ENERGY RECOVERY TECHNOLOGIES FROM MUNICIPAL SOLID WASTE: ENHANCING SOLID WASTE BRAZILIAN POLICY

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ABSTRACT

Public incentives play an important role in expanding the possibilities of using renewable energies, such as that generated from MSW (municipal solid waste) biomass, not only creating opportunities, but also several challenges. Thus, from the literature review, this paper aims to describe the feasibility (technical, economic, and environmental), potentialities, obstacles and readiness level of the technologies of energy generation from municipal solid waste. These technologies include the use of landfill gas, biogas generated by anaerobic digestion and direct burning of solid waste (incineration). Between the three technologies, landfill gas has greater economic viability, anaerobic digestion is classified as the most environmentally viable energy recovery technology, while incineration has the highest energy recovery potential. Regarding the readiness level of the technologies, incineration and anaerobic digestion are extensively used in Europe, United States and East Asia, while landfill gas is used extensively in the United States, Latin America and India. Moreover, the applicability of a technology should always have a set of factors into consideration (economic, environmental and technical), to be applied to local characteristics, in conjunction to other technologies.

Keywords: Municipal solid waste; Landfill gas; Anaerobic digestion; Mass-burn incineration.

RESUMO

As políticas públicas de incentivo desempenham um papel importante na expansão das possibilidades de uso de energias renováveis, como a proveniente de biomassa dos resíduos sólidos urbanos, gerando não somente oportunidades, mas também diversos desafios a serem vencidos. Assim, este trabalho procurou descrever a partir de revisão da literatura a viabilidade (técnica, econômica e ambiental), obstáculos e potencialidades, bem como o nível de maturidade das tecnologias de geração de energia proveniente dos resíduos sólidos urbanos. Essas tecnologias abrangem a utilização do biogás gerado em aterros sanitários e o gerado a partir do tratamento da fração orgânica em biodigestores anaeróbios, bem como da queima direta dos resíduos. Entre as três tecnologias, a energia gerada a partir do biogás de aterro possui maior viabilidade econômica, a biodigestão anaeróbia possui o menor impacto ambiental, enquanto o maior potencial de recuperação de energia é originário de usinas de incineração. Com relação ao nível de maturidade, a incineração e a digestão anaeróbia são amplamente utilizadas na Europa, Estados Unidos e Leste Asiático, enquanto o biogás de aterro é amplamente utilizado nos Estados Unidos, América Latina e Índia. Além disso, a aplicabilidade de uma determinada tecnologia deve sempre levar em consideração um conjunto de fatores (econômicos, ambientais e potencial energético) aplicados à características locais e podem ser aplicadas conjuntamente com outras tecnologias.

Palavras-chave: Resíduos sólidos urbanos; Biogás de aterro; Digestão anaeróbia; Incineração.

1. INTRODUCTION

A diversified and renewable energy mix is a strategy for developing the economic, technological, social and political sectors for any country (ERDIWANSYAH et al., 2019). And this type of energy can be transformed from natural sources such as water, solar, biomass, wind and geothermal (ADAMS et al., 2018). So, to diversify their energy mix and potentially expand it, governments must play an important role, by applying incentive policies, reducing dependence on fossil fuels (YANG et al., 2020). This decreases their vulnerability to price fluctuations typical of non-renewable energy sources, while reducing their greenhouse gas (GHG) emissions, thus favoring economic development and clean technologies recommended worldwide (CARLEY; LAWRENCE, 2014).

The USA and the European Union (EU) were the first to implement renewable energy incentive policies in the mid-1970s (CARLEY et al., 2017). Much later, in Brazil, the energy recovery of biomass, mainly from municipal solid waste (MSW), was triggered by Federal Law no. 12,305/2010, the National Policy on Solid Waste (PNRS – Política Nacional de Resíduos Sólidos) and, more recently, governed by Interministerial Ordinance no. 274/2019. These legal documents see energy use as one of the options for appropriate final waste disposal, provided that its technical and economic viability is guaranteed, and the waste hierarchy is observed – non-generation, reduction, reuse, recycling and treatment of waste (BRAZIL, 2010, 2019). Additionally, the ANEEL Resolution No. 482/2012 (ANEEL, 2012), that was revised by ANEEL Resolution No. 687/2015 (ANEEL, 2015), established a compensation system for energy (renewable or cogeneration) produced by micro and mini generation (SILVA et al., 2017; STILPEN et al., 2018). Recently, Brazilian Zero-Dump Program (Programa Nacional Lixão Zero), launched in April 2019 by the Brazilian Ministry of Environment, defined power generation from waste as a guideline for solid waste management in the country (MMA, 2019). Technologies to achieve this include the use of landfill gas (LFG), biogas generated by anaerobic digestion (AD) and direct burning thru incineration (incineration).

Despite of more sustainable alternatives, in developing countries landfilling is still the favored final waste disposal method for being inexpensive (VILLANUEVA-ESTRADA et al., 2019). Landfill gas is composed of methane, carbon dioxide and other trace components (AGHDAM et al., 2019). Methane from LFG is a high value resource, as it is equivalent to natural gas after being purified (HORSCHIG et al., 2018, 2019). So, several studies estimated the energy recovery potential from the methane from LFG (AHMED et al., 2015; FEI et al., 2019; PURMESSUR; SURROOP, 2019; SANTOS et al., 2019). In Turkey, Yilmaz and Abdulvahitoğlu (2019) estimated a potential energy production from LFG between 1492 GWh and 5948 GWh, that would supply about 93 million inhabitants, in 2043. Conversely in Brazil, Silva et al. (2017) estimated the production 8.7 GWh (for 2016-2036) in the single landfill that serves the CIMASAS Consortium, in São Paulo state, serving an estimated population of 300,000 inhabitants in 2036.

However, in developed countries the circular economy is already the waste management trend, unlike in the developing countries, which are still transitioning to landfills (MARGALLO et al., 2019). Circular economy aims to increase the waste reuse and recycling, and to exploit the existent resources as much as possible before landfilling, therefore decreasing the need for landfills (COBO et al., 2018; RAGAZZI et al., 2017). Countries such as Germany, Slovenia, Canada and Korea already recycle plenty of the generated waste (TISI, 2019). The author adds that Austria, Belgium, Denmark, Estonia, Japan, Holland, Luxembourg, France and Norway are increasingly investing in energy generation alternatives from waste, such as incineration and AD.

AD is a promising technology to treat the organic fraction of MSW, or biowaste. The anaerobic process produces different added-value compounds, such as biogas, a biofuel, and biofertilizer (SHARMA et al., 2019), besides treating waste with lower costs and fewer environmental impacts ACHINAS et al., 2017; CAPSON-TOJO et al., 2016).

In the EU, the targets and policies implemented to expand renewable energy generation more than tripled the installed biogas production capacity from 2012 to 2015 (SCARLAT et al., 2018), reaching more than 17,000 plants in 2017. To evaluate this technological path, several studies calculated the biogas production potential from biowaste (CAPSON-TOJO et al., 2016; EPE, 2014b; GOMES et al., 2012; MATHERI et al., 2017; MOJAPELO et al., 2014). In addition to the theoretical analysis of the methane conversion potential of organic compounds, the technical, economic and conjuncture aspects that explain that potential should be emphasized in Brazil (MARIANI, 2018).

