Study of the Energy Recovery of the Reject Materials from Municipal Solid Waste Treatment Plants in Spain

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Abstract In 2012, 21.2 million metric tons of municipal solid waste were collected in Spain (MAGRAMA 2014), of which 85% corresponds to mixed waste. This is then treated in different plants with the aim of recovering materials for their subsequent recycling and the transformation of the biodegradable organic fraction into compost and biogas. However, of the total amount of material processed in these plants, 42.2% is rejected. In Spain, there are 10 energy recovery plants. In 2012, only 13.57% of the total amount of the rejected material was processed in these plants. The rest was deposited in landfills. Therefore, a significant amount of the material is rejected, and is not currently exploited. The aim of this work is to analyze, on the one hand, the potential energy recovery of the material rejected from the municipal solid waste plants in energy recovery plants, by studying the energy efficiency of the existing plants. On the other hand, it will also compare different energy valorization technologies in order to analyze the need for new Waste-to-Energy plants to take advantage of all the rejected biofuel material generated in Spain.

Keyword Energy recovery · Municipal solid waste · Rejects · Incineration · Gasification

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1 Introduction

What in most traditional societies was considered simply as rubbish, is conceptualized in modern societies as waste. This shift is a result of the recognition of the potential of these materials to be used productively. Of the total amount of waste generated, this article has focused on municipal solid waste (MSW), that is, the one coming from homes, shops, offices, services and the like. Among the many forms of exploitation, thermal processes are presented as an interesting alternative (Van Paasen et al. 2006).

Due to the Spanish energetic situation, where the main energy sources are based on the use of coal and oil, which is not renewable energy, it is important to promote renewable energies such as the combustible fraction of MSW.

In order to obtain products from MSW which have some economic interest, while at the same time minimizing the discharge, it can be subjected to various treatment processes. Depending on the objective set out in the integrated management plans, the most appropriate alternative treatment option is chosen. There are mechanical treatments to separate recyclable materials; biological treatment based on the anaerobic conversion of organic waste to obtain biogas (biomethanation) and aerobic conversion to produce compost (composting). In all these treatments, a reject stream appears and its ultimate destination is the landfill. These rejects are mainly composed of materials with a high energy content, thus presenting a theoretically high potential for use as alternative fuels in industrial thermal processes or in Waste-to-Energy (WtE) plants. This valorization can be done directly or via its transformation into a solid recovered fuel (SRF). The most widely utilized thermal processes are incineration, pyrolysis, gasification and plasma (Elias et al. 2005; Bayard et al. 2010).

Thermochemical treatment processes are an essential component of an integrated MSW management system, as confirmed by numerous studies and analyses (Brunner et al. 2004; Porteous 2005; Psomopoulos et al. 2009). Their main advantages are: (a) a great reduction of the waste by mass (about 80–90%), (Consonni et al. 2005); (b) radical space savings, since much less space is needed in a landfill for the same amount of MSW. Psomopoulos et al. (2009) estimated that a WtE plant that processes 1 Mt/year for 30 years requires less than 100,000 m^2 of space, compared with the 300,000 m^2 which would be required to dispose of 30 Mt of MSW in a landfill; (c) destruction of organic contaminants, such as halogenated hydrocarbons (Mckay 2002; Buekens; Cen 2011); (d) concentration and immobilization of inorganic contaminants, which can be treated and disposed of safely (ISWA 2008; Samaras et al. 2010); (e) recycling of ferrous and non-ferrous metals from ashes and slag (ISWA 2006; CEWEP 2011); (f) reduction of emissions of greenhouse gases from the anaerobic decomposition of organic waste. Psomopoulos estimated that a reduction of 1 metric ton of CO_2 equivalent is achieved per metric ton of waste if it is processed thermally rather than depositing it in landfills; and (g) prevention of environmental burdens (Arena et al. 2003;

Azapagic et al. 2004), as the regulations regarding emissions are much more severe compared to other sources of energy.

