HUNGARIAN JOURNAL OF
INDUSTRY AND CHEMISTRY
Vol. 53(2) pp. 17–30 (2025)
hjic.mk.uni-pannon.hu
DOI: 10.33927/hjic-2025-13

LIFE CYCLE ASSESSMENT OF TECHNOLOGICAL SHIFTS IN MUNICIPAL WASTEWATER TREATMENT PLANTS

RÉKA HARASZTINÉ HARGITAI[1]*, VIKTOR SEBESTYÉN[1], BALÁZS VOLF[2] AND VIOLA SOMOGYI[1]

1 Sustainability Solutions Research Laboratory, University of Pannonia, Egyetem u. 10, Veszprém, 8200, HUGARY
2 BAKONYKARSZT Zrt., Pápai u. 41, Veszprém, 8200, HUNGARY

The challenges faced by municipal wastewater treatment plants (WWTPs) to improve effluent quality while reducing environmental impacts are increasing. This study employs a Life Cycle Assessment to evaluate the development of effluent water quality and overall environmental impacts through seven years of technological advancements at a WWTP using real world data. Scenarios include biogas optimization, transitioning to biological phosphorus removal, solar energy integration, optimized effluent control and hypothetical quaternary wastewater treatments (ozonation and sequential H_2O_2 treatment). Transitioning to biological phosphorus removal reduced chemical use by 26.2% and achieved the highest nutrient removal efficiency but increased energy consumption, slightly raising fossil depletion (FD). Solar energy reduced FD by 18.4% and contributed 7.75% of energy needs, albeit with seasonal limitations. Optimized effluent control achieved the highest level of nutrient removal, improving freshwater eutrophication by 41.4% but increased sludge production by 10.4%, leading to a 23.9% rise in metal depletion. Ozonation significantly increased environmental burdens, while sequential H_2O_2 treatment had less of an impact, offering future potential for wastewater reuse. The findings underscore the importance of balancing energy, chemical use and effluent quality with biogas optimization playing a key role in reducing flaring. This study highlights the trade-offs inherent in WWTP upgrades and provides actionable insights into optimizing environmental performance.

Keywords: Life Cycle Assessment, wastewater treatment, technology improvement, water circularity

1. Introduction

In light of the new Urban Wastewater Treatment Directive [1], the pressure on municipal wastewater treatment plants (WWTPs) to enhance treatment efficiency while striving for energy neutrality is increasing once again. Biological wastewater treatment systems as mature technologies, effectively remove macronutrients to meet water quality requirements under various conditions [2]. When coupled with anaerobic digestion, organic matter can be converted into energy [3], potentially enabling the system to achieve energy neutrality or even a net-positive energy balance [4]. The utilization of agro-wastes in biohydrogen fermentation not only enhances waste management efficiency but also contributes to the integration of renewable energy sources in wastewater treatment plants, supporting the achievement of energy neutrality [5]. However, insufficient methane storage may lead to unintended greenhouse gas emissions [6]. On the other hand, zero-emission technologies in wastewater treatment have the potential to reduce the carbon footprint by 69.7% [7].

Wastewater treatment plants must also prepare treated water for reuse. For example, treated effluent can alleviate water stress [8] by substituting freshwater resources for irrigation purposes [9]. Many disinfection methods, such as ozonation, can simultaneously inactivate bacteria and oxidize micropollutants [10], addressing the challenges in facilitating wastewater reuse.

Addressing the aforementioned objectives requires an integrated evaluation of sustainability targets and operational modifications to ensure that new technologies are both sustainable and efficient. Life Cycle Assessment (LCA) provides a comprehensive framework for analyzing the environmental impacts of such technological shifts and comparing development alternatives [11]. While new technologies require additional resources, leading to greater environmental impacts [12], these can be balanced out by the subsequent benefits of improved effluent quality [13].

Benchmarking different wastewater treatment plants or technologies requires careful deliberation either as a result of local characteristics [14] or differences between applied technologies [15]. Inventory data are

Received: 25 April 2025; Revised: 6 May 2025;
Accepted: 6 May 2025
*Correspondence: hargitai.reka@mk.uni-pannon.hu

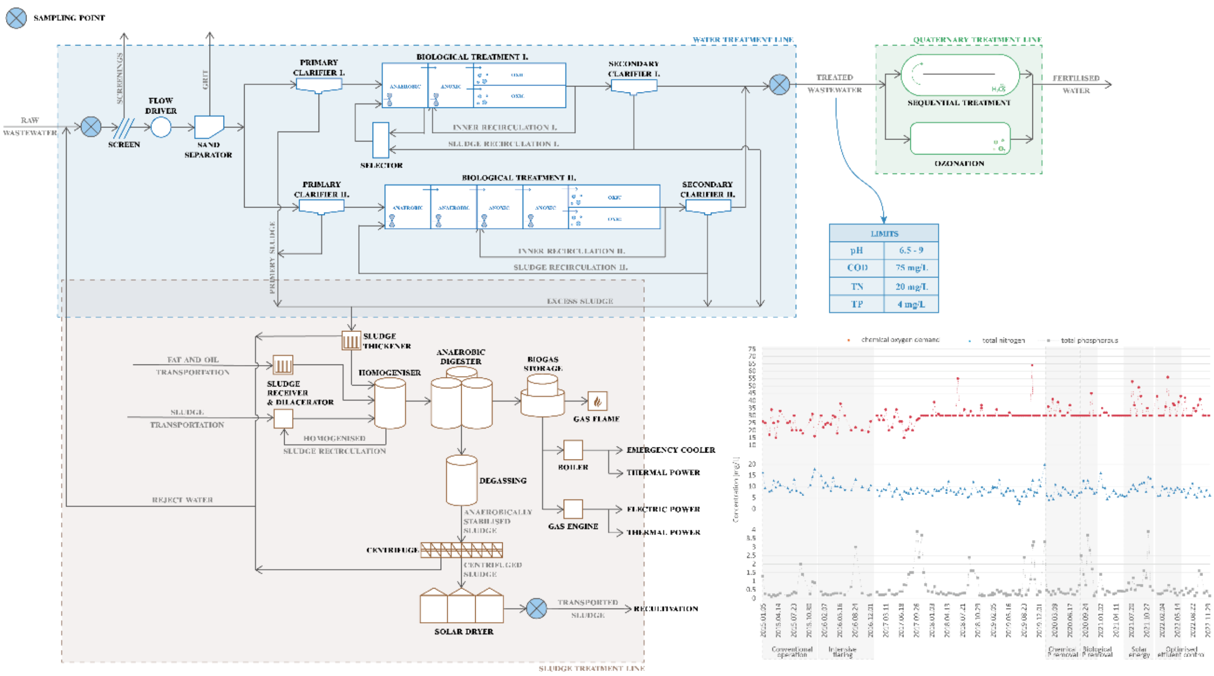


Figure 1: Structure of the analyzed wastewater treatment plant, highlighting the water and sludge treatment line

In the lower right quadrant, the quality of the effluent wastewater is shown, the former divided between the two biological processes.

created from monthly or yearly averages [11] and while the temporal variations beyond one year might not be substantial [16], they might add to the deviation caused by technological interventions. In the planning phase it could be sufficient to use the yearly averages of the key performance indicators to identify the impacts potential technological interventions would cause [17]. However, when analyzing the previous environmental performance of a facility that had continuously been upgraded over the years, fluctuations in the quality and quantity of influent may overshadow the impacts on technological changes. Recent studies have highlighted the importance of integrating advanced monitoring systems to better record these variations and improve the accuracy of environmental impact assessments in wastewater treatment processes [18].

This study aims to fill a critical gap in the literature by evaluating the environmental impacts of real-world technological advancements in WWTPs over a seven-year-long period. Using time-series operational data, the authors assess how modifications such as transitioning to biological phosphorus removal, reducing reliance on chemical additives and integrating renewable energy sources affect the overall sustainability of the plant. Furthermore, the study extends its scope to model future quaternary treatment scenarios, such as ozonation and sequential hydrogen peroxide treatment, in order to assess their feasibility of facilitating wastewater reuse.

2. Materials and methods

The impacts of technological changes made in a real wastewater treatment plant were examined in terms of Life Cycle Assessment. The criteria for selecting the facility was a robust operation ensuring satisfactory effluent water quality, distinct technological interventions that do not overlap with each other as well as the availability of and access to all data necessary for carrying out a LCA. Long-term data of operation along with detailed descriptions of developments within the chosen WWTP were collected and analyzed. The structure of the plant together with the flow rates of influent and effluent wastewater are shown in *Figure 1*. Details of the operation are provided in Section 2.1.

After processing the data, six periods were selected where the effect of technology change was measurable and all the data necessary for model (scenario) identification were available. Based on that, six different simulations were carried out with the corresponding measurement data as their inputs to assess the overall impacts of the scenarios. Two quaternary treatment solutions were added alternatively to the last configuration to evaluate the lifecycle impacts of potential future investments that will be necessary should the wastewater be further used for agricultural or other purposes.

