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# POTENTIAL OF WASTEWATER TREATMENT SLUDGE FOR BIOGAS PRODUCTION IN THE REPUBLIC OF SERBIA

*Keynote paper*

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**Abstract:** The development of wastewater treatment infrastructure in Serbia will result in an increased amount of sewage sludge that can be used to produce energy through anaerobic digestion processes. The present work evaluates the biogas and energy-substitution potential of sludge from 11 wastewater treatment plants (WWTPs) which are planned to be upgraded in the frame of the national documents. The amount of sludge was estimated according to the design capacities of the WWTPs, while the amount of digester feed was calculated using a dry-solids mass balance, including the reduction of volatile-solids during digestion. The specific biogas yield was found to have the highest impact on the results, followed by the volatile-solids reduction. Anaerobic digestion and combined heat and power production can be considered as a viable option for sludge management in large-scale WWTPs in Serbia. The results presented in this work should be considered as the gross potential, which may not be achieved due to the specific characteristics of sludge, as well as the requirements for energy and heat in individual WWTPs.
**Key words:** sewage sludge; anaerobic digestion; biogas potential; lignite substitution.

## INTRODUCTION

Wastewater treatment plays a crucial role in protecting the receiving surface waters and public health, yet it inevitably produces sewage sludge that requires further processing. Sewage sludge consists of organic matter, nutrients, microorganisms, and sometimes undesirable inorganic and organic constituents, which depend on the characteristics of wastewater. Anaerobic digestion is one of the most suitable routes for sludge stabilization and energy recovery at wastewater treatment plants (WWTPs). During the process, biodegradable organic matter is converted into methane-rich biogas, which can be used for combined heat and power generation. In parallel, anaerobic digestion reduces the volatile solids content and stabilizes the remaining digestate, thereby reducing the amount and environmental burden of sludge in need of subsequent treatment, transport or disposal(Appels, 2008; Cao, 2012).

The main difference between primary and waste activated sludge is that the former typically has a larger readily biodegradable fraction, while the latter is more resistant to hydrolysis due to the microbial-cell structure. As a result, methane production primarily depends on primary and waste activated sludge mass and their content of total solids (TS) and volatile solids (VS), biodegradability, retention time, temperature, organic loading rate, and the presence of inhibitory components(Carrère, 2010).

Recent studies therefore focus on improving the anaerobic digestion of sludge organic matter by means of thermal, mechanical, chemical, and biological pretreatments as well as co-digestion with complementary biodegradable feedstocks (Carrère, 2010). These approaches can enhance organic matter accessibility and thus methane yields, but their technical and economic viability needs to be evaluated in relation to the local sludge quantity, plant size and existing configuration, energy demand and logistics.

This study analyses the quantity of wastewater-treatment sludge generated at WWTPs with capacities exceeding 100,000 population equivalents, which represents the principal nationally identified feedstock for anaerobic digestion and biogas production in Serbia.

Accordingly, the present study aims to assess the potential of wastewater-treatment sludge for biogas production in the Republic of Serbia and to support the incorporation of sludge-to-

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biogas systems in Serbia's future wastewater, energy and circular-economy planning.Specifically, the work is intended to: (i) compile and spatially analyze available national data on existent/expected sludge generation; (ii) identify those sludge streams and WWTP categories technically relevant for anaerobic digestion; (iii) estimate methane, biogas and energy potential under transparent scenario assumptions; and (iv) distinguish potential resources based on theoretical potential, while taking into account the impact of treatment technology, sludge characteristics and regional logistics. By this information base, the study is expected