In Spain, incineration technologies are mostly used. These have been developed for different types and physical forms of waste, some of the more frequent being liquid injection designs, rotary, fixed furnaces and fluidized beds (Opel 1986; Kisuk 1998). Currently there are 10 MSW WtE plants, where 13.57% of all the rejected material generated in 2012 was processed. The rest was deposited in landfills, therefore, a significant amount is wasted. Furthermore, as in most of Southern Europe, these are conventional thermoelectric plants, i.e., they only generate electricity in the processing of waste. This fact makes it difficult to achieve the values set by EC Directive 2008/98 on waste (Waste Framework Directive) regarding energy efficiency and they can therefore be categorized, in accordance with Annex II of the Directive, as R1 plants, i.e., as having an energy recovery status.

2 Objective

The aim of this paper is to analyze, on the one hand, the current situation of MSW treatment in Spain and the potential energy contained in the rejected materials from the different MSW treatment plants. On the other hand, it also intends to conduct an analysis of the performance and capacity of these rejects in WtE plants. To this end, different bibliographical sources have been reviewed and studied, to enable the analysis of the regulatory framework and the parameters that determine energy efficiency under the regulations concerning WtE plants. A comparative analysis among different plants was also performed.

3 Current Situation of the Treatment of MSW in Spain

The study focused on the year 2012, since this is the last year for which complete data are available. That year 21.2 million metric tons of MSW (MAGRAMA 2014) were collected, of which 18 million corresponded to mixed waste. The rest was collected separately. Of the total amount of waste, 63% was treated in different facilities (Fig. 1), 27% was deposited directly in landfills, and 10% was incinerated (Eurostat 2012). The waste is treated in these facilities according to the fraction to which it belongs so as to be able to reuse and recover materials by recycling, as well as to transform biodegradable organic waste into compost and biogas (Colomer and Gallardo 2007). However, of the total material processed in the different facilities (12.5 million metric tons), a very significant amount is rejected. This rejected material is mainly composed of combustible material (Gallardo et al. 2014).

Rejected material flows vary depending on the type of treatment plant. Thus, the rejection rate of each plant is 42.33% for light packaging plants (LPP), 37.03% for

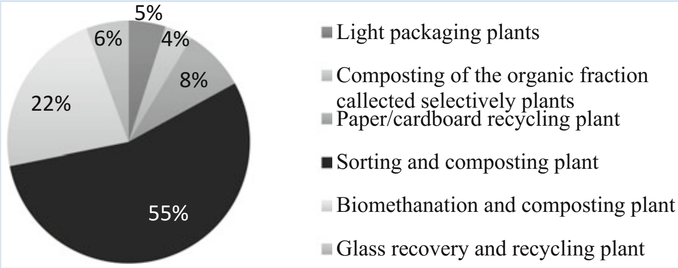

Fig. 1 Percentage of the incoming material at MSW treatment plants in Spain, 2012

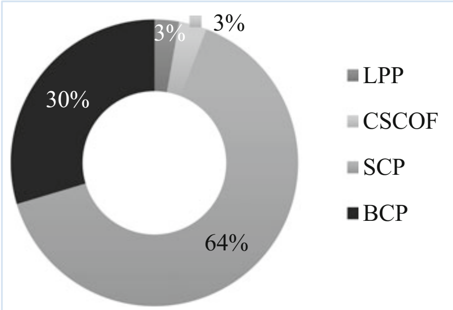

Fig. 2 Reject materials from MSW treatment plants, 2012

composting of the selectively collected organic fraction (CSCOF), 60.99% for sorting and composting plants (SCP) and 75.38% for biomethanation and composting (BCP) (MAGRAMA 2014; Edo 2012). In 2012, the total amount of reject material from MSW treatment plants was 7.8 million metric tons, thereby accounting for 61.82% of the total amount that was processed. The greater part of all the reject materials came from the SCP (Fig. 2).

Continuing with the analysis of the MAGRAMA data, with respect to the total amount of reject materials generated in these plants, only 13.57% of the nearly 8 million metric tons entered WtE plants. The remaining reject, 86.43%, was sent to landfills, which represents 47.79% of all the material they received.

To determine the feasibility and performance of the WtE plants for both mass waste and reject materials, it is essential to determine their calorific value. Depending on the type of treatment plant, the composition of the reject will be higher in some fractions than in others, and therefore they have a different calorific value.

Table 1 (Edo 2012), shows the lower heating value (LHV) of the different fractions that may be present in the reject materials of MSW treatment plants. Most of the LHV values are quite high when compared to other fossil fuels such as anthracite, with 6700 kcal/kg, or lignite, with 2177 kcal/kg.

