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Waste-to-Energy Processes as a Municipality-Level Waste Management Strategy: A Case Study of Kočevje, Slovenia

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Abstract: The escalating challenge of waste management demands innovative strategies to mitigate environmental impacts and harness valuable resources. This study investigates waste-to-energy (WtE) technologies for municipal waste management in Kočevje, Slovenia. An analysis of available waste streams reveals substantial energy potential from mixed municipal waste, biodegradable waste, and livestock manure. Various WtE technologies, including incineration, pyrolysis, gasification, and anaerobic digestion, are compared. The results show that processing mixed municipal waste using thermochemical processes could annually yield up to 0.98 GWh of electricity, and, separately, 3.22 GWh of useable waste heat for district heating or industrial applications. Furthermore, by treating 90% of the biodegradable waste, up to 1.31 GWh of electricity and 1.76 GWh of usable waste heat could be generated annually from biodegradable municipal waste and livestock manure using anaerobic digestion and biogas combustion in a combined heat and power facility. Gasification coupled with a gas-turbine-based combined heat and power cycle is suggested as optimal. Integration of WtE technologies could yield 2.29 GWh of electricity and 3.55 GWh of useable waste heat annually, representing an annual exergy yield of 2.98 GWh. Within the Kočevje municipality, this amount of energy could cover 23.6% of the annual household electricity needs and cover the annual space and water heating requirements of 10.0% of households with district heating. Additionally, CO_2-eq. emissions could be reduced by up to 20%, while further offsetting emissions associated with electricity and district heat generation by 1907 tons annually. These findings highlight the potential of WtE technologies to enhance municipal self-sustainability and reduce landfill waste.

Keywords: waste-to-energy; biogas; incineration; pyrolysis; gasification; municipal solid waste; waste management; energy conversion; waste utilization; exergy; steam turbine; gas turbine; ICE

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1. Introduction

In recent years, the increasing quantities of mixed municipal waste are presenting significant challenges for waste management systems worldwide, including in developed countries [1]. With urbanization and population growth on the rise, the generation of waste has reached unprecedented levels, straining existing waste management infrastructures and causing environmental concerns related to waste disposal [2,3]. The global production rate of waste is projected to increase significantly, increasing from 635 Mt in 1965 to 1999 Mt in 2015 and reaching 3539 Mt by 2050 (median values, middle-of-the-road scenario) [1]. Municipal solid waste (MSW), which stems from households and typically includes commercial and industrial waste, accounted for 2 billion tons of the total waste produced in 2016 [1]. Municipal solid waste is among the largest global contributors to emissions of greenhouse gases (GHGs). In 2010, solid waste landfills globally were estimated to emit approximately 31 million metric tons of methane (CH_4) annually, equivalent to 799 million metric tons of carbon dioxide (CO_2) in terms of their impact on global warming [4]. This amounted to roughly 11% of the total global emissions, notably contributing to global warming due to the GWP (global warming potential) of methane being significantly higher than that of CO_2 [5]. The traditional reliance on conventional MSW management methods, such as landfilling, has led to serious environmental issues, including ecological damage, public health risks from infections, leachate evaporation, foul odors, and contamination of waterways [6]. Landfills also represent the third largest anthropogenic source of methane emissions [7]. Global emissions of methane from landfills are projected to exhibit an increasing trend, reaching approximately 68 Mt per year in 2017, up from 57 Mt per year in 2000. These figures correspond to carbon dioxide equivalent projections of 800 Mt CO_2-eq. for 2015, as determined through IPCC inventory analysis [8–10]. Consequently, the pursuit of innovative waste management approaches emerges as a primary solution to mitigate the challenges posed by waste and foster sustainability.

Additionally, increasing levels of agricultural activities (especially increasing livestock numbers) also result in large amounts of biodegradable waste with high methane and CO_2 emissions but also with a high potential for energy production. Globally, agricultural and agro-industrial waste has been steadily increasing by 5 to 10% annually [11]. In the United States alone, these wastes amount to 998 million tons of biomass per year on a dry basis [12]. Agriculture can play a pivotal role in transitioning to clean energy, necessitating a shift away from socially and environmentally unsustainable farming practices reliant on fossil fuels and electricity [13,14]. Besides cultivating dedicated energy crops [15], utilization of crop residues and livestock manure holds significant potential for enhancing renewable energy production [16,17].

The confluence of increasing urban populations and expanding agricultural activities has intensified the urgency to explore sustainable solutions for waste management. In this context, waste-to-energy (WtE) processes have emerged as a promising avenue for the efficient utilization of both municipal and agricultural waste streams, offering not only a means of waste disposal but also a source of renewable energy. Thus, they represent a "win-win" strategy by mitigating problems with waste disposal and associated emissions with the simultaneous production of energy or energy carriers. In essence, WtE processes involve converting various types of waste materials, including municipal solid waste, into usable forms of energy. MSW can serve as a valuable resource for electricity production, contributing to a reduction in total GHG emissions by reducing the emissions from landfills (by depositing less waste) and by supplementing electricity production using traditional carbon-based (fossil) fuels, such as coal and natural gas. The most common waste-to-energy routes [18,19], including their key products, are shown in Figure 1.

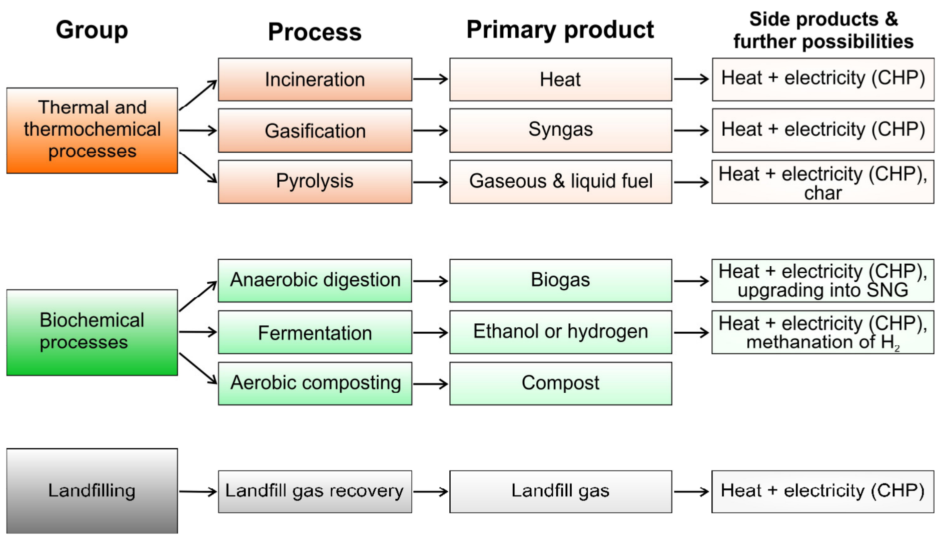

Figure 1. Overview of the most common waste-to-energy routes.

For the purpose of WtE conversion, technologies like incineration [20], pyrolysis [21], and gasification [22] are commonly used, allowing for the generation of (i) combustible fuels such as methane and hydrogen, (ii) electricity, and (iii) heat as a side-product for district heating or industrial purposes [19,23,24]. Whenever heat is produced or combustion processes take place, it makes sense from a technical standpoint to utilize combined heat and power (CHP) technology, which allows the generation of electricity (via a steam or gas turbine or with a reciprocating engine) and utilization of waste heat for low-temperature applications (e.g., heating). Similarly, organic waste can be converted into biogas using anaerobic digestion or into similar useful products using other biochemical processes, including ethanol fermentation, dark fermentation, and aerobic composting [23]. Finally, landfilling is the traditional approach to MSW disposal but can contribute to energy generation and emission reduction through landfill gas capture [25–27].

On a positive note, in many developed countries, waste separation and recycling have contributed to a reduction in the amount of mixed municipal waste, which tends to end up in landfills and does not contribute to the circular economy [28]. Furthermore, the development of new technologies continuously enables new possibilities for repurposing waste with appropriate treatment processes.

Traditionally, incineration was primarily utilized to reduce the volume of MSW and mitigate environmental hazards, although its primary purpose was not energy recovery [20]. However, advancements in technology have enabled more efficient energy recovery processes for MSW management, making it a viable option for electricity generation while also addressing waste management and environmental concerns. During incineration, waste materials are burned at high temperatures. The heat generated from combustion can be used to produce steam, which drives turbines to generate electricity, thus utilizing CHP technology. The remaining ash from incineration can sometimes be used for construction materials or disposed of in a controlled manner [29]. Moisture significantly impacts the combustibility and calorific value of MSW. As moisture content increases, the calorific value decreases due to the heat required to vaporize water. According to the literature, the calorific value of MSW ranges from 4 to 19 MJ/kg of wet mass, and the typically recommended value for analysis is 9.8 MJ/kg [30]. To assess the self-sustained combustibility of MSW, the Tanner diagram [30] is commonly used to analyze the joint effects of organic matter content, ash content, and moisture content. The proposed lower heating value (LHV), under which incineration of MSW becomes non-viable, is typically given as 7 MJ/kg of wet mass.

Similarly, pyrolysis involves heating organic materials, but this is performed in the absence of oxygen to thermally decompose the materials down into combustible products (gases and liquids), while certain solid residues may also represent valuable side-products (e.g., biochar) [31]. The gases and liquids produced can be used as fuels for electricity generation or other industrial processes, while the solid residue (char) can be used as a soil amendment or for other applications [32]. Pyrolysis can be classified as slow, fast, or flash pyrolysis, depending on the process temperatures (and, consequently, processing times). Depending on the type of pyrolysis, the type of the reactor, feedstock composition, and process parameters, the composition of the products (liquid (oily) products, syngas, char) can vary significantly [33]. Pyrolysis can utilize diverse feedstock compositions, ranging from MSW to paper and plastic waste. To conduct the process, pre-treatment of the feedstock in the form of drying to 10–20 wt.% moisture is typically necessary.