The study was carried out following the principles of the international standards ISO 14040:2006 [19] and ISO 14044:2006 [20]. Following the established standards, the initial step was to define the goal and scope of the analysis. This was followed by the collection and analysis of data. The third phase was the impact assessment which was then followed by an evaluation of the results. The Sphera modelling environment (software version 10.6.1.35) [21] was employed as it offers a comprehensive database on wastewater treatment plants and the materials used. The data utilized in the research

Table 1. Primary data on the technology change per 1 m^3 of treated water. Different periods were named after the dominant new technology

Case	Influent [m^3]	C:N:P	Flared biogas [m^3]	Electricity consumed [kWh]	Electricity generated by gas engines [kWh]	Electricity generated by solar panels [kWh]	Chemicals for P removal [L]	Chemicals for sludge dewatering [L]	Transported dried sludge [kg]
Conventional operation	1.16	100:8.29:1.21	-	0.35	0.29	-	0.02	45.48	2.06
Intensive flaring	1.14	100:7.31:1.26	0.54	0.29	0.43	-	0.01	38.39	1.91
Chemical P removal	1.19	100:7.77:1.20	0.06	0.36	0.48	-	0.01	60.84	2.66
Biological P removal	1.20	100:7.77:1.20	0.04	0.31	0.41	-	-	44.90	2.29
Solar energy	1.17	100:7.80:1.18	0.01	0.31	0.42	0.06	-	54.28	2.10
Optimized effluent control	1.15	100:10.07:1.08	0.03	0.25	0.49	0.06	-	67.38	2.32
Ozonation quaternary treatment	1.15	100:10.07:1.08	0.03	0.25	0.49	0.06	-	67.38	2.32
Sequential H_2O_2 quaternary treatment	1.15	100:10.07:1.08	0.03	0.25	0.49	0.06	-	67.38	2.32

were collected during the operational period. The authors did not consider the periods of construction and downtime.

2.1. *Technological details of the evaluated municipal wastewater treatment plant*

This section provides information on the chosen municipal wastewater treatment plant based on the technological data between the years of 2015 and 2022. The data were sourced from certified meter readings and PLC data recordings. On-site laboratory measurements were employed to derive quality parameters for raw wastewater, treated water and compost. An overview of the technological data is shown in *Table 1*.

At the time of writing, the plant was capable of biological nutrient removal equipped with anaerobic digesters and solar panels to generate energy. The flow rates during the examined period ranged between 12,331 and 13,788 m^3/d. Municipal wastewater from a number of towns and other settlements was treated as well as wastewater from industrial sources. As can be seen in *Figure 1*, two similar parallel lines utilizing activated sludge technology consisting of anaerobic, anoxic and oxic treatment tanks were used.

On average, the influent was divided between the first and second line in a 52.24:47.62 ratio but varied over time to meet operational needs. The operating hours of the blowers were split in the proportions of 54.27% and 50.40% between the aeration system of the two trains with four nozzles on the first line and five on the second. Due to the different structures and years of construction, the energy consumption was distributed differently, that is, 69.47% of it was consumed by the first line compared to just 30.53% by the second.

The quality of the wastewater fluctuated notably over the examined time period in line with the monthly and seasonal changes that are usually present in a municipal WWTP (*Figure 1*). On average, the effluent contained 1,016 mg/L COD, 142 mg/L TN and 12.37 mg/L TP with maximum values of 3,156 mg/L, 142 mg/L and 34 mg/L, respectively. The effluent contained 30.49 mg/L COD, 8.59 mg/L TN and 0.67 mg/L TP on average with peak concentrations of 64 mg/L, 19.9 mg/L and 3.9 mg/L occurring only seldomly, respectively. However, even the maximum values were below the permissible amount, namely 75 mg/L for COD, 20 mg/L for TN and 4 mg/L for TP [22], resulting in high removal percentages of the macronutrients.

As a reference, the limit values are highlighted, moreover, the effluent concentrations and respective nutrient ratios can be seen in *Figure 1*. The figures include the identified scenarios of technological additions which will be discussed in Section 2.2.

Following the sludge line, the primary and secondary sludge was sent to the anaerobic digesters after being homogenized. The digesters accepted a variety of sludge, including primary and excess sludge, as well as mixed wastes, e.g. sludge from other plants, fat and oil from industries. The quantity and quality of the biogas was contingent upon the type of sludge. Between 2015 and 2022, 0.20 to 0.69 m^3 of biogas was produced per m^3 of treated water, equating to an average of 1.32 kWh of electricity recovery per m^3 of biogas. Furthermore, the heat generated by the biogas production process is utilized for heating buildings.

The residual sludge from the digesters was transferred to a degasser before the anaerobically stabilized sludge was dewatered. Although the quality parameters of the dried sludge met the quality requirements of the compost [23], it was not utilized for composting purposes, only for reclamation.

To assist the different processes both in the biological tanks and in the solids line, chemicals can be added at three points in the facility. The first is to the biological tanks where an aluminum salt solution containing polymerized iron was used to reduce the phosphorous content before the plant turned to full biological removal. A total of 0.01-0.02 L of chemicals were utilized to treat 1 m^3 of wastewater prior to that. The second is to the thickener to remove H_2S. Poly-electrolyte, and before the end of 2020, ferric(III) chloride, was added to the sludge line. For foam control, an antifoaming agent and polyelectrolyte were added to the centrifuge. During the overall treatment process, 2.22 kg of dried sludge (15.3-18.3% d.m.) was generated while applying an average of 51.88 L of chemicals.

Over the years, improvements have been made to reduce the operating costs and further increase the removal efficiency while striving to achieve energy neutrality. In addition to utilizing biogas, a solar farm was developed. Further additions to the aforementioned detailed technology are discussed in Section 2.2 with a timeline and key points.

2.2. Identification of technological shifts using the LCA model

Based on the collected data, the operating periods were identified and considered for LCA models to better understand the impacts of municipal wastewater treatment using different configurations within the same technological set-up which is the reality of a facility serving the population. The overlap between maintenance, upgrades and testing periods led to fluctuating data, e.g. in terms of the energy consumption and operating hours of devices, which were omitted from the analysis.

The scenarios have been delineated following the technological shifts as follows:

Conventional operation: This configuration is described in detail in the previous section. The classical A2/O system serves as the baseline for comparing scenarios with a pre-treatment stage, two parallel biological treatment reactors and an anaerobic digestion phase. The impacts per 1 m^3 of treated water in terms of the conventional operation are shown in *Appendix A*.

Intensive flaring: In the context of this study, intensive flaring refers to introducing biogas flaring without implementing measures to minimize its quantity which happened in 2016. Even though subsequent technological developments led to a more controlled approach to biogas flaring in order to achieve the maximum level of efficiency in terms of energy recovery, they were not considered in this study.

Chemical P removal: Chemical P removal means that the biological processes were assisted with chemical means. The first two thirds of 2020 (January-August) was the last period when phosphorous removal was not achieved solely by microorganisms and thus serves as a comparison to the next stage. Additionally, this scenario is linked to the optimal performance of the gas engine.

Biological P removal: Starting from September 2020, the utilization of chemicals on the biological line was entirely discontinued. This scenario was named biological P removal which took place between July and December 2020. Similarly to the previous scenario, the gas engine performance was optimal.

Solar energy: The solar energy scenario corresponds to the year 2021 when solar panels were installed to reduce the amount of electricity drawn from the grid, meanwhile, the rate of energy consumption increased.

Optimized effluent control: The final real-life scenario is characterized by the best effluent quality. Regarding the timeline, this scenario is based on the year 2022, by which time operation of the previous modifications had already become established. Furthermore, the proportion of green energy (biogas and solar) was augmented.

Ozonation quaternary treatment: As a hypothetical scenario, ozonation, a quaternary treatment solution, was added to the plant to facilitate further use of the treated water in alignment with prevailing development trends.

Sequential H_2O_2 quaternary treatment: As an alternative to ozonation treatment, a sequential H_2O_2 quaternary treatment was investigated. The method utilizes sunlight and H_2O_2 together with the solar photo-Fenton process with Ethylenediamine-N,N'-disuccinic acid (EDDS) at a neutral pH in a raceway pond reactor. According to [24], this method has reduced the environmental impact more than ozonation.

Data on the Hungarian energy mix [25] were taken from the literature and other information was obtained from the Sphera database [21] such as data regarding electricity from solar thermal energy, the components of the chemicals and the quality of the material flows. The ReCiPe method [26] was chosen as a comparative analysis. The study by Karolinczak et al. [27] was referred to in order to determine the impact data of biogas and the impacts of quaternary treatment were calculated based on the results published by Maniakova et al. [24].

The system boundaries of all the scenarios are presented together in *Figure 1*. Although the functional unit was chosen to be 1 m^3 of treated water to align with the prevailing literature, in certain instances the results are also presented in other forms, e.g. /kWh of biogas.

