Article

Socio-Economic, Technical and Environmental Indicators for Sustainable Sewage Sludge Management and LEAP Analysis of Emissions Reduction

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Abstract: The waste management sector is transitioning from a dirty and undesirable industry towards a green and sustainable future where energy and materials are recycled. Recycling has potential in sewage sludge treatment, where energy and highly valuable nutrients can be recovered through innovative and sustainable sludge management. Although there are many technologies and techniques already used for sewage sludge, the indicators for their sustainability are not developed. In terms of sustainable and innovative sewage sludge treatment, usually, only techno-economic aspects of existing and current technologies are considered. We explore the existing indicators and propose new indicators for sustainable and innovative sewage sludge treatment technologies. The indicators are differentiated into four main categories: technical, social, environmental and economic, where specific indicators are explained, followed by a description of their impact on sustainability. We also consider a case study using the LEAP tool, which considered GHG emissions when utilizing sewage sludge as an energy feedstock to replace existing fossil fuels in the energy mix in several scenarios. The results showed a significant emissions reduction when sludge is used—37.6% and 90.9% in 2030 and 2050, respectively.

Keywords: sewage sludge; socio-economic indicators; sustainable development; waste treatment; LEAP analysis

1. Introduction

In recent decades, sustainability and social responsibility, in addition to profitability, have become the main focus of many sectors—from energy, industry, and transport to waste management and environmental protection. In terms of waste management, sustainable waste management aims to keep materials in use for as long as possible and minimize the amount of waste that is currently disposed of in landfills or incinerated. Almost all types of waste have gained popularity and have found or are looking for their place in the circular economy or bioeconomy concepts.

Biodegradable waste and biowaste are becoming extremely popular and important due to the number of valuable nutrients they contain, such as phosphorus (P), nitrogen (N) and potassium (K) [1,2]. These nutrients are present in wastewater and sewage sludge generated from wastewater treatment plants (WWTP), whose treatment resolves two problems—recovering valuable nutrients and reducing their negative impact on the environment [3–5]. In terms of sewage sludge management, the technologies need to be sustainable and efficient since the traditional approach (mainly agriculture disposal) has a potentially high negative impact on the environment [6].

A lot of research has been conducted on the topic of sustainable wastewater, as well as on sustainable sewage sludge management. Raheem et al. [7] have examined options for sustainable sludge management and distributed them in three categories: (i) energy recovery, (ii) co-production of bio refinery products from sewage sludge and (iii) resource
recovery and pollution control. They concluded that pyrolysis is superior to other options due to its fewer emissions and higher product value. Similarly, Karaca et al. [6] provided strong indications that high-temperature pyrolysis may be considered an alternative to the anaerobic digestion process in the conventional wastewater treatment scheme as a more efficient energy recovery process. Hao et al. [8] proved in their research that the anaerobic digestion process, followed by incineration, can be beneficial only in the case when WWTP wants to be viewed as energy-independent. They conclude that wastewater treatment operations should maximise resource recovery with minimal energy usage. In order to select the best solution for sewage sludge (thermal) treatment, Tsybina and Wünsch [9] analysed incineration, pyrolysis and gasification treatment processes and concluded that all three sewage sludge thermal treatment technologies are relatively energy efficient but are quite inefficient in terms of nutrient recovery.

Other main technologies researched and examined include: anaerobic digestion [8,10], composting [11,12], plasma gasification [13], torrefaction [13], material recovery [14–16], and hydrogen [17] and biofuels production [18–20].

All the aforementioned technologies have a specific impact, which can be measured via various indicators: environmental, socio-economic, financial, technical, etc. This is needed in order to see the benefits of utilizing different technologies, in this case, sustainable technologies for sewage sludge management. However, most research conducted in this area is related to indicators showing benefits from wastewater treatment.

