]. The nitrogen and sulphur content were ignored. Each sample was weighed on an analytical scale before it was loaded in the bomb vessel of the instrument. IKA Thread was used for better ignition of the sample. Its calorific value was excluded from the determined gross calorific value automatically by the apparatus. Oxygen was used as a gas carrier for the combustion process.

- ***Volatile suspended solids (VSS) and Dry mass (DM) of the sludge***

The VSS and the DM of each sample were determined according to BDS EN 15934-2012 and BDS EN 15935-2021 standardized methods [44, 45].

3. Results and Discussion

3.1. Determination of the WWSI

The WWSI was determined according to the procedure described in the *Materials and Methods* section and presented in Table 3.

Table 3. Calculation of the WWSI

WWTP	WW fraction			BOD pollution loss (Load factor)			WWSI			Average
	2020	2021	2022	2020	2021	2022	2020	2021	2022	
1	2	3	4	5	6	7	8=2*5	9=3*6	10=4*7	
WWTP 1	0.58	0.55	0.55	0.67	0.71	0.69	0.39	0.39	0.38	**0.39**
WWTP 2	0.46	0.51	0.44	0.81	0.65	0.82	0.37	0.33	0.36	**0.35**
WWTP 3	0.90	0.75	0.71	0.7	0.62	0.67	0.63	0.46	0.47	**0.52**
WWTP 4	0.56	0.57	0.67	0.53	0.51	0.43	0.3	0.29	0.29	**0.29**
WWTP 5	0.22	0.20	0.19	0.65	0.52	0.61	0.15	0.11	0.11	**0.12**
WWTP 6	0.45	0.45	0.45	0.91	0.67	0.65	0.41	0.3	0.29	**0.33**

The data presented in Table 3 show that the WWSI is below 0.50 for all WWTPs included in the study, with the exception of WWTP 3. However, the value for this plant is 0.52 - very close to the defined threshold indicating that all investigated WWTPs operate with low-strength municipal wastewater. This outcome can primarily be attributed to two factors: 1) dilution with extraneous water and 2) loss of pollution load.

- ***Dilution with extraneous water***

Data from the investigated WWTPs indicate that all plants receive influent volumes exceeding the total billed wastewater from domestic, commercial, and industrial users (Figure 4). For half of the studied WWTPs, the volumes of infiltration and inflow (I/I) water are equal to or even greater than the volumes of actual wastewater, indicating substantial dilution within the sewer systems.

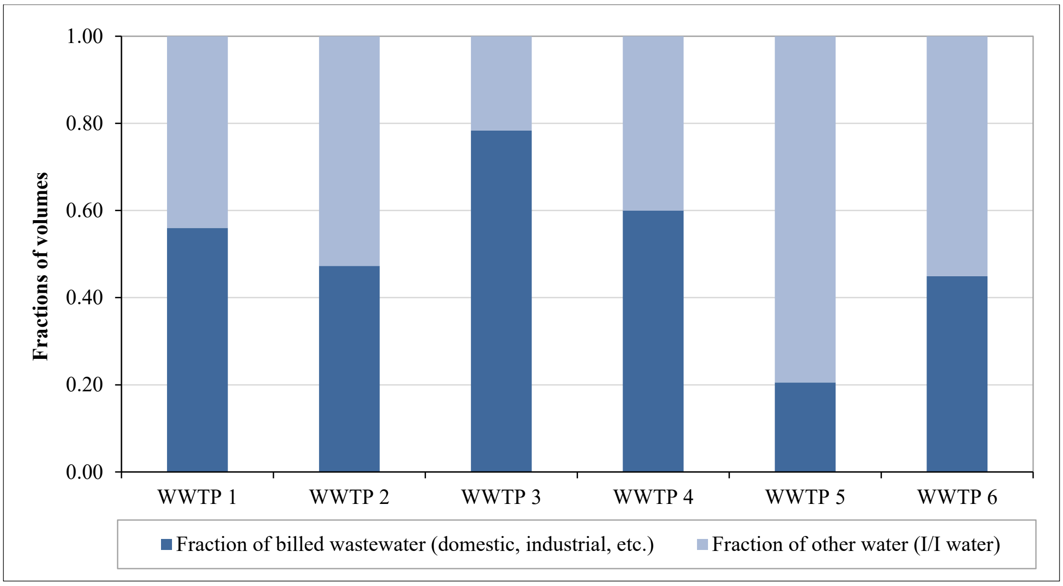

Figure 4. Fractions of billed wastewater and other water at WWTP inlet (average for the three-year period 2020 – 2022)

