

WtE plants with energy recovery as part of Europe's energy sustainability

Research Article

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Abstract: The relevance of this study is determined by the need to reduce dependence on fossil fuels in order to reduce greenhouse gas emissions and improve long-term performance of municipal energy systems. This article analyzes trends in municipal solid waste (MSW) management in European countries during 2019–2024 and examines the role of residual MSW as an alternative local fuel. Statistical and comparative analysis methods were applied using data from Eurostat and Organisation for Economic Cooperation and Development (OECD). It highlights the impact of recent political and socio-economic crises on the pressing need for reduction in fossil fuel share in energy supply using renewable and alternative – including local – energy sources. The effectiveness of waste-to-energy (WtE) plants with energy recovery is demonstrated in addressing both environmental and energy challenges. The results show that in several Northern and Western European countries (Sweden, Finland, Norway, and United Kingdom) the share of residual MSW incinerated with energy recovery exceeds 50% and largely supplies district heating networks. In contrast, in Southern Europe, residual MSW is primarily utilized for electricity generation as a substitute for fossil fuels. In Ukraine, a high potential was identified for integrating WtE plants into existing district heating systems of major cities, which could replace up to 10% of natural gas consumption. These findings confirm the feasibility of developing WtE infrastructure as a tool for decarbonizing municipal energy systems and reducing landfilling of waste.

Keywords: *Alternative fuel for municipal energy systems • Energy decarbonization • Residual municipal solid waste • Sustainable development*

1. Introduction

The early twenty-first century is marked by a series of profound global transformations, among which rapid demographic growth, coupled with accelerated urbanization and rising standards of living, are particularly significant [1]. These systemic shifts have led to a substantial increase in the generation of municipal solid waste (MSW). Despite progress in recycling policies, landfilling remains the predominant waste management practice in many regions of the world, resulting in high methane emissions and the loss of potential material and energy value. Currently, approximately 70% of residual municipal waste is either deposited in controlled and managed landfills, disposed of at open dumps, or subjected to open burning without energy recovery [2]. Even within the European

Union, around 22% of municipal waste continues to be disposed of through landfilling [3].

At the same time, sustained economic growth across many countries has intensified dependence on fossil fuels, increasing the share of fossil fuels in heat and power supply and further increasing greenhouse gas emissions and temperature growth rates [4].

Thus, on the one hand, large volumes of residual municipal waste remain unused as a potential energy resource; on the other hand, energy systems continue to rely predominantly on fossil fuels, resulting in increased emissions and dependence on imported fuels. These processes are not independent: residual municipal waste is generated in the same urban areas where energy demand is concentrated and can therefore serve as a locally available fuel to partially substitute fossil fuels when appropriate conversion and district heating infrastructure is present.

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The global energy crisis, aggravated by the ongoing war in Ukraine, has further highlighted the operational sensitivity of fuel-based energy systems to supply disruptions and reinforced the need to replace fossil fuels with local, renewable, and alternative sources. This change is essential not only for reducing CO₂-equivalent emissions but also for reducing dependence on imported fuels and maintaining the reliability of national energy supply systems.

Addressing these global challenges requires coordinated international action to maintain long-term energy supply and waste management efficiency. Within this context, utilizing residual municipal waste as an energy resource represents a technically viable pathway to simultaneously reduce landfill disposal, mitigate methane emissions, and partially substitute fossil fuels in urban energy systems.

2. Research methods

This article analyzes approaches to municipal waste treatment in European countries and assesses the potential of residual MSW for energy recovery as a substitute for fossil fuels.

Approaches to municipal waste treatment across European countries are examined, along with an assessment of correlation between the presence of domestic hydrocarbon fuel sources, the geographical location of a country, the volume of waste landfilled (in million tonnes), and the country's tendency to implement incineration of residual waste at waste-to-energy (WtE) plants with energy recovery. The analysis also includes the dynamics of the share of electrical and thermal energy produced from renewable and non-renewable municipal waste. The study demonstrates the technical rationale for utilizing surplus heat from residual municipal waste to support the decarbonization of district heating systems in European cities.

The baseline year for the study is 2019, which is considered a pre-crisis reference point. The subsequent period of 2020–2021 was marked by the COVID-19 pandemic, which affected waste generation patterns. From 2022 to 2025, the political and economic crisis triggered by Russia's war in Ukraine has been accompanied by the migration of millions of refugees and a decline in household incomes. These factors have led to changes in both the quantity and morphological composition of MSW.