Another promising energy-recovery technology is direct MSW burning, also named mass-burn incineration, for large waste amounts (KUMAR; SAMADDER, 2017). Incineration can reduce the waste volume by 80% without pretreatment (OLIVEIRA, 2018), in addition to producing 0.5 MWh.t-1 of MSW (SINDICIC, 2011; CARDOSO, 2019). Countries such as Denmark, Sweden, Estonia and Finland reduced final MSW disposal by more than 90% due to incineration (MAKARICHI et al., 2018). Observing this potential, with 1/5 of the world's population, China has released 11 normative acts to encourage technology, between 2000-2014. In this period, a growth of approximately 1 GW per year was observed, over five years, with 339 operating power plants. In 2017, the largest power generation capacity for was installed, at 7.3 GW (IEA, 2019). And in 2014, the UK incinerated 35% of all MSW, generating 3.94 TWh, 1.1% of its total power generation (MAKARICHI et al., 2018; TISI, 2019). Alas, in Brazil, the technology has not yet been implemented yet, although there is great potential. For example, Jauregui et al. (2017) indicate that São Paulo state, Brazil's largest MSW generator, would need 13 incineration plants to reduce MSW to ashes and slag, generating energy with a daily capacity of 968 MW.

By observing with the challenges and opportunities for MSW energy recovery, this paper aims to describe viability, obstacles and potentialities of generating energy from LFG combustion, treating biowaste in anaerobic biodigesters, as well as incineration. For this, a literature comprehensive review has been conducted to identify environmental, technical and economic aspects of these technologies, as well as potentialities and obstacles faced. Moreover, Technology Readiness Level (TRL) was used to assess the readiness of technologies for full-scale commercial implementation (NGO et al., 2021). The concept was first used by National Aeronautics and Space Administration (NASA) and classify the level of application of the technology in research and development, pilot and demonstration, early commercial deployment and commercially established (LYTRAS et al., 2021).

2. POWER GENERATION FROM BIOGAS

Biogas is considered a GHG, as it contains carbon dioxide and methane, which has a global warming potential 21-25 times higher than CO2 (YILMAZ; ABDULVAHITOĞLU, 2019; AHMED et al., 2015). However, if collected, biogas can easily replace fossil fuels for heating, electricity generation, transportation or as raw material in the chemical industry (HORSCHIG et al., 2018, 2019). This results in significant economic and social benefits, such as revenue generation through carbon markets and job/income creation (PURMESSUR; SURROOP, 2019), and reduces energy costs for its users, promoting growth due to investments (NASCIMENTO et al., 2019). As an environmental benefit, air pollution is reduced by not being released to the atmosphere, and the replacement of fossil fuels to produce electricity, reduces emissions of pollutants like sulfur dioxide and nitrogen oxides (EPA, 2017; PURMESSUR; SURROOP, 2019).

In Brazil, organic matter represents 51.4% of the gravimetric composition of the collected MSW, totaling 28.5 million t.year-1 (BRAZIL, 2012). In addition to the significant volume, biowaste is responsible for the greatest environmental impacts on dumps or landfills due to leaching and GHG emissions (CAPSON-TOJO et al., 2016; EPE, 2014a). Thus, while biowaste disposal is a problem around the world, it is also a resource with high potential energy, which has moved nations for its use (LIN et al., 2018; SCARLAT et al., 2015; US DEPARTMENT OF ENERGY, 2019). To produce energy, the water content of the biowaste makes the incineration process less efficient, by requiring much energy to evaporate it and polluting air (CAPSON-TOJO et al., 2016).

International regulations have required the development of new biowaste treatment technologies. In 2007, the EU committed to reduce GHG emissions by 2020 compared to 1990, with a mandatory target of producing 20% of energy with renewable sources. As a result, the installed biogas production capacity nearly doubled from 2005 to 2015, from 2,665 MW to 8,339 MW. Power generation from biogas almost quadrupled from 2005 to 2012, from 12.5 TWh to 46.4 TWh, and is expected to reach 63.9 TWh in 2020 (SCARLAT et al., 2015). In Brazil, in 2019, 39 thermoelectric plants were registered as biogas power plants (ANEEL, 2019a), with a total installed power of approximately 186 GW. Of those, 14 treat animal waste, three treat agricultural waste and 22 use LFG. As a result of the distributed energy production compensation system of the Resolutions 482/2012 and 687/2015, the number of plants registered in this system rose from two (in 2014) to 159 (in 2019), Figure 1.

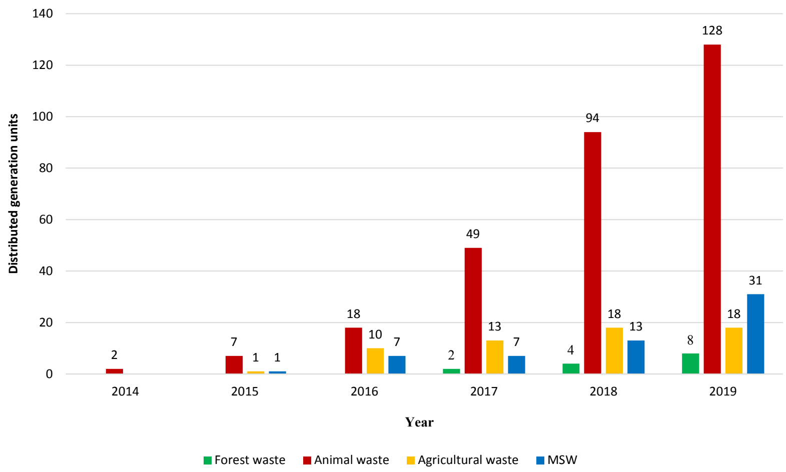

Figure 1 - Number of units generating electricity from biogas registered by ANEEL in the distributed generation model in 2019

Actually, the number of AD plants in Brazil is higher than those reported by ANEEL, as some of them use biogas for purposes other than power generation. Mariani (2018) registered 159 biodigesters in 2015, usually small and medium sized in rural properties. Aiming to potentiate the use of biofuels in Brazil, in 2017 the Ministry of Mines and Energy established RenovaBio, a program that induces mandates to increase biofuel content in fossil fuels sold by distributors, by not proposing additional taxes (CARDOSO; COSTA, 2020; STILPEN et al., 2018). In respect to Brazilian States, Rio Grande do Sul pioneered by establishing the methane State Law no. 14,864/2016, incenting the methane generation and use, in addition to the State Decree no. 48,530/2011, which aims to find alliances in institutions to carry out power generation from biogas (DALPAZ, 2019).

Conversely, developing actions for biogas use depends on other sectors, such as the market supplying adequate technology, and the legal sector clarifying the regulatory frameworks on sanitation and commercialization of biogas or energy. The inclusion of biogas into gas distribution and commercialization networks for vehicular fuel are examples of solutions that increase opportunities and reduce costs for its production and marketing (MARIANI, 2018; CARDOSO; COSTA, 2020), as seen on Table 1 (MARIANI, 2018).