## PROJECTED SLUDGE QUANTITIES IN REPUBLIC OF SERBIA

In the Republic of Serbia, the higher wastewater-treatment levels are expected to turn sludge management into a more important environmental and resource-management issue. The national Sludge Management Programme for the Republic of Serbia for the period 2023–2032 explicitly addresses sludge as one of the by-products of municipal wastewater treatment and provides an overview of the development of treatment infrastructure and capacities for sludge management. The annual sludge generation from the existing WWTPs was estimated at approximately 11,000–15,000 t dry solids (DS). At the end of the projected infrastructure-development period, the total generation of stabilized municipal sludge is estimated at 115,390 t DS $yr^{-1}$ under the 50th-percentile loading scenario and 135,190 t DS $yr^{-1}$ under the 85th-percentile scenario. These values correspond to approximately 461,600–540,800 t $yr^{-1}$ of digested and dewatered sludge at an average dry-solids content of 25%(Government of the Republic of Serbia, 2023).
The projected national volumes of sludge show the scale of the emerging situation but should not be read straight away as the quantity available for biogas generation. The Programme specifically anticipates anaerobic digestion for WWTPs with capacities over 100,000 population equivalents (PE), while the choice between aerobic and anaerobic stabilization for medium-sized plants depends on their capacity and economic viability. It also contemplates high-efficiency anaerobic digestion, energy recovery, and regional sludge-management centers for the largest plants.

## ASSESSMENT OF THE WASTEWATER SLUDGE POTENTIAL BIOGAS PRODUCTION

Based on the National Sludge Management Programme for Republic of Serbia, eleven projected wastewater treatment plants with a capacity of over 100,000 PE are planned to use anaerobic digestion(Government of the Republic of Serbia, 2023). The data on the number of plants and the quantity of dry solids are available directly for Vrbas and Subotica. According to the source, these two treatment plants are expected to produce 4,200 – 5,100 t of dry solids per year. However, the total amount of sludge from all eleven projected large treatment plants is not presented. Therefore, the amount of sludge from these treatment plants should be calculated individually by using the selected specific production of sludge (40 – 45 g of dry solids per population equivalent per day).

### Methodology

The analysis considered wastewater treatment plants (WWTPs) with a design capacity above 100,000 population equivalent (PE), for which the Serbian Sludge Management Programme envisages anaerobic digestion. Where plant-specific sludge quantities were unavailable, the annual production of stabilized sludge was estimated from the design capacity:

$$M_{DS,i,s} = \frac{PE_i \cdot q_S \cdot 365}{10^6} \quad (1)$$

Where:$M_{DS,i,s}$ is the annual mass of digested sludge at WWTP *i* under scenario *s;*$PE_i$ is the design capacity of the WWTP $q_S$ is the specific sludge-production factor (g DS $PE^{-1}d^{-1}$); *s*denotes the loading scenario.
For WWTPs above 100000 PE $q_S$was set to 40 g DS $PE^{-1}$ $d^{-1}$for the 50th-percentile loading scenario and 45 DS $PE^{-1}$ $d^{-1}$for the 85th-percentile scenario
Because national reports typically quantify stabilized or digested sludge rather than raw substrate, the dry-solids mass entering anaerobic digestion$M_{feed,DS}$was estimated to account for volatile solids reduction:

$$M_{feed,DS} = \frac{M_{digestate,DS}}{1 - (f_{VS} \cdot r_{VS})} \quad (2)$$

Where:$M_{\mathrm{feed,DS}}$ = estimated feed sludge entering the digester (t DS $yr^{-1}$);$M_{\mathrm{digestate,DS}}$ = stabilised/digested sludge reported or estimated from the Programme (t DS $yr^{-1}$);$f_{\mathrm{VS}}$ = volatile-solids fraction in feed sludge (kg VS $kg^{-1}$ DS);$r_{\mathrm{VS}}$ = volatile-solids reduction efficiency during anaerobic digestion.