By way of example, Edo (2012) determined the LHV of an LPP, the result being 3883.87 kcal/kg, calculated on dry matter.

Table 1 LHV of the MSW fractions in dry matter

Fraction	LHV (kcal/kg)
Paper/cardboard	2658.00
Mass waste[a]	2600.00
Textile/cellulose	3929.34
Plastic film	8344.57
Rigid plastic	7182.55
Wood	3393.09
Organic matter	2810.47
Cork	8303.37
Rubber	3931.22
Polyurethane	6057.29

[a]Data estimated by Grau and Farré (2011)

If, furthermore, the reject materials from different MSW treatment plants are processed to be transformed into an SRF by mechanical treatments (grinding, drying, removal of metals, etc.), it is possible to obtain a fuel with homogeneous and well-defined properties. For example, in the case of rejects from an SCP, an SRF with an LHV between 5600 and 6100 kcal/kg can be obtained (Gallardo et al. 2013).

From the data analyzed, it is possible to estimate the energy potential of the reject materials generated by MSW treatment plants in Spain for the year 2012 (7.8 million metric tons). If one considers that these rejects are used as mass waste (2600 kcal/kg), then 84,631,600 GJ are obtained from the potential energy contained in them. For the same year, taking into account an average LHV of 5800 kcal/kg (Gallardo et al. 2013) and considering that 28% of the material is lost during processing of SRF makes it possible to obtain a total of 188,793,571 GJ of potential energy contained in them.

4 Current State of the Energetic Valorization of MSW in Spain

The Directive 2008/98/EC of the European Parliament and of the Council on waste (Waste Framework Directive) accepts the incineration of MSW as an energetic valorization of waste operation provided that minimum energy efficiency is achieved. This lower limit is given by the R1 Formula (Eq. 1), to which reference is made in its Annex II, on recovery operations (R for recovery). If the minimum values required regarding energy efficiency (0.60 for installations in operation and permitted in accordance with applicable community legislation before 1 January 2009, or 0.65 for installations permitted after 31 December 2008) are not achieved, this process will be considered a disposal operation, thus being categorized as D10 (D for disposal), according to Annex I of the Directive.

These requirements of an energy efficiency of 0.60 and 0.65 mean that the equivalent energy produced by WtE plants is at least 60% or 65% of the energy that a classical plant which burns conventional fuels would produce, either in the form of electricity or heat.

$$EE = (Ep - (Ef + Ei))/(0.97 \times (Ew + Ef)) \quad (1)$$

where

- Ep: means the annual energy produced as heat or electricity, which is calculated by multiplying the energy in the form of electricity by 2.6 and the heat produced for commercial use by 1.1 (GJ/year). The 2.6 factor for electricity is based on a value of 38% of a European average coefficient of coal-fired plants, which means an energy demand of 2.6 kWh to produce 1 kWh of electricity. The 1.1 factor for heat generation is based on a value of 91% of a European average coefficient of heat generating plants.
- Ef: is the annual energy input to the system from fuels contributing to the production of steam (GJ/year).
- Ew: is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year).
- Ei: is the energy imported annually, excluding Ew and Ef (GJ/year).
- The 0.97 factor represents energy losses due to bottom ash and radiation.

It can be seen how, in the R1 Formula, the term Ep (energy produced) is subtracted by "(Ef + Ei)", indicating that the external supply of energy for the process is counterproductive when it comes to complying with the values for minimum energy efficiency.

The R1 Formula is used to determine the efficiency of the system for recovering energy contained in waste and generating electricity, heat or steam.

In this regard, in a study on the efficiency of the WtE plants in Europe, Reimann (2009) classified plants according to three criteria:

- Generation type: only electricity, only heat or cogeneration (electricity + heat).
- Plant size: small, medium or large.
- Geographical location: Southern Europe, Central Europe or Northern Europe.

Thus, the plants with poorer outcomes in terms of energy efficiency are those only generating electricity. This is because the transformation into electrical energy with respect to the LHV of waste varies between 20 and 30% due to losses in the exhaust gases by radiation, in ash and in slag. However, the thermal energy available is 75% of the energy input into the process. In turn, this thermal energy can be converted into electricity with an efficiency of around 30% by using exhaust steam turbines (Romero 2010). This is important, since the vast majority of the plants in Southern Europe generates only electricity, and would therefore be giving priority to plants from colder climates, which have a heat demand, in the form of either hot water or heating, that is much higher than in areas with warmer climates.

