Waste-to-Energy Recovery from Municipal Solid Waste

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Inadequate disposal of Municipal Solid Waste (MSW) is one of the greatest environmental issues confronted nowadays. One of the techniques used for its final disposal is incineration, otherwise known as mass burning.

Keywords: waste heat recovery ; energy recovery ; waste-to-energy

1. Different Technologies Used in Waste-to-Energy Recovery

All methods of heat treatment of waste with energy recovery, as well as waste fuels, are collectively referred to as Waste-to-Energy (WtE) [1]. WtE technologies include biological and thermochemical conversion systems [2].

As the main thermochemical conversion systems, there are the processes of (a) incineration, also called mass burning, (b) pyrolysis, and (c) gasification, which differ mainly due to the amount of oxygen present in the reaction medium. Mass-burning incineration operates with excess oxygen, while in gasification combustion occurs partially, that is, with oxygen deficit, and pyrolysis with a total absence of it [3].

The most used form of the combustion process is complete oxidation (mass burning), that is, burning USRs in designed ovens [1]. Data from the Intergovernmental Panel on Climate Change [4] confirm the predominance of the technique by pointing out that 90% of the WtE plants in the world are of the type combustion mass burning with mobile grid because this is the most cost-effective method today.

Other treatment technologies, such as gasification and pyrolysis, are still very uncommon worldwide because they are complex technologies. The first, for example, requires a drying pretreatment of the US [5] and the second needs an external power source [1]. These additional costs diminish its competitiveness in the face of mass-burning technology. However, despite the financial unfeasibility of these techniques for many contexts, many advances have been made in these new heat treatment technologies, especially in Japan, which has been the world leader in the development and application of these non-traditional treatments, with more than 100 plants for these relatively new processes [6].

Mass-burning technology, also called incineration, can be defined as a thermochemical process that through the oxidation of USRs, in which furnaces are subjected to high temperatures, between 750 °C and 1100 °C, and with the presence of oxygen under stoichiometric or excess conditions, aims to decrease the volume and mass of waste, extending the life of landfills [3][7][8][9][10]. It is currently possible to reduce the initial volume of USRs by 90% and their mass by 75%, depending on the composition and degree of recovery of the materials [11].

The great advantage of the technique, given other thermal processes, is that it can accept a wide variety of waste, of various sizes and sources [12]. In addition to the destination of the US, the process also has the benefit of power generation.

In this process, oxygen reacts with combustible elements present in the waste, such as carbon, oxygen, and sulfur, converting chemical energy into heat [13]. In addition to heat production, it is possible to produce electricity through the heating energy of the materials [14]. In this process, the generation of energy occurs after the generation of steam in boilers, which is sent to the turbines resulting in electricity [9][10].

The generation of electricity by the incineration of RSU is similar to the process of conventional thermal power plants of Cycle Rankine, in which the vapors generated in the boilers are driven using steam turbines that drive electric generators that produce electricity [10][15]. The generation capacity will depend on the efficiency of the process of transformation of heat into electric energy and the calorific value of the incinerated material [15]. Plastic, paper, and rubber components are the ones that contain the highest calorific values [13].

Modern incinerators can recover around 50 to 70% of the energy present in the US so 15 to 25% of this energy is transformed into electricity and the rest is transformed into thermal energy [16]. The relatively low electrical performance of the process reflects the limitation of the system operating at very high temperatures [15].

Although energy recovery is not the main objective of the incineration of UUs, this is an additional benefit, which helps maintain the viability of the operation, since the operational cost of the technique and also that of maintaining waste treatment is high [16], because in order to meet environmental legislation, incineration plants need to have more technical equipment to control air pollution, thus generating a higher cost [16].

On average, the technology can generate between 0.3 and 0.7 megawatt-hours (MWh) of electricity per ton of waste, depending on the size of the plant and the Lower Heating Value (LHV), i.e., the lowest waste heating value [10].