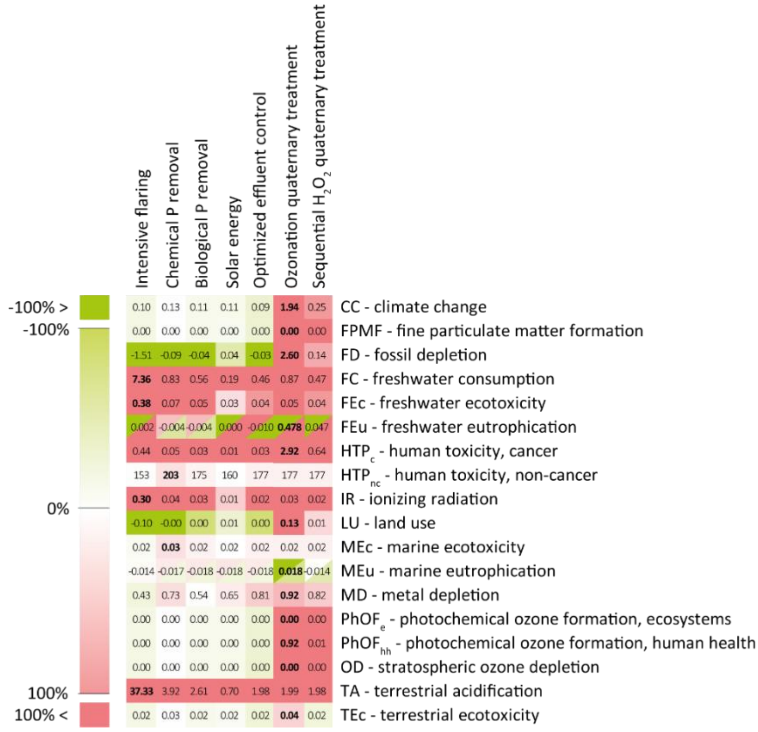


Figure 2: Comparison of the scenarios against the Conventional operation scenario

In the upper triangle of the cells, a negative change is denoted in red while a positive one is indicated in green. The coloring is reversed for the lower triangle, as a change from negative to positive represents a negative impact on the environment (FEu, MEu). The scatter of values above 100% and below -100% are shown in a darker shade for both negative and positive changes.

3. Results

3.1. Performance evaluation in terms of effluent

The mean efficiency values of the WWTP over the whole examined period were 97.2%, 88.8% and 93.7% for COD, TN and TP, respectively, suggesting that the plant performed excellently even in the baseline "Conventional operation" scenario (COD: 98.0%, TN: 87.6%, TP: 92.3%). The best performance was achieved in 2022 (96.6%, 90.5%, 95.7%). Even though the COD removal rates gradually decreased from 98.0% to 96.6%, both TN and TP removal slightly improved during the examined time period.

The changes in performance can be attributed partly to the interventions and partly to the influent nutrient ratios. The best removal efficiencies were achieved at COD:TN:TP ratios of approximately 100:10:1 which coincided with those at the end of the study period. Although the literature suggests that the ratio of 100:5:1 is appropriate for municipal wastewater treatment [27], others have found that 100:11:2 is also suitable [28].

3.2. Performance evaluation in terms of life cycle aspect

The scenarios are discussed in the same order listed in Section 2.2. To illustrate changes in environmental impacts, a heat map chart was used. It should be noted that to interpret the data, a dual representation was applied in instances where the data series yielded negative values (*Figure 2*). The upper triangle of the cells indicates the method employed for the other impacts. The negative gradient is denoted by red, while the positive one is indicated by green. The scattering of values above 100% and below -100% yielded a darker shade visible when the gradient was both positive and negative. In the cells, coloring is reversed for the lower triangle as a change from negative to positive represents a negative impact on the environment.

3.2.1. Conventional operation

The main material flows associated with the impacts per m^3 of treated water are shown in *Appendix A* together with the results from other scenarios. Each indicator is highlighted in a specific color indicating the main drive within that impact category. Since the majority of the impact categories (ten out of eighteen) are influenced by energy consumption, the substantial amount used by the biological reactors (first line 49.30% and second line 26.32%) was notable in the results from the Conventional operation scenario (*Appendix B*). The impacts related to the sludge line made up 3.92%, the receiving station 0.54% and the other energy-consuming activities of the plant accounted for the remaining 19.92%.

Biological treatment dominated the freshwater and marine eutrophication (FEu, MEu) indicators accounting for 46.92% of the first line and 53.09% of the second, moreover, only 0.01% was related to other activities. In terms of indicator values, this equated to $-2.46 \cdot 10^{-3}$ kg P eq. and $-1.45 \cdot 10^{-2}$ kg N eq. per m^3 in the Conventional operation. In terms of the remaining six out of eighteen impact categories, the sludge line dictated the results with values between 98.74% and 100.00%: human toxicity potential cancer (HTP_c) and non-cancer (HTP_{nc}), freshwater consumption (FC) and ecotoxicity (FEc), marine ecotoxicity (MEc) and metal depletion (MD). The remaining less than 1.5 % was associated with the biological reactors.

Considering MD and FC, the chemicals in the sludge (for P removal, foam control and sulfide removal) contributed 99.97% and 98.69%, while the activity of microorganisms was responsible for only 0.02% and 0.99% of the total values of the parameters, respectively. Furthermore, the addition of chemicals did not have an effect on the other parameters. It should be noted that even though the amount of chemicals can be reduced, they are necessary to counteract the impacts of potential disturbances in terms of biology and essential with regard to sludge dewatering. The HTP_{nc} indicator stands out among the indicators determined by the sludge characteristics with a value of 156.93 kg 1,4-DB eq. per FU, due to the manner in which the dried sludge is disposed of. The elements in the sludge contributing to the indicator are 98% metallic with the remaining 2% comprising semi-metallic and non-metallic elements.

3.2.2. *Intensive flaring*

The main change in the second scenario compared to the first one was that 71.54% of the biogas was flared in an intensive manner due to uneven production and subsequent safety concerns. Regarding the timeline, this scenario covers the year 2016 in its entirety. As a comparison, 0.54 m^3 of biogas per 1 m^3 of treated water was flared while in other years this value was between 0.01 and 0.06 m^3 of gas/m^3 of water. The energy consumption was 0.72 kWh per m^3 of treated water, 59.32% of which was produced from the biogas and the remaining amount purchased from the electrical network. The impact of flaring can be observed across all impact types (*Figure 2*). Additionally, the annual wastewater flowrate increased by 1.85%, while the influent load between the two lines became more balanced with the first line receiving 50.86% and the second 48.28%. The influent C:N:P ratio changed from 100:8.29:1.21 to 100:7.31:1.26 which led to an increase in energy consumption, however, a reduction of 15.58% in chemical usage was observed. Although the energy consumption of the receiving station reduced to 51.42% (from 0.0035 kWh to 0.0018 kWh per m^3 of treated water), this was only associated with a reduction in the influence of the station on the impact categories from an average of 0.30% to 0.08%.

Six of the impact indicators that are determined by energy consumption (climate change (CC), fine particulate matter formation (FPMF), photochemical ozone formation on ecosystems ($PhOF_e$) and human health ($PhOF_{hh}$), stratospheric ozone formation (OD), terrestrial ecotoxicity (TEc)) resembled those from the Conventional operation scenario. The waterline accounted for 65.40% while the sludge line accounted for 3.73%, moreover, 30.62% was due to other activities. Despite the loss of biogas due to flaring, an average reduction of 17.04% per 1 m^3 of treated water in the values of the aforementioned parameters was consistent with the change in energy sources. While the energy consumption increased by 11.54%, the proportion of utilized biogas also increased from 45.30% (0.29 kWh/m^3 of treated water) to 59.32% (0.43 kWh/m^3 of treated water).

In the Intensive flaring scenario, the two indicators concerning eutrophication reflected the change in the biological load. Even though the MEu value decreased by 5.14%, it remained within the favorable range. The FEu value shifted from within the negative range (favorable condition) to the positive range (unfavorable condition) compared to the previous range of $-2.46 \cdot 10^{-3}$ kg P eq. to $2.18 \cdot 10^{-3}$ kg P eq. per 1 m^3 of treated water.

A shift in both the manner by and extent to which technological categories dominated certain impact indicators was observed. The heavy impact of sludge management on HTP_{nc}, MEc and MD remained the same while flaring gained a substantial level of influence in HTP_c, FC and FEc accounting for 94.44 to 99.47%. Regarding FC, Intensive flaring even masked the positive effect of reduced chemical usage which defined 98.69% of the FC category in the Conventional treatment scenario, whereas in the intensive flaring scenario, the share of the chemical dosing effects reduced to 0.52%. As a result, FC increased from 0.05 to 7.36 m^3 per FU.

The introduction of biogas flaring led to a change in the composition of four additional impact categories: fossil depletion (FD), ionizing radiation (IR), land use (LU) and terrestrial acidification (TA). The share of flaring ranged from 97.0% (IR) to 109.0% (LU) compared to their overall values. Percentages over 100 were associated with the offset effect of the biological line: -2.72% for FD and -5.91% for LU. The most prominent change was experienced in the case of TA from $1.25 \cdot 10^{-4}$ kg SO_2 eq. to 37.33 kg SO_2 eq. per FU.

3.2.3. *Minimizing the amount of chemicals used for biological treatment*

Phosphorus was removed by both biological and chemical means during the earlier periods. However, in 2020, the management decided to eliminate chemicals from the process. This process can be divided into two phases. During the initial period, which spanned the first eight months of the year, a gradual reduction in chemical phosphorous removal was observed and was named the Chemical P removal scenario for the sake of simplicity. In contrast, the second half was characterized by the full implementation of biological phosphorous removal and named as the Biological P removal scenario.

The performance of both scenarios was primarily determined by a reduction in the value of flared biogas from 0.54 to 0.06 m^3 per 1 m^3 of treated water, which represented a decline of nearly 90%. Energy consumption increased from 0.72 to 0.85 kWh during the

Chemical P removal scenario and returned to 0.72 kWh in the Biological P removal scenario. The self-produced energy ratios were 57.28 and 56.37%, respectively. Furthermore, a change in aeration was observed, namely an increase to 122.45 m^3 during the Chemical P removal scenario from 98.58 m^3 in the Intensive flaring scenario before declining to 70.68 m^3 during the Biological P removal scenario. The relationship between aeration and energy consumption was evident with the waterline accounting for approximately 92.65 to 98.74% of the total volume. A gradual reduction in the chemicals used led to a continuous and simultaneous increase in energy consumption and biological respiration. This transition can be considered gradual with biological adaptation occurring in a similar manner.

