

# Potential of Green Hydrogen Synthesis from Sewage Sludge: Assessing Emission Factors

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The study aims to explore the feasibility of synthesizing hydrogen from sewage sludge in EU countries, with a particular focus on assessing associated emission factors. This research is driven by the increasing interest in utilizing wastewater as a valuable resource for clean energy production in the context of the global energy transition. Despite the need for extensive treatment of the resulting sludge, research efforts are focused on the production of clean energy, particularly hydrogen. The research methodology uses statistical approaches to derive potential values from baseline data through emission factors and categorizes study areas based on this information. Europe produces approximately 10 million tons of sewage sludge annually, with Hungary contributing nearly a quarter of a million tons, hence this significant byproduct should be treated as a valuable resource in accordance with the principles of a circular economy. The paper delves into hydrogen generation from sewage sludge, specifically through anaerobic digestion, and thoroughly reviews and contrasts existing systems, examining key factors and prospects influencing hydrogen production efficacy within the EU context. Overall, this study addresses a topic of growing significance, offering insights beneficial for both policy formulation and practice in the spheres of energy management and environmental conservation, with a special emphasis on its application and implications for European Union countries.

## 1. Introduction

The rising world population, estimated to reach 9.5 billion by 2050, is putting additional strain on wastewater treatment resources (Chong et al., 2021). Wastewater treatment consumes a significant portion of energy in the water sector, emphasizing the need to address its energy usage to enhance efficiency (di Cicco et al., 2019) and minimize environmental impacts (Zseni et al., 2019). Sewage sludge, a by-product of wastewater treatment, can exist in various forms and contains organic and inorganic pollutants, as well as microorganisms (Demirbas et al., 2017). Before reuse or disposal, further processing and safe handling are necessary due to its harmful substances. The composition varies based on the source of the wastewater and treatment methods used.

The Urban Waste Water Treatment Directive has been updated to establish stricter standards for waste water quality and promote the recycling of sludge from waste water treatment (Fytili and Zabaniotou, 2008). This emphasizes the importance of efficiently managing sewage sludge to move towards sustainability and a circular economy that minimizes waste disposal and maximizes energy production (Lundin et al., 2004). In this context, a comparative evaluation across EU regions is particularly relevant, since differences in wastewater treatment capacity, sludge composition, and regional energy needs can significantly influence the feasibility of hydrogen production. The development of hydrogen technology is driven by factors such as climate change and depletion of fossil fuels, leading to a shift away from conventional methods towards alternative ones. The European Union has set ambitious targets for renewable hydrogen production including using biomass as a primary feedstock (Khan et al., 2024). Sewage sludge as a locally available biomass stream represents a potential yet underexplored resource that could contribute to these targets, particularly in regions with limited renewable energy infrastructure. The proper management and appropriate disposal of solid sewage sludge from wastewater treatment facilities is essential for safeguarding the environment (Kumar et al., 2017). Anaerobic

digestion is a commonly employed method to stabilize sewage sludge wherein microorganisms break down organic matter in the absence of air (Sheng et al., 2022). The process of anaerobic digestion involves four main mechanisms: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Bajpai, 2017). Hydrolysis breaks down complex organic compounds, while acidogenesis converts them into volatile fatty acids. Acetogenesis then converts intermediate metabolites into acetate and hydrogen (Ferdeş et al., 2020). In the final stage of methanogenesis, specific microorganisms convert acetate and hydrogen into methane. This process not only stabilizes sludge but also produces biogas, which can be used as a renewable energy source. Currently, biogas is primarily used for direct combustion to generate heat, steam, and electricity (Rao et al., 2018).

