Sustainable Wastewater Treatment at Sopron WWTP: A Life Cycle Assessment of Environmental and Energy Performance

Mahdi Echajari[1*], Ismail Nime[1], and Andràs Polgàr[2]

[1] PhD Student, Institute of Environmental Protection and Nature Conservation, University of Sopron, Hungary

[2] Associate Professor, Institute of Environmental Protection and Nature Conservation, University of Sopron, Hungary

Abstract

Wastewater treatment is essential to the resilient strengthening of our environment, especially in terms of climate and energy resilience. This multi-year LCA of a Hungarian WWTP, providing a replicable framework for carbon-neutral transitions in medium-sized European facilities. This work examines the performance and carbon impacts of the Sopron Wastewater Treatment Plant (WWTP), located in Sopron, Hungary, using a Life Cycle Assessment (LCA). Data collected from 2018–2020 were analysed using the GaBi software to assess energy use, greenhouse gas emissions, and biogas recovery. Results revealed a 62% decrease in Global Warming Potential (GWP) over the three-year period, along with an increase in energy self-sufficiency to almost 51%, attributed to biogas energy recovery. These findings indicate that improving sludge digestion and maximizing biogas utilization are key strategies for enhancing both energy performance and environmental sustainability. The data produced by this work demonstrate the value of LCA as a decision-making tool to support the transition toward carbon-neutral wastewater treatment facilities.

Keywords: Anaerobic digestion; Biogas recovery; Carbon neutrality; Climate resilience; Global Warming Potential

1 Introduction

Wastewater management is now not just seen as a vital public health requirement but as an intrinsic part of urban sustainability and initiatives to combat climate change. Modern-day Wastewater Treatment Plants (WWTPs) are typified by their intensive energy requirement, often relying on fossil fuel-based energy, and thus are significant emitters of greenhouse gas (GHG) emissions through their energy consumption and sludge treatment (Viotti et al., 2024). However, application of resource recovery technologies—in particular anaerobic digestion for biogas production—has promoted movement towards carbon-neutral wastewater treatment (CNWWT) and improved resilience to climate stress (Bravo & Ferrer, 2011).

Life Cycle Assessment (LCA) has developed into a critical tool for assessing the environmental effectiveness of wastewater treatment plants (WWTPs). Using LCA, it is possible to

systematically analyse overall energy consumption, emissions, and waste generation related to different treatment methods and their related ecological burdens (Tsangas et al., 2023). Studies have revealed that biogas recovery not only prevents Global Warming Potential (GWP) related to WWTPs but decreases electricity requirements substantially (Karolinczak., 2023). Additionally, concurrent digestion of sewage sludge along with organic fraction of municipal solid waste (OFMSW) has proved to increase methane production and energy self-sufficiency (Karolinczak , 2023). These are in line with the European strategy for sustainability, which aims to promote renewable energy via municipal systems.

Seminal WWTP LCA studies over the past two decades have established the methodological foundations for evaluating the environmental impacts of wastewater treatment processes. Early applications demonstrated that electricity consumption, aeration, and sludge handling are consistently the dominant hotspots in WWTP LCAs, while more recent reviews emphasize the need for consistent functional units and system boundaries to enable comparison across plants and technologies. Multi-country assessments and large-scale reviews have shown that GWP values for conventional activated sludge typically range from 0.3 to 0.8 kg CO_2-eq per m^3, depending primarily on aeration energy and sludge treatment performance. Despite this extensive global literature, multi-year operational LCAs remain limited, and no published study has examined long-term environmental performance trends for Hungarian WWTPs. This gap highlights the need for region-specific, multi-year evaluations to support decarbonization strategies.

From a regulatory standpoint, wastewater treatment in the European Union is strongly shaped by evolving policy frameworks. The original Urban Wastewater Treatment Directive (91/271/EEC) established minimum requirements for collection and secondary treatment, while the recent recast proposal (COM/2022/541) places new emphasis on energy efficiency, GHG emission reduction, and nutrient recovery, aligning WWTP operations with the European Green Deal (European Commission, 2019; European Union, 1991; European Commission, 2022).

Medium-sized wastewater treatment plants, like the Sopron plant in Hungary, are facing growing pressure to reduce operation emissions while increasing energy efficiency. Yet most of them still rely on conventional technologies and show a limited focus on climate resilience and holistic environmental optimization (Romagnoli, 2009).

The study adopts a Life Cycle Assessment (LCA) methodology to analyse the environmental effectiveness of the Sopron Wastewater Treatment Plant (WWTP) within a triennium period, namely 2018 to 2020. Focusing on parameters like energy consumption, biogas conversion, and carbon dioxide emissions, the research aims to identify paths for achieving energy independence and minimizing ecological implications. The findings provide a template for developing traditional WWTPs into eco-friendly, low-carbon facilities consistent with European sustainability standards.

2 Methodology

2.1 Scope of the Study

The main objective of the research is to assess the environmental and energy performance of the Sopron Wastewater Treatment Plant (WWTP) in the 2018-2020 period by a Life Cycle Assessment (LCA). The evaluation centres around energy consumption, greenhouse gas emissions, and the share of biogas recovery in the energy autonomy equation.

2.2 System Boundaries

This study applies a gate-to-gate system boundary, covering only processes within the Sopron WWTP (mechanical and biological treatment, sludge thickening, anaerobic digestion, dewatering, composting and on-site energy generation from biogas). Upstream processes such as construction and manufacturing of plant infrastructure, and downstream activities such as sludge transport and final use or disposal are excluded.