The study applies statistical analysis of empirical data as its primary analytical approach. In addition, the method of comparative analysis is used in the preparation of tables that illustrate the dynamics of changes in the field of municipal waste management.

3. Results and discussion

3.1. EU approaches to ensuring sustainable development

To fulfill the Paris Agreement commitments on reducing greenhouse gas emissions [5] and to achieve the Sustainable Development Goals [6], the European Union has adopted the Circular Economy Action Plan [7].

The Circular Economy Action Plan provides a systemic framework aimed at reducing the volume of waste generated within the EU by prioritizing waste prevention, material recovery, and energy recovery while minimizing landfilling. All generated waste is regarded as a potential source of materials, whereas residual waste is considered a source of recoverable energy. The action plan strengthens the requirements for the waste hierarchy as defined in the EU Waste Framework Directive 2008/98/EC, which designates landfilling as the least preferable management option. This objective is addressed first by preventing waste generation, and when waste is generated, by prioritizing reuse and recycling [8].

These requirements were reinforced by Directive (EU) 2018/851, which mandates that by 2035, the reuse and recycling of municipal waste should increase to 65%, and by Directive (EU) 2018/850, which stipulates that landfilling of waste should be reduced to no more than 10% by 2035 [9,10].

Reducing the volume of landfilled waste is an essential component of decarbonization. The decomposition of MSW in landfills releases methane, a greenhouse gas with a significantly higher global warming potential than CO₂. Methane contributes to approximately 30% of the observed global temperature increase [11]. According to the Intergovernmental Panel on Climate Change Sixth Assessment Report, non-fossil methane is nearly 80 times (79.7 ± 25.8) more potent as a greenhouse gas than carbon dioxide over a 20-year time horizon [12].

The waste sector is the second-largest source of methane emissions in Europe, with landfill disposal of MSW accounting for around 80% of these emissions [13,14]. After the EU achieves its target of recycling 65% of municipal waste and limiting landfilling to less than 10%, about 25% of non-recyclable residual waste will remain in the municipal waste stream. This remaining fraction can be utilized as a fuel to partially substitute fossil energy sources.

Processing residual MSW into fuel at WtE plants with energy recovery contributes to fossil fuel substitution. At the same time, it reduces landfill volumes, prevents soil

contamination, and limits landfill gas generation. The latter typically consists of roughly 50% methane, 50% carbon dioxide, and small amounts of non-methane organic compounds [15]. The latest European Environment Agency briefing on methane emissions recognizes the role of WtE in reducing methane emissions from the waste sector [14].

Under full compliance with the waste management hierarchy, energy recovery from residual waste at thermal WtE plants with energy recovery – particularly where infrastructure exists to utilize surplus heat generated from waste incineration on a year-round basis – represents the final stage of municipal waste treatment according to the waste hierarchy, with thermal recovery of non-recyclable fractions [16].

Therefore, energy recovery from residual waste is not merely a disposal option but a technically viable way to integrate waste streams into urban energy supply and reduce dependence on fossil fuels.

3.1.1. Development of municipal waste treatment in Europe

The analysis of municipal waste treatment in the EU and in selected European countries in 2023 is presented in Table 1.

Table 1 shows that approximately 25% of municipal waste in the EU is incinerated with energy recovery. In several European countries (Sweden, Finland, Norway, and the United Kingdom), the share of incineration with energy recovery exceeds that of recycling and composting. In Denmark, waste treatment is distributed almost evenly across the main treatment options. Estonia, Lithuania, and Switzerland show very similar figures.