Incineration, like any conversion process, generates by-products. Solid emissions include ash and slag, which are non-combustible mineral parts, which are ferrous and non-ferrous alloys that can be extracted for recycling [14], and the rest of the ashes, similar to sand and gravel, are packed for a certain time to be used later on roads, buildings, or in the cover of landfills [6]. The ash resulting from combustion corresponds to 10% of the volume or 20 to 30% by mass of RSU [17].

Ash is an inorganic solid residue formed by mineral compounds and metal oxides. They can be subdivided into bottom grey or heavy gray, which are medium-sized powder materials that are not dragged by airflow, and fly ash or light ash, which is a particulate material with a thinner particle size that can be carried by combustion gases. Slag is a solid classified with higher granulometry and consists of the addition of non-combustible materials with products of the calcination of inorganic substances and ash sintering [3].

It is important to highlight that high temperatures (higher than 420 °C) are important to limit the formation of slag and fouling, which are accompanied by corrosion due to the presence of chlorine, mainly, and the accelerated wear of heat exchange surfaces [18].

In addition to solid particles, gaseous emissions are also generated by the process, such as sulfur oxides (SOx), carbon oxides (COx), nitrogen oxides (NOx), and hazardous metals, as well as carcinogenic emissions such as dioxins and furans, and polyaromatic hydrocarbons (HPAs), which are among the Persistent Organic Pollutants (POPs). Therefore, additional treatment is required in the combustion gas cleaning system before atmospheric emission [8][19].

The incineration process is not simple, so a disadvantage of this technique is that it has a high cost of implementation and operation. Another drawback is the potential unpleasant emissions of pollutants from incineration, as mentioned earlier, but these can be minimized with advanced technologies to control air pollution and segregate waste streams [20].

Although incineration is considered a path for sustainable waste management, it may not always be a viable disposal technique, as it depends largely on the characteristics of waste, which in turn are influenced by local demographics, social status and cultural differences, seasonal fluctuations, and topography [21]. Residues with high humidity and low calorific value can make the method unfeasible, as they decrease process efficiency. For this reason, it is very important that in the feasibility study of this process, the variable ‘gravimetric composition’ of the USR should be taken into account, since it influences the combustion power of the process.

However, the technique also has advantages, because it does not require large areas for installation, when compared to landfills, as the feeding of waste is continuous and drastically reduces the volume of waste, an advantage that is seen as the most important benefit of the incineration process.

Table 1 summarizes the main advantages and disadvantages of WtE technologies described in this subtopic.

Table 1. Advantages and disadvantages of energy generation technologies from waste.

Burning Mass	
Advantages	**Disadvantages**
• They make it possible to process various types of waste [1]. • Reduction of volume and mass by 90% and 75%, respectively, without long periods of residence [3][14][17][18][22][23][24]. • There is enormous experience and international know-how in the face of a large number of plants in operation [1]. • Continuous operation that enhances scale gains [3]. • Energy use, especially when the residue (as received) has a lower calorific value (PCI) above 8000 kJ/kg (1911 kcal/kg) [25][26], which can be used in the form of water heating or transformed into electricity [17][23]. • Smaller area is required when compared to landfill disposal [3][18][22]. • Controlled incineration has less environmental impact than landfills [7] because it has lower greenhouse gas (GHG) emissions when compared to landfills [14][27].	• Not feasible for small plants [27]. • High capital costs of the plant [18][22]. • Viability of the plant conditioned to processing capacity, usually above 6250 kg/h for RSU [3][25]. • The USRs have low energy content and high humidity, that is, relatively low heating value (LHV), especially in developing countries [27]. • The combustion of waste results in the formation of air pollutants (particulate matter, SO_2, HCl, HF, NO_X, CO, dioxins, furans, etc.) that require treatment to meet environmental legislation [3] and in the production of solid particles and metal-rich residues [7]. • Negative perception of the public strongly influenced by the emission of pollutants [1][28].
Gasification	
• Application in small and medium scales [29]. • Possibility of using syngas in high-efficiency thermal devices (ICE and gas turbines or for biofuel synthesis) [10][29]. • Waste gasification has more favorable environmental results than incineration [10][18][29][30][31], as a limited form of dioxins, furans, nitrous oxides, sulfur oxides, and ash [18][32]. • Lower amount of secondary waste, which in some cases is produced in a less dangerous way, such as vitrified slag [18].	• High operating cost [31]. • Need for pre-treatment to adjust moisture [31][33] and particle size [32]. • Still in the research phase [27]. • Not viable for large-scale commercial purposes [27].
Pyrolysis	
• Reduction in the volume of waste from 70 to 90% [19]. • Shorter treatment time than in biological processes [19]. • Generation of more stable products, free of odor and pathogens [19].	• Still in the research phase [27]. • Not viable for large-scale commercial purposes [27].