Reimann also found a series of conditioning standards that must be met so that a WtE plant exceeds the values of energy efficiency without any problems. These are as follows:

- The WtE plant must be connected to a heat distribution network, which is rare in Southern Europe.
- Ensure a stable and continuous heat demand, since it is not possible to store it. In any case, for the energy recovery process to be efficient, it must be both continuous and stable.
- The plant should be located in urban areas or in close proximity to urban centers or industrial estates so as to be able to output the heat that is generated.

In 2012 the Joint Research Centre of the European Commission, issued a report (Energy recovery Efficiency in Municipal Solid Waste-to-Energy plants in relation to local climate conditions), which states that:

- Weather conditions significantly influence the amounts of energy that can be produced or used in the form of electricity, heat or steam.
- To equate WtE facilities affected by local climatic conditions, it is reasonable to apply a climate correction factor (CCF) to the R1 Formula.
- The CCF should be based on both the document regarding best available techniques for waste incineration and local climatic conditions.

This has led to a draft being drawn up with amendments to Annex II of the Waste Framework Directive, which takes into account the CCF. The application of this factor would mean some incineration plants categorized as D10, would reach the threshold of the R1 Formula and thus become R1 facilities.

5 Analysis of the Waste-to-Energy Plants in Spain

In 2012 the total input of MSW at the 10 WtE plants in Spain was 2.1 million metric tons, of which 1.04 million metric tons were mass waste and 1.06 million metric tons consisted of reject materials, according to MAGRAMA, 2014.

Table 2 shows the location of these facilities, their capacity and the power output generated. It can be seen that the plant with the highest capacity is in the Autonomous Community of the Balearic Islands, since it has four furnaces. However, the plant in the Autonomous Community of the Basque Country (Zabalgarbi) is the one that generates the most power because it is a special plant, since incineration is integrated within a combined cycle together with natural gas. This fact allows it to work with steam parameters that are different from those of a conventional WtE, and more advantageous from the standpoint of thermodynamic efficiency and levels of corrosion in pipes (BREF-WI, pp. 311–313). At the same time, Catalonia is the autonomous community with the most plants and a treatment capacity of around 700,000 metric tons/year. All the plants appear in the

Table 2 Distribution of the Spanish WtE plants by Autonomous Communities, 2012

AACC	No. Facilities	Capacity		Power generated (kWh/year)
		No. Furnaces	Nominal capacity (metric tons/year)	
A.C. Balearic Islands	1	4	732,000	[a]245,680,000
A.C. Cantabria	1	1	96,000	84,564,785
A.C. Catalonia	4	9	690,620	288,525,500
A.C. Galicia	1	2	533,742	344,096,500
A.C. Madrid	1	3	300,000	183,641,240
A.C. Basque Country	1	1	245,910	727,000,000
Autonomous City of Melilla	1	1	36,000	3,212,080
Total Spain	10	21	2,634,272	1,631,040,105

Source MAGRAMA; [a]AEVERSU

administrative register of the special regime of electricity production facilities, which is published on the website of the Spanish Ministry of Industry, Tourism and Trade, except for the plant in the Autonomous Community of the Basque Country (Zabalgarbi, S.A., in Bilbao).

At the European Union level, there are about 450 WtE plants with an annual processing capacity of about 78 million metric tons (CEWEP 2014), and so the Spanish plants, with 2.6 million metric tons, would represent around 2% of the total treatment capacity of the European plants.

As shown in Table 3, the Spanish WtE facilities are conventional incineration/combustion plants. Their normal processing capacities range between 3 and 50 metric tons/hour per line, and they can treat waste with an LHV of between 1400 and 4500 kcal/kg without the addition of auxiliary fuel (Muruais and Maíllo 2010).