However, there are limitations to its widespread use due to its high and variable carbon content, inadequate flame stability, and low calorific value (Dang et al., 2022). Biogas utilization technologies are classified as first or second generation, with first generation technologies focusing on direct use for heat or electricity generation. To efficiently produce renewable energy without causing further environmental damage, it is crucial to optimize these energy sources and explore second-generation technologies (Fernández et al., 2014). In the field of hydrogen production, biogas conversion is given special attention for green hydrogen production. Nevertheless, comprehensive environmental assessments are required to evaluate not only the reduction in landfilling but also possible drawbacks such as emissions, energy demand, and secondary pollutants, which are rarely addressed in existing studies. The most common methods for storing hydrogen involve liquid or gas states, typically using pressure vessels or piping systems (Nash et al., 2012) capable of withstanding high pressures ranging from 350 to 700 bar (Razmi et al., 2023). Gaseous hydrogen storage systems rely on high-pressure cylinders to achieve optimal storage densities. The current industry target is set at 70 MPa, with a mass of 110 kg, resulting in a gravimetric density of 5.0% to 6.0%, and a volumetric density of 30 kg/m<sup>3</sup> (Razmi et al., 2023). However, storing hydrogen in liquid form requires extremely cold temperatures due to its low boiling point of -252.87 °C at ambient pressure (Razmi et al., 2023). The lack of infrastructure for storing, transporting, and distributing hydrogen fuel is a challenge for its widespread use. This hinders the use of hydrogen in fuel cell electric vehicles. Safety concerns arise from potential leaks and inadequate ventilation, which can lead to explosions or fires (Vodovozov et al., 2022). The loss of hydrogen from production to end use can range from 0.2% to 20% (Esquivel-Elizondo et al., 2023). However, these estimates can vary depending on the production stage and end use. While previous studies have analyzed emission factors and loss coefficients for hydrogen production from various sources, there is a gap in the literature regarding the application of these factors to sewage sludge.

This paper aims to fill this gap by estimating the hypothetical hydrogen potential of sewage sludge using comprehensive literature data. The paper goes beyond a simple data compilation by introducing a structured assessment that highlights regional disparities, evaluates environmental implications, and identifies technological and infrastructural challenges. The study uses a unique assessment methodology that combines these parameters to provide insights into efficiency and other factors.

## 2. Materials and methods

The paper analyzes the management of sewage sludge waste in Hungary, with a focus on assessing the potential for hydrogen production using theoretical data and loss factors. The chosen timeframe was determined based on the availability of extensive data. This study aims to experimentally apply emission and loss factors to estimate the potential quantity of hydrogen obtainable from sewage sludge. In addition to the national focus, the methodology is designed to be scalable for regional comparison within the European Union, allowing an assessment of how local variations in sludge generation, treatment infrastructure, and energy demand may influence hydrogen potential.

### 2.1 Data

The data has been carefully analyzed to find patterns and inconsistencies over time or other factors. The methodology used in the research has been thoroughly assessed to ensure its reliability. This report uses data from the Hungarian National Environmental Information System, Unified Waste Management Information System Module, focusing on a numerical evaluation of sewage sludge production and treatment in Hungary from 2004 to 2022. The research utilized data for wastes classified as "*190805-Municipal wastewater treatment sludge*." These values were cross-checked with Eurostat and EU-wide reports to contextualize Hungarian results within broader regional trends.

### 2.2 Summary of emission factors and loss coefficients

Table 1 shows factor values for each stage of the process model, along with scientific explanations. These factors help determine potential hydrogen yield from sewage sludge and compare it with traditional waste treatment methods. The production and loss parameters at different stages were determined by referencing current international literature to assess standard performance. To improve transparency, assumptions and

uncertainty ranges were explicitly considered, recognizing that emission factors may vary significantly depending on sludge composition, treatment technology, and regional practices.

### 2.3 Calculation of hydrogen production potential

The net potential hydrogen production ( $m_H$ ) was calculated in accordance with the method described Eq(1).

$$m_H = m_s \times r^* \times \rho \times \mu \quad (1)$$

where  $m_s$  represents the mass of sewage sludge,  $r^*$  is the biogas production factor in cubic meters per ton ( $m^3/t$ ),  $\rho$  denotes the density of the biogas, and  $\mu$  signifies the rate of hydrogen production through reforming. The energy stored  $E_H$  equals  $m_H$  multiplied by 39.39 kWh/kg.