Based on published WWTP LCAs, construction and infrastructure usually account for around 5–10% of total GWP, while sludge transport and additional upstream processes typically add a few further percent. Assuming a representative contribution of 5% from infrastructure and about 3% from sludge transport and chemical upstream processes, extending the boundary beyond the plant fence would be expected to increase the total GWP by roughly 8% relative to the gate-to-gate result. This indicates that the main conclusions about the dominance of on-site operations are robust, even when broader life cycle stages are considered.

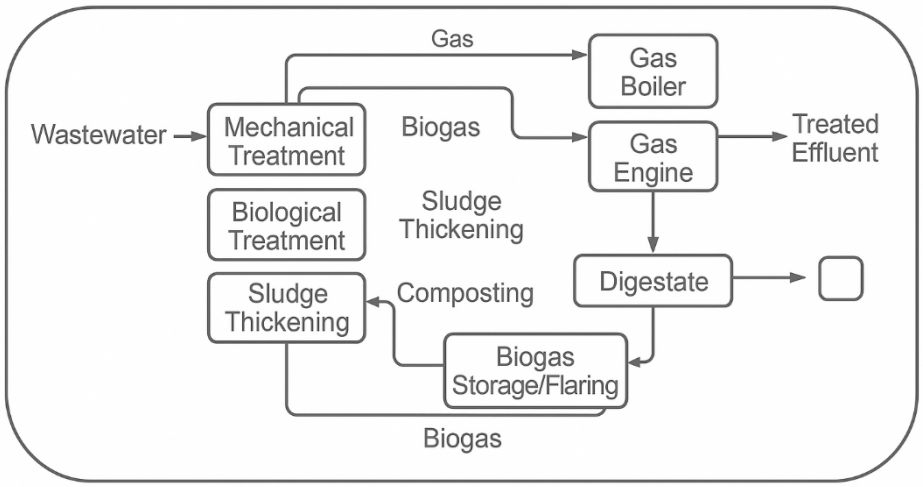

Figure 1: System boundaries of the Sopron Wastewater Treatment Plant of the gate-to-gate LCA.

The wastewater treatment process at the Sopron WWTP begins with the introduction of raw sewage into the mechanical treatment stage, where coarse solids, sand, and grease are removed through screening and grit separation. The pre-treated wastewater then enters the biological treatment stage, where dissolved organic matter and nutrients—primarily nitrogen and phosphorus—are degraded by microbial communities in aeration and anoxic basins.

Excess sludge generated from these treatment processes is pumped to sludge-thickening units to reduce water content and increase solids concentration. The thickened sludge is subsequently transferred to anaerobic digesters, where microbial decomposition occurs under controlled mesophilic conditions (35–38 °C). This process produces biogas composed mainly of methane and carbon dioxide. The biogas is stored in a buffer tank and can be directed to a gas engine for combined heat and power (CHP) generation or to a gas boiler for thermal energy production. Surplus or unusable biogas is safely destroyed in a flare system to prevent methane emissions into the atmosphere.

Following digestion, the remaining sludge—referred to as digestate—is routed to a composting facility for stabilization and reuse or disposal. Meanwhile, the treated wastewater, now largely free of contaminants, is discharged from the plant as final effluent for environmental release or potential reuse. In addition to pollutant removal, the system supports resource recovery through energy generation and nutrient recycling. Figure 1 presents the system boundaries and the main material and energy flows incorporated into the LCA model.

If the system boundary were extended from gate-to-gate to cradle-to-grave, additional contributions from plant construction, chemical production, sludge transport, and land application would have to be included. Based on published WWTP LCAs (e.g., Romagnoli, 2009; Corominas et al., 2013; Tsangas et al., 2023), civil works and equipment typically add 5–15 % to total GWP, while chemical use and sludge transport contribute a further 3–10 %, depending on local conditions. For Sopron WWTP, using representative values from this literature, total GWP would be expected to increase by approximately 10–20 % relative to the gate-to-gate result, but the ranking of major hotspots (biological treatment and sludge management) would remain unchanged.

Conversely, including the downstream benefits of sludge compost application would introduce potential credits for nutrient substitution. The compost produced at Sopron WWTP is applied to local land, where it can partially replace synthetic nitrogen and phosphorus fertilizers. Literature values for such substitution suggest GWP credits on the order of 3–8 % of the operational emissions, together with reductions in eutrophication and ecotoxicity (Karolinczak, 2023). Because detailed data on nutrient contents, application rates, and displaced fertilizers are not available for the present case, these credits were not quantified in the model. As a result, the gate-to-gate results presented here may be considered conservative: a full cradle-to-grave system with nutrient substitution would likely show slightly lower net impacts than reported.

2.3 Functional Unit

The functional unit was defined as one full operational year for WWTP's treatment activities. This unit captures all associated energy use, material flows, emissions, and biogas generation within that time frame.

To enable comparison with other LCA studies, a second, normalized FU of 1 m^3 of treated wastewater was established. The annual inventory data were divided by the total treated volume for each year (2018–2020) to express results on a volumetric basis.

This conversion allows direct benchmarking with other WWTPs and ensures consistency with the standard reporting practice in wastewater LCAs.

2.4 Data Collection and Inventory Modeling

Operational data was obtained directly from the Sopron WWTP through on-site visits and consultation with plant engineers. The dataset covers the period 2018–2020 and includes influent and effluent volumes, electricity consumption by subprocess (pumping, biological treatment, sludge management, composting), biogas production and utilization, and sludge quantities before and after dewatering.