Table 1 - Comparison of the favorable conditions for the use of Biogas between Brazil and Europe

Usage types	Brazil	Europe
Biogas (storage)	Low-tech storage, such as geo-membrane reservoirs.	High tech level, such as reservoirs with double geomembrane layer.
Biogas (H_2S filtering)	Uncommon, or low-tech.	High grade biogas filtration.
Electric energy	Internal consumption, injection into the distribution network or sale in the free market.	Governmental subsidies for biogas electricity generation and sales.
Thermal energy	Use for industrial processes, with low-technology burners.	Use in heating of households, bio-digesters and industrial processes.
Methane usage (regulation)	Under development. For use and in-jection in gas distribution networks.	Advanced. For use and injection into the natural gas network.
Methane (transport)	Particular cases with cylinder use; lacks dense network of pipelines.	Good gas transport and distribution infrastructure, facilitating injection into the network.
Methane (supply network)	Few projects of network injection or direct supply of vehicles.	Already consolidated, large-scale vehicle supplying systems.

Biogas recovery occurs through two distinct ways, either through landfills or AD. For both cases, a treatment/purification process precedes electricity production. This “upgrading” process is done to remove excess moisture, particles and other impurities that bring problems to the system (EPA, 2017), which are exposed in Table 2 (KUNZ et al., 2019).

Table 2 - Problems caused by contaminants in the biogas

Contaminant	Problems
Water	Water corrosion of compressors, fuel tanks and engines by the formation of acids with H_2S, NH_3 and CO_2; water accumulation in the ducts; conden-sation or freeze by pressure
Particulate matter	Clogging by accumulation in compressors, fuel tanks and engines
Oxygen (O_2)	Danger of explosive mixtures by high O_2 concentration in biogas
Ammonia (NH_3)	Corrosion by dissolution in water
Hydrogen sulfide (H_2S)	Corrosion of compressors, fuel tanks and engines; toxic concentrations in biogas (>5 ppm); SOx formation by combustion
Carbon dioxide (CO_2)	Decrease in biogas heating value
Siloxanes	Formation of SiO_2 and microcrystalline quartz by combustion; deposition in spark plugs, valves and cylinders
Halogens	Corrosion in combustion engines

To correctly size the treatment/purification system, it is necessary to determine the volume, physicochemical characteristics and, mainly, the aimed gas purity level (KUNZ et al., 2019). For example, water removal, occurs by physical methods, like condensation or chemical drying, and generally removes particulate material together with water. The most used physical methods are cyclone separators, pipes containing traps with fine mesh screen; while the most popular chemical methods are cylindrical reactors containing adsorbents such as triethylene glycol, hygroscopic salts, zeolites, silica gel or oxide aluminum (NOVAK et al., 2016). Chemical drying is more predominant than physical processes but requires frequent replacement of adsorbent materials to maintain the moisture removal efficient (KUNZ et al., 2019).

Likewise, hydrogen sulfide (H_2S) can be also removed by physical, chemical, in addition to biological processes. Membranes can physically separate methane from other biogas contaminants by diffusion, at a high pressure, and have an efficiency between 96-98% (RYCKEBOSCH et al., 2011). In chemical processes such as absorption, the contaminants are removed during biogas washing, using water, for contaminants with greater solubility, or organic solvents, obtaining a methane concentration between 93-98% (BEIL; BEYRICH, 2013). Biological processes use bacteria capable of oxidizing H_2S into sulfate and/or elemental sulfur in the presence of O_2 or nitrate as an electron acceptor (KUNZ et al., 2019). Another technique under development is cryogenics. It consists of compressing biogas at high pressure, under specific temperature conditions, resulting in the separation of methane, with an efficiency >97%, and CO_2 removal by condensation. However, despite the efficiency, the technology is still not widespread and feasible due to high energy consumption and investment costs (BUDZIYEARWSKI, 2016).

The most common energy converters are internal combustion engines (ICE), gas turbines, and fuel cells (PURMESSUR; SURROOP, 2019; YILMAZ; ABDULVAHITOĞLU, 2019). About 70% of the projects use ICE, suitable for projects with power lower than 3 MW (EPA, 2017), for economic and operational issues (AGUILAR-VIRGEN et al., 2014). As for gas turbines, they are used in projects usually with more than 5 MW, despite lower efficiency than other technologies. Microturbines, with specific capacity between 30 and 250 kW, are generally used for projects smaller than 1 MW (EPA, 2017). Table 3 shows a comparison between the three technologies discussed above (PURMESSUR; SURROOP, 2019). As for fuel cells, they operate in high temperature and are more adequate for direct use of biogas, as they are more resistant to contaminants, remaining efficient (ALVES et al., 2013).

Table 3 - Features and costs associated with energy recovery technologies

Feature	Internal combustion engines	Gas turbines	Fuel cells
Electrical efficiency	33%	28%	50%
Fuel consumption (kJ.kWh^{-1})	10,972	12,872	7,174
Investment (million US$)	1.2 (1 MW)	1.26 (0.84 MW)	5.25 (1.5 MW)
Operating cost (US$.kW^{-1}.year $^{-1}$)	115.20	99.84	84.00

Regarding biogas generation technologies, several authors compared economic, energy and environmental aspects of landfills and biodigesters. Santos et al. (2019) concluded that landfills are more economical to produce energy, with a unit cost of 3,010.4 US$.kW^{-1}, while AD costs 4,200.5 US$.kW^{-1}. Regarding the energy potential, Dalmo et al. (2019) compared various technologies, including AD and landfills for the entire São Paulo state. According to the authors, the energy potentials of AD and landfill are 1.80 GWh.year^{-1} and <1.17 GWh.year^{-1}, respectively. This difference is possibly explained by the operation process of biodigesters to control parameters, such as humidity, temperature and pH, and mainly composition, characteristics that influence biogas generation (MBOOWA et al., 2017; NASCIMENTO et al., 2019). However, AD is much more environmentally viable, since landfills contribute to global warming, require large areas, in addition to the possibility of groundwater and soil contamination (SANTOS et al., 2019).

2.1 Energy production from landfill gas

Although energy production from LFG is incipient and emerging in most developing countries, it has gained more notoriety recently. (FEI et al., 2019). This is the case in Latin America, where countries try to replace their unlicensed landfills and dumps by licensed landfills as a primary MSW final disposal method (MARGALLO et al., 2019). According to Guerrero et al. (2013) landfills have a significantly higher environmental impact than other technologies, such as AD, recycling and incineration. However they have lower environmental and social impacts than unlicensed landfills and dumps, and their low cost and well-known technology makes them still considered the best disposal method in these countries. Santos et al. (2019) add that landfills do not require skilled labor, sometimes use unproductive land, and can generate electricity or heat with a low cost. Figure 2 shows the percentages of waste treatment and final disposal in the Latin America countries (ABRELPE, 2019; MARGALLO et al., 2019).