Several countries have already met the requirements of EU Directive 2018/850, which limits landfilling to 10%. In Sweden, Finland, Denmark, Estonia, Belgium, Germany, the Netherlands, and Austria, only about 1% of municipal waste is landfilled; in Luxembourg – about 3% and in Lithuania – about 8%. In Switzerland, landfilling of

Table 1. Municipal waste treatment in Europe in 2023 [17,18]

Countries	Treatment, %				
	Recycled	Composted	Incinerated with energy recovery	Landfilled	Other
EU	29.0	19.0	25.0	22.0	4.0
Sweden	20.2	19.2	58.9	1.1	0.6
Finland	28.9	15.7	54.0	0.5	0.8
Denmark	26.9	19.1	51.0	1.8	0.1
Switzerland	28.7	23.3	48.0	0.0	0.0
Norway	31.4	10.4	47.0	5.4	5.8
Estonia	41.8	10.6	47.0	0.6	0.0
Belgium	33.6	20.8	45.0	0.1	0.4
United Kingdom (2022)	26.2	16.3	44.2	9.2	1.5
Ireland (2020)	29.8	11.0	42.5	16.3	0.4
Luxembourg	31.8	24.9	40.9	2.9	0.0
Lithuania	25.0	24.3	40.8	7.9	2.0
Netherlands	27.6	30.8	39.3	1.4	0.9
Austria	40.8	21.5	35.5	1.7	0.1
France	22.4	19.6	34.6	22.5	0.2
Germany	46.1	22.6	29.3	1.0	1.1
Poland	20.1	15.0	25.5	38.5	0.9
Italy	34.6	24.2	21.2	18.4	1.0
Portugal	12.4	16.6	17.4	53.7	0.0
Spain	20.7	20.7	10.6	48.0	0.0

municipal waste has been eliminated to 0%, while in Norway, it accounts for about 5%, and in the United Kingdom, about 9%, even though these countries are not EU members.

3.2. Energy from waste as an alternative source of local energy

3.2.1. EU approaches for the utilization of residual waste

The European Union has adopted a new strategy, the Clean Industrial Deal, aimed at strengthening the competitiveness of its industrial sector while accelerating decarbonization [19]. The main objective of this plan is to reduce Member States' dependence on imported fossil fuels for both industry and households.

According to the International Energy Agency, renewable sources are increasingly used for electricity generation (in February 2025, 34.9% of electricity in OECD countries was generated from renewables). However, up to 90% of fuel used in the heating sector still comes from fossil sources [20,21]. Therefore, district heating systems offer significant technical potential for reducing fossil fuel use and associated emissions.

Because minimizing the amount of municipal waste is the primary objective of waste incineration, heat generated during the MSW combustion at WtE plants is considered residual heat and can be used to decarbonize district heating systems where heat recovery infrastructure is available [22].

WtE plants with energy recovery produce surplus heat that can be directly supplied to district heating networks, which provide an efficient means of its utilization. Consequently, fossil fuels currently used to produce heat

for district heating can be partially replaced with energy recovered from residual municipal waste. WtE plants with energy recovery therefore represent a reliable source of locally available residual heat, derived from domestic rather than imported fuels.

The European Commission has confirmed that one of the most effective methods to enhance the energy efficiency of WtE processes is the distribution of heat recovered from waste through low-temperature district heating networks [23].

Data on gross electricity production and gross derived heat generation in the EU, including the contribution from municipal waste in 2019–2024, are presented in Table 2.

Table 2 shows that although gross electricity production in 2024 fell by 3.7% compared to 2019, the share of residual municipal waste remained almost unchanged (1.4% in 2024 vs 1.3% in 2019). However, despite a 14% reduction in gross heat production over the same period, the use of residual municipal waste increased to 12.7%. This included both renewable (6.5%) and non-renewable (6.2%) municipal waste, representing a 2.6% increase from 2019.

Currently, about 10% of the energy supplied to Europe's district heating networks comes from WtE plants. In cities with well-developed district heating infrastructure – such as Brescia (Italy), Malmö (Sweden), or Klaipėda (Lithuania) – WtE plants cover 50% or more of heating demand [25]. In Sweden, the district heating sector is well developed, and waste incineration makes a significant contribution to the energy balance. Waste incineration accounts for approximately 25% of total district heating and about 1.8% of electricity in Sweden. In 2023, Swedish waste incineration plants recovered 19.5 TWh of energy: 17.3 TWh as heat and 2.2 TWh as electricity [26]. The consumption of waste used for gross production of district heating in Norway amounts to 45–50% [27].