All data were modelled in GaBi 10.5 software (Sphera Solutions). Foreground data from the plant were combined with background data from GaBi's European Union and Hungarian databases, which include updated information on materials, fuels, and the regional electricity mix. The electricity mix applied represents the Hungarian medium-voltage grid, consisting mainly of nuclear (≈45%), natural gas (≈37%), and renewable (≈18%) sources.

Process emissions of CH_4 and N_2O were modelled using IPCC (2006) default emission factors integrated in GaBi's wastewater treatment modules. Missing or minor inputs—such as lubricants and office electricity—were filled using GaBi default values, with a cut-off threshold of 1% of total energy use.

Data quality was evaluated according to technological, temporal, and geographical representativeness. Foreground data are site-specific and refer directly to the years of study, while background datasets are European and current within ±5 years of the study period. Internal cross-checking between WWTP reports and energy bills confirmed deviations below ±5%, indicating medium-to-high data quality for energy and GHG indicators.

Table 1: Summary of inflow and outflow of each process

Category	Flow description	Unit	2018	2019	2020
Wastewater treatment	Influent wastewater to WWTP	m^3	5,623,920	4,939,155	5,993,045
	Screenings and grit to disposal	kg	674,880	674,880	674,880
Electricity consumption	Electricity – pumping	kWh	515,830.4	474,579.1	332,408.2
	Electricity – biological treatment	kWh	1,477,175	1,607,626	1,474,093
	Electricity – secondary settling	kWh	71,673.28	58,866.86	79,727.99
	Electricity – sludge management	kWh	453,930.8	443,183.4	443,377.6
	Electricity – biogas process	kWh	19,275.77	20,463.24	18,744.83
	Electricity – composting	kWh	19,275.77	10,932.42	10,247.17

Category	Flow description	Unit	2018	2019	2020
	Electricity generated from biogas (CHP)	kWh	1,741,200	1,363,300	1,492,600
Sludge processing	Sludge fed to anaerobic digestion	m^3	59,916	70,944	58,507
	Dewatered sludge (final output)	kg	47,932,800	56,755,200	46,805,600
Biogas system	Biogas produced (SCADA metered)	m^3	770,923	691,894	778,824
	Used biogas (to CHP engine)	m^3	673,783	535,265	599,081
	Electricity per m^3 of biogas	kWh/m^3	2.26	2.24	2.12
Water output	Treated wastewater reused in composting	L	11,983,200	14,188,800	11,701,400

CHP efficiency and gas utilisation. The CHP engine converts biogas into electricity with a measured electrical yield of 2.12–2.26 kWh/m^3, corresponding to an electrical efficiency of 33–38%, which aligns with values reported for municipal wastewater treatment plants. The remaining energy fraction is recovered as heat and used internally for digester heating. Differences between produced and used biogas (9–14%) reflect routine operational flaring, digester heating requirements, and short periods of engine downtime. These values confirm that the mass–energy balance of the system is physically realistic and consistent with European WWTP performance benchmarks.

2.5 Allocation Rules and Treatment Efficiencies

All operational inputs and emissions are attributed to the wastewater-treatment function of Sopron WWTP.

Electricity and heat produced from biogas are treated by system expansion, assuming substitution of the Hungarian medium-voltage grid electricity mix. Heat recovered from the combined heat-and-power (CHP) unit is used internally for digesting heating and building demand and is therefore not credited externally.

Sludge compost produced after digestion and dewatering is applied to land within the municipality; because of data limitations on nutrient substitution, no external credit for fertilizer replacement was included, which makes the results conservative.

The WWTP is designed for 21 000 m^3 day^{-1} hydraulic capacity and typically operates at 70–75 % of design flow. Primary and secondary sludges are thickened and digested together under mesophilic conditions (35–38 °C, ≈25 days retention time). The digester feed averages 4.5–5 % dry solids, and dewatered sludge leaves the plant with ≈22 % dry-matter content. Annual Biogas production data were obtained from the plant's SCADA gas-flow meters and represent monthly aggregated values reported in the annual operational records. Annual biogas production ranged between 691,894 and 778,824 m^3/year during 2018–2020, while used biogas

(effectively supplied to the CHP engine) ranged between 535,265 and 673,783 m³/year. The difference between produced and used biogas reflects internal heat demand for digester heating and minor operational losses. CHP electricity generation was measured directly from the on-site electricity meter and yielded 1.36–1.74 GWh/year, corresponding to a specific electrical efficiency of 2.12–2.26 kWh per m³ of biogas, which is consistent with typical municipal WWTP CHP performance.

Typical pollutant-removal performance based on 2018–2020 operational records is summarized below.

Table 2: Summary of pollutant removal 2018-2020

Parameter	Influent (mg L^{-1})	Effluent (mg L^{-1})	Removal (%)	EU limit (mg L^{-1})*
COD	≈ 754	≤ 125	83–90	125
BOD_5	≈ 405	≤ 25	≥ 93	25
Total Nitrogen (TN)	≈ 184	≤ 55	≈ 70–80	55
Total Phosphorus (TP)	≈ 50	≤ 10	≈ 80	10
Total Suspended Solids (TSS)	≈ 450	≤ 35	≥ 90	35

These results confirm that the Sopron WWTP consistently meets both national and EU discharge standards. High COD and BOD_5 removal, together with stable nutrient removal, demonstrate reliable biological treatment performance that supports the energy-recovery strategy and the validity of the LCA inventory.

2.6 Impact Assessment Methods

Life Cycle Impact Assessment (LCIA) was performed using the CML 2001 baseline method implemented in GaBi 10.5 software. The assessment quantifies midpoint-level environmental impacts associated with the operational phase of the Sopron WWTP for each functional unit (one operational year and 1 m³ of treated wastewater).