Source: prepared by the authors.

Through **Table 1**, it is noted that the mass-burning technology has greater economic viability to treat waste on a large scale. In this way, there is a greater number of plants in the world that use mass-burning technology instead of other techniques. However, there has recently been a greater interest in studying the other two techniques for the advantages they have, especially in environmental issues.

The next item will present the global scenario of Waste-to-Energy technologies.

2. Global Scenario

It is assumed that 1.2 billion tons of post-recycling MSW are generated annually in the world, but only 16.6% of it is treated using WtE technologies [1]. The International Renewable Energy Agency [34] estimates that the WtE recovery sector has enough capacity to generate 13 gigawatts (GW) of electricity on a global scale.

The first incinerator was built in 1875 in the city of London to satisfactorily carry out waste treatment, and there were already 121 incinerators in 1900 in England. However, the author states that it was only at the beginning of the 20th century that electricity started being produced from MSW incineration in Europe [35].

There has been a significant increase in European WtE plants only when the European Union introduced targets for diverting MSW from landfills to encourage energy recovery and recycling. In 1999, Directive 1999/31/CD [36] was proposed to reduce biodegradable waste disposal into landfills to minimize the production of methane and reduce global warming. In 2008, Directive 2008/98/EC [37] established a hierarchy of priorities for MSW disposal, in which waste-to-energy recovery takes greater priority over disposal into landfills. **Figure 1** illustrates the hierarchy of these priorities in waste management.

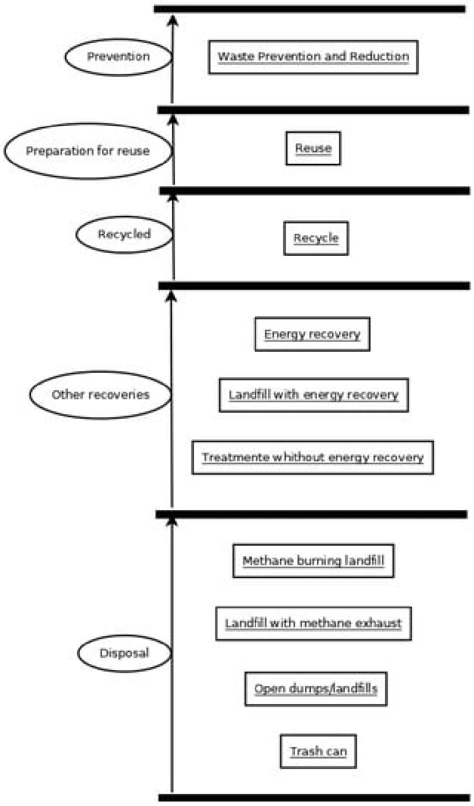

Figure 1. Waste priority hierarchy according to the European Union (Source: [6] adapted from the [9]).