A further thermal MSW treatment process is gasification, which converts carbonaceous materials into synthesis gas (also known as syngas), which is primarily composed of carbon monoxide, hydrogen, and methane [34]. Syngas can be used as a fuel for generating electricity or producing chemicals and fuels through further processing [35]. As with other WtE processes, the efficiency of gasification depends on many factors related to the calorific value of the feedstock, process parameters, and the exact gasification technology. In general, approx. 25% electrical efficiency can be expected in a CHP plant, with another 25% of the input energy flow being converted into waste heat available for further utilization [36]. In a gasifier, diverse waste can be treated with suitable adjustments, including MSW, refuse-derived fuel, hospital waste, industrial waste, and biodegradable waste. As with pyrolysis, drying of the feedstock is commonly required.

Finally, organic waste materials, such as food scraps, yard waste, sewage sludge, and agricultural waste, can undergo anaerobic digestion (AD) [37]. In this process, microorganisms break down the organic matter in the absence of oxygen, producing biogas (primarily composed of methane and carbon dioxide) and a nutrient-rich digestate [38]. The biogas can be used as a fuel for generating electricity and heat [39], or it can be upgraded through CO_2 removal into a renewable equivalent of natural gas [40], while the digestate can be used as a fertilizer [41]. Several factors influence the efficiency of anaerobic digestion, such as temperature, pH, the C/N ratio of the substrate, the amount of volatile solids fed into a digester, and the retention time [42]. Different feedstock often leads to the use of co-digestion of two or more feedstock types, which can harness the individual benefits of both or avoid the drawbacks of one type. For example, lignocellulose matter that mainly consists of crop residue is hard to digest by itself, due to recalcitrant materials (e.g., cellulose), which made previous studies consider its co-digestion with organic matter, such as with livestock manure [43]. Combining two substrates can also be beneficial in terms of gas production efficiency, with some authors reporting an increase in biogas production by up to 337% during co-digestion [44]. In terms of scale, the methane yield of anaerobic digestion, depending on the type of organic waste and digestion process employed, ranges around 180 to 680 L of gas per kilogram of volatile solids [45], yet the technology requires relatively long retention times, which limits the daily production of biogas (1.1 to 16.4 L of biogas per day for the above-referenced range) and requires large scale-up to achieve substantial gas production.

In addition to the aforementioned processes, several other technologies, such as landfill gas recovery, are also available. Furthermore, novel technologies, including plasma gasification [46], hydrothermal carbonization [47,48], and catalytic depolymerization [49], are also gaining prominence and may replace some of the traditional WtE processes in the future. Figure 2 shows the common waste flow in WtE processing and the core benefits of such an approach to waste management.

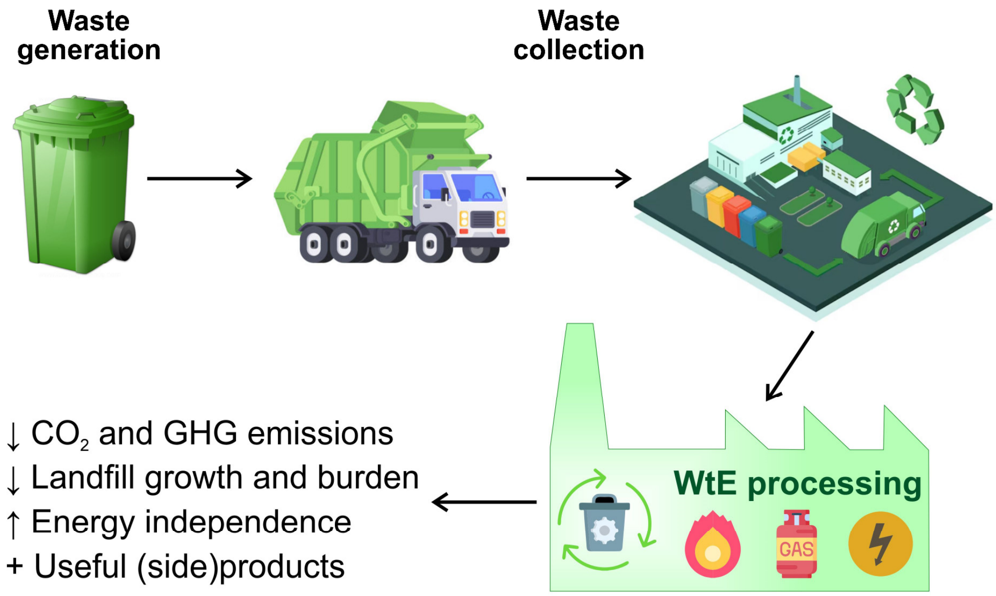

Figure 2. Waste processing using the waste-to-energy approach and its key benefits.

Implementing WtE strategies at the municipality level as a waste management method has several benefits [50]. Firstly, it reduces the amount of waste and repurposes it, thus diverting waste from landfills and reducing the environmental impact of waste disposal. By converting waste into energy or other valuable products, these strategies promote a circular economy approach, where resources are recycled and reused, minimizing the need for virgin materials [51]. WtE technologies provide an alternative source of energy, contributing to local energy security and reducing reliance on fossil fuels. Moreover, WtE technologies offer cleaner and more efficient energy production, with lower emissions and a lower environmental footprint compared to traditional waste management methods.

There have been several studies detailing the possible use of WtE on a municipality level or on a scale similar to the one we aim to study herein. Alao et al. [52] presented a case study of Lagos, Nigeria, where they estimated that incineration was not a suitable approach for the city and instead proposed other alternatives. In terms of the least energy cost, pyrolysis performed best, while anaerobic digestion had the highest emission reduction potential. The optimal solution turned out to be a hybrid integration of anaerobic digestion, landfill gas recovery, and pyrolysis with an emission reduction potential of 91% and a 0.07 USD per kWh cost of energy. Korai et al. [53] studied the waste-to-energy potential in Hyderabad, Pakistan, and found that no one strategy was able to provide a complete solution for the variety of components found in the city's waste and pointed out the need for hybrid solutions. Similarly, Guiliano et al. [54] showed that different points of view result in different technologies being found optimal. When studying WtE in an Italian district, gasification with subsequent syngas cleaning and co-combustion was found to be the most optimal solution in terms of energy production, while the emission reduction potential was highest when using the well-established method of combustion of unsorted waste in a dedicated grate combustor. Moya et al. [55] considered the municipal solid waste of Quito, Ecuador, to obtain a power generation potential of thermochemical and biochemical processes of 0.78 and 0.07 MW per ton of MSW, respectively. Esfilar et al. [56] considered the life-cycle cost of converting 3500 tons of annual waste at the University of Victoria to renewable electricity and heat. Standalone gasification was estimated to be able to supply 400 kW of electricity and 500 kW of heat per day, resulting in an investment payback period of 2.38 years and a substantial reduction in greenhouse gas emissions. For a high-energy-consuming building, they proposed a cost-optimized hybrid system, consisting of the biomass gasifier, photovoltaics, wind turbine, and batteries.

This study aims to explore and evaluate the possibility of using several technologies on a municipality level to harness the energy potential of diverse waste streams, including mixed municipal waste, biodegradable municipal waste, and agricultural waste (livestock manure). The proposed waste-to-energy systems would include the production of electricity and heat for district heating or industrial purposes. Several scenarios are analyzed based on the amount of waste successfully repurposed for energy production, and various technologies are compared. GHG emissions in terms of CO_2-eq. are estimated, alongside the percentage of people and households in the Kočevje municipality whose needs could be served with the proposed WtE facilities.

2. Materials and Methods

2.1. General Information on the Kočevje Municipality

The Kočevje municipality is located in the southern part of Slovenia. It is situated within the Dinaric Alps (bordering Croatia to the south) and surrounded by the Kočevje Forest to the north. The Kočevje municipality spans approximately 555.6 km^2 and had 15,674 inhabitants in 2023 and 3540 households in 2021. The predominant land use in the Kočevje municipality is forestry, with extensive forests covering a significant portion of its land area (460.9 km^2). Additionally, agricultural land is utilized for farming purposes, including livestock rearing and crop cultivation. The industrial activities within the municipality are diverse, ranging from wood processing to manufacturing of melamine-based resins and industrial automatization/robotization solutions.

2.2. Municipal Waste in Kočevje

Data on the collected municipal waste, including historical trends, were provided by the municipality's waste management company (Komunala Kočevje, d.o.o., Kočevje, Slovenia). Five main types of municipal waste are collected: paper and paper packaging, glass and glass packaging, mixed (plastic) waste, biodegradable waste, and mixed municipal waste. Of these categories, the latter two represent the most potential for WtE processes, while the other categories undergo well-established recycling processes. Figure 3 shows how the amount of waste per capita changed over the years from 2013 to 2023 in the Kočevje municipality, alongside the composition of the waste. Additionally, population numbers for the same timespan are plotted on the right axis.