Balkema et al. [21] determined the sustainability of indicators related to wastewater treatment through an extensive literature overview. They determined the following indicators as decisive within the sustainability assessment of wastewater treatment: organic matter, nutrients, costs, heavy metals and land use. Hussain et al. [22] presented an approach for analyzing the socio-economic, health, and environmental aspects of urban wastewater use in peri-urban agriculture, using typical characteristics of a major city in a developing country. This was done through quantification of the impact of wastewater use in irrigation on several values: economics, crop production, soil resources, property, groundwater, public health, the environment and social aspects. Furthermore, Buonocore et al. [23] conducted a life cycle assessment (LCA) analysis to determine the environmental impacts of several WWTP and sewage sludge treatment options. The circularity option has shown the best overall environmental impact of WWTP. Firmansyah et al. [24] have analyzed the impact of wastewater treatment technologies and concepts (including transport, collection, treatment/recovery, reuse in agriculture and final disposal) on technology, social, economic and ecologic indicators.

There is also research conducted on the topic of indicator development and monitoring related to outputs of wastewater treatment. For example, Tassinari et al. [25] quantified the direct and indirect impacts of replacing a synthetic fertilizer with fertilizers derived from wastewater. The results show that the development of a biorefinery for the valorization of nutrients from sewage sludge has great relevance in creating added value and employment for rural areas. Grönlund [26] made an analysis of systems ecology indicators’ perspective on sustainability in wastewater sludge management. The analysis concluded that no method covered every aspect of the developed ecology models, and it is necessary to develop a complementary approach of methods and indicators to assess sustainability. Furthermore, Sarov and Tsveyatkova [27] researched the socio-economic and behavioral aspects of sewage sludge utilization on farms through extensive in-depth interviews with Bulgarian farmers. The results showed that there are many issues related to the technological introduction of sludge in arable agricultural land and a lack of public acceptance of sludge utilization in agriculture. There are also other research papers focused on environmental [28,29], economic [29,30] and various other [31,32] indicators.

Due to a lack of research on the topic of defining a holistic approach to sustainability indicators for sewage sludge management (socio-economic, technical and environmental), especially in terms of innovative and new technologies, this paper aims to propose indica-
tors that allow the presentation of the (assumed) positive impact of the aforementioned technologies.

The goal of this paper is to identify and elaborate on new key indicators that show the impact of sustainable sewage sludge technologies on the socio-economic, environmental and technical aspects of sewage sludge management. Moreover, we use the long-range energy alternatives planning system (LEAP) modelling tool to present a case study focusing on gasification of sewage sludge management as a sustainable option of energy recovery, which has a positive impact on the environment in terms of emissions reduction.

However, it should be noted that sewage sludge as such cannot be considered a purely renewable energy source, even though it is produced on a regular basis. Additionally, it cannot be completely considered a “clean source”, since its energy recovery still generates emissions [33]. Still, as it is considered a biogenic source of waste, within this paper, it will be considered an emission-free fuel within the gasification process.

The paper is divided into four chapters. Following the introduction, we present the methods and the data that were used in the analysis. The third chapter presents and discusses the results of the analysis through the development of sustainable indicators (technical, socio-economic, and environmental) and a subsequent LEAP case analysis of a sewage sludge gasification project. Concluding remarks are given in the final chapter.

2. Materials and Methods

The major objective of this paper is to identify and propose the key indicators that show the impact of sustainable sewage sludge technologies on the socio-economic, environmental and technical aspects of sewage sludge management. The data used for the analysis and development of indicators is obtained from a comprehensive literature overview, which is based on the following sectors: wastewater treatment and sewage sludge treatment.

The development of indicators that can measure the impact of specific technology on various aspects can be very complicated, especially if the considered technologies are new and innovative. Since this paper is considering sewage sludge treatment technologies and methods, within the sustainability concept, developed indicators could fall under the scope of existing indicators that are related to wastewater and sewage sludge management concepts. Therefore, this segment will provide an overview of existing literature that has examined such indicators.