Figure 1 reveals that there is great concern regarding waste minimization, since waste prevention, reuse, and recycling stand first in the hierarchy of priorities, followed by waste-to-energy recovery, and finally waste disposal into landfills with no energy recovery. It is worth mentioning that the Directive in question [37] emphasizes the importance of avoiding landfills as vehemently as possible, as well as recyclable material incineration.

Although these directives encourage the use of waste-to-energy recovery instead of landfill disposal, Directive 2000/76/EC [38] is forceful in establishing that all WtE plants must comply with strict atmospheric emission standards through waste collection, constant monitoring, and proper treatment.

Between 1995 and 2012, there was a 42% reduction in the amount of MSW dumped into sanitary landfills as a result of the encouragement of waste-to-energy recovery in Europe. On the other hand, the amount of waste recovered in WtE plants increased by 80%. In 2012, energy was recovered in 456 WtE plants across Europe, which prevented 79 million tons of solid waste from being disposed of in landfills. In 2015, 90 million tons of waste were treated by WtE plants, which supplied 18 million inhabitants with electricity and 15.2 million inhabitants with heat. In 2016, the number of WtE plants in operation rose to 514 units which processed 263,314 tons of MSW daily [6].

Currently, 10% of district heating across Europe comes from WtE plants. In cities like Brescia, Malmö, or Klaipėda, heating from these plants covers 50% or more of the heating demand. Regarding electricity generation, around 19 million people a year are supplied by WtE plants in Europe [39].

Figure 2 shows the trend of MSW treatment in 2019.

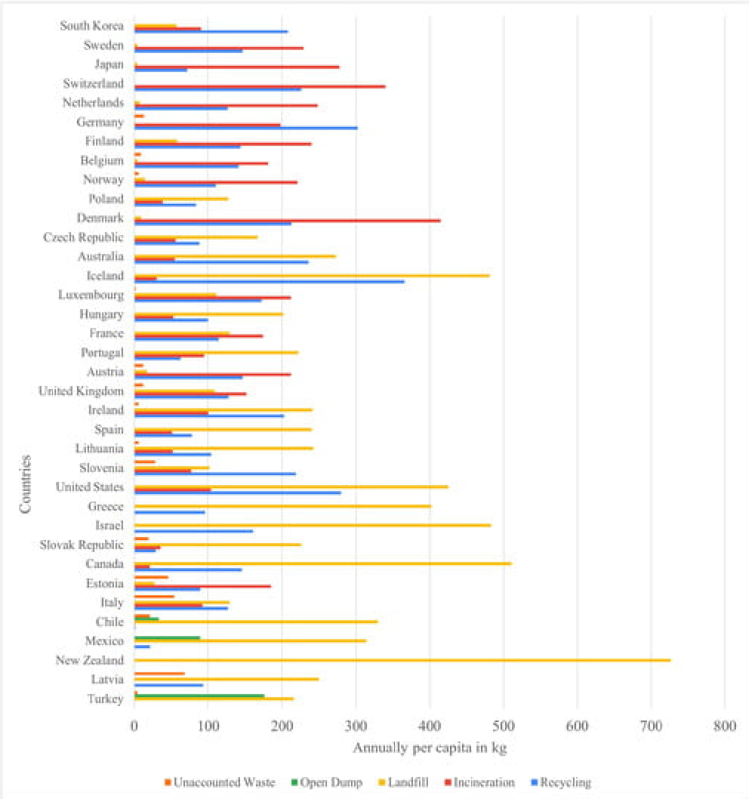

Figure 2. Municipal waste treatment in 2019 (Source: [40]).

It can be concluded from **Figure 2** that in several countries around the world, incineration stands out compared to other sources of disposal, as is the case in some European countries, such as Germany, Denmark, Switzerland, Holland, and Sweden, among other countries, as well as in Japan. It can be concluded that the countries that most use this technology are countries with a smaller territorial area and this may be due to the lack of space for landfilling their waste.