- ***Loss of pollution load (Load factor)***

The ratios between the measured and theoretical BOD pollution loads were calculated for all WWTPs included in the study. The results show that the ratio of measured to theoretical load is 0.49 to 0.76 (average 0.66), which may indicate a significant loss of pollutant load due to biodegradation processes (Figure 5).

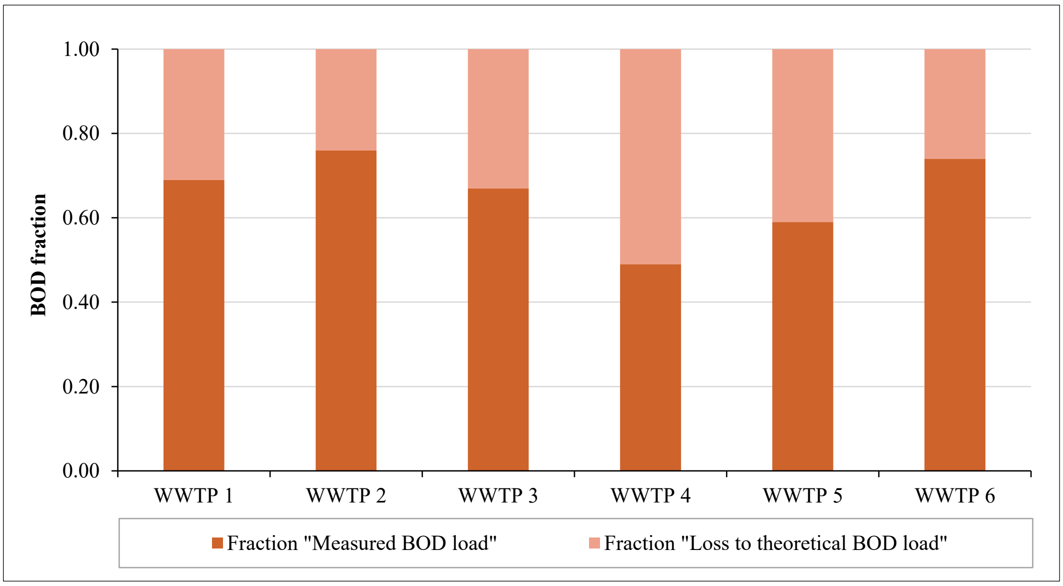

Figure 5. Fractions of measured and calculated BOD loads at WWTP inlet (average for the three-year period 2020 – 2022)

3.2. The proposed WWSI and the Assessment of WWTP Energy Performance

3.2.1. Assessment of Energy Performance Using Two Existing KPIs

Two of the most widely used indicators for evaluating the energy performance of WWTPs are employed as reference points in the present study: **KPI 1:** energy consumption per cubic metre of treated wastewater, and **KPI 2:** energy consumption per kilogram of COD removed (Table 4).

Table 4. Energy performance of the studied WWTPs using two existing KPIs (data for 2022)

WWTP	WWTP1	WWTP2	WWTP3	WWTP4	WWTP5	WWTP6
$E_{consumed}$, kWh/per a	19 272 403	3 564 971	2 732 179	957 323	1 918 519	292 344
$E_{consumed}$, kWh/m^3	0.17	0.26	0.38	0.31	0.20	0.47
$E_{consumed}$, kWh/kg COD reduced	0.57	0.80	0.80	1.20	2.49	1.37

The specific energy consumption per cubic metre of treated wastewater ranged from 0.17 to 0.47 kWh/m³, while the specific energy consumption per kilogram of COD removed ranged from 0.57 to 2.49 kWh/kg COD (Table 4). The six WWTPs included in the study employ different technologies for sludge stabilization: two use anaerobic digestion, three utilize aerobic stabilization tanks, and one operates with an open digester. These technological variations likely explain part of the observed differences in specific energy consumption. Another significant factor is plant size. As shown in Table 4, WWTP1, more than eight times larger than the others, demonstrates better energy performance. Nevertheless, the calculated range of energy consumption values is consistent with findings reported in other studies (Table 5).