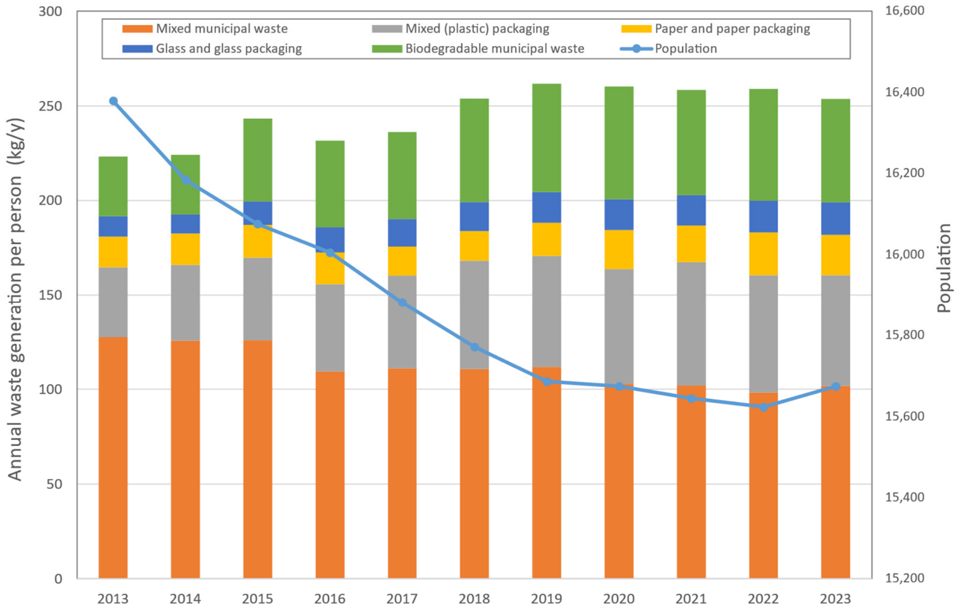

Figure 3. Per capita annual waste generation in the Kočevje municipality, including various categories of waste (left axis) and population of the municipality between 2013 and 2023 (right axis).

Further specific types of waste (e.g., metals, building materials, larger objects, etc.) are collected separately and not taken into account in this analysis, because of the relatively small quantities and low WtE potential.

Figure 4 shows the absolute amount of generated waste from 2013 to 2023 for the mixed municipal waste and biodegradable waste. Based on the relatively stable population within the last 6 years (15,679 inhabitants on average between 2018 and 2023), stable trends in total produced waste are also observable. Specifically, an average of 1712 t/y of mixed municipal waste and 931 t/y of biodegradable waste was produced between 2018 and 2023. These numbers is used as input data for further calculations and represents the maximal amount of municipal waste available in the Kočevje municipality.

It is worth noting that typical WtE processing plants (e.g., incinerators) only operate with economic viability when processing significantly larger amounts of waste (typically above 25,000 or 50,000 t/y) [30]. Nevertheless, the goal of this study is to analyze how waste streams from a single municipality could be incorporated into a WtE strategy and how the positive effects (e.g., produced electricity, heat, and biogas/SNG) from the single municipality's waste would affect the municipality. To achieve economic viability, waste from a wider region should undergo WtE processing in a single facility. The latter would process waste for at least 460,000 people based on the per capita annual waste production given in Figure 3.

Figure 4. Absolute quantities of collected mixed municipal waste and biodegradable waste in the Kočevje municipality between 2013 and 2023.

2.3. Agricultural Waste in Kočevje

Agricultural waste in Kočevje has three main sources. Firstly, manure from livestock represents a mostly unexploited potential for WtE due to its high biogas production in processes such as anaerobic digestion. Secondly, crop residue could also represent an additional source of biomass feedstock for biochemical WtE processes. Finally, forestry residue in the form of low-quality wood and wood waste could be used in thermochemical WtE processes. Table 1 provides values on livestock headcount and estimated daily and annual manure generation for 2023. The manure generation estimates are made based on the available literature [57–60]. Furthermore, waste availability is considered, accounting for possible preferential alternative uses and difficulties in collection [57]. The total annual generation of manure theoretically amounts to 21,296 t/y of animal manure available for WtE processing (with the unavailable share already subtracted).

Table 1. Livestock numbers per individual groups of animal species and estimated manure potential for biogas production.

Group	Nr. of Animals	Estimated Daily Manure Generation (per Animal; kg/day)	Availability for WtE Processing (%)	Estimated Annual Manure Potential for WtE (Total; t/y)
Cattle	4069	29.6	45	19,783
Sheep	3910	1.75	35	874
Pigs	199	5.18	80	301
Ungulates	279	24.2	10	246
Goats	355	1.75	35	79.4
Poultry	531	0.09	70	12.2
Rabbits	69	0.15	5	0.19

Table 2 provides the acreage of individual crops in the Kočevje municipality in 2023.

Table 2. Crop acreage in the Kočevje municipality in 2023.

Crop	Acreage (ha)	Description
Grasses	2373	Permanent grassland (grasses, grass-clover mixtures, Sudan grass)
Corn	1158	For silage (88%) or for grain (12%)
Cereal	689	Winter barley, winter wheat, winter triticale, winter rye, wheat, sunflower, barley, winter oilseed rape, soybean, millet, winter spelt, hemp, buckwheat, etc.
Potatoes	247	
Vegetables	128	
Other	91.1	Alfalfa, beans, clover, oil pumpkin, fodder beet, vine
Land not in use	63.2	
Mixed use	57.4	Mixed fruit species, chiefly apple, pear, walnut, etc.

As evident from the data in Table 1, the vast majority of manure in the municipality is generated by cattle (92.9%), with only sheep (4.1%), pigs (1.4%), and ungulates (1.2%) contributing over 1% of the total potential. As for the crops and utilization of their residue, it is evident that most land is used for agricultural purposes without biomass residue of notable worth as a feedstock for biochemical or thermochemical WtE processes. Most crops either leave insignificant amounts of residue (e.g., corn for silage), or the residue is typically already repurposed (e.g., straw from cereal crops).

2.4. Proposed WtE Scenarios for Kočevje

Currently, the three types of waste of interest to this study (mixed municipal waste, biodegradable municipal waste, and livestock manure from agriculture) undergo the following separate treatment and disposal processes. Mixed municipal waste is centrally collected and handed over to a waste management company, which treats the waste using the D8 and D9 processes (biological treatment and physico-chemical treatment, respectively) following the EU Waste Framework Directive 2008/98. Approximately 38% of the original weight of the collected mixed municipal waste is disposed of at the regional landfill after the treatment according to municipality data for 2023. Secondly, biodegradable waste, which is collected separately, is composted at a central location by the municipality's waste management service. The compost is used to produce biofilters and as fertilizer to maintain the recultivation layer in landfills. No data on the use of manure in the municipality are available as centralized collection is not performed. It can be assumed that most of the manure is eventually spread on the fields as fertilizer considering typical local farming practices.

As can be seen from the description above, some activities related to the utilization of waste are already implemented (i.e., composting of biodegradable waste), but no WtE processes are used to treat the mixed municipal waste and livestock manure. Therefore, we propose three possible scenarios for implementing WtE technologies in the waste management procedure in the Kočevje municipality. The three scenarios chiefly differ in the percentage of existing annual waste to be subjected to WtE processes. The scenarios were selected based on two factors. Firstly, they can represent the temporal progression of WtE implementation in the Kočevje municipality, where only a small fraction of waste would be processed at first (i.e., according to the pessimistic scenario), while larger shares of total waste in each category would become involved in the WtE waste management approach in the following years/decades (i.e., according to the balanced and optimistic scenario).

The other way to view the scenarios is based on the success of onboarding. If only a fraction of the waste can be treated using the WtE pathways, this would result in the pessimistic scenario. If more institutions and people (especially farms and farmers) would get on board, the balanced or optimistic scenarios (where nearly all the waste is subjected to

WtE processing) would ensue. The three scenarios are outlined in Table 3. In the pessimistic scenario, 25% of all collected mixed municipal waste is subjected to WtE processing. No biodegradable waste is processed, and the current treatment method (composting) is retained. In total, 25% of all available annually generated manure is collected and undergoes WtE processing. In the balanced scenario, 50% of all collected mixed municipal waste is subjected to WtE processing. Totally, 50% of the collected biodegradable waste is processed, and 50% of all available annually generated manure is collected and undergoes WtE processing. In the optimistic scenario, 100% of all collected mixed municipal waste is subjected to WtE processing, while 90% of both the collected biodegradable waste and of all available annually generated manure are collected for WtE processing. It is assumed that 100% of biodegradable waste and manure either cannot be collected or might be reused (e.g., by farmers as fertilizer).

Table 3. Three proposed WtE scenarios for the Kočevje municipality.

Scenario	Utilization of Mixed Municipal Waste	Utilization of Biodegradable Waste	Utilization of Manure
1 (pessimistic)	25% (428 t/y)	0% (0 t/y)	25% (5324 t/y)
2 (balanced)	50% (856 t/y)	50% (466 t/y)	50% (10,648 t/y)
3 (optimistic)	100% (1712 t/y)	90% (838 t/y)	90% (19,166 t/y)

In all three scenarios, the treatment technology is the same, while several processing pathways are evaluated (e.g., incineration, gasification, and pyrolysis of the mixed municipal waste). Furthermore, the techno-economic feasibility of equipment is not included in this study, since it is assumed that WtE processing would take place at a regional center as the waste flows generated by the Kočevje municipality are at least an order of magnitude too small for a municipal thermochemical WtE plant (e.g., an incinerator) to be feasible.

Figure 5 shows the current waste management processes for the selected waste categories (top part) and the proposed WtE routes (bottom part). In our analysis, we propose that mixed municipal waste undergoes thermochemical processing, where different options such as incineration, gasification, and pyrolysis are assessed. Both the collected household organic (biodegradable) waste and the manure (agricultural waste) are proposed to be treated using anaerobic digestion.

Three thermochemical WtE pathways are compared in the present study; WtE systems and efficiency data as collected and proposed by Dong et al. [61] are used with sensible modifications as the aforementioned study generally does not account for the utilization of all usable waste heat. Incineration can generally only be used to produce steam for either industrial or district heating and/or to power a steam turbine. For pyrolysis and gasification systems, employing a steam cycle is the simplest option as it allows the hot syngas to undergo combustion in a gas boiler without requiring purification. Alternatively, the syngas can be utilized in a gas turbine/combined cycle or an internal combustion engine, offering higher electrical efficiencies (set at 35.5% and 25.0% for gas turbine/combined cycle and engine, respectively). In all scenarios, the final electrical efficiency is reduced by 20% to account for the internal energy requirements. The residual ashes, consisting of bottom ash and air pollution control (APC) residues, undergo appropriate management before disposal in a landfill.