The low, reference and high scenarios applied $f_{\mathrm{VS}}$ values of 0.60, 0.70 and 0.80,respectively, and $r_{\mathrm{VS}}$values of 0.35, 0.45 and 0.55, respectively. The selected VS range is consistent with the 60–88% VS content reported for wastewater sludge study (Milovanović, 2024), whereas the range of VS reduction reflects anaerobic-digestion performance reported in the literature (Appels, 2008; Cao, 2012; Carrère, 2010).
To express the results in terms of wet sludge supplied to the digester $M_{feed,wet}$the following conversion was applied:

$$M_{feed,wet} = \frac{M_{feed,DS}}{TS} \quad (3)$$

where TS is the total-solids fraction. A reference value of TS= 0.05 was adopted based on data from the study (Milovanović, 2024) and reported specifications for thickened sludge entering the Subotica anaerobic digestion system.
To evaluate energy recovery, a biogas factor ($Y_{\mathrm{BG}}$) was derived from literature data. Data indicate that biogas yields from full-scale anaerobic digestion of municipal sewage sludge commonly range from approximately 350 to 450 Nm3 $t^{-1}$ DS. Conventional mesophilic anaerobic digestion has been reported to produce approximately 350 $Nm^3$ $t^{-1}$ DS, whereas thermal-hydrolysis- assisted configurations may achieve 387–450 $Nm^3$ $t^{-1}$ DS. A full-scale survey of eight UK wastewater treatment plants reported approximately 400 $Nm^3$ $t^{-1}$ DS as a typical yield, while a further WWTP case study reported an annual average of 410 $Nm^3$ $t^{-1}$ DS (Gandiglio, 2017; Shen, 2015; Shana, 2016). Accordingly, a yield of 400 $Nm^3$ biogas $t^{-1}$ DS was adopted as the referencescenario for municipal wastewater sludge.
The annual biogas potential was calculated from the estimated dry-solids feed to anaerobic digestion:

$$V_{BG} = M_{feed,DS} \cdot Y_{BG} \quad (4)$$

Where $V_{BG}$is the annual biogas potential ($Nm^3$ $yr^{-1}$); $M_{feed,DS}$is the estimated dry-solids mass supplied to the digester (tDS $yr^{-1}$) and $Y_{BG}$is the specific biogas yield ($Nm^3t^{-1}DS$).
Energy recovery was estimated from the lower heating value (LHV) of the produced biogas and the conversion efficiencies of a combined heat and power (CHP) unit:

$$LHV_{BG} = x_{methane} \cdot LHV_{methane} \quad (5)$$

$$E_{el,gross} = \frac{V_{BG} \cdot LHV_{BG} \cdot \eta_{el}}{1000} \quad (6)$$

$$E_{heat,gross} = \frac{V_{BG} \cdot LHV_{BG} \cdot \eta_{heat}}{1000} \quad (7)$$

Where:$x_{\mathrm{methane}}$ is the methane volume fraction in biogas;$LHV_{\mathrm{CH_4}}$ is the lower heating value of methane (9.97 kWh $Nm^{-3}$);$\eta_{\mathrm{el}}$ and $\eta_{\mathrm{th}}$ are the electrical and thermal efficiencies of the CHP unit, respectively$E_{\mathrm{el,gross}}$ and $E_{\mathrm{heat,gross}}$ denote gross annual electricity and heat production (MWh $yr^{-1}$).
Gross electricity and useful-heat production were estimated using CHP conversion factors of (2.094kWh$Nm^{-3}$for biogas and 2.633kWh$Nm^{-3}$for heat, respectively.
These factors correspond to electrical and useful-heat recovery efficiencies of approximately 35% and 44%, respectively, assuming a biogas lower heating value of about 6kWh $Nm^{-3}$.
The selected values are consistent with reported CHP performance, according to which approximately 35% of biogas energy can be converted into electricity and a further 40–50% can be recovered as useful heat where a suitable heat demand exists(IEA, 2020).
The potential displacement of lignite was estimated under the assumption that biogas-derived electricity substitutes electricity generated in lignite-fired power plants. Electricity-related lignite displacement was calculated as:

$$M_{lignite,el} = \frac{3600 \times E_{el}}{\eta_{el} \times LHV_{lignite}} \quad (8)$$