The following impact categories were evaluated:

- Global Warming Potential (GWP 100 years) – kg CO_2-eq
- Acidification Potential (AP) – kg SO_2-eq
- Eutrophication Potential (EP) – kg PO_4^{3-}-eq
- Freshwater Aquatic Ecotoxicity Potential (FAETP) – kg 1,4-DCB-eq

Characterization factors were applied according to the CML 2001 baseline (April 2016 update) and are consistent with the IPCC 2006 guidelines for GWP. For each category, results were generated in GaBi using process-specific inventories for energy consumption, material use, and direct emissions of CH_4 and N_2O.

Process emissions of nitrous oxide (N_2O) and methane (CH_4) were modelled using default factors from the IPCC (2006) Guidelines as implemented in GaBi's wastewater treatment datasets. N_2O emissions were calculated as a fixed fraction of nitrogen removed in the biological stage, using an emission factor of 0.005 kg N_2O–N per kg TN removed (equivalent to 0.0079 kg N_2O per kg TN removed). Methane emissions from sludge digestion and organic degradation were modelled using the IPCC default factor of 0.1 kg CH_4 per kg COD degraded. These emissions were then characterized using 100-year global warming potentials (CH_4 = 28; N_2O = 265) consistent with the CML 2001 (Jan. 2016) method in GaBi.

Plant-specific monitoring of N_2O and CH_4 emissions is not available at Sopron WWTP; therefore, IPCC Tier 1 default factors were applied. These values represent the internationally accepted baseline for facilities without direct gas measurements. The expected uncertainty range for these factors (±30–50%) does not materially affect the relative year-to-year comparison, which is the primary objective of this study.

To evaluate the robustness of the results, a deterministic sensitivity analysis was performed in which key parameters—electricity consumption, biogas yield, and N_2O emission factors—were varied by ±10 %. The resulting variation in total GWP remained below ±7 %, indicating that the overall trends and process rankings are stable within realistic uncertainty ranges.

CML 2001 was selected instead of ReCiPe or EF 3.1 for three main reasons. First, CML provides midpoint indicators (e.g., GWP, AP, EP, FAETP) that are widely used in wastewater LCA studies, enabling direct comparison with earlier work (e.g., Corominas et al., 2013; Tsangas et al., 2023). Second, the implementation of CML in GaBi is closely aligned with European reference models and has been extensively validated for infrastructure systems (Herrmann & Moltesen, 2015; Silva et al., 2019). Third, the regulatory discussion in this paper focuses on climate and eutrophication-related burdens, for which the CML midpoint indicators remain fully compatible with the policy metrics applied in the recast Urban Wastewater Treatment Directive. For these reasons, CML 2001 was considered the most appropriate method for this gate-to-gate assessment, while acknowledging that ReCiPe and EF 3.1 offer complementary perspectives that could be explored in future work.

2.7 Uncertainty Analysis

Uncertainty in the assessment arises mainly from measurement errors in operational data and from methodological assumptions used in the life-cycle model. Variability in electricity-meter readings, biogas-flow measurements, and the selection of CH_4 and N_2O emission factors may influence calculated impacts. To evaluate the robustness of the results, a deterministic sensitivity analysis was performed.

Key parameters were individually varied by ±10 % relative to their baseline values:

- total electricity consumption in all process units,
- annual biogas yield and CHP conversion efficiency, and
- process-emission factors for CH_4 and N_2O.

For each variation, total Global Warming Potential (GWP) and the contribution of main subsystems were recalculated. The overall GWP changed by less than ±7 %, and the relative ranking of major contributors—biological treatment > sludge management > other units—remained unchanged. These results indicate that the main conclusions of the study are robust within realistic uncertainty ranges, and that moderate variations in key parameters do not significantly affect the interpretation of the environmental performance of the Sopron WWTP.

2.8 Data Processing

Life Cycle Assessment (LCA) modeling for this study was conducted using GaBi 10.5 software, developed by Sphera Solutions. Several comparative assessments have shown GaBi to be one of the most reliable and widely adopted tools for environmental modeling in wastewater management. Herrmann and Moltesen (2015) performed a direct comparison between GaBi and SimaPro using identical datasets, showing that while both tools are credible, GaBi offers more consistent implementation of European environmental impact categories and better error-handling for inventory modeling (Herrmann & Moltesen, 2015).

Similarly, Silva et al. (2019) demonstrated that although all leading LCA software tools (SimaPro, GaBi, OpenLCA, Umberto) can deliver valid results, differences in background dataset integration and LCIA method support can lead to substantial variation in outputs. They recommended GaBi for applications involving gate-to-gate system boundaries and municipal infrastructure, citing its reliable mid-point impact calculations and alignment with ILCD and CML baseline indicators (Silva et al., 2019).

Gabi software enabled:

1. Input-Output Analysis: All collected values were entered into GaBi to simulate the energy consumption, emissions, and waste outputs of each treatment stage.

2. Life Cycle Inventory (LCI): An inventory of all material and energy inputs and outputs was developed (Table 1: Summary of inflow and outflow of each process), covering the following categories:

- Electricity consumption across mechanical, biological, and sludge management stages
- Biogas utilization metrics highlighted its role in covering nearly half of the plant's electricity demand.
- Sludge generation and processing, detailing the environmental impact of its treatment and disposal.