Table 5. Comparison of the obtained results with literature data

Values/range	Notes	Reference
KPI 1	**kWh/m³**	
0.17 to 0.47	Low strength wastewater; combined sewer; size from 5 000 to 1 200 000 people.	This study
0.35	Median value of Italian WWTPs with combined sewer.	Vaccari et al. [18]
0.26 to 0.30	Based on data from six thousand WWTPs in China.	Xu et al. [46]
0.119 to 0.849	Estimates also that the specific energy consumption is dependent on the COD concentration. COD = 200 mg/L the value is 0.212 kWh/m³. COD = 400 mg/L, the value is 0.612 kWh/m³.	Yang et al. [47]
0.25 to 0.71	Poland, a five-year monitoring period.	Masłoń et al. [48]
0.0845 to 3.18	This range pertains to the broader category of conventional activated sludge treatment.	Cardoso et al. [15]
0.64±0.08	German WWTP before energy improvement solutions; increased efficiency by 24% after implementing solutions.	Macintosh et al. [27]
0.26 to 0.985	Based on review on published studies around the world.	Sarpong et al. [12]
KPI 2	**kWh/kg COD reduced**	
0.57 to 2.49	Low strength wastewater; combined sewer; size from 5 000 to 1 200 000 people.	This study
0.85 to 3.2	3.2 kWh/kgCOD for plants <2,000 PE; 1.76 for plants with 2,000–10,000 PE; 1.45 for plants with 10,000–100,000 PE; 0.85 for plants >100,000 PE.	Vaccari et al. [18]
0.54 to 4.61	Ten Italian WWTPs with size range from 9500 to 800 000 PE.	Sabia et al. [23]

In addition to confirming that the values obtained in this study fall within the ranges reported by other authors, this comparison highlights the advantage of the proposed composite WWSI, which simultaneously accounts for both the quantity and quality of the treated wastewater. In doing so, it eliminates the need for additional clarification of input parameters, as required, for example, in the study by Yang et al. [47] or Vaccari et al. [18].

3.2.2. Correlation Between the Two Existing KPIs and the Proposed WWSI

The proposed Wastewater Strength Indicator (WWSI) was correlated with the two selected KPIs (KPI 1 and KPI 2) to evaluate their respective advantages and limitations (Figures 6 and 7).