Table 1: Applied emission and loss factors

Factor	Value	References
Biogas production factor from sewage sludge (l/t)	44.82	Chua et al., 2013; Demirbas, 2016
Average density of biogas ( $kg/m^3$ )	1.15-1.20	Akbulut et al., 2021; Cruz-Monterrosa et al., 2024; Gerber and Schneider, 2015
H <sub>2</sub> production by methane reforming (H <sub>2</sub> kg/kg)	0.25 - 0.50	Cudjoe et al., 2022; Tashie-Lewis and Nnabuife, 2021
Liquefaction loss (%)	0.15-10.0	Esquivel-Elizondo et al., 2023; Cooper et al., 2022; Ocko and Hamburg, 2022
Transport loss of liquid hydrogen (%)	2.00-13.2	Esquivel-Elizondo et al., 2023; Cooper et al., 2022; Ocko and Hamburg, 2022
Storage, distribution, refuelling losses (%)	2.00-15.0	Esquivel-Elizondo et al., 2023; Cooper et al., 2022; Ocko and Hamburg, 2022
Transport loss of gaseous hydrogen (%)	0.002-5.00	Esquivel-Elizondo et al., 2023; Ocko and Hamburg, 2022; Colella et al., 2005
Losses during above ground storage of gaseous hydrogen (%)	2.80-6.50	Esquivel-Elizondo et al., 2023; Ocko and Hamburg, 2022; Colella et al., 2005
Loss at gas filling stations (%)	0.25-3.00	Esquivel-Elizondo et al., 2023; Ocko and Hamburg, 2022; Colella et al., 2005
Loss by end users (%)	0.01-3.00	Esquivel-Elizondo et al., 2023; Ocko and Hamburg, 2022; Colella et al., 2005

### 3. Results

Based on the available data, it can be determined that between 2004 and 2022, a total of 19,573,165.2 metric tons of sewage sludge was generated, with the quantity in 2004 amounting to 683,742.8 metric tons and in 2022 to 1,435,308.0 metric tons (+109.9 %). The mean quantity during the study period was  $1,030,166.6 \pm 258,886.03$  metric tons. As shown in Figure 1, sewage sludge production exhibited a fluctuating trend, with the minimum point in 2004. In contrast, the maximum value was recorded in 2017, with 1,482,416.4 metric tons of sewage sludge generated. As observed, from 2004 to 2008, there was a period of decelerating growth, followed by a decline and subsequent growth until 2013. The year 2014 marked a local minimum, followed by a growth rate that peaked in 2017. This was followed by a decrease until 2020, the year impacted by the COVID-19 pandemic, after which a stable, plateau phase ensued.

For the NUTS-2 (nomenclature of territorial units for statistics) regions of Hungary, one region (Western Transdanubia) experienced a negative change between 2004 and 2022 (-54.0 %). The largest increase (+797.3 %) occurred in the Northern Hungary region. This is attributable to the rise in produced sewage sludge from 48,723.697 metric tons in 2004 to 437,196.01 metric tons in 2022. The Central Transdanubia region ranked second with an increase of +185.8 %, followed by Pest with +161.7 %. However, in terms of total quantities, a different ranking emerged: the Northern Hungary region (3,898,205.3 metric tons), the Southern Great Plain region (2,700,704.4 metric tons), and the Southern Transdanubia region (2,562,628.3 metric tons) constituted the top three NUTS-2 regions. While the numerical results show clear trends, they also highlight strong regional disparities in sewage sludge generation. This indicates that region-specific waste management and hydrogen utilization strategies will be required.

Based on the available treatment data, it can be determined that between 2004 and 2022, a total of 18,271,533.6 metric tons of sewage sludge was treated in Hungary. This quantity was 431,081.5 metric tons in 2004 and increased to 1,463,594.3 metric tons in 2022 (+239.5%).