Both P removal scenarios were distinguished by sludge swelling, the dominance of filamentous organisms and poor settling. In mid-February, the nutrient composition of the wastewater was 100:3.9:1, caused by a COD concentration of 2,042 mg/L. In mid-June, the ratio shifted to 100:4.3:0.8 with a COD concentration of 1,548 mg/L. By mid-July, it had decreased to 100:3.5:1.4, with a COD concentration of 1,179 mg/L. In light of the imbalance between COD and nitrogen, it is understandable that organisms reacted to the situation in terms of filamentation along with increased energy consumption as the proportional increase in oxygen concentration, in conjunction with an increase in organic matter, serves to prevent the proliferation of filamentous organisms [29]. The quantity of chemicals utilized for the sludge treatment increased by approximately 50% compared to the Conventional operation scenario, which is closely related to sludge swelling due to the extracellular polymeric substances (EPS) produced by filamentous microorganisms [30].

Despite the aforementioned operational challenges, both the Chemical P removal and Biological P removal scenarios performed better when compared to the Intensive flaring scenario as can be seen in *Figure 2*. Moreover, the indicators that exhibited a significant increase due to flaring (FC, FEc, HTP_c, IR and TA) decreased by 82-89%. However, the increase in electricity consumption at the beginning of the year resulted in a 23% increase in the energy-related impacts (CC, FPMF, $PhOF_e$, $PhOF_{hh}$, OD, TEc) which translated to 2.21% higher values compared to the Conventional operation scenario.

The indicators related to eutrophication improved due to the higher removal efficiency during this period (90% N and 94% P), which was approximately 2% better than in the Conventional operation scenario. A slight difference between the two P removal scenarios was observed due to the change in flow rates with FEu and MEu decreasing by 2.19 and 1.26% in the Biological P removal scenario, respectively.

Nevertheless, it is also worthwhile contrasting between the two scenarios in terms of technological advancements. The blowers operated for 43.31% fewer hours per day during the Biological P removal scenario, resulting in a 42.47% reduction in energy consumption. Consequently, this led to a 12.91% decrease in the effects influenced by energy (CC, FPMF, FEc, $PhOF_e$, $PhOF_{hh}$, OD, TEc). Additionally, a 26.20% reduction in the amount of chemicals used in the sludge line was observed during the Biological P removal scenario. Moreover, the 32.14% reduction in biogas flaring contributed to mitigation of the effects.

Furthermore, the reduction in the amount of chemicals used for phosphorous removal resulted in a 26.15% decrease in the value of MD. For the impacts affected by biogas flaring, a reduction in the impact value was observed, ranging from 28.41 to 51.24%. In the case of MEc and HTP_{nc}, the impacts are still determined by the sludge treatment. Between the two scenarios, a decrease of 14.03 and 14.11%, respectively, was observed, although the former showed a 30% increase compared to the Intensive flaring scenario. This can be attributed to the quantity of treated sludge initially increasing from 1.91 to 2.66 kg before subsequently decreasing to 2.29 kg per 1 m^3 of treated water.

3.2.4. Solar energy

As a supplementary energy source, solar panels were installed producing 0.06 kWh energy per m^3 of treated water. While the amount of energy generated was lower than the 0.42 kWh generated by gas engines from biogas per FU, it accounted for 7.75% of the total energy consumption during the sunny periods as opposed to 4.13% over the entire year. In the Conventional operation scenario, 54.70% of the energy consumed was purchased from the electrical network, which was gradually reduced. During the Solar energy scenario (15th June to 31st December 2021), the percentage remained at 39.09% compared to as high as 46.62% over the entire year due to gas engine failures. The failures were offset for by the purchase of electricity.

The compositions of the energy consumption in the different scenarios (*Appendix C*, left) as an indication of the fraction of purchased electricity during 2020 and 2021 (when the different scenarios did not cover the whole year) are indicated in red in *Appendix C*. On the right-hand side, the amount of energy generated and purchased daily is shown with the flared biogas given as negative values. Although the energy output of gas engines gradually increased over time, the total energy consumption at the plant fluctuated according to technological shifts. The highest energy consumption in total and per m^3 of treated water was the highest registered in the Chemical P removal scenario while the lowest values were observed in the conventional operational stage. Although introducing solar energy did not result in a massive reduction in the amount of energy consumed (0.8 kWh/m^3), 129 MWh was saved during this period. On the other hand, solar energy exhibits seasonal variations which must be considered a factor in the operation. It is possible to mitigate the impact of reduced solar irradiation by increasing the amount of energy generated from biogas during critical periods. Additionally, the quantity of flared biogas was reduced to 0.02 kWh per m^3 of treated water. Despite the occurrence of malfunctions in the gas engine, the amount of biogas energy utilized increased by 3.91%.

In the Solar Energy scenario, the use of chemicals for sludge thickening increased by 20.88% compared to during the previous year, resulting in a deterioration of 21.31% in MD, corresponding to an increase of 0.54 to 0.65 kg Cu eq. per 1 FU. Although the added dewatering agent contributes to a higher environmental impact associated with chemical usage, the reduced moisture content of the sludge leads to lower transportation costs and emissions.

On the other hand, the environmental impact was mitigated in most of the indicator categories, achieving the best results among the scenarios with investments, attributing to the combined effects of reduced flaring, the adoption of solar energy and the increased proportion of biogas energy utilized. The degree of aeration increased by 52.65% per cubic meter of treated water, whereas the energy consumption increased by only 10.19%. The first biological line accounts for 69.77% of electricity consumption, while the second for 28.96%. The use of solar energy contributes, on average, 1.17% of energy consumed by all impacts but 7.75% of the total energy used. Among the effects closely related to energy, OD is influenced the least by the new energy source, that is, by up to 0.73%. The results indicate that TEc increased by 4.75%, FPMF by 1.71%, $PhOF_e$ by 0.95% and $PhOF_{hh}$ by 0.94%.

The influence of the technological units within the individual categories of impacts is comparable to that presented in the Intensive flaring scenario with two exceptions: The value of LU increased 2.6-fold due to solar panels, while IR reduced by half because of the lower flaring rate. The values were 0.01 annual crop eq.·y and 0.01 kBq Co-60 eq. to air per 1 FU, respectively.

Opposing trends could be perceived with regard to the two indicators influenced by the biological processes. Due to the changes in the hydraulic and nutrient load, FEu increased from $-4.00\cdot10^{-3}$ to $4.02\cdot10^{-4}$ kg P eq./FU while MEu improved by 1.86% (from $-1.76\cdot10^{-2}$ to $-1.80\cdot10^{-2}$ kg N eq./FU). In comparison to the Biological P removal scenario, the daily volume of influent decreased by 1,071 m^3/day resulting in a 2.31% drop in the influent-effluent ratio (from 1.20 to 1.17 m^3 of wastewater / m^3 of treated water). Altogether the pollution mass flow rate was reduced by 7% and due to optimization, the effluent mass flow rate decreased by 12%.

3.2.5. *Optimized effluent control*

At the beginning of 2022, the optimization efforts were twofold. The share of purchased energy was reduced from 39.09 to 31.16%, corresponding to a decrease from 0.31 kWh/m^3 of treated water to 0.25 kWh/m^3 of treated water compared to in the previous scenario. This improvement could be achieved although the amount of electricity consumed increased compared to other scenarios. Solar panels supplied 7.14% of the total annual energy consumption (6.78% on average over the year) and energy generated from biogas increased by 15.30% even though the amount of the flared biogas tripled during this time period, reaching 0.03 kWh/m^3 of treated water.

Simultaneously, the nutrient composition of the wastewater was nearly ideal (100:10.07:1.08), enhancing the nutrient removal efficiency in the biological train. This manifested in the highest phosphorous removal rate without added chemicals: between the Conventional operation scenario and the optimized control phase, the total phosphorous content of the treated water decreased from 0.93 to 0.46 mg/L, achieving a 96.33% removal rate as opposed to the initial 93.38%. The nitrogen removal efficiency also improved, rising from 87.66 to 90.53% and reducing the total nitrogen content of the effluent from 10.28 to 7.87 mg/L. These efficiency gains were outstanding, particularly when compared to the discharge limit values of 4 mg/L for total phosphorus and 20 mg/L for total nitrogen as shown in *Figure 1*. However, since the increased efficiency was due to the optimal ratio of food to biomass, the sludge yield was also higher, which led to some drawbacks. Despite replacing the membranes in the aeration system, which were supposed to reduce the energy consumption, the higher sludge yield resulted in a 2.35% increase in energy consumed for aeration contrary to the fact that the number of daily operating hours of the blowers was reduced by 4.66%. Additionally, 24.13% more chemicals were used for sludge thickening compared to in the Solar energy scenario and 10.38% more dried sludge produced from the sludge treatment line per FU.