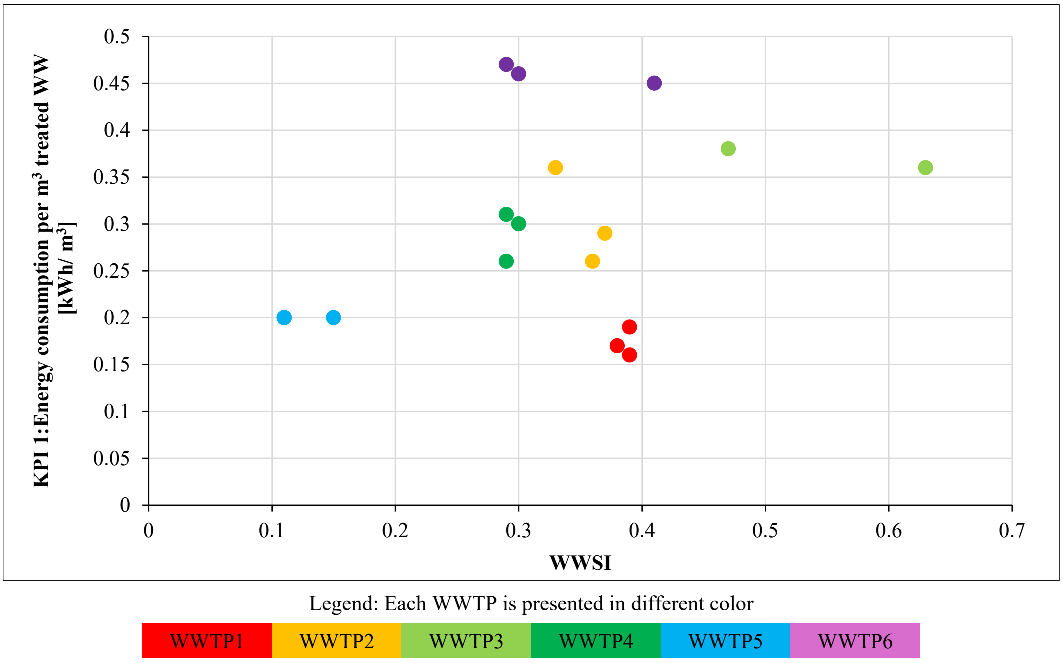

Figure 6. Correlation between KPI 1 and the proposed WWSI (data for years 2020, 2021 and 2022)

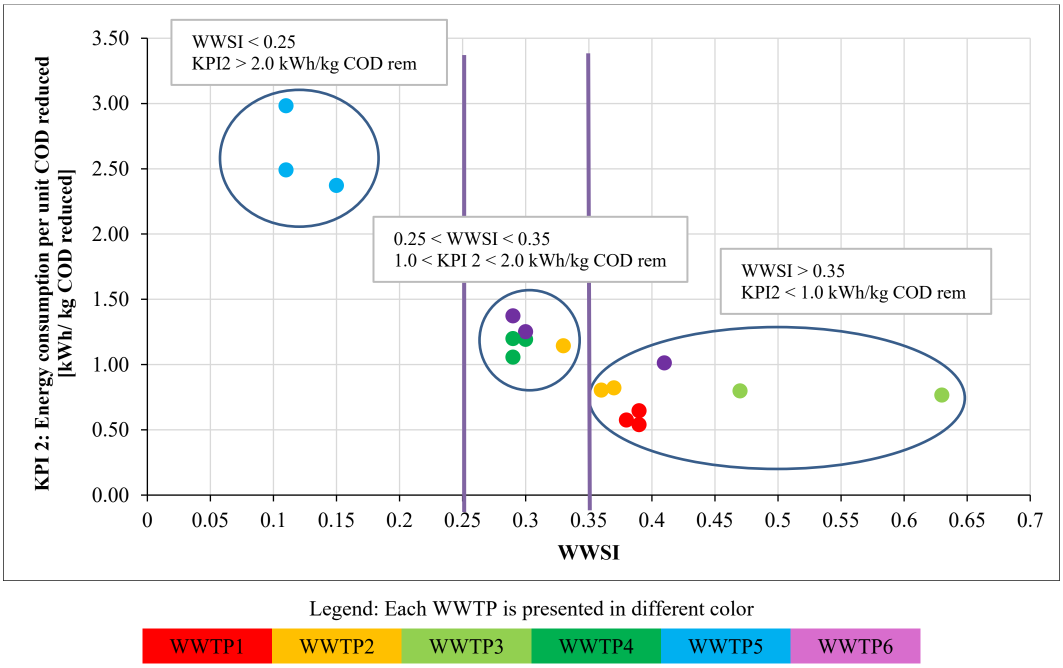

Figure 7. Correlation between KPI 2 and the proposed WWSI (data for years 2020, 2021 and 2022)

Figure 6 shows that no significant correlation (R^2=0.08) exists between KPI 1 and the proposed WWSI. This is, in fact, a positive finding, as it highlights one of the key advantages of the WWSI and the key disadvantage of the KPI 1. As explained by Vaccari et al. [18], in combined sewer networks, the presence of stormwater introduces an apparent energy discount due to the higher denominator in the kWh/m³ calculation. Consequently, the use of KPI 1 for systems treating diluted wastewater may result in misleading comparisons between plants. Furthermore, diluted wastewater is typically characterized by low COD concentrations, which, in turn, increase the specific energy requirements. These two effects are not adequately addressed by KPI 1 when considered as a standalone indicator.

It should be noted that the study by Sabia et al. proposed a composite indicator, the Global Energetic Index (GEI), which represents a weighted sum of the three most commonly used indicators: energy per cubic metre, energy per person equivalent (PE), and energy per kilogram of COD removed [23]. Regardless of the weighting assigned to KPI 1, our findings confirm previous research indicating that this indicator is not suitable for reliable assessment and should be applied with caution even as part of a composite metric, such as in the work of Sabia et al.