Firstly, waste incineration is considered, where the mixed municipal waste is combusted in a moving grate incinerator without pre-treatment. Following combustion, the flue gas proceeds into the heat recovery boiler, generating steam. This steam can be utilized for district heating or electricity generation using a steam turbine. Three sub-scenarios are proposed. In the technological scenario "INC-ST1", waste is incinerated, and steam is produced in a boiler with an efficiency of 80%. All steam is used in a condensing steam turbine to maximize electricity production, considering an overall net electricity efficiency of the turbine system of 30% and no useable waste heat production due to the low pressure and temperature of the condenser. However, the flue gases from the boiler are cooled to produce useable waste heat for district heating, with the percentage set at 5% of the total energy input in the form of the waste's calorific value (matching 25% of the initially unrecovered waste heat exiting the boiler). The technological scenario "INC-ST2" matches the "INC-ST1" scenario, but only 50% of the steam is used for electricity generation, while the other 50% is used to prepare hot water for district heating with a heat recovery efficiency of 80%. Finally, in the scenario "INC-ST3", all steam is fed into either an extraction or a backpressure turbine to maximize heat recovery, while the electricity production is of secondary importance. Here, 8% net electrical efficiency of the turbine and 80% thermal efficiency (i.e., generation of useable waste heat for district heating) is considered, matching the typical power-to-heat ratio of 0.1 for such turbines.

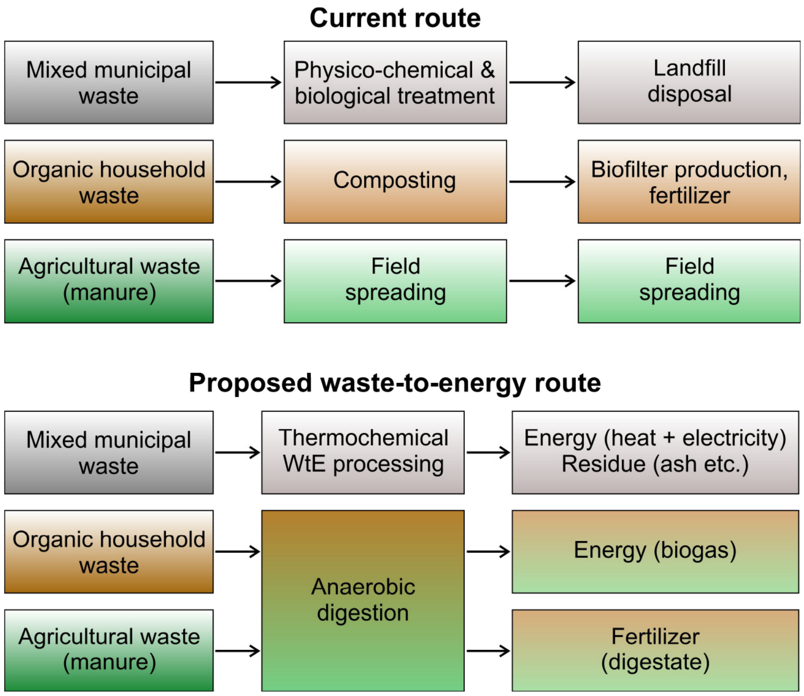

Figure 5. Current and proposed waste management of relevant waste flows in the Kočevje municipality.

Secondly, waste pyrolysis is considered with three downstream processes (steam turbine (ST), gas turbine (GT), or an internal combustion engine (ICE)) to convert the pyrolysis products into useable forms of energy. In pyrolysis, the distribution of products (syngas, tar, and char) heavily relies on factors such as reaction temperature, residence time, and heating rate. Industrial plants commonly operate at temperatures ranging from 500 to 550 °C for waste processing. The proposed process utilizes a rotary kiln reactor with a residence time of approximately 1 h. Around 85% of the energy is converted into hot gas (i.e., hot gas efficiency), while the cold gas efficiency typically reaches around 53%. Cold gas efficiency represents the ratio of the energy content of the cold syngas to that of the feedstock. The remaining portion constitutes char, making up approximately 30% of the mass. In the system with a steam turbine "PYR-ST", the raw syngas is combusted in a boiler to power a steam turbine for energy retrieval, using the same efficiency values as in the "INC-ST1" scenario. This setup stands as the most straightforward and prevalent WtE solution with waste pyrolysis as it eliminates the necessity for syngas purification (tar can also be directly burned in the combustion boiler). It is worth noting that both the pyrolysis reaction and waste drying processes in the system require an energy input, which is met by utilizing the heat from the hot flue gas downstream of the combustion chamber, following a common practice in industrial plants. The waste heat recovered from the boiler's flue gas is therefore self-consumed by the plant to pre-treat (i.e., dry) the waste before pyrolysis, so no useable waste heat is available for district heating. In the system with a gas turbine "PYR-GT", prepared and dried waste undergoes pyrolysis to generate syngas, which then serves as fuel in a gas turbine/combined cycle for enhanced electricity generation efficiency. Before entering the turbine, the raw syngas must be cooled and tar removed to meet stringent gas quality standards. Energy for the pyrolysis reaction is also derived from hot flue gas, while char and separated tar are combusted to produce heat for district heating. In this case, the useable waste heat for district heating is supplied from three sources: (i) from the heat recovery from the gas turbine's flue gas, (ii) from the cooling of syngas (5% of the input energy in the form of mixed municipal waste's calorific value), and (iii) from the burning of the char and other pyrolysis side-products (8% of the input energy). The third system "PYR-ICE" closely resembles the gas turbine system, with the key difference being the utilization of syngas in an internal combustion engine for electricity production. Syngas purification remains critical, and the energy supply for pyrolysis and waste-drying processes mirrors that of the gas turbine system. Heat is also recovered from the ICE cooling (cooling of the engine and the engine oil and heat recovery from the exhaust gas). Net electrical efficiency of 25% and thermal efficiency of 40% (in terms of generated useable heat for district heating) are assumed for the ICE. In this case, the useable waste heat for district heating is supplied from three sources: (i) from the heat recovery from the engine, (ii) from the cooling of syngas (5% of the input energy), and (iii) from the burning of the char and other pyrolysis side-products (8% of the input energy).

Finally, three gasification systems with the same variations in the downstream energy recovery technology as for pyrolysis are proposed. Gasification is primarily aimed at producing syngas, although tar formation is inevitable. Compared to pyrolysis, gasification typically occurs at higher temperatures, namely, between 550 and 900 °C in air gasification and 1000 and 1600 °C when using pure oxygen, oxygen-enriched gas, or steam. Based on operational data from various existing plants, the cold gas efficiency falls within the range of 50–80%. Assuming a hot gas efficiency of 90%, syngas can be directly utilized in a boiler without requiring pre-cooling. The three proposed gasification systems share similar configurations with their pyrolysis counterparts. However, thermal support for maintaining the thermal conversion process is not necessary, as gasification can achieve self-sustaining heat through partial oxidation reactions [62]. Typically, the energy utilization of gasification char and tar is not factored in due to their low energy content [63]. In the "GAS-ST" scenario, the syngas is directly combusted, and a steam turbine is used to primarily produce electrical energy the same way as in scenarios "INC-ST1" and "PYR-ST". As with the "PYR-ST" scenario, the waste heat obtained from the hot flue gases is self-consumed for waste drying. The "GAS-GT" and "GAS-ICE" scenarios match the pyrolysis counterparts except for the absence of heat recovery from the burning of the char and other pyrolysis side-products. In "GAS-GT" and "GAS-ICE" scenarios, useable waste heat is obtained from the heat recovery from the turbine's flue gas (gas turbine scenario) or the engine and its exhaust gas (ICE scenario), while additional energy is obtained in both cases from the cooling of syngas before it can be combusted.

Table 4 summarizes the efficiencies of individual WtE processing facilities, accounting for the energy flows entering the facility as waste with a calorific value (i.e., a lower heating value) of 9.8 MJ/kg (typical value for waste composition in Europe [62]) and exiting energy flows such as electricity and heat for district heating. For all nine processes, internal energy needs (electricity and heat) are already subtracted from the generated energy flows and accounted for in the efficiency determination. For all analyzed systems, 20% of the generated electricity is assumed to be self-consumed in the plant, with the remaining 80% sent to the power grid. A pretreatment step is assumed before the pyrolysis and gasification processes. Here, the incoming mixed municipal waste is shredded and subsequently dried to reach a final moisture content of approximately 10%. The heat required for drying is internally supplied either from the syngas purification unit or from hot flue gas with a thermal efficiency of 90%.

Table 4. Proposed thermochemical WtE processes for treatment of mixed municipal waste.

Abbreviation	Process	Electrical Efficiency *	Thermal Efficiency **
INC-ST1	Incineration + steam turbine #1	19.2%	5.0%
INC-ST2	Incineration + steam turbine #2	9.6%	37.0%
INC-ST3	Incineration + steam turbine #3	5.1%	69.0%
PYR-ST	Pyrolysis + steam turbine	20.4%	0.0%
PYR-GT	Pyrolysis + gas turbine	15.1%	36.9%
PYR-ICE	Pyrolysis + ICE	10.6%	34.2%
GAS-ST	Gasification + steam turbine	18.2%	0.0%
GAS-GT	Gasification + gas turbine	21.0%	38.4%
GAS-ICE	Gasification + ICE	14.8%	34.6%

* percentage of input energy converted into electricity supplied to the grid; ** percentage of input energy converted into useable waste heat supplied to the district heating.

For the WtE processing of biodegradable municipal waste and manure, anaerobic digestion is proposed. Briefly, all feedstock is fed into a digestor, where it undergoes co-digestion. While some effects of co-digestion such as increased biogas yields have been reported, it is assumed that each type of waste and manure produces specific quantities of biogas as if it were processed alone. Table 5 summarizes the key parameters of the anaerobic digestion of biodegradable municipal waste and manure.

Table 5. Dry matter content and estimated biogas yield for animal manure and biodegradable municipal waste through anaerobic digestion [57].