The impacts related to energy savings (CC, FPMF, $PhOF_e$, $PhOF_{hh}$, OD, TEc) yielded an average saving of 20.50%. However, the increase in flaring resulted in between 60.21 and 182.78% higher values for FC, HTP_c, IR and TA. Nonetheless, the FD value decreased by 182.76%, indicating a positive effect of purchasing less energy from the grid.

Considering the indicators related to the quality of the effluent water, a 2.66% rise in the value of MEu was observed compared to the Solar energy scenario due to the opposing effect of a slightly improved nitrogen removal efficiency and an increase in the amount of dissolved solids by 4.87%. However, the value of FEu decreased by a factor of 2.7, indicating that 0.011 kg P eq. was saved for every m^3 of treated water due to the reduction in the emitted phosphorous content by 41.44%.

The impacts related to the sludge treatment line increased in value when compared to the Solar energy scenario. The MD value rose by 23.96% due to increased chemical usage. In the case of FEc, which grew by 49.20%, biogas flaring accounted for 42.69% of the impact. However, the values of HTP_{nc} and MEc were determined solely by the dried sludge, so the 10.43% increase in the impacts equates to 1 m^3 of treated water, resulting in a 10.38% rise in quantity.

3.3. *Impact of the introduction of quaternary treatment*

While the examined wastewater treatment plant was not required to disinfect its effluent before being discharged, this might change in the future when different usage options will have to be considered. The potential introduction of quaternary treatment to meet legislative requirements was examined [1] using information published by Maniakova et al. [24] on the processes: ozonation (O_3) and sequential H_2O_2 treatment (ST). The chosen solutions were shown to remove organic micropollutants besides disinfecting the effluent. Utilization, which would require the consideration of further infrastructure, was beyond the scope of the current study. However, quaternary treatment of some sort would be a prerequisite for further usage of treated water. Two main aspects of the proposed processes were considered: energy consumption and chemical dosage. For the treatment plant under consideration, the impact of 1 kWh of local energy used, the chemical impact of the disinfection experiment referenced and the energy demand of the equipment were used to calculate the impact of quaternary treatment. The energy consumption of ozonation was taken to be 0.42 kWh/m^3 and because the ST was solar driven, the energy increment was three degrees of magnitude less ($3 \cdot 10^{-4}$ kWh/m^3). To ensure continuity over time, the technological properties of the last scenario (Optimized effluent control) were used as an input in the quaternary treatment scenarios. The resulting impacts were also plotted in the form of a heat map chart to compare the two options for disinfection with the current level of technological development (*Figure 2*).

3.3.1. Ozonation quaternary treatment

The introduction of the disinfection step increased the environmental burden of the wastewater treatment plant across multiple indicators, consistent with the findings of Maniakova et al. [24] (see *Appendix A*), with twelve of the eighteen indicators showing the highest values. Exceptions included FC, FEc, HTP_{nc}, IR, MEc and TA; however, even in these cases, the values for ozonation exceeded the optimized effluent control scenario. The largest increment was observed in ozone depletion (OD), which rose by five orders of magnitude compared to the preceding scenario ($3.82 \cdot 10^{-3}$ kg CFC-11 eq. per FU). Small increases of less than 1% compared to the Optimized effluent control scenario were noted for HTP_{nc}, TA and MEc in ascending order.

The higher energy consumption associated with the new processes naturally had a detrimental effect on energy-related indicators, albeit to varying extents. Although TEc nearly doubled (91.22%), it remained low (0.04 kg 1,4 DB eq./m^3 of treated water). However, many indicators previously heavily influenced by energy usage became more strongly influenced by chemical consumption during quaternary treatment. These indicators were CC, FPMF, LU, $PhOF_e$, $PhOF_{hh}$ and OD. The most particular concern was the increased impact caused by chemical usage in the ozonation process compared to the Optimized effluent control scenario. In terms of ozonation, the increases were 21 times higher for CC, 107 times higher for HTP_c, 124 times higher for FPMF and 9,323 times higher for $PhOF_{hh}$. Additionally, land usage increased to 0.13 annual crop eq.·y per m^3 of treated water.

Another consequence of ozonation was the loss of the benefits of freshwater eutrophication achieved by the earlier technical interventions with values reaching 0.48 kg P eq. per FU. This number is in line with the value in the Biological P removal scenario.

A few of the indicators remained in the same category in terms of their primary influencing factors. Freshwater and marine ecotoxicity were both governed by sludge treatment and exhibited only modest increases. Freshwater consumption, ionizing radiation and terrestrial acidification were all primarily determined by the amount of flared biogas. IR increased by 15.92% compared to the Optimized effluent control scenario but accounted for only 8.55% of the value observed during the introduction of flaring. Metal depletion changed only by 13.84% and was mainly influenced by the chemicals used for sludge dewatering.

3.3.2. Sequential H_2O_2 quaternary treatment

The sequential H_2O_2 treatment exhibited only moderate increases in environmental burdens as opposed to ozonation. Notably, none of the indicators yielded maximum values relative to the other scenarios. Regarding governing processes, the primary influences across most categories remained similar to those observed in the other quaternary treatment. An exception was MEc where the effects were governed by the biological processes, as in other scenarios, whereby an environmental benefit continued to be evident. While OD was still substantially higher than in the Optimized effluent control scenario, the impact was only 16% of that observed with regard to ozonation. FD decreased due to the use of renewable energy but remained within the positive range, indicative of environmental costs along with FEu. Human health impacts were 1.8 times higher for CC, 23 times higher for HTP_c and 1.8 times higher for $PhOF_{hh}$ compared to the Optimized effluent control scenario.

The sequential treatment also retained some benefits present when implementing previous technical interventions. TEc increased by only 2.85% while the impact of ionizing radiation rose marginally, namely by just 0.01%, compared to the Optimized effluent control scenario. This figure represented 7.37% of the IR values observed when flaring was introduced, indicating minimal environmental concerns. Regarding other indicators, negligible increases were observed for FEc, HTP_{nc}, MEc and TA.

Given these results, the sequential H_2O_2 treatment appears to be a more viable option due to its less significant environmental impacts overall. This method may also have long-term impacts, particularly if wastewater reuse, e.g. for irrigation, becomes feasible.

4. Discussion

Biogas optimization played a pivotal role in mitigating the environmental impacts of the wastewater treatment plant. In the Conventional operation scenario, 1.35 kWh/m^3 of biogas was produced, which increased to 1.98 kWh/m^3 in the Intensive flaring scenario. However, 71.54% of the biogas was flared due to uneven production, suggesting a potential for additional energy recovery. Other WWTPs have achieved biogas yields of 6.0 [31] or even 6.5 kWh/m^3 [32], demonstrating the feasibility of increased energy production. Achieving this would require expanding biogas storage capacity and incentives to feed excess electricity into the mains electricity network. In the long term, the digester efficiency can be improved by the co-digestion of industrial and agricultural waste [33]. Incorporating food waste, manure and grease trap sludge into biogas production enhances methane extraction [34], facilitating the goal of energy neutrality and reducing its environmental footprint [35].

In terms of energy efficiency, the total energy consumption of the plant was 0.72 kWh per m^3 of treated water on average with 59.32% of this energy being self-generated. For the sake of comparison, secondary treatment consumes between 0.272 to 1.27 kWh/m^3 of treated water [36] depending on factors such as the size, age and location of the facility as well as the climate. These findings, combined with the fact that 13 impact categories were affected by flaring due to imbalanced biogas production and utilization, underscore the potential for environmental savings and energy neutrality simultaneously. However, variations in biogas production highlighted the need for improved storage solutions and the proactive maintenance of biogas engines. Regulating the quality of the feedwater is also critical to ensure a more consistent output and improved energy portfolio.

Despite advancements in biogas production, energy-related trade-offs have persisted. The introduction of solar energy while reducing grid dependency highlighted the importance of taking into account seasonal variations. Nevertheless, increasing solar energy production may assist in achieving energy neutrality [37], though decarbonizing energy production on a national level would yield the greatest life-cycle benefits [38]. Until that happens, the importance of balancing renewable and biogas-based energy sources during critical operational periods is crucial to achieve an optimal operation.

Environmental trade-offs were also expected. Technological advancements in terms of nutrient removal improved effluent quality but at the cost of increased sludge production and higher chemical consumption during dewatering. Improved effluent quality can also ramp up energy consumption as noted in [39]. Similar issues arose when phasing out chemicals for phosphorous removal along with suboptimal nutrient ratios, resulting in increased aeration demand due to the appearance of filamentous microorganisms. These bacteria tend to reduce the oxygen transfer efficiency by up to 50% [40].

Future quaternary treatment requirements will introduce further compromises in terms of effluent quality, energy requirements and overall environmental impacts. In the near future, wastewater treatment plants above 100,000 PE will have to monitor antimicrobial resistance and by the year 2045, WWTPs above 10,000 PE in areas at risk will have to implement quaternary treatment solutions [1]. Ozonation has proven to remove 90% of micropollutants [41] and further mitigate chemical oxygen demand by 16–71% [42]. However, its environmental feasibility is limited due to the impacts of high chemical usage and ozone depletion. The level of removal efficiency can be modified by the level of ozone production at the expense of energy consumption [43]. Great degrees of pollutant removal and thus reduced toxicity could be achieved at the cost of greenhouse gas emissions.

On the other hand, sequential H_2O_2 treatment exhibited relatively lower environmental costs, comparable to some of the other real-world scenarios. Its application still resulted in trade-offs such as increased terrestrial ecotoxicity. It has to be stated that the current model did not consider micropollutants in the life cycle inventory, therefore, ecotoxicity values might differ from current calculations.