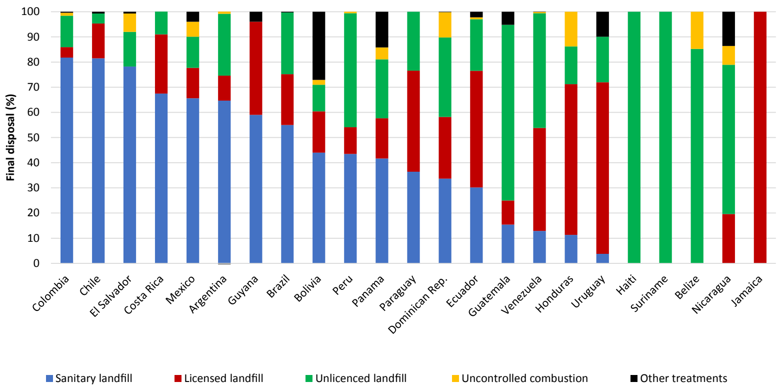

Figure 2 – Final waste disposal and destination percentages in Latin America and the Caribbean

Of all Latin America countries, Colombia deserves to be highlighted for currently sending more than 80% of its waste to landfills, through various policies to encourage new energy generation projects from LFG. Some examples are: reductions of up to 50% of the total investment cost, by reducing income taxes, among others; prohibition of inappropriate waste disposal methods, such as water bodies, dumps, uncontrolled burning and temporary ditches. In that country there are incentives to mitigate taxes on products and services related to landfill energy recovery technologies. These measures are intended to increase the number of LFG power plants, that currently represent 3.1% of the MSW generated in the country (ALZATE-ARIAS et al., 2018).

LFG recovery technologies include those related to LFG collection (ZHENG et al., 2019), landfill moisture control and energy conversion systems, like ICE, turbines, among others. Regarding collection technologies, three well types are used: vertical wells, horizontal wells or a combination of both (ZHENG et al., 2019). However, regardless of the collection technology, part of the LFG in the landfill cell is lost by fugitive surface emissions (ZHENG et al., 2019). This gas usually escapes through the weakest areas of the landfill cover, like slopes, cell intersections and cracks, the leachate collection system or even pipe leaks (MØNSTER et al., 2015). In this case, the efficiency of the collection system can be influenced by operational factors, such as coverage type and collection system operation, as well as environmental factors such as barometric pressure, ambient temperature, wind speed and moisture content in the cover layers (BOURN et al., 2019).

Bourn et al. (2019) found LFG collection efficiencies between 20-90% in different landfills, suggesting the influence of controlling the operational and environmental factors. In landfills with geomembrane cover, Wang et al. (2013) found efficiencies of 90%. Silva et al. (2017) claim an efficiency of 65% for active LFG recovery systems; 85% for cells with a final clay cover, plus active LFG recovery; and 90% for cells with final geomembrane coverage, plus active LFG recovery. In the active recovery system, induced vacuum energy is used to control gas flow (TCHOBANOGLOUS; KEITH, 2002). These systems are projected to match the methane extraction rate with the generation rate (BOURN et al., 2019). Besides collection efficiency and waste composition, local rainfall is a factor that interferes with landfill moisture and the conversion of organic matter to methane in the landfill, therefore in energy production. Thus, wetter landfills, with an annual rainfall >1,000 mm, have higher generation rates (THE WORLD BANK, 2004). World Bank (2004) suggests values (Table 4) for the methane generation rate (k). This parameter is inputted in estimation models, such as the Landfill Gas Generation Model (LandGEM) by the US Environmental Protection Agency (US EPA – ALEXANDER et al., 2005).

Table 4 - Suggested values for k, based on annual rainfall and waste

Annual rainfall (mm)	**k range (year^{-1})**		
	Relatively inert	**Moderately inert**	**High Decomposition**
<250	0.01	0.02	0.03
250-500	0.01	0.03	0.05
500-1,000	0.02	0.05	0.08
>1,000	0.02	0.06	0.09

Figure 3 shows the influence of moisture and waste composition in the methane production curves for wet landfills. The k values range between 0.05 and 0.06 year^{-1}, and 0.02 and 0.03 year^{-1} for dry landfills (ALEXANDER et al., 2005). LandGEM was used for this simulation as well as for other studies by Barros et al. (2014), Purmessur and and Surroop (2019), Santos et al. (2019), Silva Dos Santos et al. (2018), Silva et al. (2017), and Yilmaz and Abdulvahitoğlu (2019). It is also noteworthy that the input data on waste amount, methane generation potential (L_0) and the methane percentage in the LFG were the same for the four annual rainfall scenarios. The methane generation peak is higher for the wettest conditions (k = 0.06 year^{-1} – PURMESSUR; SURROOP, 2019; SANTOS et al., 2019; SILVA DOS SANTOS et al., 2018; SILVA et al., 2017) and the production drop is lower, over the years, for the driest conditions (k = 0.02 year^{-1} – AMINI et al., 2013; SUN et al., 2019; YILMAZ; ABDULVAHITOĞLU, 2019).

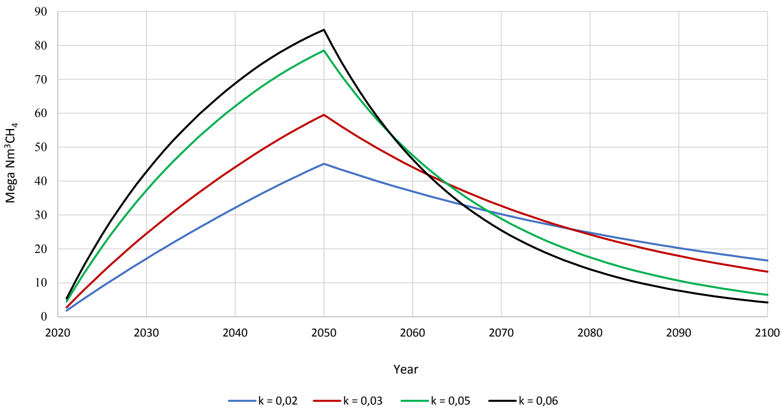

Figure 3 - Influence of methane generation rate (k) on methane production estimation

Reichert (2014) discerns a relation between waste quantity and energy production. According to the author, a metric ton of waste should generate between 0.1 and 0.2 MWh of electricity. However, most LFG power plants currently operating in Brazil do not reach that standard, like the *Bandeirantes* and *Recreio* power plants, in São Paulo and Rio Grande do Sul states, respectively, producing just 0.07 MWh.t^{-1} (NASCIMENTO et al., 2019). This middles the Mauritian *Mare Chicose* landfill, with a climate similar to Brazil's, where 0.14 MWh.t^{-1} were reached (PURMESSUR; SURROOP, 2019), while a drier Italian landfill reached just 0.06 MWh.t^{-1} (SISANI et al., 2016).

Finally, economic viability is a decisive factor to be considered in LFG projects. EPA (2017), points the estimation of the LFG recovery potential as one of the primary steps for developing energy LFG projects. Thus, authors like Barros et al. (2014) indicate that LFG collection and use is economically viable without public policy incentives if the Brazilian cities have more than 200,000 inhabitants. Additionally, Yilmaz and Abdulvahitoğlu (2019) claim that energy production from LFG is financially viable when the plant's installed capacity is greater than 1 MW. For Santos et al. (2019), Zhou et al. (2019) and Ogunjuyigbe, Ayodele and Alao (2017) the landfill has the least unit operation and investment costs. These last authors separately assessed several North Nigerian cities and concluded that payback time of the LFG generation system would vary between 4.9-7.8 years, depending on the city. Some important factors in the landfill construction phase are the land price, as well as the proximity of the infrastructure to the served area, which has a strong influence on transport costs and energy consumption (ABEDINIANGERABI; KAMALIRAD, 2016). In the operation phase, the leachate treatment costs can be reduced with some measures, such as leachate evaporation, using heat from LFG combustion or cogeneration (WEI et al., 2017). Another alternative would be to treat the leachate in conventional units, along with the sanitary sewage or through a low-cost technology as the phytoremediation (KALOUSEK et al., 2020). So, Table 5 shows the cost comparison between energy generation technologies from MSW, in the initial and operational phase (KUMAR; SAMADDER, 2017).