Group	Dry Matter Content (kg Dry Matter per kg)	Average Biogas Yield (nm^3/kg Dry Matter)
Cattle manure	0.14	0.281
Sheep manure	0.35	0.120
Ungulate manure	0.29	0.160
Pig manure	0.11	0.649
Goat manure	0.35	0.120
Poultry manure	0.29	0.359
Rabbit manure	0.52	0.359
Biodegradable municipal waste	/	0.120 *

* nm^3 per kg of wet waste.

For each source of manure, individual dry matter and estimated biogas yield are considered, using literature-sourced data [57]. For biodegradable municipal waste, the literature-reported biogas production of approx. 0.120 nm^3/kg of wet matter is used, while values can range from as low as 0.090 nm^3/kg for green garden waste to as high as 0.150 nm^3/kg for food waste [64–66]. The produced biogas is assumed to have a lower heating value of 21.6 MJ/nm^3 [57] and is used to power an internal combustion engine with an electrical efficiency of 30% and a thermal efficiency of 45% (representing the produced heat for the anaerobic digestion process or for district heating) [67–69]. These numbers are further offset by the estimated self-consumption by the anaerobic digestions of the plant, requiring 16% of the produced electricity and 25% of the produced heat [70].

The annual biogas yield for each scenario was determined by summing up all contributions from different feedstocks. To determine the individual contributions (in nm^3/y), the estimated annual production of the specific type of waste (e.g., cattle manure; in kg of wet matter per year) was multiplied by the availability factor, the dry matter content (in kg of dry matter per kg of wet matter), and the average biogas yield (in nm^3 per kg of dry matter). Conversions to electrical energy and waste heat were determined following the description in the previous paragraph.

To calculate the exergy values for both thermochemical and anaerobic digestion processes, it was assumed that the produced electrical energy (E_{el}) represents pure exergy (E_{ex}), while the exergy of useable waste heat (E_{th}) was determined by accounting for the temperature of the environment (T_∞ = 20 °C = 293.15 K) and the typical temperature of the feed into the district heating system (T_{heat} = 90 °C = 363.15 K) per the equation:

$$E_{ex} = E_{el} + E_{th}\left(1 - \frac{T_\infty}{T_{heat}}\right). \quad (1)$$

2.5. Emissions of Greenhouse Gasses

CO_2-equivalent emissions and their reduction with WtE technologies were estimated using the following methodology. It was assumed that the mixed municipal waste deposited at the landfill realistically emits 0.0324 t of methane per metric ton of deposited MSW [71], which results in 0.907 t of CO_2-eq. considering the lower range of the IPCC's recommended conversion (1 kg CH_4 = 28–36 kg CO_2-eq.). Furthermore, considering the information that 38% of the collected mixed municipal waste is deposited in landfills, this percentage was also used in the estimation of GHG emissions of the mixed municipal waste not undergoing WtE processing. The remainder of the mixed municipal waste was assumed to have been recycled with no data on the GHG emissions.

GHG emissions from manure also highly depend on the type of manure and processing technology (if any processing, such as field spreading, is applied). For small farms, which are typical for the Kočevje municipality, we estimated the GHG emissions from manure as 0.0455 t of CO_2-eq. per metric ton of manure [72,73]. This value is primarily valid for cattle manure, which is the prevalent source of manure in the municipality.

The CO_2-eq. emissions of composting of biodegradable municipal waste were conservatively estimated to be 0.100 t of CO_2-eq. per metric ton of wet waste [74].

WtE technologies also cause CO_2 and other GHG emissions. The emissions of CO_2-eq. of thermochemical MSW processing technologies as proposed in this study were estimated to be 0.330 t of CO_2-eq. per metric ton of processed mixed municipal waste [61]. As for the GHG emission of the anaerobic digestion, the study by Cuéllar and Webber showed that 1.8 kg of CO_2 is released during stoichiometric combustion of 1 nm^3 of biogas regardless of its methane content [73].

Furthermore, a reduction in CO_2-eq. emissions by producing electricity and heat via WtE processes was evaluated using data from the Slovenian Environment Agency and the Statistical Office of the Republic of Slovenia. Considering the mix of production sources, the electricity produced in Slovenia is associated with emissions of 0.306 kg of CO_2-eq. per 1 kWh (data for 2022). Furthermore, the emission factor for heat from district heating for 2022 is 0.34 kg of CO_2 per 1 kWh of heat. These values were used to determine the reduction in emissions stemming from the use of the WtE technologies proposed in this study.

It should be noted that the exact values of GHG are very hard to determine due to a lack of data on the specifics of the current waste management processes and manure treatment. Furthermore, estimated emissions of WtE technologies only account for the main process without accounting for auxiliary processes that might generate CO_2 or other GHG (e.g., leaks in anaerobic digestion, etc.).

2.6. Limitations of the Present Study

The purpose of this study was to broadly investigate the applicability of WtE technologies for a specific case (the Kočevje municipality), accounting for the locally available municipal and agricultural waste. Therefore, several simplifications and assumptions were made. To fully assess the optimal WtE strategies, further detailed studies are likely necessary. Some of the major limitations of the present study are listed below.

1. All data on the annual amount of collected municipal waste and the number of animals in the municipality are historical data in the form of either the most recent values or an average of several past years. No extrapolation to estimate the possible future values is made.
2. The WtE processing technologies including the thermochemical processes and anaerobic digestion are considered in a simplified manner and using predominantly literature-sourced efficiency values.
3. The exact composition and calorific value of the local mixed municipal waste is not known, and a conservative estimate is used for the LHV.
4. The availability of animal manure for WtE processing is estimated based on the literature-sourced availability factors per each group of animals. Existing local manure utilization practices are not analyzed.
5. The possibility of using crops and crop residue for anaerobic digestion is neglected due to low quantities and preferential other uses.
6. The effects of co-digestion of multiple biodegradable materials, which can have a positive effect on the overall biogas yield, are not considered due to many different types of biodegradable waste (e.g., different types of animal manure).
7. The transportation of all kinds of waste to the processing facility is not accounted for.
8. While a district heating network is available in Kočevje town, and several industrial consumers of heat are present, no analysis is made on whether all produced useable waste heat could be utilized. The feed temperature into the district heating network is estimated to be 90 °C.
9. Biodegradable municipal waste is already utilized through composting and biofilter production in the Kočevje municipality. No comparison is made on whether WtE processing offers significant advantages over the existing processes.
10. The annual amount of waste in the municipality is one order of magnitude lower than the typically required value for making a WtE plant feasible. Therefore, waste from a wider region would have to be collected and processed in a single facility to achieve technical (and possibly economic) feasibility.
11. No estimates are made on the environmental and economic aspects of the proposed WtE treatment processes and facilities.

To move towards the implementation of WtE-based waste management practices in the municipality and the wider region, individual WtE technologies ought to be investigated in more detail in the future. Furthermore, an economic analysis would be required to assess whether the WtE pathway would process waste and produce energy at a competitive price point. Finally, a study of environmental impacts would highlight whether the WtE technologies would meet the environmental and pollution constraints set forth by local legislation.

3. Results and Discussion

3.1. Analysis of Thermochemical WtE Processing of Mixed Municipal Waste

Table 6 shows the evaluation of seven types of thermochemical WtE technologies designed to process mixed municipal waste. Three scenarios are analyzed according to the percentage of the annually collected data to be subjected to WtE processing (25, 50, or 100%, denoted as the pessimistic, balanced, and optimistic scenario, respectively). Since the produced energy is linearly dependent on the amount of waste input, the annual electricity and useable heat production scale equally with the increasing amount of waste to be processed. Judging from the optimistic scenario, under which all collected mixed municipal waste would be treated in a WtE facility, the maximal annual electricity production is 0.98 GWh, and, separately, the maximal annual useable heat production amounts to 3.22 GWh.

Table 6. Comparison of annual electricity (E_{el}), useable waste heat (E_{th}), and exergy (E_{ex}) yield for three scenarios and nine thermochemical WtE technologies for processing of mixed municipal waste.

Input / Technology	Pessimistic Scenario (428 t/y)			Balanced Scenario (856 t/y)			Optimistic Scenario (1712 t/y)		
	E_{el} (MWh/y)	E_{th} (MWh/y)	E_{ex} (MWh/y)	E_{el} (MWh/y)	E_{th} (MWh/y)	E_{ex} (MWh/y)	E_{el} (MWh/y)	E_{th} (MWh/y)	E_{ex} (MWh/y)
INC-ST1	224	58	235	447	117	470	895	233	940
INC-ST2	112	431	195	224	862	390	447	1724	780
INC-ST3	59	804	214	119	1608	429	238	3216	858
PYR-ST	238	0	238	475	0	475	951	0	951
PYR-GT	176	430	259	352	860	518	704	1720	1035
PYR-ICE	124	398	200	247	797	401	494	1594	801
GAS-ST	212	0	212	424	0	424	848	0	848
GAS-GT	245	447	331	489	895	662	979	1790	1324
GAS-ICE	172	403	250	345	806	500	690	1613	1001

Figure 6 shows a comparison between the three main thermochemical waste treatment technologies (incineration, pyrolysis, and gasification), together with variations in these processes with different utilizations of the steam turbine or through the use of a gas turbine or an internal combustion engine where applicable. Furthermore, the annual exergy production is compared in Figure 7 for all nine technologies to give a more accurate picture of the sum of useable energy obtained from the mixed municipal waste. It can be seen that the highest total amount of energy in the form of either electricity or heat can be obtained by using incineration coupled with a steam turbine aimed at predominantly producing useable waste heat ("ICE-ST3" scenario). Several other scenarios provide similar but slightly lower total output, such as either pyrolysis or gasification coupled with either a gas turbine or an ICE. While the highest total usable heat output is provided by incineration coupled with a steam turbine in scenario "INC-ST3", the highest amount of electricity can be obtained using either a condensing steam turbine fed by steam from incineration or combustion of pyrolysis products (scenarios "INC-ST1" and "PYR-ST") or by a gas turbine/combined cycle powered by syngas from gasification ("GAS-GT" scenario). Based on these results, further analyses will focus on investigating different scenarios for the "INC-ST3" and "GAS-GT" technologies, which output the largest amount of usable heat (and energy in total) and the largest amount of electricity, respectively.