A much stronger correlation is observed when comparing KPI 2 with the proposed WWSI (Figure 7). A plausible explanation for this result is that KPI 2 is inherently a more meaningful indicator, as it directly relates energy consumption to the primary objective of WWTP operation - COD (consequently BOD) removal.

Figure 7 also demonstrates that lower WWSI values correspond to higher specific energy requirements. Numerous studies have reported that low-strength wastewater requires a higher energy input per unit of degraded organic matter, a finding corroborated by the present research [17–19]. The most straightforward explanation is that dilution by infiltration and inflow (I/I) water increases the total volume to be treated, thereby raising the energy demand.

The results illustrated in Figure 7 confirm this trend, showing a consistent pattern of increasing energy consumption in municipal WWTPs treating lower-strength wastewater. For the analyzed set of six WWTPs, the results reveal that WWTPs with a WWSI below 0.25 perform unsatisfactory, exhibiting specific energy consumption levels above 2.0 kWh/kg removed COD, whereas those with a WWSI above 0.35 demonstrate higher energy efficiency, with specific consumption below 1.0 kWh/kg removed COD. WWTPs within the intermediate WSSI range (0.25 to 0.35) exhibit moderate energy efficiency, with values between 1.0 and 1.5 kWh/kg COD removed. This provides additional evidence that the proposed WWSI is a robust and reliable indicator for assessing energy performance and recovery potential.

3.3. The Proposed WWSI and the Assessment of Energy Recovery Potential

The potential for energy recovery was estimated following the calculation procedure described in the *Methodology* section. The first step involves determining the amount of volatile suspended solids (VSS) subject to degradation, as the quantity of recoverable energy is directly proportional to the amount of VSS degraded.

Among the six WWTPs analyzed, two facilities are equipped with existing digester tanks. For these plants, the procedure for determining the degraded VSS quantity was adapted to reflect the availability of operational data. The calculation steps are summarized in Table 6, where the fourth row lists the equations applied in the analysis.

Table 6. Calculation of the degraded quantity of VSS for WWTPs with existing digesters

WWTP	Digester inlet					Digester outlet				Degraded VSS	Degradation rate
	Sludge volume	DM in sludge	VSS in TS	VSS in sludge	Mass of VSS	DM in sludge	VSS in TS	VSS in sludge	Mass of VSS		
	m³	%	%	%	t	%	%	%	t	t	%
1	2	3	4	5=3*4	6=2*5	7	8	9=7*8	10=2*9	11=6-10	12=11/6
WWTP1	744 630	4.3	69	2.98	22 189	2.7	55	1.46	10 835	11 355	51
WWTP3	46 427	3.6	68	2.46	1 142	2.2	58	1.28	593	549	48

Note: In columns 6 and 10 the conversion from volume to mass is performed using the volumetric rate of 1 t/m³.

For the remaining WWTPs without existing digester tanks, the mass of VSS prior to stabilization was used as the input parameter in the calculations (see the *Methodology* section). The calculated values of electrical energy production are summarized in Table 7.

Table 7. Estimation of the electrical energy recovery potential (data for 2022)

WWTP	WWTP1	WWTP2	WWTP3	WWTP4	WWTP5	WWTP6
TS before digestion, t	32 157	582	1 679	154	197	106
VSS before digestion, t	22 189	419	1 142	108	113	60
$E_{consumed}$, kWh/per a	19 272 403	3 564 971	2 732 179	957 323	1 918 519	292 344
$E_{produced}$,kWh/per a(1) (calculated)	19 633 479(2)	362 495	949 862(3)	89 202	97 319	52 258
$E_{produced}$,kWh/per kg TS (calculated)	0.61	0.62	0.56	0.58	0.49	0.49
% recovery of energy	>100%	10%	35%	9%	5%	18%

Notes: (1) Calculated electrical energy according to the methodology described in "Materials and methodology section"; (2) The measured produced electrical energy is 22 506 457 kWh/y; good consistency with the calculated values; (3) The measured produced electrical energy is 940 576 kWh/y; very good consistency with the calculated values.