Table 5 - Comparison between energy recovery technologies

Technology	Investment costs ($US\$.t^{-1}.year^{-1}$)	Operation costs ($US\$.t^{-1}.year^{-1}$)
Incineration	400-700	40-70
Pyrolysis	400-700	50-80
Gasification	250-850	45-85
Anaerobic digestion	50-350	5-35
LFG recovery	10-30	1-3

2.2 Biogas from anaerobic digestion

Anaerobic digestion has been indicated as the best option to treat biowaste, compared to landfill, gasification, or incineration, based on Life Cycle Assessment, or LCA (HENRÍQUEZ, 2016; SANTOS et al., 2019; XU et al., 2015). Using AD biogas as an energy source mitigates between 100 and 160 kg $CO_2eq.t^{-1}$ of inputted food waste (GRANT et al., 2017). Moreover, this biowaste treatment produces biogas and high-quality biofertilizers, which cost less than mineral fertilizers and promote the better use of nitrogen by plants. Furthermore, biofertilizers balance other essential nutrients in the crop, such as phosphorus and potassium (SHARMA et al., 2019). Generally, 10 kg of biowaste (wet weight) produce 1 m³ of biogas, generating approximately 6 kWh, or

21.6 MJ as electricity (VÖGELI et al., 2014). At the same ratio, but considering a 35% power conversion efficiency, the estimated AD electricity generation potential in Brazil is 6.9 TWh, which could meet 1.5% of the national power consumption (EPE, 2014a). Most AD plants in Brazil meet the demand for animal waste treatment, mostly from pig farming waste; these effluents have suitable characteristics for treatment (total solids content between 0.5-2.5%) in anaerobic lagoon systems, widely used in Brazil (AIRES, 2012). This kind of biodigester is considered low cost, easy to build and operate, as they do not have stirring or heating systems (KUNZ et al., 2019). In contrast, there are more robust technologies, suitable for waste with higher complexity and total solids content, as presented in Table 6 (CAPSON-TOJO et al., 2016; KUNZ et al., 2019).

Table 6 - Description of AD technologies applied to biowaste

System	Pros	Cons	Feed	VOL / TS content
Anaerobic lagoon	Single-stage process; simplified operation; reduced cost.	High hydraulic retention time (HRT or τ); difficulties in heating and agitation; troublesome sludge disposal and biogas collection.	Low % TS	TS: < 3% VOL: 0.3-0.5 $kgVS.m^{-3}$
UASB	Low HRT; multi-stage process in a single tank; allows sludge disposal and biogas collection.	Possibility of sludge drag and biogas loss; high investment cost; requires TS adjustment % in the feed.	Flexibility to operate with high VOL rates	TS: < 2% VOL: 0.5-8 $kgVS.m^{-3}$
CSTR	Operational flexibility in maintaining HRT and SRT; multi-stage process in a single tank; heat and mass transfer promoted by stirring (mechanical or hydraulic); allows sludge disposal and biogas collection.	Complex operation; high investment and operating cost; HRT between 15-20 days; stirring system increases solids content; increased energy consumption.	Flexibility to operate with high VOL rates	TS: > 10% VOL: 1-4 $kgVS.m^{-3}$
Solid-state anaerobic digester	Biogas with high methane concentration; can operate in sequential batches; feeding with high TS%.	High HRT; high investment and operating cost; lower biogas productivity than in the wet system (15-40).	Flexibility to operate with high VOL rates and TS%	TS: 20-40%

Legend: UASB – Upflow Anaerobic Sludge Blanket; CSTR – Continuous Stirred Tank Reactor; VOL – Volumetric Organic Load; TS – Total solids; SRT – Sludge retention time

Anaerobic digestion is a complex metabolic process that requires redox potential conditions (≤ 200 mV) and depends on microorganism association in four phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis (KUNZ et al., 2019). Different microorganism groups act in each phase, in syntrophy, requiring specific environmental conditions. In the hydrolysis phase, the enzymes excreted by hydrolytic bacteria decompose carbohydrates, proteins and lipids into monomers, in a few hours or days. Lignocellulose and lignin are subject to incomplete decomposition and may limit the process. Thus, the type of substrate determines AD speed and, depending on its composition and the biodigester, pretreatments may be necessary to enable it (KUNZ et al., 2019). Acidogenesis is a critical phase for the whole process – in which anaerobic and facultative bacteria produce volatile fatty acids (VFA), lactate, ethanol, H_2 and CO_2 – due to restrictions that may limit the process later. In the acetogenic phase, the compounds formed during acidogenesis are oxidized to produce acetate and hydrogen, which are consumed in the next phase. In the last (strictly anaerobic) phase, methanogenesis, dynamic relationships occur between Methanogenic archaea and Homoacetogenic bacteria that directly act in CH_4 and CO_2 production (CAPSON-TOJO et al., 2016).

Biowaste composition varies according to region, source (restaurants, residences, large suppliers, source-separation of the organic fraction of MSW) or mixing, but generally has high AD potential (CAPSON-TOJO et al., 2016; FISGATIVA et al., 2016). Scientific literature reports values of methane production potential ranging from 260-648 $mL_{CH4}.gVS^{-1}$ for food waste, higher than the potential observed for dairy residues, sewage sludge, wheat straw (CAPSON-TOJO et al., 2016) and microalgae biomass (DĘBOWSKI et al., 2017). The analysis and monitoring of the bacteria and archaea population are key to explain the performance of AD systems (MARTINS, 2018). The microbiota involved in methanogenesis is mostly sensitive to changes in temperature, pH, redox and inhibitors, thus this step is considered the most limiting of the AD process (ACHINAS et al., 2017).

About acidification, pH restrictions occur due to the occurrence of instabilities in the AD process, resulting in low methane production and increased CO_2 content in biogas (FISGATIVA et al., 2016). A pH below 6.6 indicates inhibition of methanoarchaea growth (KUNZ et al., 2019). These restrictions are caused especially when digesting monosubstrates, either for overloading (due to the NH_3 excess) or methanoarchaea inhibition, caused by a low C/N ratio (CAPSON-TOJO et al., 2016). The quality of the treated material may also explain acidification in reactors, because of the acidic nature of food waste (pH=5.1±0.7). This is associated with high carbohydrate and protein contents, that quickly producing VFA and NH_4+ in quantity, thus acidifying the reactors and inhibiting acetogenesis and methanogenesis (FISGATIVA et al., 2016). However, corrective treatments during AD or aerobic pretreatment are indicated, such as: the addition of water or mixing substrates with lower dry matter content, adjusting the organic loading rate of the digester to avoid the pH decrease; water dilution or stripping extraction to avoid instabilities under conditions of high ammoniacal nitrogen content (FISGATIVA et al., 2016).