$$M_{lignite,heat} = \frac{3600 \times E_{heat}}{\eta_{boiler} \times LHV_{lignite}} \quad (9)$$

$$M_{lignite,total} = M_{lignite,el} + M_{lignite,heat} \quad (10)$$

Where: where $M_{lignite,el}$, $M_{lignite,heat}$, and $M_{lignite,total}$ are expressed in t $yr^{-1}$; $\eta_{el}$=0.30) is the assumed electrical efficiency of lignite-fired power generation; $\eta_{boiler}$=0.85) is the assumed efficiency of a lignite-fired heat-only boiler; and $LHV_{lignite}$=7.85) GJ $t^{-1}$ is the average lower heating value reported for Serbian lignite (European Association for Coal and Lignite, 2017). The factor 3600 converts energy from GWh to GJ.

**Scenario-based assessment of national biogas potential**

Three distinct scenarios were modeled to evaluate the biogas potential of wastewater treatment plants (WWTPs) with a design capacity exceeding 100,000 PE. These scenarios account for combined uncertainties in specific sludge production, volatile-solid (VS) content and degradation efficiency, and specific biogas yields.
The conservative scenario applies the Serbia-specific factor derived from the Sremska Mitrovica co-digestion model(Milovanović, 2024). The reference scenario uses a biogas yield of 400 $Nm^3t^{-1}$DS, consistent with full-scale municipal sludge digestion data. The high-potential scenario represents improved digestion performance, potentially achieved through optimized operation, a higher biodegradable organic-matter content, or pretreatment. Full-scale studies have reported typical sludge-biogas yields of approximately 350–450 $Nm^3t^{-1}$DS (Gandiglio, 2017; Liu, 2022; Shen, 2015).
The Sludge Management Programme identifies 11 WWTPs above 100,000 PE. Explicit capacity data were available for seven facilities, with a combined capacity of 2,819,250 PE. Since capacities were not reported for the remaining four facilities, each was conservatively assigned 100,000 PE. The resulting total capacity of 3,219,250 PE therefore represents a lower-bound estimate.
Based on the 3 scenario assumptions, the aggregated biogas potential of the 11 planned large WWTPs was estimated at 18,3 – 42,5 (million $Nm^3$ $yr^{-1}$) (with a reference value of 29, (million $Nm^3$ $yr^{-1}$).

***Table 1.*** *Overview of Scenario Parameters*

| Parameter | Conservative scenario | Reference scenario | High-potential scenario |
|---|---|---|---|
| Specific digestate production, $q_S$(g DS PE$^{-1}$d$^{-1}$ | 40.0 | 42.5 | 45.0 |
| VS fraction in feed sludge, $f_{VS}$ | 0.60 | 0.70 | 0.80 |
| VS reduction in anaerobic digestion, $r_{VS}$ | 0.35 | 0.45 | 0.55 |
| Biogas yield, $Y_{BG}$(Nm$^3$t$^{-1}$DS) | 308 | 400 | 450 |

It should be noted that the actual potential will be higher once plant-specific capacities and sludge-characterization data become available.

***Table 2.*** *National-Level Results and Capacity Assumptions*

| Indicator | Conservative scenario | Reference scenario | High-potential scenario |
|---|---|---|---|
| Digestate production (t DS yr$^{-1}$) | 47,001 | 49,939 | 52,876 |
| Estimated digester feed (t DS yr$^{-1}$) | 59,495 | 72,903 | 94,422 |
| Biogas potential (million Nm$^3$ yr$^{-1}$) | 18.32 | 29.16 | 42.49 |
| Gross electricity potential (GWh yr$^{-1}$) | 38.37 | 61.05 | 88.96 |
| Gross heat potential GWh yr$^{-1}$) | 48.23 | 76.75 | 111.84 |
| Lignite displaced by electricity (10³ t yr$^{-1}$) | 58.7 | 93.3 | 136.0 |
| Total lignite displacement with full heat utilization (10³ t yr$^{-1}$) | 84.7 | 134.7 | 196.3 |