An analysis of the total exergy yield as shown in Figure 7 reveals an important additional insight. Since usable waste heat is at a relatively low temperature above the environment, its exergy content is low. On the other hand, electricity can be considered as pure exergy; therefore, the exergy analysis favors scenarios that predominantly produce electricity and not useable waste heat. This is especially evident in the case of the "INC-ST3" scenario, which produces by far the largest amount of usable waste heat, but its annual exergy yield is below average among all nine of the compared technologies. The annual exergy yield is the highest for gasification coupled with a gas turbine ("GAS-GT"), which logically stems from the highest annual electricity yield and an average useful waste heat yield.

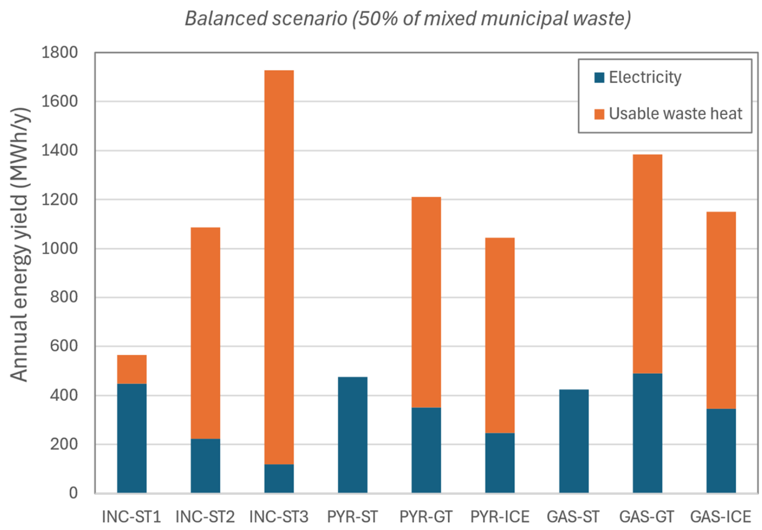

Figure 6. Analysis of annual energy yield in terms of electricity and usable waste heat from mixed municipal waste using nine different thermochemical processes. Data are shown for the balanced scenario.

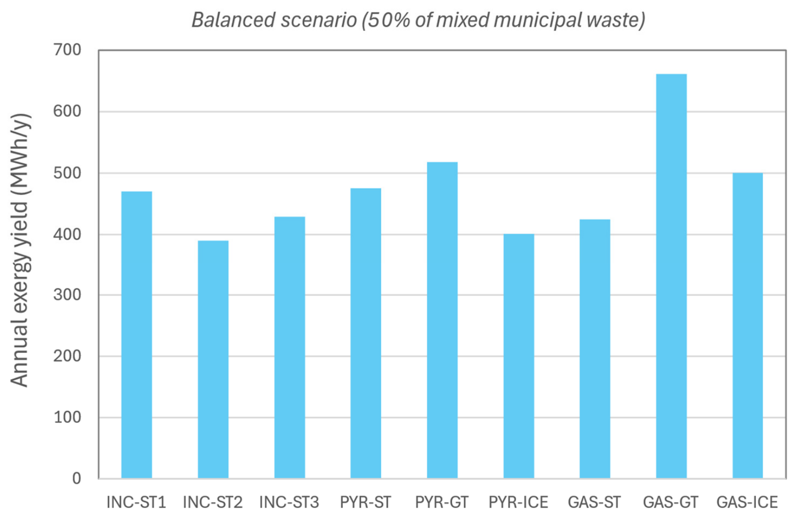

Figure 7. Analysis of annual exergy production using nine different thermochemical processes. Data are shown for the balanced scenario.

3.2. Analysis of Anaerobic Digestion of Organic Municipal Waste and Animal Manure

Table 7 shows the evaluation of anaerobic digestion for the processing of organic municipal waste and animal manure. Three scenarios are analyzed according to the percentage of the annually collected data to be subjected to WtE processing as given in the second and third columns of Table 7.

The total annual energy yield from the anaerobic digestion of waste is compared further in Figure 8, where all three scenarios are analyzed together with the total potential, representing the scenario where all biodegradable municipal waste and manure would be subjected to WtE processing.

The annual energy yield with anaerobic digestion relies mainly on the processing of livestock manure, the quantity of which far exceeds the quantity of biodegradable municipal waste. Furthermore, cattle manure represents the predominant source of manure in the Kočevje municipality and, therefore, chiefly influences the results shown in Table 7 and Figure 8. The main factor concerning cattle manure is its availability for WtE processing, which was estimated at 45% using the literature data. To assess the importance of this piece of information, a sensitivity analysis was performed for the balanced scenario of anaerobic digestion by varying the availability between 15 and 75%. The results are shown in Figure 9. It is noticeable that the cattle manure availability bears a predominant and nearly linear influence on the total energy yield of anaerobic digestion. Therefore, this value should be verified in further studies and optimized to enhance the energy yield of WtE processes by repurposing the use of cattle manure for energy production as much as possible.

Table 7. Analysis of anaerobic digestion performance for three scenarios and the total potential in terms of the annual volume of produced biogas (V_{biogas}) and the annual energy yield in the form of biogas (E_{biogas}). Furthermore, annual electricity (E_{el}), useable waste heat (E_{th}), and exergy (E_{ex}) yield from biogas are shown.

Scenario	Utilization of Biodegradable Waste	Utilization of Manure	V_{biogas} (nm^3/y)	E_{biogas} (MWh/y)	E_{el} (MWh/y)	E_{th} (MWh/y)	E_{ex} (MWh/y)
Pessimistic	0%	25%	213,132	1279	322	432	405
Balanced	50%	50%	482,123	2893	729	976	917
Optimistic	90%	90%	867,822	5207	1312	1757	1651
Total potential	100%	100%	964,246	5785	1458	1953	1834

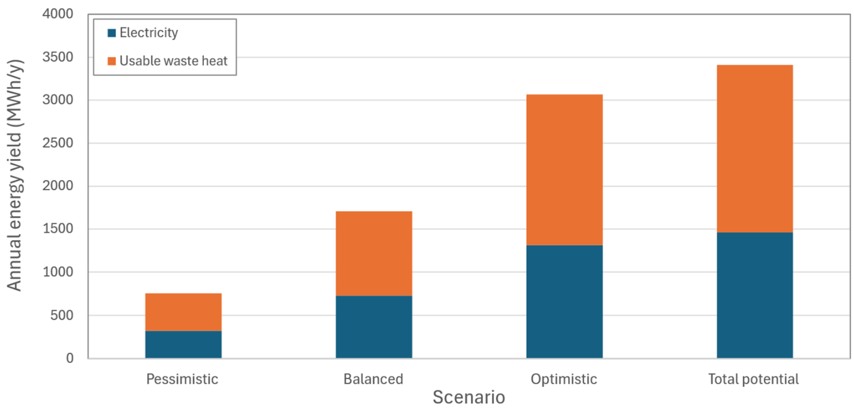

Figure 8. Analysis of annual energy yield in terms of electricity and usable waste heat from biodegradable municipal waste and livestock manure using anaerobic digestion and combustion of the biogas in an internal combustion engine.

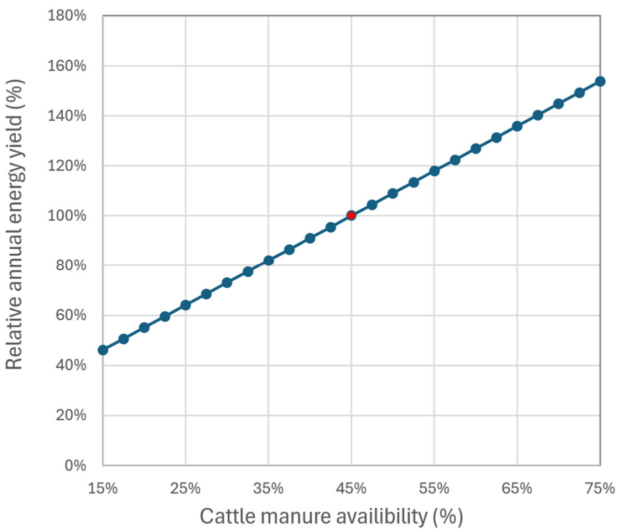

Figure 9. Sensitivity of the annual energy yield of anaerobic digestion towards the availability of cattle manure. The values are given relative to the base scenario using an availability of 45% (denoted with red color).

3.3. Overall Energy and Waste Effects

Total annual energy yield as electricity and usable waste heat are given in Table 8 for four cases. The first two cases consider waste inputs of the balanced scenario and two thermochemical processing technologies (incineration with a steam turbine, maximizing useable waste heat production, or gasification with a gas turbine, maximizing electricity production), which were previously selected in Section 3.1. In all cases, each thermochemical technology is combined with anaerobic digestion (AD). Cases 3 and 4 consider identical combinations of WtE technology but with waste input amounts from the optimistic scenario.

Table 8. Comparison of cases of four different scenarios and combinations of WtE technology, including the total annual electricity (E_{el}), useable waste heat (E_{th}), and exergy (E_{ex}) yield, and the number and percentage of people and households in the Kočevje municipality served with household electricity and heat (for space and water heating) from WtE processes.