Most research is done with a specific focus. For example, in terms of technical assessment, Ghimire et al. [34] analyzed WWTPs from an energy point of view. They considered energy consumption and energy recovery potential in wastewater treatment and concluded that sustainability can be achieved if the following steps are considered: enhancing carbon capture (by accepting external organic feedstock for energy recovery) and implementing anaerobic bioelectrochemical treatment for electricity generation. Sun et al. [35] referred to WWTP as a waste resource recovery facility since it has new goals and faces new challenges in terms of sustainability. They concluded that new and sustainable plants need a multi-criteria concept that provides a holistic assessment of wastewater treatment alternatives. This study defined sustainable wastewater management as selecting systems that do not threaten the quantity and quality of resources as well as have the lowest costs and benefits with respect to the physical, socio-cultural and economic environments.

Furthermore, Popovic and Kraslawski [36] determined the complexity of social indicators and the need for understanding interactions among social sustainability indicators. This starts to become evident as it contributes to a deeper understanding of the phenomena of sustainability and reduction of the costs of its assessment by limiting the amount of required data and information. Moreover, Smol and Koneczna [37] proposed economic indicators that can assess the transformation progress towards the circular economy concept within the waste and wastewater sector. Yet, the developed indicators remained flexible in order to be used and adjusted by users—water supply and sewerage companies.

In terms of environmental aspects, Özerol and Güntner [38] specified indicators related to waters, with a specific focus on wastewater. Their research presented a closeness of envi-
environmental and social indicators, especially in terms of wastewater treatment. Avramenko et al. [39] developed a decision support method for the selection of sustainable wastewater treatment technologies based on a set of chosen environmental indicators. Moreover, in assessing the sustainability of wastewater treatment technologies, Molinos-Senante et al. [40] described a set of economic, environmental and social indicators, where environmental indicators represented the majority and had the most impact.

There are a number of indicators specified differently in various research. In the following table (Table 1), indicators are most often presented and divided into themes—most often the following: environmental, economic, social and technical. In terms of category, they are separated into wastewater treatment and sewage sludge treatment, depending on which waste source the research focuses on. The selected themes and observed indicators are based on a literature overview.

Table 1. Literature overview of existing indicators, differentiated by wastewater and sludge treatment.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Category</th>
<th>Indicator</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Sludge treatment</td>
<td>Occupied land, Environmental risk, Emissions, Hazardous by-products and products</td>
<td>[30,47–50]</td>
</tr>
<tr>
<td>Technical</td>
<td>Wastewater treatment</td>
<td>Energy consumption, Energy production, Reliability, Performance (nutrient removal), Flexibility/resilience, Durability</td>
<td>[21,24,35,41,43]</td>
</tr>
<tr>
<td>Technical</td>
<td>Sludge treatment</td>
<td>Operation ability, Site selection, Applicability, Energy efficiency, Material stabilization, Resources utilization efficiency, Commercially acceptable products</td>
<td>[30,46–48]</td>
</tr>
<tr>
<td>Economic</td>
<td>Wastewater treatment</td>
<td>Construction cost, Operation and maintenance costs, Required land area cost, Possibility of producing valuable products, Tariffs</td>
<td>[21,32,35,41–43,45,46,51]</td>
</tr>
<tr>
<td>Economic</td>
<td>Sludge treatment</td>
<td>Capital cost, Operational cost, Energy savings</td>
<td>[30,47,48,52]</td>
</tr>
<tr>
<td>Social</td>
<td>Wastewater treatment</td>
<td>Visual impact, Public acceptance, Complexity, Noise, Job opportunities, Need for international/non-local experts, Land value decrease, Valuable products that can be inputs to other activities/industries, Safety, Institutional requirements, Public health risk</td>
<td>[21,32,35,41–43,46,51]</td>
</tr>
<tr>
<td>Social</td>
<td>Sludge treatment</td>
<td>Social acceptability, Contribution to society, Required labor</td>
<td>[9,47,48,52]</td>
</tr>
</tbody>
</table>
Additionally, this paper will present an example of the positive impact of utilizing energy recovery of sewage sludge via gasification as sustainable technology using LEAP. LEAP [53] is a software tool for energy policy analysis and climate change mitigation assessment. It is an integrated, scenario-based modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both the energy sector and non-energy sector greenhouse gas (GHG) emission sources and sinks.