## Sensitivity analysis

A one-at-a-time sensitivity analysis was performed around the reference national biogas potential of 29.16 million (million Nm$^3$ yr$^{-1}$). Each parameter was varied across its defined low and high values while all other parameters were retained at their reference values. The specific biogas yield was the dominant source of uncertainty: changing$Y_{BG}$ from 400 to 308 (Nm$^3$t$^{-1}$DS) reduced the estimated potential by 23.0%, whereas increasing it to 450 (Nm$^3$t$^{-1}$DS)increased the potential by 12.5%. Volatile-solids reduction was the second most influential parameter, causing changes of −9.3% to +11.4%.
In comparison, variation in the VS fraction and specific sludge-production factor resulted in narrower ranges of −6.2% to +7.0% and ±5.9%, respectively.

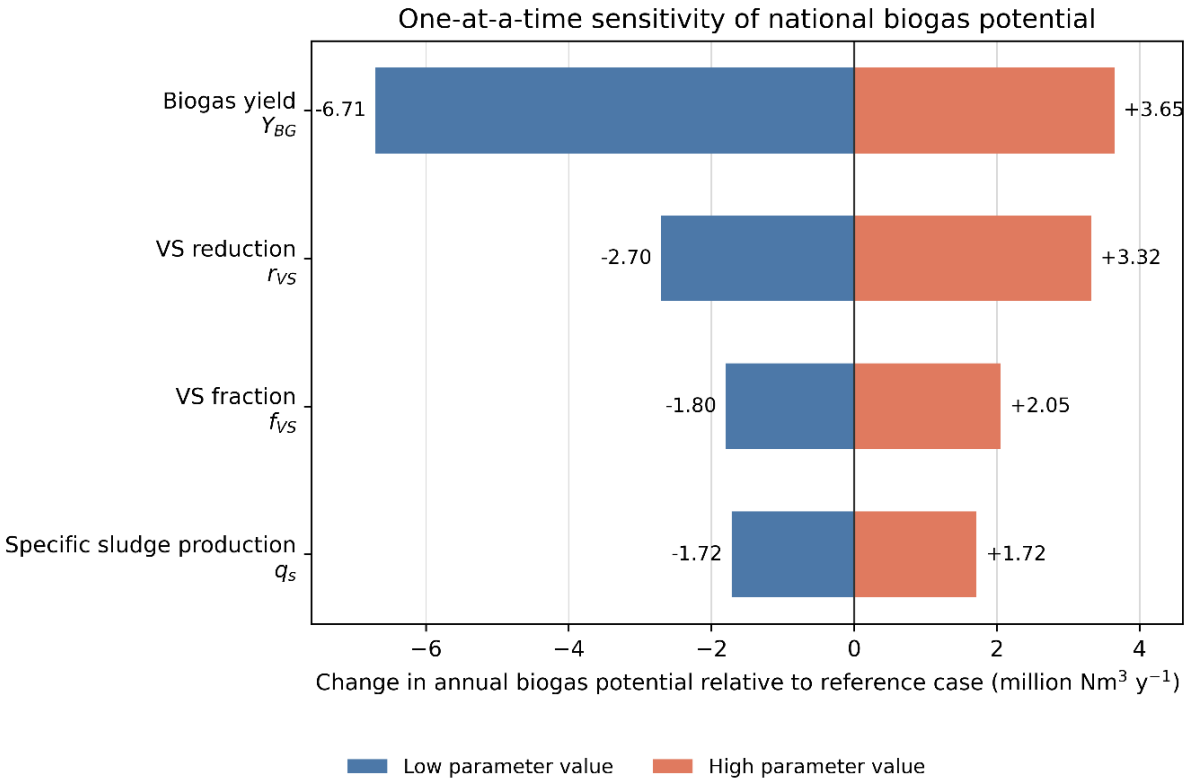



***Fig. 1.*** *One-at-a-time sensitivity of the estimated annual biogas potential from 11 planned WWTPs above 100,000 PE. Bars indicate the absolute change relative to the reference case*

The key source of uncertainty was related to the biogas-yield factor, followed by VS reduction, VS fraction and sludge-production rate. The same parameters proportionally impact on the gross electricity and heat production. In addition, the CHP electricity and heat conversion factors should be considered when estimating energy recovery. The total-solids content was not included as a direct driver of gross biogas production since it affects wet-sludge flow and operational energy demand rather than the dry-solids based biogas yield.