Input Scenario	Technology	E_{el} (MWh/y)	E_{th} (MWh/y)	E_{ex} (MWh/y)	Electricity		Heat	
					People Served	% of the Municipality	Households Served	% of the Municipality
Balanced scenario	INC-ST3 & AD	848	2584	1346	1372	8.8%	258.4	7.3%
	GAS-GT & AD	1218	1871	1579	1971	12.6%	187.1	5.3%
Optimistic scenario	INC-ST3 & AD	1550	4973	2509	2508	16.0%	497.3	14.0%
	GAS-GT & AD	2291	3547	2975	3707	23.6%	354.7	10.0%

The annual energy yield is compared in Figure 10, while Figure 11 shows a comparison of the annual exergy yield of individual combinations of WtE technologies. For the balanced input scenario, incineration combined with anaerobic digestion yields 0.84 GWh of electrical energy and 1.35 GWh of exergy annually, while yielding the greatest annual output of usable waste heat (2.58 GWh). On the other hand, gasification with a gas turbine and coupled with anaerobic digestions annually yields 44% more electricity (1.22 GWh) and 17% more exergy (1.58 GWh), while providing 28% less usable waste heat (1.87 GWh). The incineration pathway, which produces approx. 3× the amount of usable waste heat compared to its annual electricity yield, provides space and water heating for approx. 7.3% of households in the Kočevje municipality, while the gasification pathway serves 5.3% of households. On the other hand, the superior electricity yield of the gasification pathway provides household electricity for approx. 12.6% of Kočevje municipality inhabitants, while the incineration pathway serves 8.8% of the municipality.

Under the optimistic scenario, the annual energy and exergy yields are roughly doubled compared to the balanced scenario as approximately twice the amount of waste is processed. Under this scenario, which would possibly come into play several years or decades since the start of WtE implementation in the region and with very successful onboarding, up to 1.55 GWh of electricity and 4.97 GWh of useable waste heat could be produced using incineration of mixed municipal waste and anaerobic digestion of biodegradable waste, while up to 2.29 GWh of electricity and 3.55 GWh of usable waste heat might be produced by combining waste gasification with a gas turbine to exploit mixed municipal waste while also using anaerobic digestion to process biodegradable waste. In terms of exergy production, the "INC-ST3 & AD" combination of technologies could yield up to 2.51 GWh of exergy on an annual basis, while the "GAS-GT & AD" combination could increase this number to 2.98 GWh.

It should be noted that the generation of electricity from waste is favorable in the Kočevje municipality in comparison with the production of usable waste heat, since the municipality is composed of one major settlement (Kočevje town), where a district heating network is available, and many smaller settlements at a considerable distance with no district heating capabilities. Therefore, the combination of mixed municipal waste gasification, syngas exploitation with a gas turbine, and anaerobic digestion of biodegradable waste is pointed out as the superior solution for the municipality since the electricity can be easily distributed to nearly all homes within the Kočevje municipality.

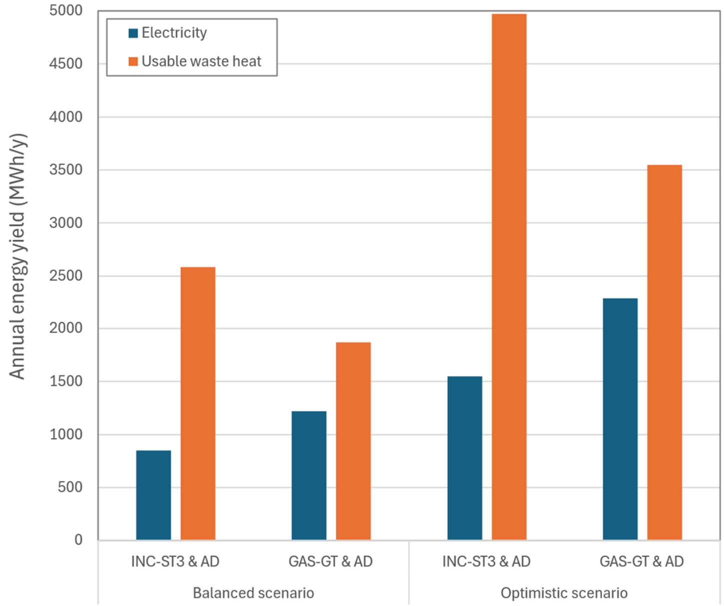

Figure 10. Analysis of annual energy yield in terms of electricity and usable waste heat utilizing all waste sources and combining two thermochemical processes with anaerobic digestion. Data are shown for the balanced and the optimistic scenario.

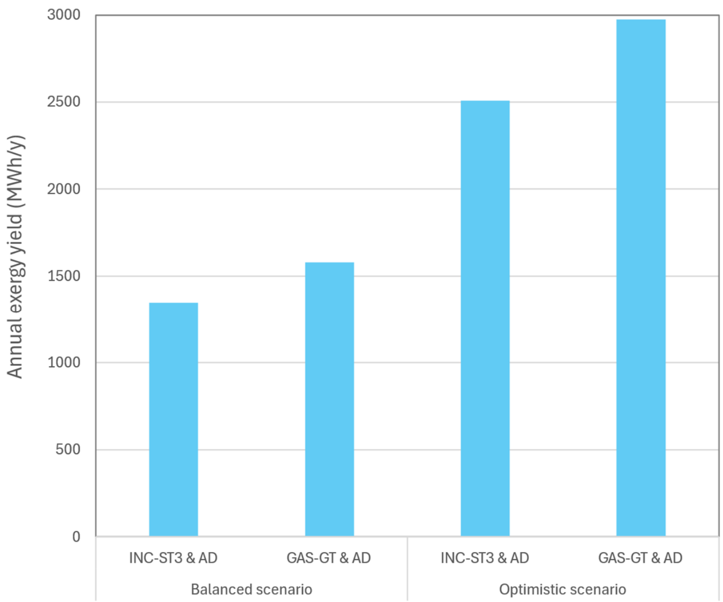

Figure 11. Analysis of annual exergy yield utilizing all waste sources and combining two different thermochemical processes with anaerobic digestion. Data are shown for the balanced and the optimistic scenario.

The latter finding is also substantiated by the annual exergy yield comparison as shown in Figure 11, where it is shown that the overall amount of exergy heavily relies on electricity yield and, therefore, favors the generation of electricity at the expense of much lower usable waste heat yield. Specifically, for the optimistic scenario and the incineration technology (scenario "INC-ST3 & AD"), electricity represents only 24% of the total energy yield but, at the same time, 62% of the total exergy yield. In the optimistic "GAS-GT & AD" technological scenario, where the electricity and useable waste heat yields are most closely matched (electricity represents 39% of the annual energy yield), the electricity also represents 77% of the total annual exergy yield.

To analyze the effect the WtE implementation could have on the Kočevje municipality, Figure 12 estimates what percentage of people in the Kočevje municipality could have their annual household electrical energy use covered by the output of WtE processes. Furthermore, we also estimate how many households could be supplied with the heat annually required for domestic space and water heating. Specifically, the annual household electricity consumption of 1608 kWh per capita is considered, as reported by the Statistical Office of the Republic of Slovenia for the Kočevje municipality for 2022. The annual heat requirement for a single household is estimated at 10,000 kWh. The results, which are also provided in Table 8, show that the electricity annually produced using WtE technology and utilizing waste from the Kočevje municipality could cover the household electricity needs of between 8.8 and 12.6% of the inhabitants of Kočevje. If more waste is redirected into WtE processes (i.e., in the optimistic scenario), these numbers can reach 16.0–23.6%. On the other hand, the produced useable waste heat would suffice to cover the needs of approx. 5.3–7.3% of households in Kočevje in the balanced waste input scenario and 10.0–14.0% in the optimistic scenario. Since useable waste heat is harder to distribute amongst the community as a district heating network is required (which already exists in Kočevje town), it would make more sense to focus on electricity production, which is easier to distribute and can cover the needs of a larger portion of the municipality's population. Furthermore, relatively cheap local or district heating is possible in the Kočevje municipality as large amounts of wood and wood residue are available. Therefore, gasification of mixed municipal waste (and the use of syngas in a gas turbine to produce electricity and minor amounts of useable waste heat) combined with anaerobic digestion is pointed out as the optimal choice for the municipality.

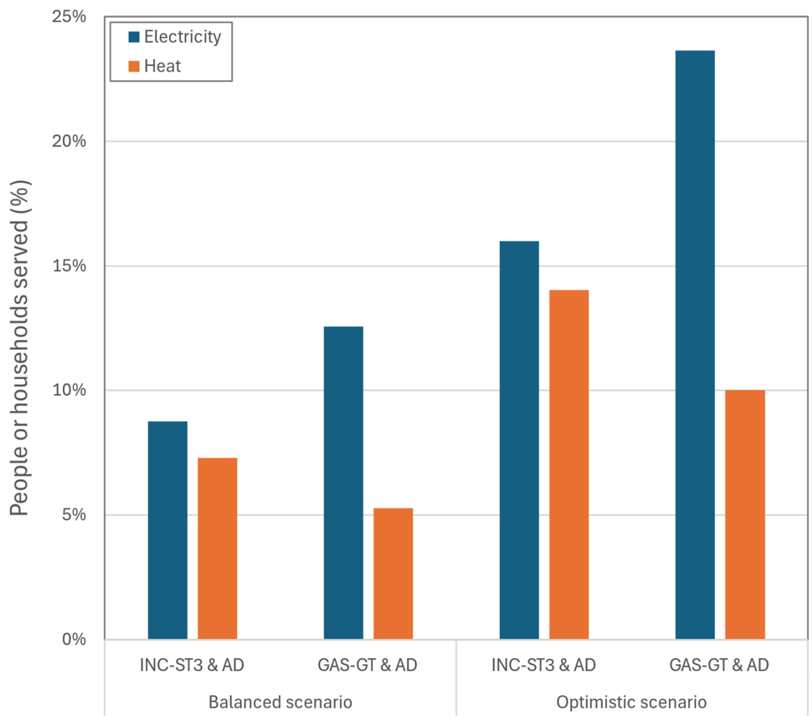

Figure 12. Percentage of people and households within the Kočevje municipality served with their annual requirements for household electricity and heat for space and water heating, respectively.