Table 2. Gross electricity production and gross derived heat generation EU in 2019–2024 [24]

Gross production	Fuel	Year					
		2019	2020	2021	2022	2023	2024
Electricity (GWh)	Renewable municipal waste	19,003	18,866	19,562	19,378	18,593	19,519
	Non-renewable municipal waste	18,592	18,340	18,776	18,581	17,819	18,465
	Total	2,882,496	2,762,007	2,890,106	2,792,345	2,718,397	2,777,146
Heat (TJ)	Renewable municipal waste	120,662	123,996	130,395	125,861	121,919	130,886
	Non-renewable municipal waste	115,969	119,393	124,487	121,227	115,797	124,503
	Total	2,345,020	2,256,035	2,312,677	2,124,815	2,043,124	2,015,961

3.2.2. Development of WtE plants with energy recovery in Europe

As of 2022, approximately 500 WtE plants were operating in Europe [28]. France (116 units), Germany (91 units), and the United Kingdom (57 units) had the highest number of WtE plants with energy recovery. These countries also had the largest amounts of thermally incinerated residual waste. A significant number of WtE plants are also located in Sweden and Italy (more than 30 units each) and Switzerland (29 units) (Table 3).

Table 3 shows that between 2019 and 2022, the number of plants in some countries declined – by nine units in Germany, eight units in France, and one unit each in Italy and Switzerland. However, the amount of thermally incinerated residual waste in France remained almost unchanged, while in Italy and Switzerland, it decreased only slightly.

Table 3. WtE plants and residual waste thermally treated in Europe [28,29]

Countries	2019		2022	
	WtE plants (unit)	Residual waste thermally treated (million Mg)	WtE plants (unit)	Residual waste thermally treated (million Mg)
Europe	499	99.0	498	100.0
Sweden	36	6.16	37	6.83
Finland	9	1.39	9	1.55
Denmark	23	3.58	23	3.55
Switzerland	30	4.07	29	3.85
Norway	18	1.63	18	1.63
Estonia	1	0.21	1	0.21
Belgium	17	3.36	17	3.48
United Kingdom	48	12.6	57	15.32
Ireland	2	1.24	2	0.81
Luxembourg	1	0.17	1	0.16
Lithuania	1	0.25	3	0.62
Netherlands	12	7.39	12	7.39
Austria	11	2.6	12	2.7
France	124	14.5	116	14.0
Germany	100	27.1	91	25.0
Poland	7	1.0	9	1.26
Italy	37	6.3	36	6.02
Portugal	4	1.2	4	1.08
Spain	12	2.92	13	2.97

Nevertheless, the overall trend of increasing the incineration of residual waste at WtE plants continues.

In nine EU countries, as well as in Norway, Switzerland, and the United Kingdom, the share of residual municipal waste incinerated with energy recovery in 2023 was approximately 40–60%. In France, Austria, and Germany, incineration with energy recovery accounted for about 30% of residual municipal waste (Table 4).

In Sweden, Austria, and Spain, one additional plant was added, increasing the amount of residual waste incinerated by 11, 4, and 2%, respectively. WtE plants work stably in Finland, Denmark, Norway, Estonia, Belgium, Luxembourg, and the Netherlands.

In the United Kingdom, Lithuania, and Poland, new WtE plants are being actively developed. During this period, nine plants were built in the United Kingdom, increasing the amount of incinerated residual waste by 22%, and two plants were built in Lithuania, increasing the incineration of residual waste by 2.5 times.

In Poland, until 2013, municipal waste was incinerated at the only WtE plant in Warsaw. By 2025, Poland had 11 WtE plants in operation. A new WtE plant in Warsaw is at the final stage of modernization and expansion.

The active development of WtE plants with energy recovery in Poland is driven by the need to phase out coal-fired power plants and by the extensive district heating network. Municipal waste accounts for a 2.0% share in heat generation in district heating in Poland [31].

3.2.2.1. Development of WtE plants with energy recovery in Poland

Before 2013, MSW in Poland was thermally treated only at a single WtE plant located in Warsaw.