Due to the microorganism sensitivity and the sequence and complexity of the digestion phases, the degradability of biowaste inserted in the process is important to ensure speed and efficiency in the decomposition and conversion into biogas. This involves segregation and pretreatment technologies for some kinds of raw materials. The conditions of the medium affect the AD, requiring that multiple parameters be considered and controlled, which are presented in Table 7 (KUNZ et al., 2019; CAPSON-TOJO et al., 2016; MARTINS, 2018).

Table 7 - Waste composition and environmental requirements for the development of microorganisms involved in anaerobic digestion

Parameters	Hydrolyse/ Acidogenesis	Acetogenesis	Methanogenesis	Influence
Partial hydrogen pressure	–	$10^{-4} – 10^{-6}$	–	Inhibition of acetolactic bacteria; production of short chain acids for methane formation.
Temperature	25 – 35	–	32 – 42	Growth and metabolism of microorganisms; kinetics of syntrophic metabolism; endothermal reactions; exothermic reactions; solubility of organic compounds; speed of biochemical reactions; pathogens elimination; dissociation of ammonia may cause inhibitory effect.
pH	5.2 – 6.3	–	6.7 – 7.5	Very sensitive methanogenic archaea; low values indicate excess volatile fatty acids.
C/N Ratio	10 – 45	–	20 – 30	Values well below 25 lead to imbalance in the production and consumption of volatile fatty acids, overloading methanogenic archaea.
Dry matter concentration (%)	<40	–	<30	High concentrations can be inhibitory and cause low methane production.

Table 7 - Waste composition and environmental requirements for the development of microorganisms involved in anaerobic digestion (cont.)

Parameters	Hydrolyse/ Acidogenesis	Acetogenesis	Methanogenesis	Influence
Total Ammoniacal N	–	–	< 200 mg.L^{-1}	From the decomposition of amino acids, proteins and urea, high levels inhibit the activity of methanogenic archaea.
Trace elements	–	–	Essencial: Ni, Co, Mo, Se	Structure of the bacterial community and biodigester performance.

Environmental control has greatly evolved for its critical impact on the productivity of the AD phases. Controlling biomass temperature is fundamental to ensure uniformity in biogas production, especially in colder regions or with large thermal amplitude, because without substrate heating the external temperature promotes a significant drop in biogas production (AIRES, 2012). Monitoring the pH to detect excessive VFA production is highly recommended, in order to perform corrective measures after sudden variations (KUNZ et al., 2019).

To avoid limiting microbial growth because of high VFA generation and pH decrease, several studies with significant results in batch or continuous/semi-continuous systems propose: reduction of the added organic load rate or the VS ratio of substrate/inoculum, which should require increased reactor size, buffer addition, pH adjustment, addition of trace elements, mixing granular sludge; digestate recirculation or the decoupling of the solid retention time in relation to the hydraulic retention time, achieved for example by separating of liquid and solid fractions of the digestate and feedbacking first (CAPSON-TOJO et al., 2016). On the other hand, the chemical complexity of biowaste makes it a source of several valuable compounds such as chemicals (enzymes, organic acids, glycerol), materials (bioplastics, biopolymers, nanoparticles, fibers) or fuels (methane, hydrogen, biodiesel, ethanol). In this sense, the AD processes can be applied to hydrogen production and VFA, in dark and acidogenic fermentation processes, respectively, for the production of fuels and other chemicals (CAPSON-TOJO et al., 2016), requiring additional research.

In the US, advances in science and technology are enabling the economic viability of AD facilities: development of membrane bioreactors; transformation of AD chemistry to produce short-chain intermediate organic acids that can be used to create higher value fuels and commodity chemicals such as acetone and naphtha; co-digestion strategies; biodigester design; organism genetics to improve the biological biogas conversion and thermocatalytic processes to convert biogas and LFG into fuels and finer co-products. Dalmo et al. (2019) refer that industrial-scale anaerobic reactors are currently recommended to maximize methane production in processes called Biological Mechanical Treatment (MBT), processing materials by dry fermentation (15-25% TS).

The gravimetry and kinetic AD parameters were analyzed for Santo André, São Paulo state, a city with 718,773 inhabitants, which landfilled about 750 $t.day^{-1}$ (CETESB, 2019). This resulted in 44.3% of biowaste in the MSW (DALMO et al., 2019); an average of 0.257±0.081 $t_{VS}.t_{MSW}^{-1}$ and 0.345±0.099 $t_{TS}.t_{MSW}^{-1}$, representing a VS/TS ratio of 74%, and a mean Biochemical Methane Potential of 278±146 $Nm^3_{CH4}.t^{-1}$ of reduced VS (LIMA, 2016). The methane production, considered from the availability of waste, can be calculated as shown in Equation 1 (DALMO et al., 2019). From this data, the energy production potential of the Santo André municipality via AD was then estimated.

$$P_{CH_4} = OM \times TS \times VS \times MBP \quad (1)$$

Where:

PCH_4 = methane production ($m^3.t^{-1}$);
OM: amount of organic matter in MSW (t);
TS: total solids content in MSW (%);
VS: volatile solids content (%);
MBP: methane biological potential ($mL_{CH4}.g_{VS}^{-1}$ = $m^3CH_4.t_{VS}^{-1}$)

Applying the mean values above, Santo André generates 332 $t.day^{-1}$ of biowaste, with 84.8 t of VS, translated into a generation potential of 23,581 m^3_{CH4} via AD. An efficiency value of 39.6% (DALMO et al., 2019) for the electricity generator from biogas, a LHV of 9.97 $kWh.Nm^3$ for the methane (GERMANY, 2010), and a potential of 93 $MWh.d^{-1}$, i.e., 0.28 $MWh.t^{-1}$ were considered. This production is sufficient to supply over 14,803 homes, with a mean consumption of 191.3 $kWh.month^{-1}$ (EPE, 2017). Table 8 presents information on various MSW and/or food AD plants in various locations of the world (WILKEN et al., 2019).

Table 8 - Biowaste power plants deployed in several countries

Country	Waste type	Treated waste (t.year^{-1})	Biogas production (Nm^3.h^{-1})	Productivity (Nm^3.t^{-1})	Energy (MW)	Investment (million €)
Brazil	Market and sewage sludge	109,500	1,100	92	2.8	20
Portugal	Biowaste	25,000	-	-	0.5	7.5
England	Markets, slaughterhouses and other	108,701	-	-	4.988	20.8
Canada	Source-separated, garden waste and other	40,000	490	107	-	58 CAD**
Germany	Food, business and household waste	12,000	-	-	1.48	-
Germany	Food, potatoes	150,000	-	50-80*	4.2	-
Sweden	Food and other biowaste	25,000	600	212		9.7

* Calculated values, with the exception of 50-80 (reported); ** Canadian dollars

3. ENERGY RECOVERY FROM MASS-BURN INCINERATION

For decades, the EU countries, the US, South Korea, Japan, China, India, among others, have adopted the waste hierarchy to incentive to reduce MSW generation, through their normative acts. This consists of changes in public MSW management policies, prioritizing recycling, composting and energy recovery from thermal conversion technologies (AZAM et al, 2019; CARDOSO, 2019). The main thermal conversion technology used is mass-burn incineration (TOZLU et al., 2016), which consists of a thermochemical process where the MSW is burned (or oxidized) in an oven, producing heat (OGUNJUYIGBE et al., 2017). Then, this heat is used to generate steam in a boiler that drives an electricity-generating steam turbine (JOSEPH; PRASAD, 2020).