LEAP is a tool that enables the planner to independently determine the parameters used in the calculation of future energy consumption. In each consumption sector, different parameters can be determined that affect the calculation result. However, all calculations of future consumption can be subordinated to a common generic equation for the calculation of energy demand forecast:

\[
ED_{FY} = \left( \frac{ED}{DP} \right)_{BY} \times DP_{FY} \times CH_{FY}
\]

where \(ED_{FY}\) represents the energy demand in a future year, \(\left( \frac{ED}{DP} \right)_{BY}\) represents the specific energy demand per unit of the driving parameter in the base year, \(DP_{FY}\) represents the driving parameter in a future year, and \(CH_{FY}\) is a coefficient to reflect the evolution of specific energy demand per unit of the driving parameter.

Driving parameters are values such as value added (VA) by industry, ton kilometers transported, passenger-kilometers transported, service floor area, number of dwellings, etc. On the other hand, coefficients of change are indicators such as electricity consumption per dwelling, non-thermal electricity consumption per VA, fuel consumption per 100 km, etc.

Within this paper, the research steps followed are described in the following flowchart (Figure 1):

Gasification is the thermal decomposition of the organic material in sewage sludge, performed at higher temperatures (around 700 °C) by controlling the amount of oxygen and
steam in the reactor. The product is syngas with hydrogen, methane and carbon monoxide as flammable gases. Gasification is usually performed after pyrolysis, and the excess heat from gasification is used for sludge drying and heating the pyrolysis reactor. The syngas can be utilized in gas turbines or cogeneration (CHP) systems to generate heat and electricity, while emissions are significantly reduced (in comparison to the direct incineration process) due to the accumulation of emissions in the solid fraction of the product [54].

As a basis for further modelling, the energy model of the city of Zagreb was considered [55]. The model was created with the LEAP tool, and a climate-neutral scenario until 2050 was designed, which includes an integrated analysis of energy consumption scenarios and the potential for implementing measures to improve energy efficiency and increase the share of renewable energy sources. The energy model on the energy consumption side defines five sectors, each of which is further divided into subsectors in which energy consumption is then defined according to specific purposes.

In this paper, a specific model is developed as a follow-up on the existing energy model in order to present a sustainable process of sewage sludge gasification. Within this developed model, all power plants in the city of Zagreb (in the transformation sector) were modeled, as well as the infrastructure for the distribution of electricity, hot water, and steam. This enables the modelling and analysis of measures such as decarbonization of energy production.

In the electricity generation sector, an unchanged energy mix was defined as a baseline scenario (S1_Baseline) so that the contribution of sewage sludge management in additional scenarios could then be evaluated. The baseline scenario was based on the year 2019, as the data for this year are the last available. Additionally, this year was selected as it best represents the baseline scenario before the COVID-19 pandemic. Since the information and data for the years 2020 and 2021 are not available, it cannot be presented how they impact the projections until 2030 and 2050. The second scenario was created to present the maximum potential in the context of all power plants in the city of Zagreb (S2_Max_potential). The third scenario analyzes the realistic potential of sewage sludge utilization in the cogeneration plant (S3_Realistic).

3. Results and Discussion

3.1. Development of Sustainable Indicators

Sustainable waste management aims to keep materials in use for as long as possible and minimize the amount of solid waste that is disposed of in a landfill or through incineration [56]. With the development of new technologies, it is possible to obtain energy and material recovery through specific technologies, oriented towards obtaining only specific output or through simultaneous recovery.