Future implementations must carefully weigh up the aforementioned trade-offs to achieve long-term sustainability. Water-saving measures could significantly shift priorities [44]. With increasing water scarcity even in Europe, benefits arising from the utilization of treated water for non-potable purposes may outweigh other environmental impacts [45]. An earlier study [46] found that reclaiming 1 m^3 of treated water can save 0.8 m^3 of freshwater. Although quaternary treatments may increase environmental impacts, carefully selected methods remain viable for addressing antibiotic-resistant microorganisms and micropollutants. With regard to the reuse of treated water for irrigation purposes, which is currently supported, it is important that crops intended for human consumption are free of these types of contaminants.

5. Conclusions

This study delivered a comprehensive LCA of technological advancements implemented at a Hungarian municipal WWTP over a seven-year-long period. The management of the WWTP sought to improve effluent water quality in a cost-effective manner, including a reduction in chemical consumption and an increase of renewable energy generation at the plant. By incorporating real operational data, the authors evaluated the environmental impacts of transitions to renewable energy, improved nutrient removal processes and hypothetical quaternary treatments. The novelty of this work lies in its integration of real-time operational scenarios with standardized LCA methodologies to address trade-offs between energy consumption, effluent quality and environmental burdens.

The key findings indicate that transitioning to biological phosphorus removal and optimizing biogas utilization can significantly reduce chemical dependency as well as greenhouse gas emissions, however, these benefits are offset by increased energy demands. Similarly, while solar energy integration showed promise, seasonal limitations underscore the need for complementary energy solutions. The study demonstrated that achieving low environmental impacts requires balancing technological upgrades with operational efficiency. Quaternary treatments, though necessary for future wastewater reuse, present notable environmental trade-offs requiring the careful selection of technologies such as sequential H_2O_2 treatment to mitigate impacts. Future technological advancements will necessitate assessing the long-term impacts of effluent reuse, particularly in relation to emerging pollutants such as microplastics and pharmaceuticals.

The insights from the analysis highlight the importance of using LCA to guide decision-making in WWTP operations, ensuring that technological upgrades align with both environmental and regulatory goals. This work provides a framework for WWTP operators and policymakers to evaluate sustainable solutions that balance operational efficiency with long-term environmental performance.

SYMBOLS

BOD_5	biological oxygen demand
CC	climate change
COD	chemical oxygen demand
EDDS	Ethylenediamine-N,N′-disuccinic acid
EPS	extracellular polymeric substances
FC	freshwater consumption
FD	fossil depletion
FEc	freshwater ecotoxicity
FEu	freshwater eutrophication
FPMF	fine particulate matter formation
HTP_c	human toxicity potential, cancer
HTP_{nc}	human toxicity potential, non-cancer
IR	ionising radiation
LCA	Life Cycle Assessment
LU	land use
MEc	marine ecotoxicity
MEu	marine eutrophication
MD	metal depletion
OD	stratospheric ozone formation
$PhOF_e$	photochemical ozone formation, ecosystems
$PhOF_{hh}$	photochemical ozone formation, human health
TA	terrestrial acidification
TEc	terrestrial ecotoxicity
TKN	total Kjeldahl nitrogen
TN	total nitrogen
TP	total phosphorous
TSS	total suspended solids
WWTP	wastewater treatment plant

Acknowledgements

The research presented in this article was carried out within the framework of the Széchenyi Plan Plus program with the support of the RRF 2.3.1-21-2022-00008 project.

REFERENCES

[1] European Parliament. Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment (recast), 2024 https://eur-lex.europa.eu/eli/dir/2024/3019/oj/eng (retrieved 22 January 2025)

[2] Meng, X; Huang, Z.; Ge, G.: Upgrade and reconstruction of biological processes in municipal wastewater treatment plants, *Desalin. Water Treat.*, 2024, **317**, 100299, DOI: 10.1016/j.dwt.2024.100299

[3] Morello, R.; Di Capua, F.; Cesaro, A.; Esposito, G.; Pirozzi, F.; Fratino, U.; Spasiano, D.: Solutions for solid minimization in the sludge streamline of municipal wastewater treatment plants: Current state and recent developments, *J. Water Process Eng.*, 2024, **64**, 105725, DOI: 10.1016/j.jwpe.2024.105725

[4] Yilmaz, M.; Guven, H.; Ozgun, H.; Ersahin, M.E.; Koyuncu; I.: The application of life cycle assessment (LCA) to anaerobic technologies for the treatment of municipal wastewater: A review, *Process Saf. Environ. Prot.*, 2024, **182**, 357–370, DOI: 10.1016/j.psep.2023.11.078

[5] Bélafi-Bakó, K.; Tóth, G.; Bakonyi, P.; Nemestóthy, N.: Utilization of agro-wastes in biohydrogen fermentation by various microorganisms, *Hung. J. Ind. Chem.*, 2022, **50**(2), 57–60, DOI: 10.33927/hjic-2022-19

[6] Smith, A.L.; Stadler, L.B; Cao, L.; Love, N.G.; Raskin, L.; Skerlos, S.J.: Navigating wastewater energy recovery strategies: A life cycle comparison of anaerobic membrane bioreactor and conventional treatment systems with anaerobic digestion, *Environ. Sci. Technol.*, 2014, **48**(10), 5972–5981, DOI: 10.1021/es5006169

[7] He, X.; Li, Z.; Xing, C.; Li, Y.; Liu, M.; Gao, X.; Ding, Y.; Lu, L.; Liu, C.; Li, C.; Wang, D.: Carbon footprint of a conventional wastewater treatment plant: An analysis of water-energy nexus from life cycle perspective for emission reduction, *J. Clean. Prod.*, 2023, **429**, 139562, DOI: 10.1016/j.jclepro.2023.139562

[8] Leonel, L.P.; Tonetti, A.L.: Wastewater reuse for crop irrigation: Crop yield, soil and human health implications based on giardiasis epidemiology, *Sci. Total Environ.*, 2021, **775**, 145833, DOI: 10.1016/j.scitotenv.2021.145833

[9] Mehmeti, A.; Canaj, K.: Environmental assessment of wastewater treatment and reuse for irrigation: A mini-review of LCA studies, *Resources*, 2022, **11**(10), 94, DOI: 10.3390/resources11100094

[10] Trommetter, G.; Khaska, S.; Le Gal La Salle, C.; Brosillon, S.; Goetz, V.; Plantard, G.; Mendret, J.: Removal of 39 contaminants of emerging concern found in wastewater effluent by coupling nanofiltration and infiltration into saturated soil column, *Chemosphere*, 2024, **363**, 142705, DOI: 10.1016/j.chemosphere.2024.142705

[11] Corominas, L.; Byrne, D.M.; Guest, J.S.; Hospido, A.; Roux, P.; Shaw, A.; Short, M.D.: The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review, *Water Res.*, 2020, **184**, 116058, DOI: 10.1016/j.watres.2020.116058

[12] Paulu, A.; Bartáček, J.; Šerešová, M.; Kočí, V.: Combining process modelling and LCA to assess the environmental impacts of wastewater treatment innovations, *Water*, 2021, **13**(9), 1246, DOI: 10.3390/w13091246

[13] Viotti, P.; Tatti, F.; Bongirolami, S.; Romano, R.; Mancini, G.; Serini, F.; Azizi, M.; Croce, L.: Life cycle assessment methodology applied to a wastewater treatment plant, *Water*, 2024, **16**(8), 1177, DOI: 10.3390/w16081177

[14] Risch, E.; Loubet, P.; Núñez, M.; Roux, P.: How environmentally significant is water consumption during wastewater treatment?: Application of recent developments in LCA to WWT technologies used at 3 contrasted geographical locations, *Water Res.*, 2014, **57**, 20–30, DOI: 10.1016/j.watres.2014.03.023

[15] Fitzsimons, L.; McNamara, G.; Doherty, E.; Clifford, E.: Optimal design and operation of small-scale wastewater treatment plants: The Irish case, 2018 https://www.epa.ie/publications/research/water/research-255.php (retrieved 17 December 2024)

[16] Lorenzo-Toja, Y.; Vázquez-Rowe, I.; Marín-Navarro, D.; Crujeiras, R.M.; Moreira, M.T.; Feijoo, G.: Dynamic environmental efficiency assessment for wastewater treatment plants, *Int. J. Life Cycle Assess.*, 2018, **23**(2), 357–367, DOI: 10.1007/s11367-017-1316-9

[17] Rufí-Salís, M.; Petit-Boix, A.; Leipold, S.; Villalba, G.; Rieradevall, J.; Moliné, E.; Gabarrell, X.; Carrera, J.; Suárez-Ojeda, M.E.: Increasing resource circularity in wastewater treatment: Environmental implications of technological upgrades, *Sci. Total Environ.*, 2022, **838**, 156422, DOI: 10.1016/j.scitotenv.2022.156422

[18] Iskander, B.R.; Sebestyén, V.; Tóth-Nagy, G.: The role of raising awareness in ensuring the resilience of cities, *Hung. J. Ind. Chem.*, 2024, **51**(2), 43–49, DOI: 10.33927/hjic-2023-17

[19] ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. Standard, International Organization for Standardization, Geneva, CH, 2006 https://www.iso.org/standard/37456.html (retrieved 2 September 2024)