These results demonstrate that reliable plant-specific measurements of sludge biodegradability, volatile-solids removal and biogas yield are more important for refining the national estimate than further refinement of the specific sludge-production factor. The uncertainty associated with the capacity of four WWTPs not explicitly specified in the Programme was treated separately: each additional 100,000 PE increases the reference biogas potential by approximately 0.91 million Nm$^3$ yr$^{-1}$.

In the reference-case scenario, biogas from sludge could provide 61.05 GWh yr $^{-1}$ of electricity and 76.75 GWh yr $^{-1}$ of useful heat. The electricity content is theoretically equivalent to 93.3 kt lignite yr $^{-1}$ of substituted emissions, and a total of 134.7 kt lignite yr $^{-1}$ if all recoverable heat energy is efficiently used.

In the different scenarios considered here, the electricity-related lignite displacement potential varies between 58.7 and 136.0 kt lignite yr $^{-1}$, while the combined electricity and heat utilization leads to a range between 84.7 and 196.3 kt lignite yr $^{-1}$.

The values are to be considered theoretical gross substitution potentials and do not necessarily imply a change in power-system operation. The electricity would substitute for on-site electrical demand at the WWTPs and, therefore, cannot necessarily be related to a particular lignite-fired electricity-generating unit. Similarly, the heat-related contribution represents a technical maximum because a continuous demand for heat is required, and the necessary infrastructure for distribution must be available. Parasitic energy consumption, biogas losses, a possible lack of combined heat and power (CHP) generation, and electricity and heat distribution losses should be accounted for if specific plant data become available.

## CONCLUSION

This study provides a national level assessment of the biogas potential of the wastewater sludge of the 11 planned large WWTPs, each of which has a design capacity larger than 100,000 PE. The estimated amount of the produced stabilized sludge is between 47,001 and 52,876 t DS $yr^{-1}$ that corresponds to 59,495–94,422 t DS $yr^{-1}$ of the digester feed in the analyzed scenarios.The biogas potential is estimated from 18.32 to 42.49 million $Nm^3$ $yr^{-1}$, with a reference value of 29.16 million $Nm^3$ $yr^{-1}$. The corresponding amounts of electricity would be in a range from 38.37 to 88.96 GWh $yr^{-1}$, while the amounts of useful heat can provide from 48.23 to 111.84 GWh $yr^{-1}$.
The reference scenario suggests a possible total displacement of 134.7 kt lignite $yr^{-1}$ with the caveat that the heat-related component depends on the availability of a continual local heat demand coupled with appropriate heat-distribution infrastructure.
The sensitivity analysis highlighted that the specific biogas yield and VS reduction were the primary drivers of the predicted biogas potential; consequently, the results should be considered indicative of strategic planning scenarios rather than predictors of plant-specific performance. Future project development should focus on acquiring site-specific data pertaining to actual wastewater load, primary- and waste-activated-sludge ratios, TS and VS contents, methane concentration, parasitic energy demand, CHP availability, and local heat demand.
Overall, the results suggest that anaerobic digestion and CHP technologies offer a viable opportunity for enhancing the sustainability profile of large Serbian WWTPs, facilitating the transition from conventional sludge disposal practices to those focused on resource recovery whilst simultaneously contributing to decreased reliance on fossil-fuel sources. This would enable WWTP to re-position itself as an enabler of the local production of renewable electricity and heat.

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