Based on the literature overview and research presented in the previous chapter, it can be concluded that most of the research has similar indicators related to both wastewater and sludge treatment. Therefore, most of them can be used in the development of sustainable indicators, specifically related to sewage sludge treatment. Moreover, the observed indicators—socio-economic, technical and environmental—are considered in order to cover all the aspects of the potential impact of sustainable sewage sludge management.

In the following segment, each theme will be determined and described for sustainable technologies. These include energy and material recovery technologies, whose goal is to achieve maximum sustainability, with production and landfilling of as little waste as possible. Additionally, the production of valuable new materials and nutrients is a significant aspect of observed technologies—at least one of the technology segments is required to generate new material/product.

Therefore, the new technologies for sustainable sewage sludge treatment examined in various previous research and considered in this paper are the following: gasification [48,57–60], material recovery (struvite crystallization) [61–63], anaerobic digestion [64–67] and hydrothermal carbonization [68–70].
3.1.1. Technical Indicators

Technical indicators are related to technology itself. These will include the following summarized indicators, considered from Table 1 (Technical indicators):

- Energy consumption and production;
- Reliability;
- Performance (nutrient removal);
- Flexibility/resilience;
- Site selection;
- Applicability;
- Energy efficiency;
- Resources utilization efficiency;
- Commercially acceptable products.

However, some of the indicators need to be modified in order to include the sustainability aspect. Therefore, the following table (Table 2) presents the sustainable technical indicators, with a description of each indicator.

**Table 2. Technical sustainable indicators.**

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Sustainability Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy sustainability</td>
<td>Considers energy efficiency of the process, i.e., how much energy is produced during the process, in consideration of how much energy is consumed. Additionally, this indicator considers how much energy is used from the closed process, taking into account the demand for other energy sources (electricity/gas grid, other energy plants, etc.).</td>
</tr>
<tr>
<td>Flexibility/resilience</td>
<td>The impact of changes within the process on the outputs. Includes the reliability of the process and applicability in specific areas and locations.</td>
</tr>
<tr>
<td>Resources/products utilization efficiency</td>
<td>Amount of resources needed for the process and their efficiency in terms of production (material/energy output).</td>
</tr>
<tr>
<td>Commercial acceptability of products</td>
<td>The prices and situation of the outputs on the energy and/or material market. Includes the aspect of market demand and supply without a social component (acceptability by the end-users).</td>
</tr>
</tbody>
</table>

3.1.2. Socio-Economic Indicators

Due to high connectivity between social and economic indicators, in terms of sustainability, they have been merged. Following the presented indicators in Table 2, they are summarized to include:

- Capital cost;
- Operation and maintenance costs;
- Possibility of producing valuable products;
- Tariffs;
- Visual impact;
- Public acceptance;
- Complexity;
- Noise;
- Job opportunities;
- Safety;
- Institutional requirements;
- Public health risk.