In Europe, regulatory frameworks have boosted incineration, as well as recycling and composting, in recent years, as can be seen in Figure 4 (EUROSTAT, 2020). For example, Council Directive 1999/31/EC on landfills encouraged biowaste diversions from landfills, while Directive 2008/98/EC established the waste management hierarchy, considering landfill as the last disposal option (WANG et al., 2020b). Nottingham (England, UK) reduced landfilling noticeably: from 54.7% in 2001/02 to 7.3% in 2016/2017 (WANG et al., 2020a). The same trend was observed in USA, Japan (WANG et al., 2020a) and Canada (WAGNER; ARNOLD, 2008).

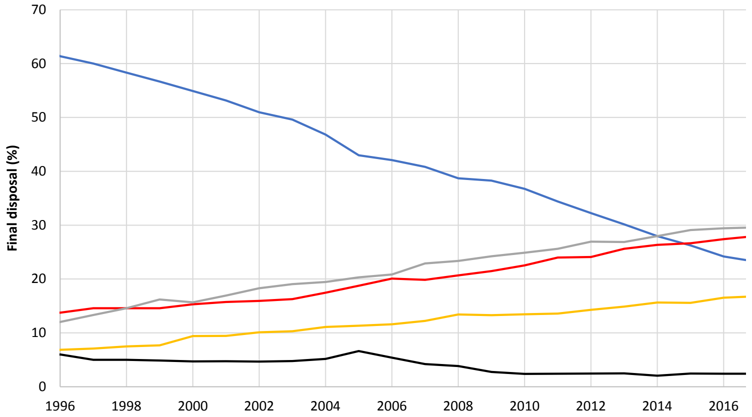

Figure 4 - Evolution of the MSW destination forms in the EU through time

In Sweden, the imposition of landfill charges, restrictions on landfilling combustible waste and biowaste, and the implementation of normative acts to regulate atmospheric emissions, have enabled to characterize thermochemical processes, such as gasification, pyrolysis and especially incineration, as a cleaner energy source (CARDOSO, 2019; KUMAR; SAMADDER, 2017). Thus, incineration, recycling and composting have become the main MSW final disposal in Sweden, a trend that can be also observed in Denmark, Germany, Finland and Switzerland, as demonstrated in Figure 5 (EUROSTAT, 2020).

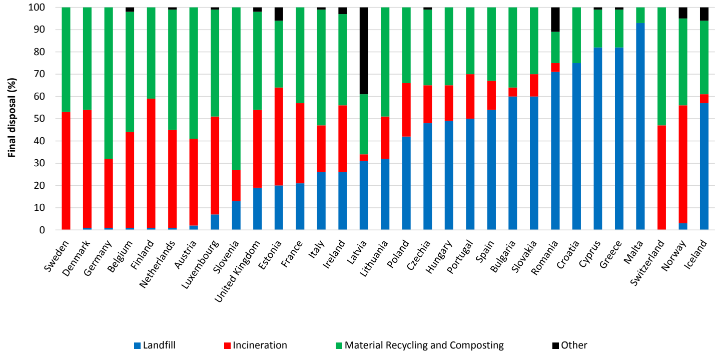

Figure 5 - MSW final destination overview in the European Union, Switzerland, Norway and Iceland

In Brazil, new guidelines aim the implementation of this technology. Interministerial Ordinance No. 274/2019 (BRAZIL, 2019a), enacted in April 2019, regulates the implementation of Energy Recovery Units. This regulation includes any MSW treatment unit with heat recovery from combustion, to reduce MSW volume and dangerousness. By the end of 2019, Federal law No. 10,117/2019 was also presented to the Brazilian society to encourage projects to expand the energy recovery capacity from MSW, under the Investment Partnerships Program, via public-private partnerships (BRAZIL, 2019b).

Adopting incineration technology brings several benefits. For all implanted cases, MSW volume reduced almost 90% (MUKHERJEE et al., 2020; SHI et al., 2018), small construction areas are needed and landfill areas were reduced, preserving soil for nobler purposes (SILVA et al., 2020). Therefore, countries with land limitations, like Japan, opt for incineration (KUMAR; SAMADDER, 2017). This technology is silent, odorless and can operate within city boundaries, reducing transport costs (TOZLU et al., 2016). In addition, replacing fossil fuels to generate heat and power, reduces CO2 emissions, therefore prevents global warming global (CARDOSO, 2019; MAKARICHI et al., 2018; THEMELIS et al., 2013; TISI, 2019).

Moreover, waste composition, especially moisture, is a critical aspect for the adoption of incineration by developing countries (AZAM et al., 2020; OGUNJUYIGBE et al., 2017), as they have higher organic content: 46% in sub-Saharan Africa (AYODELE et al., 2019), 68-81% in Bangladesh (ALAM; QIAO, 2020), 50-65% in Peru (ZIEGLER-RODRIGUEZ et al., 2019), 56% in Pakistan (AZAM et al., 2019) and an average of 52% in Brazil (BRAZIL, 2012; NASCIMENTO et al., 2019). Conversely, developed countries like the US have a lower moisture content: between 15-30% (CHICKERING et al., 2018), 37% in Romania (GHINEA et al., 2016) and 36% in England (WANG et al., 2020a). This occurs mainly due to interfering factors, such as socioeconomic profile and waste management techniques such as collection frequency, MSW diversions due to recycling and biowaste treatment, etc. (KUMAR; SAMADDER, 2017). Taking into account these MSW composition differences, incineration technologies could encourage recycling, since waste sorting improves the burning process and heat treatment efficiencies, thus generating more power (KUMAR; SAMADDER, 2017; MALINAUSKAITE et al., 2017). So, for a good performance of these plants, the effective energy recovery should be accounted, with respect to the variation in MSW composition MSW (DONG et al., 2019; MALINAUSKAITE et al., 2017; SILVA et al., 2020).

In addition, there are other reasons for the slow adoption of incineration in developing countries, such as the lack of technical knowledge, availability of low-cost land for waste disposal, and high investment and operation costs (KUMAR; SAMADDER, 2017), mainly due to exhaust gas control and treatment systems (FEAM, 2012; SILVA et al., 2020). However, even in developed countries, with advanced technology, those high costs and the lack of specific guidelines slow the construction of new incineration facilities, as well (MAKARICHI et al., 2018). The MSW energy potential is an essential factor to design an incineration plant, because of the heating value of the materials that compose it. Themelis and Kaufman (2004) indicate the lower heating value (LHV) for each MSW component, as presented in Table 9, already accounting for the water content in biowaste.