Countries having the highest recycling rate are also those with the highest waste-to-energy recovery, thus reducing the use of landfills to nearly zero, as is the case of the first eight countries shown in **Figure 2**. In Brazil, there is a discreet rejection of the application of WtE technology due to considerations that this would affect recycling cooperatives, but this objection is much more due to social, political, and economic conflicts in the country.

As future goals, Europe aims to accomplish the following: (a) expand the capacity and number of WtE plants to process over 40 million tons of MSW yearly; (b) reduce MSW disposal into sanitary landfills from 25% to 10 % until 2035; and (c) increase waste recycling by up to 65% by 2035. Through this policy, the European Union will (a) generate 18 TWh of energy, either in the form of heat or electricity, and (b) reduce 115 million tons of CO_2 generation aiming to lower greenhouse gas (GHG) emissions into the atmosphere [41].

Considering the data pointed out in **Figure 2**, and deepening the observations regarding the existence of WtE plants, we can highlight that in Japan, the large projects of WtE plants were conceived in the 1960s with the initial aim of increasing land availability due to its high cost in the country and the concern about the quality and scarcity of water, as well as economic and environmental benefits of improving the technique's effectiveness, which was posteriorly taken into account [6]. Currently, over 80% of MSW is incinerated and 20% is recycled in Brazil. From this percentage, 24.5% recovers energy at a conversion rate of approximately 200 kWh per ton of MSW. In Tokyo, the electricity conversion rate of these incinerators reaches up to 390 kWh per ton of MSW. In Kobe, 16.2% of its electricity demand and 25% of its hot water demand are supplied through incineration at an average conversion rate of 300 kWh per ton of MSW [42][43][44].

In South Korea, there are 35 WtE plants in operation, which incinerate 25.02% of all MSW produced countrywide. It should be noted that these plants have excellent performance, as they have very low levels of pollutant emissions [1][6].

China will have had 339 WtE plants in operation with an installed capacity of 7.3 GW of electricity by the end of 2017, thus being considered the country whose WtE plants have the largest installed capacity worldwide. As a reference, such installed capacity is equivalent to 40% of that of all countries belonging to the Organization for Economic Co-operation and Development (OECD) altogether. China's Five-Year Plan estimates that over 13 GW of installed power capacity will have been reached by 2023, which corresponds to the same installed power capacity as that of the Itaipu Power Plant, which satisfies 15% of the Brazilian electricity demand. Finally, it is estimated that the country's WtE plants will have been able to process 260 million tons of MSW by 2025 [6][45].

In New York, some public incineration plants started to be built incipiently after 1906. After 1950, with land value appreciation, local governments started building waste incineration chambers and used smoke to purify water. Modern charcoal filtration systems to minimize hazardous particulate emissions were only developed after the United States Environmental Protection Agency (USEPA) laboratory had identified the presence of atmospheric dioxins and other toxic substances in 1977 [46].

According to the Solid Waste Association of North America (SWANA) [47], the United States encountered several obstacles that eventually hampered the process of developing the WtE industry, among which are strict conditions for controlling atmospheric emissions, lack of proper disposal of ashes which in turn have increased the operating costs of plants, the fact that sanitary landfills are cheaper options for final MSW disposal, and the obstacles posed by the electric energy industry hindering the sale of electricity from WtE plants.

Currently, the United States' MSW is treated as follows: 26% is recycled, 9% is composted, 52% is sent to landfills, and 13% to WtE plants [6]. According to data from the United States Environmental Protection Agency (EPA) [48], in Brazil there are 86 facilities in the country recovering energy through MSW incineration, with a capacity to process 25 million tons of waste yearly, thus generating 2720 MW of electricity.

There are 5 WtE plants in operation in Canada, but only one of which uses incineration technology, which has the total capacity to treat 2272 tons daily, i.e., 3% of all MSW generated in the country [6].