[20] ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. Standard, International Organization for Standardization, Geneva, CH, 2006 https://www.iso.org/standard/38498.html (retrieved 2 September 2024)

[21] Sphera. Gabi LCA software and database v.10.6.1.35, 2022

[22] Republic of Hungary. Decree 28/2004. (XII. 25.) of the Ministry of Agriculture and Rural Development on limit values for emissions of water pollutants and certain rules for their application, 2004 https://net.jogtar.hu/jogszabaly?docid=a0400028.kvv (retrieved 22 January 2025)

[23] Republic of Hungary. Government Decree No. 50/2001 (IV. 3.) on the rules for the agricultural use and management of wastewater and sewage sludge, 2001 https://net.jogtar.hu/jogszabaly?docid=a0100050.kor (retrieved 22 January 2025)

[24] Maniakova, G.; López, M.I.P.; Oller, I.; Malato, S.; Rizzo, L.: Ozonation vs sequential solar driven processes as simultaneous tertiary and quaternary treatments of urban wastewater: A life cycle assessment comparison, *J. Clean. Prod.*, 2023, **413**, 137507, DOI: 10.1016/j.jclepro.2023.137507

[25] Ministry of National Development. National energy strategy 2030, 2012 https://2010-2014.kormany.hu/download/7/d7/70000/Hungarian%20Energy%20Strategy%202030.pdf (retrieved 20 October 2024)

[26] Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R.: ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, *Int. J. Life Cycle Assess.*, 2017, **22**(2), 138–147, DOI: 10.1007/s11367-016-1246-y

[27] Karolinczak, B.; Walczak, J.; Bogacka, M.; Zubrowska-Sudol, M.: Life cycle assessment of sewage sludge mono-digestion and co-digestion with the organic fraction of municipal solid waste at a wastewater treatment plant, *Sci. Total Environ.*, 2024, **907**, 167801, DOI: 10.1016/j.scitotenv.2023.167801

[28] Metcalf & Eddy Inc.; Tchobanoglous, G.; Stensel, H.D.; Tsuchihashi, R.; Burton, F.L.: Wastewater Engineering: Treatment and Resource Recovery (5th edition) (McGraw-Hill, New York, USA), 2013, ISBN: 9780073401188

[29] Roš, M.; Vrtovšek, J.: The study of nutrient balance in sequencing batch reactor wastewater treatment, *Acta Chim. Slov.*, 2004, **51**(4), 779–785

[30] Wanner. J.: Activated sludge: bulking and foaming control (CRC Press, Boca Raton), 2014, DOI: 10.1201/9781498710817

[31] Peeters, B.; Vernimmen, L.: Challenges of handling filamentous and viscous wastewater sludge, *Chem. Eng.*, 2016, **123**(9), 52 https://www.chemengonline.com/challenges-handling-filamentous-viscous-wastewater-sludge/

[32] Amiri, A.W.; Tsutsumi, J.G.; Nakamatsu, R.: Energy from domestic wastewater and recovering the potential energy of sewage sludge, *J. Energy Technol. Policy*, 2015, **5**(12) https://www.iiste.org/Journals/index.php/JETP/article/view/27633

[33] SWEDISH GAS CENTER SGC. Basic data on biogas. Malmö, Sweden, 2012 http://sgc.camero.se/ckfinder/userfiles/files/BasicDataonBiogas2012.pdf (retrieved 16 December 2024)

[34] Ahuja, V.; Sharma, C.; Paul, D.; Dasgupta, D.; Saratale, G.D.; Banu, J.R.; Yang, Y.-H.; Bhatia, S.K.: Unlocking the power of synergy: Cosubstrate and coculture fermentation for enhanced biomethane production, *Biomass Bioenergy*, 2024, **180**, 106996, DOI: 10.1016/j.biombioe.2023.106996

[35] Miranzadeh, M.B.; Jafarsalehi, M.; Akram, J.; Ebrahimi, M.; Mazaheri, A.; Mashayekh, M.; Boosting biogas production in the wastewater treatment plants: A narrative review on co-digestion of sewage sludge with internal and external organic waste, *Bioresour. Technol. Rep.*, 2024, **26**, 101856, DOI: 10.1016/j.biteb.2024.101856

[36] Ferella, F.; Cucchiella, F.; D'Adamo, I.; Gallucci, K.: A techno-economic assessment of biogas upgrading in a developed market, *J. Clean. Prod.*, 2019, **210**, 945–957, DOI: 10.1016/j.jclepro.2018.11.073

[37] Cardoso, B.J.; Rodrigues, E.; Gaspar, A.R.; Gomes, Á.: Energy performance factors in wastewater treatment plants: A review, *J. Clean. Prod.*, 2021, **322**, 129107, DOI: 10.1016/j.jclepro.2021.129107

[38] Li, L.; Wang, X.; Miao, J.; Abulimiti, A.; Jing, X.; Ren, N.: Carbon neutrality of wastewater treatment - a systematic concept beyond the plant boundary, *Environ. Sci. Ecotechnol.*, 2022, **11**, 100180, DOI: 10.1016/j.ese.2022.100180

[39] Lehtoranta, S.; Laukka, V.; Silvennoinen, K.: Climate change impacts of municipal water sector and mitigation pathways: A national scale analysis and perspectives to carbon neutrality, *J. Environ. Manage.*, 2025, **373**, 123732, DOI: 10.1016/j.jenvman.2024.123732

[40] Larsen, H.F.: LCA of wastewater treatment, in: Life Cycle Assessment: Theory and Practice, Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I. (Eds.) (Springer Cham), 2018, pp. 861–886, DOI: 10.1007/978-3-319-56475-3_34

[41] Liu, G.; Wang, J.; Campbell, K.: Formation of filamentous microorganisms impedes oxygen transfer and decreases aeration efficiency for wastewater treatment, *J. Clean. Prod.*, 2018, **189**, 502–509, DOI: 10.1016/j.jclepro.2018.04.125

[42] Arzate, S.; Pfister, S.; Oberschelp, C.; Sánchez-Pérez, J.A.: Environmental impacts of an advanced oxidation process as tertiary treatment in a wastewater treatment plant, *Sci. Total Environ.*, 2019, **694**, 133572, DOI: 10.1016/j.scitotenv.2019.07.378

[43] Rong, Y.; Wang, X.; Zhu, M.; Chen, W.; Maletskyi, Z.; Ratnaweera, H.; Bi, X.: Real-time ozonation monitoring and control in wastewater tertiary treatment: An ultraviolet-visible monitoring approach, *J. Water Process Eng.*, 2024, **64**, 105664, DOI: 10.1016/j.jwpe.2024.105664

[44] Rodríguez, A.; Muñoz, I.; Perdigón-Melón, J.A.; Carbajo, J.B.; Martínez, M.J.; Fernández-Alba, A.R.; García-Calvo, E.; Rosal, R.: Environmental optimization of continuous flow ozonation for urban wastewater reclamation, *Sci. Total Environ.*, 2012, **437**, 68–75, DOI: 10.1016/j.scitotenv.2012.07.084

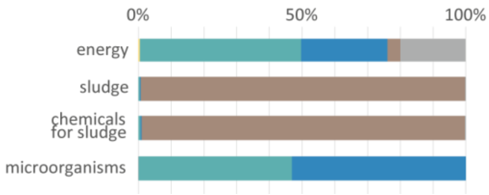
[45] Tong, L.; Liu, X.; Liu, X.; Yuan, Z.; Zhang, Q.: Life cycle assessment of water reuse systems in an industrial park, *J. Environ. Manage.*, 2013, **129**, 471–478, DOI: 10.1016/j.jenvman.2013.08.018

[46] Pintilie, L.; Torres, C.M.; Teodosiu, C.; Castells, F.: Urban wastewater reclamation for industrial reuse: An LCA case study, *J. Clean. Prod.*, 2016, **139**, 1–14, DOI: 10.1016/j.jclepro.2016.07.209