Table 7 illustrates the potential for energy recovery in each of the studied WWTPs, assuming that current energy utilization patterns are maintained and that a digester tank is constructed. The two WWTPs already equipped with digesters (WWTP 1 and WWTP 3) demonstrate the highest potential for recovering consumed energy in the form of electrical output. In contrast, the ratio between energy consumed and energy potentially produced is markedly lower for the remaining four WWTPs. The high energy consumption observed in WWTP 2 and WWTP 6 (and consequently their lower recovery rates) may be attributed to the need for pumping wastewater into the WWTP inlets. For WWTP 4 and WWTP 5, the elevated energy consumption can be explained by the use of aerobic stabilization processes.

An initial verification of the proposed methodology for estimating electrical energy production was conducted using the two WWTPs with existing cogeneration units (WWTP 1 and WWTP 3). Table 7 shows that the measured and calculated values of produced electrical energy are closely aligned. Further verification was performed using data reported by Ayoub et al. [49], whose cogeneration system produces 0.34 kWh per kilogram of total solids (TS), compared to a range of 0.49–0.61 kWh/kg TS in the present study.

An analysis was performed to determine the correlation between the proposed WWSI and the potential electrical energy recovery rate (Figure 8). WWTP 1 was excluded from the analysis due to its substantially larger capacity and distinct operational characteristics, particularly its exceptionally high energy recovery rate, which exceeds a value of 1.

Figure 8 illustrates that the WWSI is positively correlated (R^2=0.79) with the potential electrical energy recovery rate, defined as the ratio of potentially generated energy to the total energy consumed. An increase in the WWSI corresponds to a higher energy recovery potential.

Findings from previous studies indicate that for high-strength wastewater, with COD concentrations of 400–500 mg/L, the energy stored in sludge is approximately twice the energy required for conventional municipal wastewater treatment [4]. However, the results of the present study show that the energy produced in municipal WWTPs, treating low-strength wastewater, is insufficient to meet their comparatively high energy demand. This can be attributed to the combined effect of higher energy consumption required for treatment and the lower amount of biomass generated.

Based on mathematical simulations, Sarpong & Gude [50] concluded that the energy recovery potential in wastewater treatment increases with the organic strength of the wastewater. This finding is consistent with the results presented in Figure 8. In addition, their simulations showed that energy recovery potential also increases with treatment capacity. Large plants (>10 MGD, corresponding to approximately 250,000 inhabitants) have the advantage of producing more energy due to the greater availability of organic solids and lower specific energy consumption compared to smaller plants. In the present study, only WWTP 1 serves more than 250,000 inhabitants, and it exhibits a significantly higher energy recovery rate than the other facilities (Table 7). Similarly, the benchmarking study by Vaccari et al. [18], which included 200 WWTPs in Italy, confirmed that larger plants demonstrate higher energy efficiency.