Polish researchers have been actively examining the feasibility of expanding thermal treatment of residual waste at WtE plants with energy recovery. A previous research [32] reports the lower heating value of mixed municipal waste generated in rural areas, which ranges from 6.5 to 9.5 MJ/kg. After mechanical treatment, the over 80 mm fraction reaches 11.6–12.7 MJ/kg, making it suitable for use in thermal treatment systems. Wielgosiński [33] argued that, in addition to the eight WtE plants operating at the time of publication, Poland requires the construction of approximately ten additional thermal treatment facilities for residual municipal waste. Another research [34] presented an economic assessment of increasing the capacity of municipal WtE plants covering the district heating base load, considering revenues from heat sales and gate fees, as well as capital and operational expenditures. The analysis also takes into account the potential inclusion of WtE plants

Table 4. Incinerated with energy recovery in Europe [18,30]

Countries	Year				
	2019	2020	2021	2022	2023
	Incinerated with energy recovery (%)				
Sweden	52.6	60.6	59.7	59.2	58.9
Finland	55.6	57.3	60.4	55.4	54.0
Denmark	47.5	53.8	41.4	49.0	51.0
Switzerland	47.0	47.2	47.7	47.8	48.0
Norway	49.5	46.5	50.0	51.2	47.0
Estonia	48.4	49.6	49.3	47.7	47.0
Belgium	42.3	48.4	44.0	45.1	45.0
United Kingdom	40.1	43.3	42.7	44.2	n/a
Ireland	46.5	42.5	n/a	12.6	n/a
Luxembourg	46.7	43.1	40.8	41.5	40.9
Lithuania	16.8	29.1	36.7	37.8	40.8
Netherlands	40.6	40.8	40.0	40.0	39.3
Austria	38.9	35.8	35.4	35.3	35.5
France	31.3	32.2	32.2	32.4	34.6
Germany	31.6	28.7	28.3	28.9	29.3
Poland	21.5	20.3	19.8	20.2	25.5
Italy	20.5	20.7	20.2	19.7	21.2
Portugal	19.8	20.3	22.0	19.2	17.4
Spain	11.0	10.1	10.6	10.3	10.6

in the EU Emissions Trading System. The results indicate that a municipal waste incineration facility can achieve an internal rate of return of approximately 6%, confirming the economic viability of WtE development for both investors and local communities. The study by Janda and Urbańska [35] examined the prospects of using pre- refuse-derived fuels (RDF) and RDF in the Polish heating sector.

As of 2025, there are 11 WtE plants in operation in Poland. The new WtE plant in Warsaw is in the final stage of modernization and expansion. The rapid development of WtE infrastructure in Poland is driven by the country's gradual phase-out of coal-fired power plants and the presence of an extensive district heating network, which exceeds 22,800 km [36].

Municipal waste accounts for approximately 2% of heat generation in Poland's district heating systems [37].

3.2.3. Development of WtE plants with energy recovery in Ukraine

Despite the ongoing war with Russia, now in its fifth year, Ukraine is actively working on improving its municipal

waste management system. According to the Ministry of Environmental Protection and Natural Resources of Ukraine, more than 200 new facilities for processing mixed MSW are required to meet national treatment needs [38].

Ukraine also has a well-developed district heating network, which increases the relevance of integrating WtE solutions into urban energy systems. For example, the district heating network in Kyiv extends over 2,700 km [39]. In 2024, the annual generation of MSW in Kyiv was estimated at approximately 1.3 million Mg. Up to 25% of this volume is incinerated at the "Energia" WtE plant operated by the municipal enterprise "Kyivteploenergo," which supplies hot water to residents of one of the city districts [40].

According to the "Kyiv District Heating Scheme for the Period up to 2030," new WtE facilities with energy recovery are planned. The project includes a plant processing 450,000 t/year of mixed MSW as part of a natural-gas-fired combined heat and power (CHP) unit with 300 MW electric and ~2,200 GJ/h thermal capacity, as well as an RDF-fired WtE plant with 24 MW electric and ~170 GJ/h thermal capacity.

Additionally, a new technological complex is planned for processing up to 400,000 tons of mixed waste. It will

include a mechanical-biological treatment plant producing RDF and RDF-fired WtE plant with a total installed electric capacity of 20 MW and thermal capacity of about 335 GJ/h, of which 142 GJ/h comes from cogeneration. These facilities will enable utilization of nearly the entire calorific potential of Kyiv's residual MSW, producing approximately 500 GJ/h of thermal energy. Further details on WtE plants with energy recovery in Ukraine are provided in the article [41].

Based on the experience of Poland in using WtE plants with energy recovery, the municipality of Odesa invited Posco E&C (Korea) to construct WtE plant with an electric capacity of 12 MW and a thermal output of 40 MW [42]. In Zhytomyr, the company Valmet (Finland) will build a solid recovered fuel (SRF)- and mixture of wood chips-fired WtE plant with energy recovery and an electric capacity ranging from 9.9 to 13.1 MW and heat production up to 22 MW [43].