Impact	Conventional operation	Intensive flaring	Chemical P removal	Biological P removal	Solar energy	Optimized effluent control	Ozonation quaternary treatment	Sequential H_2O_2 quaternary treatment
climate change[kg CO_2 eq.]	$1.25 \cdot 10^{-1}$	$1.03 \cdot 10^{-1}$	$1.27 \cdot 10^{-1}$	$1.11 \cdot 10^{-1}$	$1.10 \cdot 10^{-1}$	$8.75 \cdot 10^{-2}$	$1.94 \cdot 10^{0}$	$2.47 \cdot 10^{-1}$
fine particulate matter formation [kg PM2.5 eq.]	$3.86 \cdot 10^{-5}$	$3.20 \cdot 10^{-5}$	$3.94 \cdot 10^{-5}$	$3.44 \cdot 10^{-5}$	$3.49 \cdot 10^{-5}$	$2.78 \cdot 10^{-5}$	$3.47 \cdot 10^{-3}$	$3.51 \cdot 10^{-4}$
fossil depletion [kg oil eq.]	$7.55 \cdot 10^{-2}$	$-1.51 \cdot 10^{0}$	$-8.76 \cdot 10^{-2}$	$-4.27 \cdot 10^{-2}$	$3.70 \cdot 10^{-2}$	$-3.07 \cdot 10^{-2}$	$2.60 \cdot 10^{0}$	$1.37 \cdot 10^{-1}$
freshwater consumption [m³]	$4.61 \cdot 10^{-2}$	$7.36 \cdot 10^{0}$	$8.30 \cdot 10^{-1}$	$5.58 \cdot 10^{-1}$	$1.92 \cdot 10^{-1}$	$4.57 \cdot 10^{-1}$	$8.66 \cdot 10^{-1}$	$4.75 \cdot 10^{-1}$
freshwater ecotoxicity [kg 1,4 DB eq.]	$2.28 \cdot 10^{-2}$	$3.81 \cdot 10^{-1}$	$6.73 \cdot 10^{-2}$	$5.06 \cdot 10^{-2}$	$3.01 \cdot 10^{-2}$	$4.48 \cdot 10^{-2}$	$4.67 \cdot 10^{-2}$	$4.49 \cdot 10^{-2}$
freshwater eutrophication [kg P eq.]	$-2.46 \cdot 10^{-3}$	$2.18 \cdot 10^{-3}$	$-3.92 \cdot 10^{-3}$	$-4.00 \cdot 10^{-3}$	$4.02 \cdot 10^{-4}$	$-1.06 \cdot 10^{-2}$	$4.78 \cdot 10^{-1}$	$4.67 \cdot 10^{-2}$
human toxicity, cancer [kg 1,4-DB eq.]	$3.08 \cdot 10^{-3}$	$4.44 \cdot 10^{-1}$	$5.03 \cdot 10^{-2}$	$3.43 \cdot 10^{-2}$	$1.15 \cdot 10^{-2}$	$2.70 \cdot 10^{-2}$	$2.92 \cdot 10^{0}$	$6.45 \cdot 10^{-1}$
human toxicity, non-cancer [kg 1,4-DB eq.]	$1.57 \cdot 10^{2}$	$1.53 \cdot 10^{2}$	$2.03 \cdot 10^{2}$	$1.75 \cdot 10^{2}$	$1.60 \cdot 10^{2}$	$1.77 \cdot 10^{2}$	$1.77 \cdot 10^{2}$	$1.77 \cdot 10^{2}$
ionizing radiation [kBq Co-60 eq. to air]	$9.40 \cdot 10^{-3}$	$2.98 \cdot 10^{-1}$	$4.01 \cdot 10^{-2}$	$2.87 \cdot 10^{-2}$	$1.37 \cdot 10^{-2}$	$2.20 \cdot 10^{-2}$	$2.55 \cdot 10^{-2}$	$2.20 \cdot 10^{-2}$
land use [Annual crop eq.·y]	$1.05 \cdot 10^{-2}$	$-9.59 \cdot 10^{-2}$	$-2.96 \cdot 10^{-4}$	$1.98 \cdot 10^{-3}$	$7.25 \cdot 10^{-3}$	$1.74 \cdot 10^{-3}$	$1.33 \cdot 10^{-1}$	$1.42 \cdot 10^{-2}$
marine ecotoxicity [kg 1,4-DB eq.]	$1.94 \cdot 10^{-2}$	$1.80 \cdot 10^{-2}$	$2.50 \cdot 10^{-2}$	$2.15 \cdot 10^{-2}$	$1.98 \cdot 10^{-2}$	$2.18 \cdot 10^{-2}$	$2.20 \cdot 10^{-2}$	$2.19 \cdot 10^{-2}$
marine eutrophication [kg N eq.]	$-1.45 \cdot 10^{-2}$	$-1.37 \cdot 10^{-2}$	$-1.74 \cdot 10^{-2}$	$-1.76 \cdot 10^{-2}$	$-1.80 \cdot 10^{-2}$	$-1.75 \cdot 10^{-2}$	$1.76 \cdot 10^{-2}$	$-1.43 \cdot 10^{-2}$
metal depletion [kg Cu eq.]	$5.48 \cdot 10^{-1}$	$4.28 \cdot 10^{-1}$	$7.30 \cdot 10^{-1}$	$5.39 \cdot 10^{-1}$	$6.54 \cdot 10^{-1}$	$8.10 \cdot 10^{-1}$	$9.22 \cdot 10^{-1}$	$8.19 \cdot 10^{-1}$
photochemical ozone formation, ecosystems [kg NO_x eq.]	$1.38 \cdot 10^{-4}$	$1.15 \cdot 10^{-4}$	$1.41 \cdot 10^{-4}$	$1.23 \cdot 10^{-4}$	$1.24 \cdot 10^{-4}$	$9.88 \cdot 10^{-5}$	$2.96 \cdot 10^{-3}$	$3.33 \cdot 10^{-4}$
photochemical ozone formation, human health [kg NO_x eq.]	$1.38 \cdot 10^{-4}$	$1.14 \cdot 10^{-4}$	$1.41 \cdot 10^{-4}$	$1.23 \cdot 10^{-4}$	$1.24 \cdot 10^{-4}$	$9.84 \cdot 10^{-5}$	$9.17 \cdot 10^{-1}$	$7.80 \cdot 10^{-3}$
stratospheric ozone depletion [kg CFC-11 eq.]	$3.48 \cdot 10^{-8}$	$2.89 \cdot 10^{-8}$	$3.56 \cdot 10^{-8}$	$3.10 \cdot 10^{-8}$	$3.08 \cdot 10^{-8}$	$2.44 \cdot 10^{-8}$	$3.82 \cdot 10^{-3}$	$6.07 \cdot 10^{-4}$
terrestrial acidification [kg SO_2 eq.]	$1.25 \cdot 10^{-4}$	$3.73 \cdot 10^{0}$	$3.92 \cdot 10^{0}$	$2.61 \cdot 10^{0}$	$7.02 \cdot 10^{-1}$	$1.98 \cdot 10^{0}$	$1.99 \cdot 10^{0}$	$1.98 \cdot 10^{0}$
terrestrial ecotoxicity [kg 1,4-DB eq.]	$2.50 \cdot 10^{-2}$	$2.07 \cdot 10^{-2}$	$2.55 \cdot 10^{-2}$	$2.22 \cdot 10^{-2}$	$2.33 \cdot 10^{-2}$	$1.86 \cdot 10^{-2}$	$3.56 \cdot 10^{-2}$	$1.92 \cdot 10^{-2}$

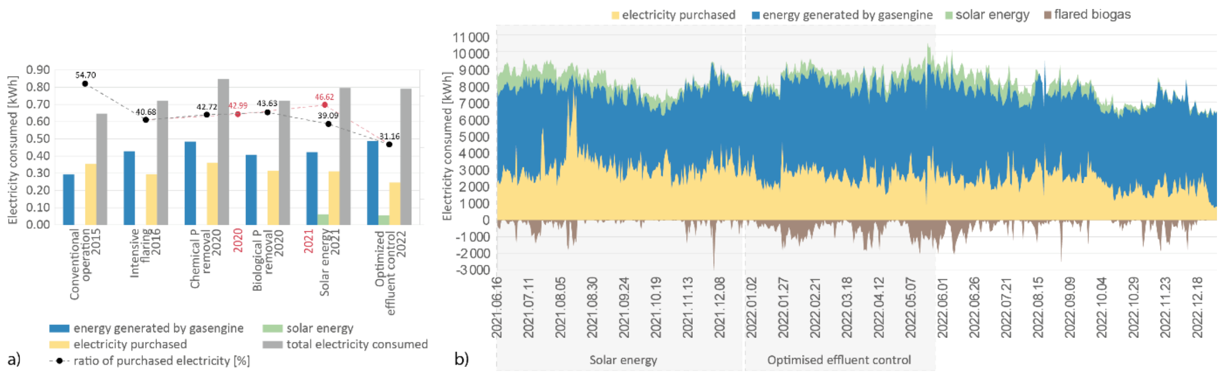
determined by energy consumption
determined by microorganisms
determined by sludge treatment line
determined by chemicals used for sludge treatment line
determined by flared biogas
determined by chemicals used for quaternary treatment

Appendix A: The results of the scenarios for the discharge of 1 m^3 of treated water - each result is highlighted by the color assigned to technological elements with the highest influence



	by energy	by sludge	by chemicals for sludge	by microorganisms
receiving station	0.54%	0.00% - 0.001%	0.00% - 0.01%	0.00%
biological line I.	49.30%	0.00% - 0.46%	0.02% - 0.64%	46.92%
biological line II.	26.32%	0.00% - 0.25%	0.01% - 0.34%	53.09%
sludge line	3.92%	99.10% - 100.00%	98.74% - 99.97%	0.00%
other	19.92%	0.00% - 0.19%	0.01% - 0.26%	-0.01% - 0.00%

Appendix B: The composition of the plant units for each impact category for the Conventional operation case of the analysed wastewater treatment plant. The impact categories with a similar composition are summarised in the figure on the left-hand side. In the corresponding table on the right-hand side, the percentage differences are indicated by minimum and maximum values. The indicators are categorised by energy (CC, FPMF, FD, IR, LU, PhOF$_e$, PhOF$_{hh}$, OD, TA, TEc), sludge (HTP$_c$, HTP$_{nc}$, FEc, MEc), chemicals for sludge (FC, MD) and microorganisms (FEu, MEu)



Appendix C: The composition of energy use in each case is illustrated on the left-hand side (a), while the composition of energy use after the implementation of the solar panels is illustrated on the right-hand side (b). It should be noted that the amount of flared biogas, which is represented by the negative value in the diagram, could have reduced the amount of electricity purchased if it had been used