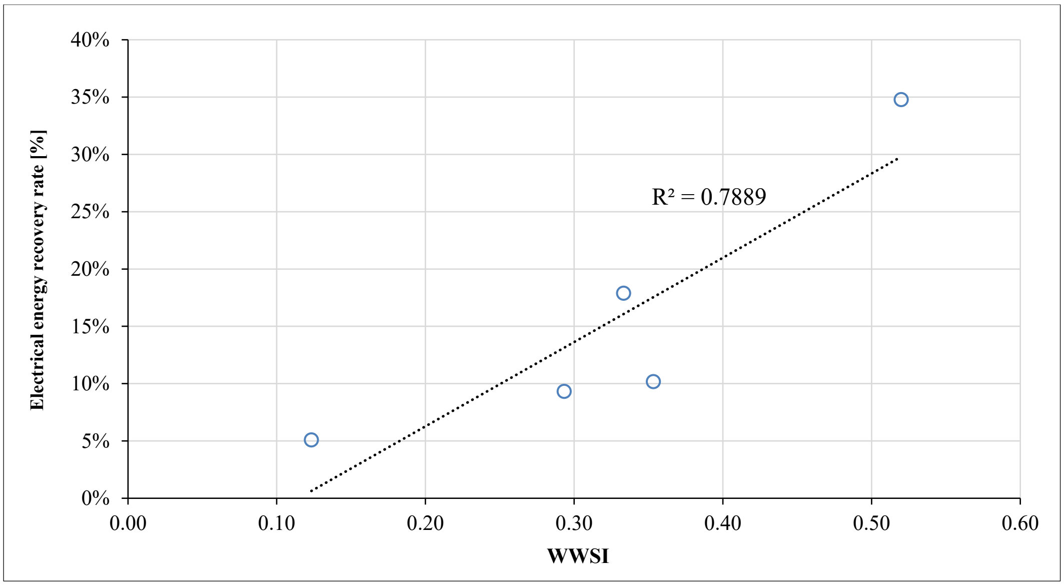

Figure 8. Electrical energy recovery rate (data for 2022) in dependence of the WWSI

The methodology for calculating energy yield developed in this study is based on several assumptions derived from the cited references (see the corresponding subsection in the Materials and Methods section). Given the direct proportionality between calorific value and produced energy, the calorific value of the sludge was experimentally determined under laboratory conditions to validate the proposed calculation method. The findings of this analysis enabled the derivation of a coefficient that can be used to rapidly estimate the potential generated energy when the calorific value of the input sludge is known (Table 8).

Table 8. Determination of the unit converting coefficient (from calories to energy)

WWTP	Produced electrical energy	TS before digestion	Measured calorific value	Sludge calorific value	Converting coefficient
	kWh	t	J/g	MJ	$kWh_{produced, electrical}/MJ_{sludge}$
1	2	3	4	5=3*4	6=2/5
WWTP1	19 633 479	32 157	16033	515 599 469	0.038
WWTP2	362 496	582	19461	11 333 252	0.032
WWTP3	949 862	1 679	13561	22 774 503	0.042
WWTP4	89 202	154	13876	2 262 604	0.041
WWTP5	97 319	197	12877	2 543 058	0.038
WWTP6	52 258	106	11575	1 227 453	0.043
Average					**0.039**

The gross calorific values of sludge from the studied WWTPs range from 11.5 to 19.4 MJ/kg (see Table 8, column 4). This range is consistent with values reported by other authors, which vary between 8 and 26 MJ/kg [33, 51–53]. Notably, a recommendation issued by the World Bank more than thirty years ago suggested that biomass with a calorific value exceeding 6 MJ/kg should be considered a potential energy source [54].

Therefore, despite the fact that the WWTPs examined in this study treat low-strength municipal wastewater, the resulting sludge still possesses sufficient calorific value to enable its valorization into biogas. In light of these considerations, the following equation is proposed for further calculations:

$$Electrical\ energy_{\ produced}\ [kWh] = Unit\ Coeff_{Cal\ to\ E} \times Sludge\ calorific\ value\ [MJ] \tag{12}$$

where, $Unit\ Coeff_{Cal\ to\ E} = 0.039$ $kWh_{produced,\ electrical}/MJ_{sludge}$

The following equation is therefore proposed to determine the potential electrical energy generation from anaerobic digestion, based on the measured calorific value of the sludge:

$$Electrical\ energy_{\ produced}\ [kWh] = 0.039 \times Sludge\ calorific\ value\ [MJ] \tag{13}$$

3.4. Applicability of the Proposed WWSI

The proposed WWSI advances the state of the art. One of its main advantages is that it reflects both the quantity and quality of wastewater entering the WWTP by integrating the effects of infiltration/inflow (I/I) water and pollutant load loss. Since WWTP energy consumption depends directly on these two aspects, the WWSI provides a more precise correlation between influent characteristics and the plant's energy use. This suggests that the composite indicator is more suitable for energy-related assessments than single-parameter indicators.

Another notable advantage of the proposed indicator is its ability to elucidate the relationship between sewer system condition and WWTP energy efficiency. The WWSI highlights the importance of optimizing the sewerage network as a critical step toward achieving energy neutrality in WWTP operations. A further benefit of the WWSI lies in its simplicity and practicality. The parameters required for its calculation are easily obtainable, commonly used, and understandable by all stakeholders. Moreover, the indicator does not rely on weighting factors, which are often subjective. Considering the inherent uncertainties in WWTP data collection, the WWSI also exhibits sufficient stability to mitigate the effects of data variability.