3.4. CO_2 Emissions

Original CO_2-eq. emissions of waste considered as a possible WtE input are estimated to be 2951 t/y if no WtE processes are applied. Table 9 provides the CO_2-eq. emissions for all three scenarios considered in this study, which are broken down into two parts: emissions stemming from WtE processing (e.g., emissions during combustion of the produced biogas) and other emissions, denoting the CO_2-eq. emissions stemming from the remainder of waste which is not subjected to WtE processing. In all three cases, a reduction in total annual emissions is achieved, ranging from approx. 6% for the pessimistic case and reaching up to ~20% for the optimistic case.

Table 9. Annual CO_2-eq. emissions from the proposed WtE processed and from the unprocessed waste and the reduction in total emissions compared to the existing situation with no WtE implementation.

Scenario	CO_2-eq. Emissions from WtE (t/y)	Other CO_2-eq. Emissions (t/y)	Reduction
Pessimistic	525	2237	6.4%
Balanced	1150	1476	11.0%
Optimistic	2127	236	19.9%

The reduction in emissions is compared graphically in Figure 13 together with the total possible reduction in CO_2-eq. emissions, which would be achieved if all mixed municipal waste, biodegradable municipal waste, and animal manure underwent WtE treatments.

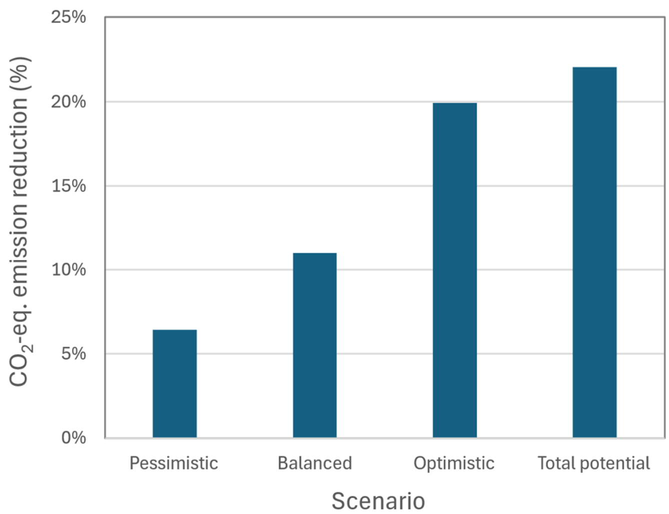

Figure 13. Reduction in CO_2-eq. emissions by implementing WtE technologies for the three proposed scenarios and the total potential if all waste underwent WtE processing.

Figure 14 shows the specific CO_2-eq. emissions per kWh of generated energy (annual electricity and heat production values are combined) and per kWh of generated exergy for different technologies and waste utilization scenarios. The specific emissions per kWh of generated useable energy (electricity and heat) are close to the average values for Slovenian electricity and district heat (0.306 and 0.34 kg of CO_2-eq. per kWh, respectively), but it should be noted that the emissions from waste would otherwise still take place with no useable conversion into energy if WtE processing were not applied, and they would be even larger (see Figure 13). Since the annual exergy yield is notably lower than the total energy yield for each analyzed scenario, specific emissions per kWh of generated exergy fall between 0.715 and 0.855 kg of CO_2-eq. per kWh, which is significantly higher than the aforementioned average Slovenian value for electricity (i.e., pure exergy).

Furthermore, it is understandable that the emissions are somewhat higher than for the production of electricity from, e.g., hydroelectric or nuclear sources and the production of district heat from biomass, since waste is mostly a low-quality feedstock with low calorific value. Furthermore, implementing advanced energy recovery technology is often not possible for the treatment of waste and primary waste-derived energy carriers (e.g., syngas and untreated biogas) due to the changing composition of the feedstock (and with it, the products) and various contaminants.

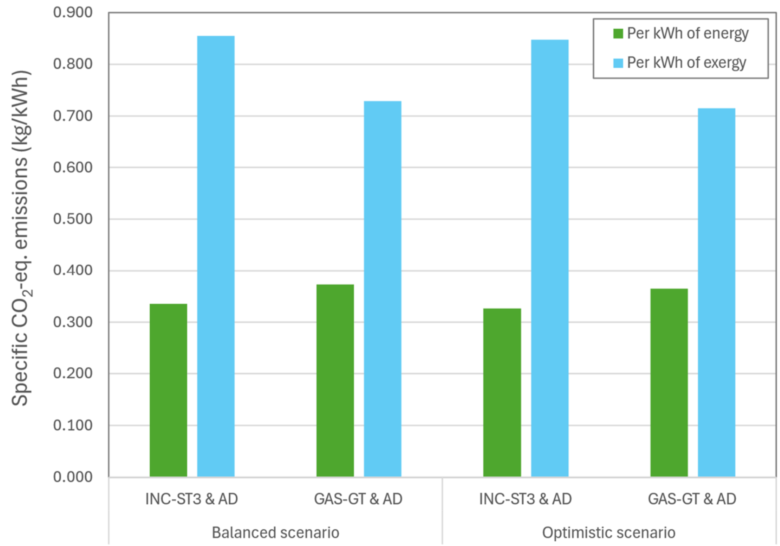

Figure 14. Specific CO_2-eq. emissions per kWh of generated energy (electricity and heat) and exergy for different technologies and scenarios.

Figure 15 shows the annual values of CO_2-eq. emissions prevented by WtE technologies, that would otherwise be generated during electricity and district heat production, which could be replaced by WtE production as shown in Figure 10. To calculate these values, emission factors given in Section 2.5 were used. These CO_2-eq. represent a further notable contribution of WtE technologies towards mitigating climate change. While the total GHG emissions were already reduced by ~20% in the optimistic scenario (Figure 13), a further 1907–2165 t of CO_2-eq. emissions could be prevented annually by replacing the traditional energy generation sources with WtE technology. These values represent 81–92% of the total emissions for the optimistic scenario, meaning the effective emissions from waste with no contribution towards useable energy generation (i.e., replacement of traditional electricity and district heat sources and the associated emissions) are close to zero, further proving the positive effects of implementing WtE technologies in waste management strategies at a municipality level.

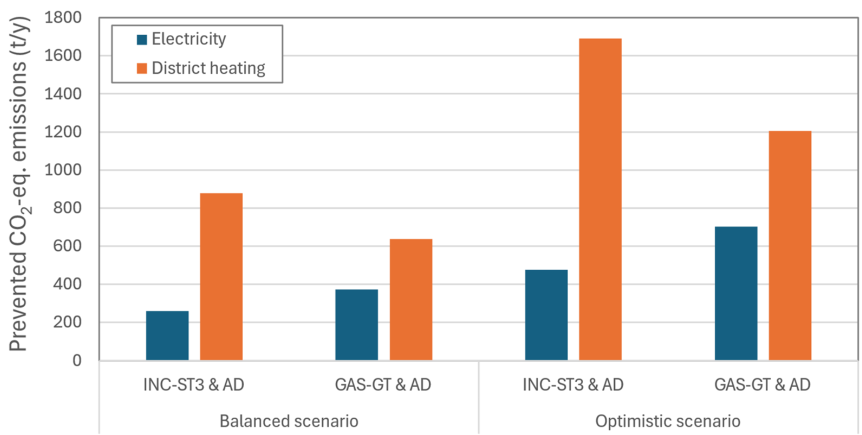

Figure 15. Annually prevented CO_2-eq. emissions based on the amount of generated electricity and heat with WtE technologies.

4. Conclusions

In this study, the possibility of implementing waste-to-energy technologies in the waste management processes within the Kočevje municipality (Slovenia) was studied. Specifically, mixed municipal waste, biodegradable municipal waste, and livestock manure were considered prime and currently unused or underused energy sources. An analysis of the waste availability showed that 1712 t of mixed municipal waste, 931 t of biodegradable municipal waste, and up to 49,548 t of livestock manure are annually produced and could be repurposed for energy recovery. Several technologies were considered and compared, including incineration, pyrolysis, and gasification of mixed municipal waste and anaerobic digestion of biological waste. Furthermore, three scenarios were developed based on the level of inclusion of individual sources of waste. The total energy potential of mixed municipal waste using thermochemical processes could yield up to 0.98 GWh of electricity annually and, separately, 3.22 GWh of useable heat annually. Furthermore, by treating 90% of the biodegradable waste, up to 1.31 GWh of electricity and 1.76 GWh of usable waste heat could be generated annually using anaerobic digestion and biogas combustion in a CHP facility from biodegradable municipal waste and livestock manure. Based on the specifics of the Kočevje region with large amounts of biomass available for heating, gasification of mixed municipal waste and a gas-turbine-based combined heat and power cycle is pointed out as a preferred solution with a preference toward higher electricity yields. We estimate that using nearly all waste available in the municipality from the three aforementioned categories, gasification and anaerobic digestion could be used side-by-side to yield 2.29 GWh of electricity and 3.55 GWh of useable waste heat annually, representing an annual exergy yield of 2.98 GWh. This amount of energy would cover the annual household electricity needs of approx. 23.6% of the municipality's population, while 10.0% of the households in Kočevje could be supplied with the annual heat requirement for space and water heating via district heating. Finally, the implementation of WtE technologies would reduce the CO_2-eq. emissions of up to ~20%, while the produced energy would offset the emissions otherwise connected with electricity and district heat generation in Slovenia by 1907 t of CO_2-eq. annually; this value also approaches the emissions from WtE processing itself and the emissions that would otherwise still occur if WtE technologies were not used (e.g., due to waste landfilling). The results clearly show that WtE technologies would greatly enhance the self-sustainability of the municipality through energy production while also reducing the amount of waste deposited in landfills or otherwise not exploited. In follow-up studies, the economic feasibility of WtE waste processing at a municipality and regional level should be assessed to comprehensively assess the WtE approach for local waste management, along with a study of the potential environmental impacts.

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