According to Wilson et al. (2013), in terms of efficiency of conversion into electricity, between 0.4 and 0.7 MWh of electrical energy can be generated with 1 metric ton of MSW through incineration. On analyzing the data about electricity production and the amount of MSW treated shown in Table 3, most of the conversion factors are within that range. Note the case of the Zabalgarbi Plant, which reflects some high values due to its particular conditions. In addition, the Plant in Melilla has a coefficient well below the expected range. Furthermore, no significant difference is observed between the values of plants using grate furnaces and fluidized bed, although it is noteworthy that the latter values are near the upper limit of the range.

All plants began operating before December 2008, so the value of energy efficiency under the premises of the R1 Formula should be at least 0.60. Data are only available for two of them and are very close to the limit set by the Waste Framework Directive, which confirms the difficulty these plants face in attempting to achieve the specific thresholds.

In turn, it can be seen that the choice of grate furnaces is the most widespread. With this system no previous selection or pre-crushing process is required and it can

Table 3 Characteristics of the WtE plants in Spain, 2012

Facility	Type waste	Incineration capacity (metric tons/hour)	Quantity waste treated (metric tons/year)	Electrical production (MWh)	Conversion ratio from MSW to electricity (MWh/metric ton)	Type of furnace	EE-R1[e]
Mallorca-Tirme (Balearic Islands)	MSW	45.75	511,999	245,680	0.48	Roller grate/moving-water-cooled	–
Meruelo (Cantabria)	RDF	11	112,500	85,500	0.76	Roller grate	–
Girona-Trargisa (Catalonia)[c]	MSW	4	–	–	–	Martin grate	–
Sant Adriá del Besós-Tersa (Catalonia)[b]	Rejects and unusable waste (70/30)	40	287,057	135,729	0.47	Sliding grate (Von-Roll)	0.627
Mataró-TRM (Catalonia)	RDF	18	190,000	115,000	0.61	Moving sliding grate (Martin) (2 furnaces)	–
Tarragona-Sirusa (Catalonia)	RDF	15.5	140,000	53,000	0.38	Roller grate	–
La Coruña-Sogama (Galicia)	RDF	47	555,440	342,486	0.61	Circulating fluidized bed	–
Madrid-Tirmadrid (Madrid)[a]	Rejects and unusable waste	37.5	265,919	183,642	0.69	Sand bubbling fluidized bed (3 furnaces)	–
Bilbao-Zabalgarbi (Basque Country)	MSW	30	224,792	658,000	2.9	Sliding grate (Martin)	0.61
Melilla-Remesa (Melilla)	Mass MSW	5	39,302	8446[d]	0.22	Cloves grate (Von-Roll)	–

Source AEVERSU, [a]Madrid City Council
[b]TERSA
[c]Girona-Trargisa data are not available
[d]Equivalent data, since only 2275 MWh were generated owing to a turbine fault during 8 months
[e]Data values published on the website of the WtE plants. The rest of the values are not available

accommodate wide variations in composition and calorific value of the MSW. Only two facilities have chosen the fluidized bed technology, since it has maintenance and capital costs that are lower than those using grate furnaces. They also provide greater overall thermal efficiency and can run on a wide range of solid and liquid fuels. However, it is necessary to monitor the size and the composition of the waste, which generally requires a pre-treatment (Arena et al. 2011).

Besides these two types of incineration technologies, there are also others that are used depending mainly on the type of waste to be valorized (Table 4). Moreover, there are other thermal valorization processes, such as pyrolysis, gasification or plasma, which, although capable of generating good theoretical data regarding energy efficiency, cannot yet be considered as mature in their application to MSW as incineration.

In order to check whether electricity production is a linear function of the amount of MSW treated in the existing plants, the possible correlation between the total amount of MSW treated and the electricity generated within the range of 38,000 and 600,000 metric tons was analyzed. Excluding data on electricity generated by Zabalgarbi, due to the uniqueness of this plant, the bivariate analysis revealed a fairly strong positive linear correlation between the two variables ($R^2 = 0.9282$) (Fig. 3).