The results presented in this study show that the WWSI correlates strongly with the specific energy consumption in WWTPs, expressed as kWh/kg COD removed. Furthermore, the proposed WWSI demonstrates a strong correlation with the electrical energy recovery rate. A limitation of the proposed WWSI is that it does not explicitly account for all variables influencing energy performance and recovery. For instance, it does not consider plant capacity, equipment energy efficiency, or the technological treatment scheme employed.

Despite this limitation, the proposed WWSI can serve as a valuable tool for benchmarking the energy performance of existing WWTPs. Based on the obtained values, targeted measures can be identified to enhance plant energy efficiency. The indicator is also applicable at the design stage, particularly when energy recovery upgrades are being planned, as it allows for preliminary estimation of potential energy recovery rates.

To promote its broader adoption and strengthen the reliability of derived correlations, further verification using additional WWTP datasets is recommended.

4. Conclusions

Two recent directives set stringent requirements for achieving energy neutrality in wastewater treatment plants (WWTPs): the recast Urban Wastewater Treatment Directive (2024) and Directive (EU) 2018/2001 on the promotion of energy from renewable sources. The practical implementation of these requirements necessitates assessing both the potential for enhancing the energy efficiency of existing WWTPs and the feasibility of energy recovery. Given the substantial number of facilities treating low-strength wastewater, it is essential to establish a robust methodology for evaluating their potential and defining the limits of feasible energy efficiency improvements. The research presented in this paper addresses the previously identified gaps and advances the state of the art in four key aspects:

- ***Development of a composite WWSI indicator***, which is straightforward to apply yet represents a significant improvement in determining wastewater strength by integrating both quantitative and qualitative wastewater characteristics into a single metric;
- ***Proposal of an approach*** for estimating the energy recovery potential from cogeneration processes in municipal WWTPs;
- ***Establishment of a correlation*** between the WWSI and the energy performance and recovery potential; and
- ***Introduction of a unit conversion coefficient*** for sludge calorific value (0.039 kWh/MJ), enabling rapid estimation of potential electrical energy recovery.

For the analyzed set of six WWTPs, the results reveal that WWTPs with a WWSI below 0.25 perform unsatisfactory, exhibiting specific energy consumption levels above 2.0 kWh/kg removed COD, whereas those with a WWSI above 0.35 demonstrate higher energy efficiency, with specific consumption below 1.0 kWh/kg removed COD. WWTPs within the intermediate WSSI range (0.25 to 0.35) exhibit moderate energy efficiency, with values between 1.0 and 1.5 kWh/kg COD removed. This provides additional evidence that the proposed WWSI is a robust and reliable indicator for assessing energy performance and recovery potential.

The findings further indicate that achieving legislative energy neutrality requirements may be challenging for WWTPs treating low-strength wastewater. This difficulty persists despite the relatively high calorific value of the sludge (ranging from 11.5 to 19.4 MJ/kg), which exceeds the World Bank's recommended threshold of 6 MJ/kg for biomass valorization. For the WWTPs studied, the energy recovery rates were below **10%** in three cases, below **20%** in one, and below **35%** in another. The treatment of low-strength wastewater leads to inherent energy inefficiencies that are difficult to overcome through sludge digestion and cogeneration alone. Notably, only the largest WWTP serving a population equivalent of over one million achieved an energy production rate slightly exceeding its consumption.

These results underscore the critical importance of implementing measures aimed at optimizing energy consumption throughout the treatment process, thereby moving closer to compliance with the principles of energy neutrality.

5. Declarations

5.1. Author Contributions

Conceptualization, B.B. and I.R.; methodology, I.R. and B.B.; validation, D.V.; formal analysis, D.V. and S.L.; investigation, B.B. and V.R.; resources, B.B., I.R., I.K., V.R., D.V., and S.L.; data curation, B.B.; writing—original draft preparation, B.B. and I.R; writing—review and editing, D.V., V.R., I.K., and S.L.; visualization, B.B., D.V., and I.R.; supervision, I.R.; project administration, I.R. and I.K.; funding acquisition, I.R. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available within the article.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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