In terms of sustainability, socio-economic indicators have to be significantly modified due to their innovativeness and potential lack of understanding from the public but also from experts. Therefore, the following table (Table 3) presents the sustainable socio-economic indicators, with a description of each indicator.
Table 3. Socio-economic sustainable indicators.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Sustainability Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs</td>
<td>Initial investment with strong consideration of environmental, social, and corporate governance factors before contributing money and resources to a particular facility.</td>
</tr>
<tr>
<td>Operation and maintenance costs</td>
<td>Long-term planning, considering new solutions and technologies. Satisfying present needs without compromising on the ability to meet future needs. Materials and energy used need to be sustainable and “green” (e.g., recycled materials, energy from renewables).</td>
</tr>
<tr>
<td>Generating job opportunities</td>
<td>Innovative aspect of new technologies includes the need for new knowledge. Therefore, a qualified workforce is needed, which can be obtained at a local level. Job opportunities could be potentially determined with information and data from research papers, describing examined technologies and processes—no. of jobs with/without sustainable treatment plants and processes.</td>
</tr>
<tr>
<td>Production of valuable products</td>
<td>Production of new products that are environmentally friendly and can be easily reused/recycled. The process by-products can also be used for other purposes, and waste production is reduced to a minimum.</td>
</tr>
<tr>
<td>Incentives</td>
<td>New technologies usually come with a high cost. Therefore, it is necessary to implement different incentive schemes and update them periodically to encourage future development.</td>
</tr>
<tr>
<td>Public acceptance</td>
<td>Waste management technologies that generate new materials within the concept of circular economy and sustainability might not be well accepted by the public. This indicator is important in order to bring new technologies in waste management closer to the general public. A general problem with social aspects is due to subjectivity and intangible aspects (such as comfort, privacy, convenience, safety, status, prestige, etc.).</td>
</tr>
<tr>
<td>Complexity</td>
<td>New technologies might potentially have a higher complexity rate, making them harder to understand. It is possible that technologies that are more sustainable have a higher complexity rate due to the combination of several methods.</td>
</tr>
<tr>
<td>Safety</td>
<td>Management of waste materials has its hazards, which need to be determined and examined. In terms of sustainability, where the goal is to extract as much energy and material from waste as possible, it is necessary to set safety measures that will prevent possible leakage into the environment.</td>
</tr>
<tr>
<td>Institutional requirements</td>
<td>Risk and policy assessment within the regulatory framework. Utilization of descriptive methods for policy assessment. Why do certain policies need to be revised in order to better manage sewage sludge?</td>
</tr>
<tr>
<td>Affordability and cost-effectiveness for citizens/end-users</td>
<td>How much will the new technologies and processes increase prices for the end-users? How long will the increase last, and at what period will it turn to cost reduction? Includes cost-benefit analysis and cost projections for the future period.</td>
</tr>
<tr>
<td>Public health risk</td>
<td>Monitoring of environmental parameters that impact human health, such as chemical oxygen demand, biological oxygen demand, leakage of nutrients (nitrogen, N, phosphorus, P, potassium, K), discharge of heavy metals, etc. A strong connection with environmental indicators.</td>
</tr>
</tbody>
</table>

3.1.3. Environmental Indicators

Within the sustainability concept, the environmental pillar addresses the ecosystems and their life support functions for mankind. Here, assessments can be based on environmental science with a higher degree of predictability and scientific consensus. This segment focuses on environmental sustainability assessment. Following the presented indicators in Table 1, they are summarized to include:

- Pollutant removal efficiency;
- Waste quantities;
- Sludge quality;
- Odor;
Water treated/water collected;
• Share of industrial wastewater treated;
• Global warming potential;
• Emissions;
• Eutrophication;
• Ozone layer depletion;
• Human toxicity;
• Occupied land;
• Emissions;
• Hazardous by-products and products.

Environmental indicators include various chemical and biological aspects, such as chemical oxygen demand (COD), biological oxygen demand (BOD), heavy metal content, emissions of various compounds to air, soil and water, etc. However, these are all monitored during the operations of the sewage sludge treatment facility, as a regulatory obligation. Therefore, in the following table (Table 4), indicators that are presented only summarize the concept of sustainability that needs to be observed within them and not each specific component.