3 Results and Discussion

3.1 Environmental Performance of Sopron WWTP

3.1.1 Energy Consumption Analysis

The energy consumption of the Sopron WWTP is analyzed where electricity consumption falls within its basic operational blocks, including mechanical treatment, biological treatment,

sludge treatment, and composting. Between the period 2018-2020, there were notable trends regarding energy demand in these processes. The biological treatment process consistently reflected the highest rate of power usage as a percentage above 50% annually. This proportion grew from 54.41% in 2018 to 58.98% in 2020 due to the energy-consuming nature of aeration and biological treatment processes, which are essential for effective wastewater treatment.

The pumping stations, which transferred water between treatment processes, employed a ratio of 19.00% of total consumption in 2018 but lowered it to 13.30% in 2020. The decline was due to operational optimization and improved process control. Trickling filters, a crucial component of biological treatment, utilized between 15.64% and 17.74% of total electricity during the appraisal period, representing stable operational requirement. In comparison, sludge dewatering and settlement end operations were relatively stable in terms of energy use and accounted for some 5% to 6% annually. The boiler, gas engine, and composter also had good energy efficiency and used less than 1% of each of the overall electricity of the plant, and this reflects the effective adoption of energy-saving technologies. These distributions are easily presented in Table 3, which presents the breakdown of energy consumption across all major components from 2018 to 2020.

Table 3: The distribution of electricity consumption 2018-2020

Machine Group	2018	2019	2020
Pumping tation	19.0%	16.93%	13.3%
Biological	54.4%	57.3%	59%
Final Settling Tanks	2.64%	2.10%	3.19%
Sludge Dewatering	5.45%	6.04%	5.60%
Trickling Filters	16.7%	15.8%	17.7%
Gas Engine and Boiler	0.71%	0.73%	0.75%
Composter	0.71%	0.39%	0.41%
Other	0.37%	0.66%	0.03%

3.1.2 Energy Efficiency Improvements (2018–2020)

During the three years, Sopron WWTP achieved measurable energy efficiency improvements. One of the most significant improvements was achieved at the pumping stations, where energy usage decreased by nearly 5.7%. The reason for the improvement is attributed to operational optimization and improved process control and optimized water transfer processes. Similarly, the optimization of biological treatment processes through advanced aeration control and process optimization allowed the plant to maintain high treatment capacity with controlled energy consumption. Sludge dewatering and composting operations also recorded energy stability, indicating competent management amid increasing sludge quantities during the review period. These streamlining initiatives translated into a more stable and efficient energy

profile for the plant, reducing overall consumption without compromising treatment effectiveness.

3.2 Environmental Impact Assessment

The environmental performance of the Sopron wastewater treatment plant (WWTP) was evaluated using the CML 2001 – January 2016 baseline method implemented in GaBi 10.5. The analysis included four key impact categories representing global and regional environmental pressures: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Freshwater Aquatic Ecotoxicity Potential (FAETP). All results were normalized to the functional unit of 1 m^3 of treated wastewater to enable comparability across years and with other studies. The values are summarized in Table 4.

Table 4: summary of Environmental impact categories 2018-2020

Year	GWP (kg CO_2-eq m^{-3})	AP (kg SO_2-eq m^{-3})	EP (kg PO_4^{3-}-eq m^{-3})	FAETP (kg 1,4-DCB-eq m^{-3})
2018	0.18	9.22×10^{-4}	2.57×10^{-4}	0.537
2019	0.21	1.18×10^{-3}	3.04×10^{-4}	0.626
2020	0.06	5.27×10^{-4}	1.91×10^{-4}	0.457

To complement the numerical results presented in Table 4, Figure 2 illustrates the temporal trends of the four impact categories—GWP, AP, EP, and FAETP—normalized per cubic meter of treated wastewater. The graphical representation enables clearer comparison of the relative magnitude and year-to-year variation of each indicator across the 2018–2020 study period.

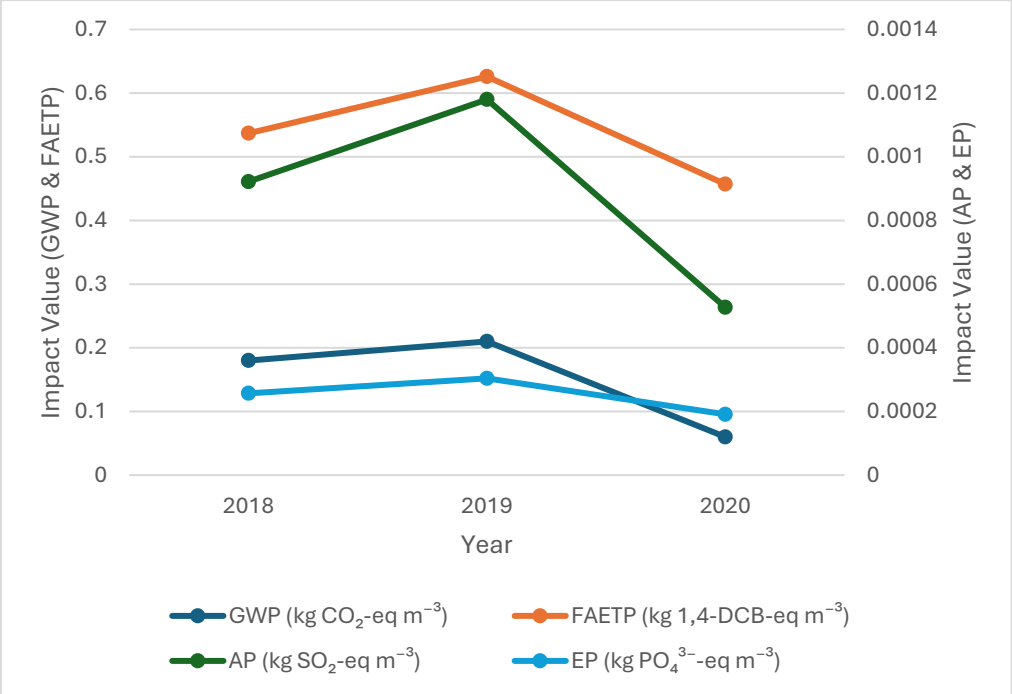

Figure 2: Environmental Impact Trends per m³ of Treated Wastewater at the Sopron WWTP (2018–2020)