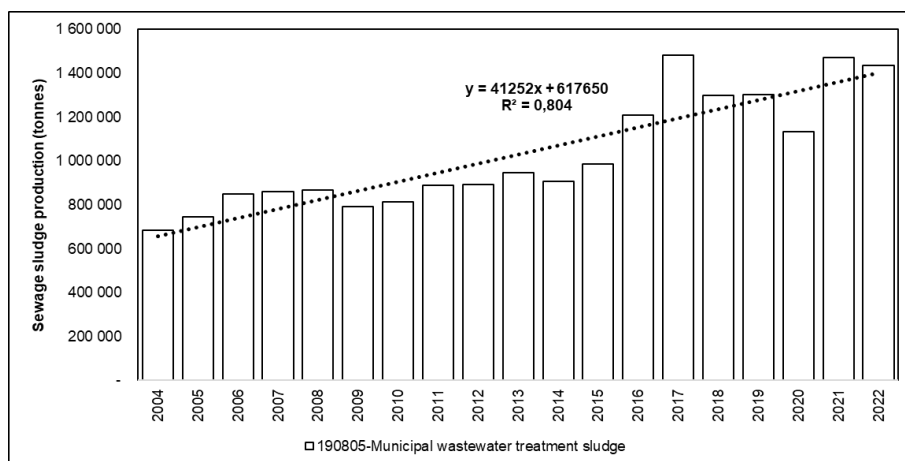


Figure 1: Municipal wastewater treatment sludge production in Hungary (tonnes, 2004-2022)

The average quantity during the study period was 961,659.7 metric tons. The amount disposed of via landfilling totaled 558,118.6 metric tons between 2004 and 2022 (-92.5%). Landfilling was the sixth most common treatment and disposal method. Concurrently, the use of sewage sludge as primary fuel or for energy production increased by +446%, and the recovery and recycling of organic substances not used as solvents (such as composting, biological transformation processes, gasification, pyrolysis) increased by +1136%. The average quantity of landfilled sludge was 29,374.7 metric tons. Based on the applied methods, the theoretical amount of hydrogen production potential determined for 2004 to 2022, assuming ideal 100% utilization, is 526.4 metric tons. The annual mean quantity was  $27.7 \pm 6.96$  metric tons. While the baseline quantity for 2004 was 18.4 metric tons, it was estimated to be 38.6 metric tons for 2022. In terms of energy content, the total amount was 20,733.4 MWh. The mean energy content between 2004 and 2022 tended to be  $1,091.2 \pm 274.2$  MWh. The average change was  $+4.83 \pm 0.12$  %.

The lower limit of losses calculated for the hydrogen supply chain based on liquid medium between 2004 and 2022 averaged  $1.14 \pm 0.29$  metric tons. Overall, this amount exceeded 21.7 metric tons. The largest quantity, averaging  $0.554 \pm 0.139$  metric tons, was attributed to transportation and storage losses. In total, this accounted for 10.5 metric tons of losses each from 2004 to 2022. The upper limit of losses for the liquid medium, based on the total sewage sludge amount for hydrogen production, was  $9.86 \pm 2.48$  metric tons. The largest loss in this regard was storage loss ( $4.16 \pm 1.04$  metric tons). This represented 79.0 metric tons of losses between 2004 and 2022, followed by transportation loss (69.5 metric tons). The total upper limit loss was 187.3 metric tons.

The lower limit of losses calculated for the hydrogen supply chain based on gaseous medium between 2004 and 2022 averaged  $0.846 \pm 0.213$  metric tons. Overall, this amount exceeded 16.1 metric tons. The largest quantity, averaging  $0.776 \pm 0.195$  metric tons, was attributed to storage losses. In total, this accounted for 14.7 metric tons of losses between 2004 and 2022, representing approximately 91.7 % of the total amount. The upper limit of losses for the gaseous medium, based on the total sewage sludge amount for hydrogen production, was  $4.55 \pm 1.14$  metric tons. The largest loss in this regard was also storage loss, amounting to  $1.80 \pm 0.45$  metric tons. In total, this represented 34.2 metric tons of losses between 2004 and 2022, followed by transportation losses of 26.3 metric tons. The total upper limit loss was 86.5 metric tons (Figure 2).