Table 4. Environmental sustainable indicators.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Sustainability Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient extraction efficiency</td>
<td>Removal of pollutants and extraction of valuable nutrients that can be used for other purposes. Potential for material recovery.</td>
</tr>
<tr>
<td>Waste quantities</td>
<td>Reduction of waste quantities with sustainable technology implementation through the utilization of waste streams as feedstock for other processes.</td>
</tr>
<tr>
<td>Emissions</td>
<td>Includes emissions to air, water and soil. Considers reduction of negative impact on the environment and decrease of emissions to natural receivers. This also includes other impacts when emissions are considered, such as a reduction in the eutrophication process, reduction in negative odors, reduction in N, P, K, discharge of heavy metals, etc.</td>
</tr>
<tr>
<td>Global warming potential</td>
<td>Impact on climate change due to a reduction in greenhouse gas emissions.</td>
</tr>
<tr>
<td>Occupied land</td>
<td>Reduction of needed area for plant construction. This considers a decrease in the utilization of agricultural land, which can be used for other purposes (mainly food production).</td>
</tr>
<tr>
<td>Agricultural efficiency</td>
<td>Amount of reduced synthetic fertilizers that can be replaced by sewage sludge or sludge treatment by-products (struvite, N-fertilizers, etc.).</td>
</tr>
<tr>
<td>Storm resilience</td>
<td>Impact of storms (heavy rainfalls) on potential dilution of materials within the sludge. Difference between sludge characteristics before and after rainfalls.</td>
</tr>
</tbody>
</table>

3.2. LEAP Analysis

One of the manners in which sustainable indicators can be presented is through the LEAP model. Within this paper, a gasification process of sewage sludge is observed with the goal of energy production, using the necessary data presented by Đurđević et al. [71], shown in Table 5. The sewage sludge used within the plant is considered to be obtained from the local WWTP for the city of Zagreb—CUPOVZ.

Table 5. Data for sewage sludge gasification process (obtained from [71]).

<table>
<thead>
<tr>
<th>Criterium</th>
<th>Ranking/Amount</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy demand</td>
<td>133.33</td>
<td>MWh/year</td>
</tr>
<tr>
<td>Electric efficiency</td>
<td>20</td>
<td>%</td>
</tr>
<tr>
<td>Heat efficiency</td>
<td>80</td>
<td>%</td>
</tr>
<tr>
<td>Energy production</td>
<td>122.22</td>
<td>MWh/year</td>
</tr>
<tr>
<td>Operational expenses</td>
<td>118,381,50</td>
<td>EUR/year</td>
</tr>
<tr>
<td>Capital expenses</td>
<td>1,210,720.50</td>
<td>EUR</td>
</tr>
<tr>
<td>Emissions</td>
<td>4800</td>
<td>tonnes of CO$_2$eq/year</td>
</tr>
</tbody>
</table>
These data were inserted in the LEAP tool, and the results of three defined scenarios were compared regarding the impact of using sewage sludge in cogeneration plants on the CO₂ equivalent emissions (CO₂eq).

The S1 scenario does not include sewage sludge as feedstock fuel for energy production but considers only the following feedstocks currently used: natural gas, biogas, solar and residual fuel oil.

In the S2 scenario, sewage sludge accounts for 46% of production in 2030 and 83% in 2050. This scenario considers the replacement of fossil fuels currently used with sewage sludge as additional renewable feedstock. In this scenario, sewage sludge is considered a feedstock, where energy demand for its preparation is not considered. The reason behind this assumption is that energy plants in the observed case study consider only the final energy content of the input feedstock and not the energy demand necessary for its preparation.

However, the remaining natural gas amount is still considered since it would not be possible to completely exclude natural gas from energy consumption, even by 2050, in the case of Croatia. The necessary amount of sewage sludge required for this scenario amounts to 475,332.93 and 855,599.27 t of dry matter (DM) per year by 2030 and 2050, respectively. These might seem to be unrealistic shares in terms of available sewage sludge quantities but are modeled to determine the maximum potential of sewage sludge that can be utilized.

In scenario S3, which is determined as a realistic potential, sewage sludge has a share of 0.9% and 2% in energy production in 2030 and 2050, respectively (Figure 2). This scenario is based on the current production of sewage sludge in Zagreb, Croatia, which amounts to 20,000 t DM per year [71]. In this scenario, the final energy content of sewage sludge is also considered, not including the energy demand necessary for its preparation.

According to the S2 scenario, emissions of 363 thousand tons of CO₂eq in 2030 and 583 thousand tons of CO₂eq in 2050 would be reduced. According to the realistic S3 scenario, a reduction of 730,000 and 140,300 t CO₂eq in 2030 and 2050 would be achieved, respectively.