3.2.1 Greenhouse-Gas Emissions and Global Warming Potential

The GWP values ranged from 0.18 to 0.21 kg CO_2-eq m^{-3} during 2018–2019 and declined sharply to 0.06 kg CO_2-eq m^{-3} in 2020. This decrease corresponds to approximately 60–65% reduction in climate-change impacts within the study period. The improvement is mainly driven by a combination of increased biogas utilization, reduced electricity demand, and higher treated wastewater volume, which together displaced grid electricity consumption and associated upstream CO_2 emissions. Enhanced aeration control also contributed to lower indirect energy-related emissions.

When compared to values reported in the literature for medium-scale European WWTPs typically 0.3–0.8 kg CO_2-eq m^{-3}; (Corominas et al., 2013) (Kampschreur et al., 2008), the Sopron facility demonstrates a significantly lower carbon intensity, confirming the effectiveness of its energy-recovery strategy.

3.2.2 Other Impact Categories

The remaining impact categories exhibit patterns consistent with the GWP trend, indicating that energy and resource efficiency improvements provided cross-cutting environmental benefits.

Between 2018 and 2020:

- Acidification Potential (AP) declined by ≈ 43%, mainly due to reduced upstream SO_2 and NO_x emissions from fossil-based electricity generation.

- Eutrophication Potential (EP) decreased by ≈ 26%, reflecting lower nutrient loads and improved nitrogen removal efficiency.
- Freshwater Ecotoxicity (FAETP) dropped by ≈ 15%, primarily linked to better sludge management and reduced heavy-metal content in the digested solids.

The parallel decline across all categories confirms that operational measures targeted at energy optimization (e.g., anaerobic digestion, CHP efficiency, optimized aeration) also mitigate a broad spectrum of environmental impacts. Although the gate-to-gate system boundary excludes upstream construction and downstream sludge-reuse effects, the observed trends provide reliable evidence of genuine environmental performance improvement within plant operations.

3.2.3 Overall Interpretation:

The integrated results highlight that the Sopron WWTP has transitioned toward more sustainable and energy-efficient operation over the analyzed period. The dominant contribution to all impact categories originates from biological treatment and sludge-handling units, consistent with findings in other European case studies. By coupling LCA with annual operational monitoring, the facility can quantitatively track progress toward carbon-neutral and resource-efficient wastewater treatment. These findings underline the importance of energy recovery and process optimization as core strategies for reducing both greenhouse-gas emissions and local environmental burdens in municipal WWTPs.

3.3 Drivers Behind the Reduction of Environmental Impacts in 2020

A consistent decrease across all environmental impact categories—Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Freshwater Aquatic Ecotoxicity Potential (FAETP)—was observed in 2020. This improvement aligns with major operational changes documented at the Sopron WWTP during the same period, particularly in biogas production, electricity use, and sludge handling (Table 1: Summary of inflow and outflow of each process).

3.3.1 Increase in Biogas Production and Utilization

Operational data show a recovery in biogas production in 2020, increasing from 691,894 m^3 in 2019 to 778,824 m^3 in 2020. This increase, together with higher utilization of biogas in the CHP engine (599,081 m^3), improved on-site electricity generation to 1.49 GWh/year, supplying more than 50% of the plant's electricity demand. Under the gate-to-gate boundary, this increased internal energy generation directly reduces GWP, AP and EP, as reliance on grid electricity—one of the dominant hotspots—decreases.

In addition to stronger CHP performance, nearly all major electricity-consuming units achieved lower consumption in 2020, notably:

- **Pumping:** 474,579 kWh (2019) → 332,408 kWh (2020)
- **Biological treatment:** 1,607,626 kWh (2019) → 1,474,093 kWh (2020)
- **Secondary treatment**: increased slightly due to higher treated volume

- **Sludge management:** broadly stable, with reduced consumption per m³ of treated wastewater

These reductions reflect improved aeration efficiency, more stable biological process conditions, and lower operational energy intensity. Because electricity consumption is the dominant contributor across GWP, AP, EP and FAETP, the combined effect of higher biogas utilization and lower electricity demand resulted in measurable reductions in environmental impacts in 2020.

3.3.2 Improved Sludge Stabilization and Dewatering Performance

Sludge feed volume decreased from 70,944 m³ in 2019 to 58,507 m³ in 2020, with proportional reductions in dewatered sludge mass.:

- Heavy metal loads → lower FAETP
- Nitrogen and phosphorus residuals → lower EP
- Energy for sludge pumping and dewatering → lower AP and GWP

Improved sludge performance also reflects a more stable biological treatment process.

3.3.3 Higher Treated Volume in 2020

The facility treated 5.99 million m³ of wastewater in 2020, significantly more than in 2019 (4.94 million m³).

Even though the total energy dropped, the higher treated volume spreads impact over more output, contributing to lower per-m³ indicators.

Together, these operational improvements produced a quantifiable decrease in carbon intensity, acidifying emissions, nutrient releases, and ecotoxicity loads. This confirms that Sopron WWTP's energy-optimization strategy is directly linked to broad environmental performance gains.