Based on the applied methods, the theoretical amount of hydrogen production potential from sewage sludge disposed of via landfilling between 2004 and 2022, assuming ideal 100% utilization, is 15.01 metric tons. The average quantity was  $0.790 \pm 0.984$  metric tons. While the baseline quantity for 2004 was 1.55 metric tons, it was estimated to be 0.117 metric tons for 2022. In terms of energy content, the total amount was 591.2 MWh. The median energy content between 2004 and 2022 tended to be  $31.1 \pm 38.7$  MWh.

Based on the results, it can be determined that basing on the landfilled quantity would account for approximately 2.85% of the total hypothetical potential value. The cumulative value of the remaining quantity is 511.4 metric tons, with an average value of  $26.9 \pm 7.59$  metric tons. Thus, the average share of produced hydrogen is 3.53%, which also corresponds to the amount of energy that can be produced under ideal conditions. The average difference in energy within this context is 1060.1 MWh.

Based on sewage sludge, the hydrogen production volume can generate an energy output ranging from 400 to 1500 kWh. This amount is relatively small and would be adequate for powering an average Hungarian household for approximately 4-5 months, considering that such households typically consume around 3500-4000 kWh of electricity per year. In terms of transportation, a medium-sized electric car could travel roughly 7500-9000

kilometers using this energy source, given that these cars have an average consumption rate of 15-20 kWh per every 100 kilometers.

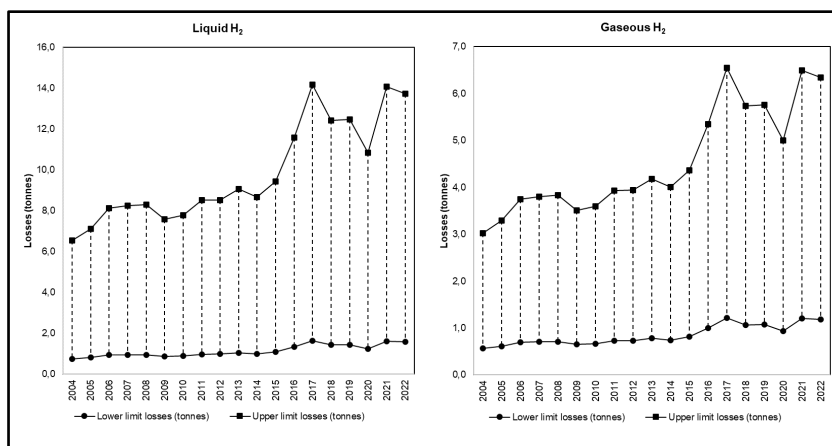


Figure 2: Losses of liquid and gaseous supply chain of sewage sludge-based hydrogen (tonnes, 2004-2022)

#### 4. Conclusions

The analysis of sewage sludge generation and treatment in Hungary from 2004 to 2022 reveals important trends related to waste management. The increasing production reflects urbanization and industrialization, necessitating more efficient solutions. Shifting towards sustainable treatment methods indicates progress towards circular economy principles, reducing environmental impact while harnessing energy potential. However, the results clearly show that the theoretical hydrogen yield from sewage sludge remains relatively low compared to national energy demand, highlighting its complementary rather than central role. Addressing regional disparities through tailored strategies is crucial, as certain NUTS-2 regions such as Northern Hungary show substantial increases in sludge generation, while others, such as Western Transdanubia, experienced decline. Nevertheless, significant supply chain losses, especially related to storage, constrain the effective energy yield. The comparison of liquid versus gaseous hydrogen pathways underlines that infrastructure and technological choices will strongly influence feasibility. Overcoming technical challenges will be essential for realizing this potential, underscoring the need for innovation and supportive policy frameworks. Enhancing hydrogen production processes can significantly contribute to Hungary's renewable energy portfolio and global sustainability efforts, but only if pursued alongside systemic measures that address scalability, infrastructure gaps, and long-term economic viability.

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