If looking at the relative reduction of both direct (demand) and indirect (transformation) emissions in the City of Zagreb, compared to the base year 2019, according to the Baseline S1 scenario, there is a reduction of 23.8% in 2030, 68.7% by 2050, and according to the realistic S3 scenario, there is a reduction of 24.0% in 2030 and 69.2% in 2050 (Table 6 and Figure 3).
As can be seen, the difference between amounts necessary for S2 in comparison to S3 is significant—over 830,000 t of sewage sludge. Even in the case of increased intensity of CUPOVZ workload, which would produce additional sewage sludge, as a result of city expansion, the amount required for S2 could not be achieved.

Therefore, in order to obtain the calculated reduction of GHG emissions (583,000 t CO$_2$eq), an additional application of renewable sources or sustainable and low-carbon fuels is needed.

4. Conclusions

Wastewater treatment plants receive increasing significance within the concepts of the circular economy and the bioeconomy due to the valuable outputs that they provide, such as energy and nutrient contents. In terms of sewage sludge, these contents have an even greater significance since sludge is the product of the WWTP process that needs to be treated in order to reduce its negative impact on the environment. Therefore, new and innovative technologies are examined each day in order to develop sustainable solutions that can provide benefits for sewage sludge produced while simultaneously benefiting the environment and human health.

In order to evaluate the positive impacts of these technologies, indicators need to be developed that encompass the aspects impacted by them. Within this paper, those indicators have been proposed based on the literature overview. They are divided into three themes: technical, socio-economic and environmental. Each of these contains a number of indicators that presents a manner in which sustainable sewage sludge technologies impact: the environment, human health, social aspects, technical availability, etc. However, even though the proposed indicators are based on the existing ones, which are similar, it would not be correct to put them in comparison. As sustainable processes differ from existing processes, they need to be compared to other research that focuses on specific sustainable

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1_Baseline</td>
<td>−23.8%</td>
<td>−68.7%</td>
</tr>
<tr>
<td>S2_Max_potential</td>
<td>−37.6%</td>
<td>−90.9%</td>
</tr>
<tr>
<td>S3_Realistic</td>
<td>−24.0%</td>
<td>−69.2%</td>
</tr>
</tbody>
</table>

Figure 3. Relative CO$_2$eq reduction by scenarios (in relation to 2019).

Table 6. Relative CO$_2$eq reduction by scenarios (in relation to 2019).
technology. Currently, there is no existing research on this topic, which creates a new research field that can be examined.

Furthermore, a LEAP model analyzed two scenarios—one with the maximum possible replacement of fossil fuels with sewage sludge (S2) and one with realistic replacement, based on the current amount of sewage sludge produced at CUPOVZ (S3). The results showed a decrease in GHG emissions (in comparison to 2019) of 37.6% and 24% for S2 and S3, respectively, in 2030. Additionally, the reductions increased in 2050—by 90.9% and 69.2% for S2 and S3, respectively. This presents the potential and possibility of utilizing sewage sludge for the replacement of fossil fuels with the purpose of reducing emissions. However, this sludge needs to be considered biogenic and emission-free.

However, the analysis also showed that the decrease in emissions seen in S2 is not realistic due to the significant demand for sewage sludge, which could not be obtained by CUPOVZ, even in 2050 with emissions increase related with city expansion. Therefore, in order to achieve the decarbonization of the energy sector, it is necessary to include additional renewable sources or low-carbon fuels in the energy mix. Additionally, there is a vast new research area where waste can be examined as a sustainable solution for energy generation.

Yet, sewage sludge proves to be a good solution for contributing to the decarbonization process. Moreover, considering its potential for material recovery, it can significantly contribute to the concepts of the circular economy and the bioeconomy. From this analysis, it can be concluded that sewage sludge could have more potential in material recovery and should be considered as a tool in that area in comparison to energy production and recovery.

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