3.4 Comparative Analysis

To contextualize the findings of the Sopron Wastewater Treatment Plant (WWTP), a comparison was conducted with similar studies that applied Life Cycle Assessment (LCA) to medium- and large-scale wastewater facilities in Europe. This comparison focuses on energy efficiency, biogas utilization, and environmental performance, notably Global Warming Potential (GWP).

3.4.1 Energy Self-Sufficiency through Biogas

Sopron WWTP demonstrates a strong level of energy recovery from anaerobic digestion compared with facilities of similar scale. Based on measured electricity balances, biogas-derived electricity supplied 56.1% of total demand in 2018, 42.8% in 2019, and 50.8% in 2020. These values reflect both biogas utilisation efficiency (535,265–673,783 m³/year) and stable CHP performance (1.36–1.74 GWh/year).

When compared to other European WWTPs applying anaerobic digestion, Sopron performs competitively. Barcelona WWTP (Bravo & Ferrer, 2011) reported substantially lower renewable self-generation because a significant share of biogas was diverted to natural gas boilers rather than CHP electricity. Similarly, Daugavgrīva WWTP (Riga) achieved only ~3% reduction in climate impact through biogas recovery (Romagnoli et al., 2009), far below Sopron's ~30–60% GWP reduction resulting from offsetting grid electricity.

These comparisons indicate that Sopron's anaerobic digestion system is highly effective for a medium-sized plant, both in terms of energy recovery and its contribution to reducing environmental burdens under gate-to-gate system boundaries.

3.4.2 Global Warming Potential (GWP)

The Sopron WWTP reduced its GWP from 998,000 kg CO_2-eq in 2018 to 384,000 kg CO_2-eq in 2020, representing a 61.5% decrease over three years.

Comparable figures from literature:

- Tsangas et al. (2023) found that upgrading to biogas-based systems in Greek WWTPs reduced GWP by ~40%, but Sopron's reduction was steeper.
- Viotti et al. (2024) observed that combining biogas with photovoltaics led to an even more dramatic reduction in fossil energy dependence, though the addition of PV is not yet implemented at Sopron.
- Karolinczak (2023) showed that co-digestion of sewage sludge with municipal solid waste could further reduce GWP by up to 50% compared to mono-digestion—an opportunity for further improvement in Sopron.

Sopron's GWP trend reflects both process optimization and efficient biogas utilization, positioning it at the higher-performing end of the spectrum.

Additional Benchmarking:

To contextualize Sopron WWTP's performance within broader European ranges, the plant's energy intensity (0.39–0.55 kWh/m³) and GWP per m³ (0.06–0.18 kg CO_2-eq) fall within the lower end of published EU values. Previous studies report energy intensities of 0.45–0.90 kWh/m³ for medium-scale WWTPs and GWP values commonly ranging between 0.10 and 0.45 kg CO_2-eq per m³. Sopron's comparatively low GWP is primarily linked to its high biogas utilisation rate and reduced reliance on grid electricity. These results indicate strong operational efficiency relative to similar EU facilities.

3.5 Effectiveness of Biogas Utilization

The utilization of biogas produced from anaerobic digestion is a central contributor to the plant's sustainability performance. Anaerobic sludge treatment enables the capture of methane-rich biogas, which is converted on-site into electricity and heat through a combined heat and power (CHP) unit. Based on measured operational data, biogas-derived electricity supplied 56.1% of total plant electricity demand in 2018, 42.8% in 2019, and 50.8% in 2020. These

values indicate that, across all three years, approximately half of WWTP's energy needs were met through internal biogas recovery, substantially reducing reliance on grid electricity and the associated upstream emissions.

Sensitivity analysis further highlights the importance of biogas optimization. A 10% increase in biogas production was estimated to reduce GWP by approximately 1.8%, whereas a 10% decrease led to an increase of around 1.3%. These findings suggest that improving anaerobic digestion performance—through enhanced sludge stabilization, better feedstock management, and operational optimization—could yield additional environmental and economic benefits.

Overall, the results demonstrate that integrating biogas recovery within wastewater treatment not only strengthens energy autonomy but also provides significant climate mitigation potential. This positions Sopron WWTP as a strong example of sustainable wastewater management for medium-scale facilities.

3.6 Interpretation of Results

The findings of the Life Cycle Assessment (LCA) for the Sopron Wastewater Treatment Plant (WWTP) demonstrate notable improvements in environmental sustainability between 2018 and 2020. Reductions in Global Warming Potential (GWP) and improved energy performance reflect more efficient biological treatment, more stable sludge management operations, and optimized overall process performance.

A key achievement is the plant's ability to meet 43–56% of its annual electricity demand through biogas-based CHP generation, significantly reducing dependence on grid electricity and associated upstream emissions. This level of energy autonomy aligns with EU objectives for increasing renewable energy use within essential infrastructure sectors. Over the study period, GWP decreased substantially—from 998,000 kg CO_2-eq in 2018 to 384,000 kg CO_2-eq in 2020—highlighting the combined effect of reduced electricity demand, improved biogas utilization, and steady operational optimization.

Overall, the Sopron WWTP demonstrates that medium-sized municipal plants can achieve meaningful progress toward climate mitigation and energy sustainability by integrating anaerobic digestion with efficient energy management practices.

3.7 Limitations

Despite the robustness of the LCA methodology applied in this study, several inherent limitations should be acknowledged. One of the most persistent challenges in wastewater-related LCA is the uncertainty in life cycle inventory (LCI) data and life cycle impact assessment (LCIA) models. Alyaseri and Zhou (2019) highlighted that uncertainties from data quality, allocation choices, and LCIA methods can introduce significant variability in LCA results—up to 63% in sludge incineration processes alone (Alyaseri & Zhou, 2019).