The authors conducted an analysis of the potential for utilizing residual municipal waste as a local energy resource to substitute natural gas in district heating systems in Ukrainian cities with populations exceeding 300,000 inhabitants. Population data, MSW generation volumes, and waste morphology were obtained from Ukrstat, the Ministry for Development of Communities and Territories of Ukraine, and the Design and Technology Institute of Municipal Economy.

To determine the energy potential of residual MSW, the authors conducted experimental combustion studies using samples of mixed waste from multiple Ukrainian cities and an experimental boiler. The amount of heat released during combustion was determined using an experimental-analytical methodology developed by the authors.

Initial statistical data were evaluated with an accuracy of $\pm 10\%$. Based on variability in morphological composition, average accuracy was estimated at $\pm 15\%$. It was determined that approximately 30% of MSW constitutes residual waste, and the amount suitable for incineration with energy recovery was estimated at $\pm 15\%$ of this value, resulting in a total range of 25.5–34.5%.

Variations in the heat released from combustion were attributed to mechanical unburned residue associated with different combustion technologies, with an uncertainty of $\pm 15\%$.

The integrated uncertainty of the calculations was determined as

$$10\% + 15\% + 4.5\% = 19.5\% (\approx 20\%)$$

Thus, the potential reduction in heat output from combustion of residual MSW may reach up to 20%.

Based on these results, the authors estimate the need for RDF/SRF-fired WtE plants with energy recovery in Kyiv (two facilities), Kharkiv, Odesa, Dnipro, Zaporizhzhia, Lviv, Zhytomyr, Ternopil, and Chernivtsi. Utilizing the energy potential of residual urban MSW could substitute up to 10% of natural gas currently used to provide heating and domestic hot water in these cities [44].

3.3 Barriers

Achieving the EU recycling targets will reduce the amount of energy-containing materials, such as plastics, textiles, paper, and cardboard, in mixed waste. This will lead to a decrease in both the quantity of RDF and the calorific value of the waste being incinerated.

This may result in the need for supplementary fuel to ensure continuity of the effective combustion process.

4. Conclusion

The use of residual MSW as fuel provides a practical method to reduce the share of fossil fuels in district heating systems. In Europe, residual municipal waste already accounts for approximately 25% of the waste treated through incineration with energy recovery, and in countries such as Sweden, Finland, and Norway, it supplies up to 50% of the fuel used in district heating. Between 2019 and 2024, its contribution to gross heat production in the European Union increased from 10.1 to 12.7%, despite a decline in total heat output.

Residual municipal waste has therefore become a regular local fuel source in European heat supply and is beginning to be applied in Ukraine. Because municipal waste is generated in the same urban areas where heat demand is concentrated, residual fractions can serve as a local fuel source for these heating systems, reducing transportation needs and reliance on imported fuels.

Achieving higher rates of recycling in Europe and elsewhere will reduce the share of high-calorific components in mixed municipal waste, decreasing the lower heating value of residual fractions. This requires expanded mechanical pre-treatment and production of RDF/SRF, as well as combustion technologies capable of maintaining stable thermal output at lower calorific values.

The effectiveness of WtE systems depends on the availability of district heating networks capable of utilizing recovered heat on a year-round basis. For this reason, thermal treatment of residual waste with energy recovery is most suitable in urban areas with sufficient and stable

heat demand; electricity-only configurations may be less efficient in locations without heat recovery.

In Ukraine, planned and existing projects in cities such as Kyiv, Odesa, Zhytomyr, and Cherkasy demonstrate the potential to replace a portion of natural gas in district heating systems with fuel derived from residual municipal waste. Experimental combustion studies carried out by the authors and their colleagues indicate that using residual MSW as a fuel could replace up to 10% of natural gas consumption for heating and hot water supply in major Ukrainian cities, depending on fuel preparation and boiler efficiency.

Overall, integrating residual municipal waste into district heating networks provides a combined waste-treatment and heat-supply option for urban areas. When applied alongside recycling, biomethane production, and energy-efficiency measures, WtE can reduce landfill disposal, lower methane emissions, and decrease demand for fossil fuels while maintaining stable thermal output.

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