Furthermore, using data on the electricity production and total amount of MSW treated by the 10 WtE plants enabled to determine the average production of electricity per metric ton valorized in 2012, obtaining a value of 785 kWh/metric ton. If valorized with this type of plant, the total amount of reject material generated during that year (7.8 million metric tons), could generate around 6,103,046 MWh of electricity. Given that the average electricity consumption per household (≈3 people) is 3487 kWh per year (IDEA 2013), the demand for 1,750,228 households

Table 4 Comparison of the technologies used for incineration

Type of waste	Furnaces type			
	Grate	Fluidized bed	Rotatory	Liquid injection
Granular, homogeneous	Appropriate	Appropriate	Appropriate	–
Irregular	Very appropriate	–	Appropriate	–
Low melting solids	–	Appropriate	Appropriate	–
Organic with melting ashes	Very appropriate	–	Appropriate	–
Voluminous bulk waste	–	–	Very appropriate	–
Organic fumes	Appropriate	Appropriate	Very appropriate	Appropriate
Organic liquids	–	–	Appropriate	Very appropriate
Halogenated sludge	–	–	Appropriate	Appropriate
Organic muds	–	Appropriate	Appropriate	–

Source Prepared by the authors, Centro de Tecnologías Limpias (CTL)

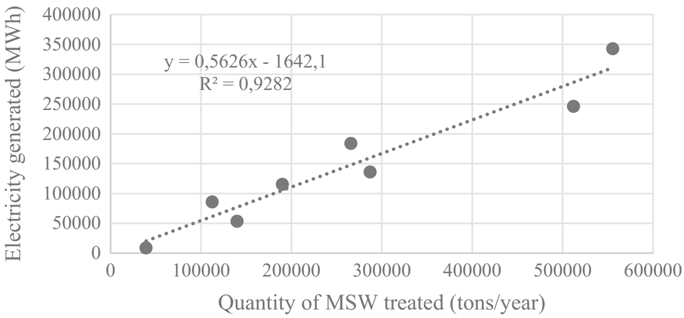

Fig. 3 Correlation between electricity generated and amount of MSW treated by WtE plants, 2012. *Note* No data are available for the Girona-Trargisa Plant

or, to state it in other terms, 5,250,684 people, could be satisfied. In addition, the amount of electrical energy produced per unit of energy contained in the MSW has been determined. Thus, for each kWh of energy contained in the rejects, 0.25972 kWh of electricity are obtained in the existing plants. This is calculated taking into account the average LHV of the reject materials estimated by Grau and Farré (2011).

In the event that all the rejects were transformed into SRF (with an average LHV of 5800 kcal/kg) and considering the same coefficient of conversion as that of the existing plants, it is estimated that the average electricity production would be 1752 kWh/metric ton. Based on this, 9,807,168 MWh of electricity could be generated, thereby satisfying the electricity demands of 2,812,494 households, which is equivalent to 8,437,483 people.

Finally, the number of plants that would be required to cater for the total amount of reject materials generated in 2012 has been estimated. From the data in Table 2 and assuming a nominal treatment capacity of 100,000 metric tons, the construction of 63 new plants would be necessary.

6 Conclusions

In Spain an energetically useful flow of reject materials from different MSW treatment plants is generated every year and, in accordance with today´s waste management and treatment systems, most of it is deposited in landfills. The largest amount of reject materials is generated in sorting and composting plants.

By processing and transforming reject materials into an SRF, it is possible to obtain a fuel with homogeneous properties and a high calorific value. Their use in WtE plants, according to the R1 Formula of the Waste Framework Directive, would increase energy efficiency, because even though there is an energy expenditure in the processing of SRF, this is not taken into account in the calculation of the R1.

As defined by the R1 Formula, it will be very difficult for the WtE plants in Southern Europe to exceed the minimum values set for energy efficiency, because by producing basically electricity and not taking advantage of the heat that is produced (co-generation), it is very difficult to reach the energy efficiency thresholds set by the Waste Framework Directive. In this study it has only been possible to collect energy efficiency values for two plants, both of which slightly exceeded the defined threshold.

The main technology for energy recovery in Spain is incineration, and more specifically grate furnaces. The amounts treated per year range from 40,000 metric tons at the smallest plant to 555,000 metric tons for the largest, and there is a strong positive linear relationship between the amount of MSW treated and the amount of electricity produced.

In 2012 only 13.57% of the reject materials generated were valorized. If all these materials were used successfully, it is estimated that it could satisfy the electricity demands of more than 5 million people. In the case of transformation into SRF, the number would rise to 8.5 million people. Yet this would require the design and construction of new WtE plants.

Finally, it should be said that in Spain there exists room for potential development in this field, both in the design of alternative fuels and in the design and construction of new WtE to valorize them.

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