Additionally, subjective modeling choices, such as system boundaries, impact categories, and normalization methods, play a major role in influencing LCA outcomes. A recent study emphasized that different cultural or philosophical standpoints (e.g., egalitarian vs.

individualist) can lead to divergent LCA conclusions even when analyzing the same sludge treatment processes (Alyaseri & Zhou, 2024).

Corominas et al. (2013) further noted that inconsistent application of ISO standards across studies, and the lack of regionalized emissions factors, continue to limit the comparability and transparency of wastewater LCAs. They call for stricter standardization, improved regional modeling, and better integration with decision-making processes (Corominas et al., 2013).

Given these findings, the results of this LCA should be interpreted as an indicative environmental performance profile, rather than an absolute ranking. Future work should include stochastic uncertainty analysis, and where possible, the use of real-time emissions data to improve data quality.

4 Conclusion

The Life Cycle Assessment (LCA) of the Sopron Wastewater Treatment Plant (WWTP) demonstrates substantial progress in environmental sustainability between 2018 and 2020. Improvements in energy performance, particularly through biogas utilization, played a central role in reducing the plant's overall environmental impacts. Across the three-year period, biogas-derived electricity supplied between 42.8% and 56.1% of total plant electricity demand, significantly reducing reliance on grid electricity and the associated upstream emissions.

The Global Warming Potential (GWP) decreased markedly from 998,000 kg CO_2-eq in 2018 to 384,000 kg CO_2-eq in 2020, reflecting the combined influence of enhanced biogas utilization, reduced electricity consumption, and more efficient biological treatment. These findings highlight the effectiveness of integrating anaerobic digestion with energy-efficient operational practices in medium-sized municipal wastewater treatment plants.

Despite these positive outcomes, several areas offer potential for further optimization. The present study applied a gate-to-gate system boundary, and future work would benefit from expanding the assessment to include upstream and downstream processes, such as chemical production, sludge transport, and end-use pathways. Additionally, more detailed monitoring of biogas quality, digester performance, and operational variability would help refine emission estimates and reduce uncertainty.

Overall, Sopron WWTP illustrates how targeted operational improvements and energy recovery strategies can meaningfully reduce environmental burdens. Continued optimization, together with broader system-boundary analysis can support the plant's progression toward carbon-neutral wastewater treatment in alignment with national and EU sustainability objectives.

Reference

Alyaseri, I., & Zhou, J. (2019). Handling uncertainties inherited in life cycle inventory and life cycle impact assessment method for improved life cycle assessment of wastewater sludge treatment. *Heliyon, 5*(11), e02793. https://doi.org/10.1016/j.heliyon.2019.e02793

Alyaseri, I., & Zhou, J. (2024). Impact of subjective choices on life cycle assessment of wastewater sludge treatment processes. *Sustainability, 16*(24), 11125. https://doi.org/10.3390/su162411125

Bravo, L., & Ferrer, I. (2011). Life cycle assessment of an intensive sewage treatment plant in Barcelona (Spain) with focus on energy aspects. *Water Science and Technology, 64*(2), 440–447. https://doi.org/10.2166/wst.2011.522

Corominas, Ll., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S., & Shaw, A. (2013). Life cycle assessment applied to wastewater treatment: State of the art. *Water Research, 47*(15), 5480–5492. https://doi.org/10.1016/j.watres.2013.06.049

European Commission. (2019). *The European Green Deal (COM/2019/640 final).* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640

European Commission. (2022). *Proposal for a Directive of the European Parliament and of the Council concerning urban wastewater treatment (recast) (COM/2022/541 final).* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022PC0541

European Union. (1991). *Council Directive 91/271/EEC of 21 May 1991 concerning urban wastewater treatment.* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271

Herrmann, I. T., & Moltesen, A. (2015). Does it matter which life cycle assessment (LCA) tool you choose? A comparative assessment of SimaPro and GaBi. *Journal of Cleaner Production, 86*, 163–169. https://doi.org/10.1016/j.jclepro.2014.08.004

Kampschreur, M. J., van der Star, W. R. L., Wielders, H. A., Mulder, J. W., Jetten, M. S. M., & van Loosdrecht, M. C. M. (2008). Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment. *Water Research, 42*(3), 812–826. https://doi.org/10.1016/j.watres.2007.08.022

Karolinczak, B. (2023). Life cycle assessment of sewage sludge mono-digestion and co-digestion with the organic fraction of municipal solid waste at a wastewater treatment plant. *Science of the Total Environment, 907*, 167801. https://doi.org/10.1016/j.scitotenv.2023.167801

Romagnoli, F. (2009). Life cycle assessment of Daugavgriva wastewater treatment plant. *Scientific Journal of Riga Technical University, 5*, 1–8. https://doi.org/10.2478/v10145-009-0012-9

Silva, D. A. L., Azevedo, F., & Medeiros, G. (2019). Why using different life cycle assessment software tools can generate different results for the same product system? A cause–effect

analysis of the problem. *Sustainable Production and Consumption, 20*, 254–271. https://doi.org/10.1016/j.spc.2019.07.005

Tsangas, M., Noutsopoulos, C., & Mamais, D. (2023). Life cycle assessment of municipal wastewater treatment. *Chemosphere, 341*, 139952. https://doi.org/10.1016/j.chemosphere.2023.139952

Viotti, P., Pastore, C., & Stanzione, D. (2024). Life cycle assessment methodology applied to a wastewater treatment plant. *Water, 13*(20), 2807. https://doi.org/10.3390/w16081177