India has 8 WtE plants in operation, totaling 94.1 MW of installed power. Also, according to the same author, 50 more plants are being built with enough capacity to process 30,000 tons of MSW a day, which totals 398 MW of installed capacity [49].

In Russia, there are only 4 WtE plants (located in Moscow) with enough capacity to process 1179 tons of MSW a day [6].

Latin America faces a major problem regarding waste management, especially concerning poor environmental governance and, consequently, Integrated Waste Management practices. Due to low financial investments in the sector, hiring more workers and investing in new technologies is impractical [50]. Moreover, [50] states that Latin America is also lagging regarding WtE plants. However, the first plant is going to be built in Mexico City whose daily processing capacity is 4500 tons of MSW. This plant is regarded as the plant having the largest installed capacity (110 MW) in the world to date. Its electricity production is going to be sold to the Mexico City Subway System at R$ 414.00/MWh based on the collection of a tipping fee of R$ 80.00 (US$ 15.47—07/31/2022) per ton of waste [6].

In Brazil, there were some experiments on incinerators (**Table 2**), but these have no pollution control system or are incapable of estimating energy recovery. Given such a lack of equipment to control emissions, especially of dioxins, furans, and other toxic substances, incineration plants were banned.

Currently, a few small pyrolysis and gasification plants are operating on Refuse Derived Fuel (RDF) in Brazil, as is the case of a plant located in the municipality of Mafra, Santa Catarina. In Boa Esperança, Minas Gerais, construction began on a plant consisting of an MSW processing unit, a gasification unit, and a generation unit. This plant will process 30 tons per day of CDR [51].

Table 2. Some Brazilian experiments on incinerators.

cidades brasileiras	Implementação	Conclusão
Manaus (AM)	**1896**	**1958**
Belém (PA)	**Início do século 20**	**1978**
Araçá (SP)	**1913**	**1948**
São Paulo – Pinheiros (SP)	**1949**	**1990**

Source: Adapted from [52].

There are also several studies [51][53] and pilot plants [54] that study the viability of the gasification method using MSW, mainly for small and medium-sized municipalities, since 97% of Brazilian municipalities have less than 200,000 inhabitants [54].

There are still prospects for the construction of two other Waste-to-Energy Recovery (WtE) Plants using the mass-burning technology, both in the state of São Paulo [6].

In addition to these plants that have already been through or are currently undergoing a licensing process, there are also studies carried out by Brazilian researchers on the possibility of implementing WtE plants in different contexts of the country. One study pointed out that incineration can generate enough electricity to supply 39% of local residences in the city of Campinas, while biodigesters are capable of generating enough electricity to supply 1% of its residences, as long as MSW plants keep using 20% of recyclable materials available [17].

In a work on Isolated Systems covering a large region of the state of Amazonas, the author points out that, for such a scenario, waste-to-energy recovery through pyrolysis would be attractive for larger municipalities and the use of gasification for small communities would be interesting since these remote places are not connected to the National Interconnected System (SIN) and are thus dependent on thermoelectric generation from fossil fuels, which are highly polluting and have elevated costs [55].

Another Brazilian case study on WtE recovery from MSW was conducted in the city of Santo André, state of São Paulo [56]. The authors found that the electricity generated from the city's MSW would be enough to supply 8.89% of the population with electricity; thus, it would be possible to diversify its energy matrix.

In another study, different scenarios were considered for MSW treatment in Varginha, state of Minas Gerais. Through this research, the authors showed that only 150 kW of electrical energy recovery is economically viable, while the greatest environmental benefits in terms of gas emissions and energy recovery were found in a scenario consisting of energy recovery through recyclable materials, anaerobic digestion, and incineration used simultaneously [28].

Thus, WtE recovery from MSW is still incipient in Brazil, although studies and some initiatives are being developed to show that it can be a solution to some scenarios in the country, in addition to the fact that it can also be associated with other alternatives to reap greater economic, environmental, and even social gains.

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