Table 9 - Lower heating value of materials found in MSW

Material	Plastic	Rubber	Leather	Textiles	Wood	Food	Paper
LHV (kcal.kg^{-1})	6,300	6,780	3,630	3,480	2,520	1,310	4,030
LHV (kJ.kg^{-1})*	26,366	28,374	15,192	14,564	10,546	5,482	16,866

*Conversion rate from kcal.kg^{-1} para kJ.kg^{-1} = 4.185

Thus, to calculate the LHVi of each MSW fraction (Equation 2), the LHV value of the respective material in the gravimetric composition is used, as indicated by Silva et al. (2019), Jauregui et al. (2017) and Sindicic (2011).

$$LHV_i = LHV \times F_i \times k_1 \tag{2}$$

Where:

LHV_i = lower heating value of each MSW fraction, in kJ.kg^{-1};
LHV = lower heating value of each component material, in kcal.kg^{-1};
k_1 = 4,185, constant to convert kcal into kJ;
F_i = fraction of each type of waste removed from the gravimetric fraction.

Therefore, by adding the LHVi of each MSW fraction, the total MSW LHV is obtained. For example, to calculate the total LHV of the Brazilian waste, the gravimetric composition indicated by the PNRS is used (BRAZIL, 2012), obtaining a total LHV of 8.6 MJ.kg^{-1}. This value is higher than 7.66 MJ.kg^{-1}, obtained by Alzate-Arias et al. (2018) for Colombia, however, it is within 6.5 9.0 MJ.kg^{-1}, estimated by Tisi (2019) and Sindicic (2011) for Brazil. In Europe and the USA, this value ranges between 10 and 11.17 MJ.kg^{-1}. It is worth mentioning that, in order to define the technical feasibility of incineration, studies indicate that the incineration is unfeasible if LHV<5 MJ.kg^{-1}; if 5<LHV<6.5 MJ.kg^{-1}, the waste must be pretreated to raise the heating value; for an LHV>6.5 MJ.kg^{-1} incineration is technically feasible (EPE, 2008; JAUREGUI et al., 2017; SINDICIC, 2011).

Therefore, to estimate the electrical potential, in addition to the total LHV and the energy efficiency of the incineration plant (22% – LEME et al., 2014), the daily waste production is considered (DONG et al., 2019). To calculate the electrical generation, the electrical potential is used (SILVA et al., 2019; FEAM, 2012). Depending on the MSW composition, the generation capacity is between 0.3-0.7 MWh.t^{-1} of waste (KINGHOFFER; CASTALDI, 2013; DALMO et al., 2019b). Some authors evaluated scenarios with different technologies and concluded that incineration is the most effective technology in terms of power generation (ALZATE-ARIAS et al., 2018; JOSEPH; PRASAD, 2020). Of several studies that estimated the power generation from incineration, Dalmo et al. (2019b) concluded that the incineration plants in São Paulo state could generate 5.7 TWh.year^{-1}. And Santos et al. (2019) found out that the energy generated from the LFG could supply an average consumption of 38,000 inhabitants in Brazil; instead, if incineration was considered, the produced electricity could supply 107,688 inhabitants. Silva et al. (2020) demonstrates that MSW generation is directly linked with the capacity of generating electricity from incineration; thus, it is possible to estimate the generation potential of a given location simply by associating its population (see Table 10, based on SILVA et al., 2020).

Table 10 - Estimated energy and power production for Brazilian cities

Population (inhabitants)	Waste generation (t.day^{-1})	Power (kW)	Energy (MWh.year^{-1})
2,000	1.4	26.8	187.5
5,000	3.4	66.9	468.8
10,000	6.9	133.8	937.6
20,000	13.7	267.6	1,875.2
50,000	35.1	684.1	4,794.4
100,000	70.2	1,368.3	9,588.9
500,000	331.5	6,461.3	45,280.9
1,000,000	725.2	14,138.9	99,085.4
3,000,000	2,386.3	46,521.6	326,083.1

4. COMPARISON BETWEEN ENERGY RECOVERY TECHNOLOGIES

Regarding environmental aspects, several authors used LCA to compare energy recovery technologies, such as LFG, AD and incineration. Sharma et al. (2019) mentioned that in AD the GHG reduction is $4{,}78\times10^2$ kg CO_2eq per tonne of MSW, while in landfills this reduction is $4{,}68\times10^2$ kg CO_2eq. In Brazil, Leme et al. (2014) concluded that incineration has less environmental impact than landfills, with or without energy recovery from LFG, when properly controlled. Additionally, incineration has 40% less global warming potential than landfills. Another study by Fernández-González et al. (2017) also mentions that in Spain AD and incineration are 50% and 40% less harmful than landfills, respectively. Emission control takes place after the power generation stage; the gases emitted in combustion must undergo treatment and environmental controls (OLIVEIRA, 2018). To treat them, a washer with injection of sodium bicarbonate and activated carbon is used to remove acid gases, organic and inorganic micropollutants; sleeve filters for particulate removal; a final system for selective removal catalytic of NOx, and their release is made according to specific legislation standards on atmospheric emissions (MALINAUSKAITE et al., 2017). According to Santos et al. (2019), landfills are considered the worst alternative, since they contribute to global warming and the depletion of the ozone layer through the emission of polluting gases. Moreover, they require large land areas and allow greater contamination of the local environment, such as groundwater and soil. Fernández-González et al. (2017) classified incineration as the second-best alternative in environmental terms, since AD is considered the most environmentally viable technology, as it does not contribute to global warming or ozone depletion, does not generate bad odors, and can be performed on a smaller scale, using a smaller area (HENRÍQUEZ, 2016).

Regarding economic viability, Fernández-González et al. (2017) affirm that if the costs of energy recovery processes are analyzed separately, incineration costs 57.70 US$.$t^{-1}$ of MSW, almost doubling the gasification cost of 30.00 US$.$t^{-1}$. However, the revenues of electricity sales would be higher in incineration. Joseph and Prasad (2020) concluded the same: incineration would yield 32.24 US$.$t^{-1}$, 27.72 US$.t^{-1} for gasification and 12.02 US$.$t^{-1}$ for biomethanization. On the other hand, Santos et al. (2019) claim that the landfill has the lowest costs, when compared to incineration and AD. This is because AD has higher costs for the need to separate and crush the waste, while incineration has high installation and operation costs, due to the environmental controls to prevent the emission of dioxins, solid particles and metal-rich residues (FEAM, 2012).

Another important aspect is the readiness for commercial implementation of technologies. Currently, there are around 1,179 incineration plants worldwide, most of them in the EU, US, and East Asia. However, countries of Latin America e Africa, as well as Australia, are in the initial deployment phase of this technology (MAKARICHI et al., 2018), similar to AD, widely used in European Union, US and East Asia (RAFIEE et al., 2021). For example, Europe already had 459 biomethane production plants in 2015, producing about 1.23 billion m³. However, this technology is also on early commercial deployment in countries of Latin America and Africa, as well as in Australia (RAFIEE et al., 2021). On the other hand, LFG is still widely used in US, Latin America, India. Although also used extensively in Europe, landfills were discouraged in recent years for European directives (MUKHERJEE et al., 2020). So, Table 11 presents a comparison between incineration, landfill and AD (FEAM, 2012; SANTOS et al., 2019; MAKARICHI et al., 2018; RAFIEE et al., 2021).

Table 11 - Comparison between waste destination technologies

Parameter	Landfill	Incineration	Anaerobic digestion
Investment (106 US$.$t^{-1}$)*	10.37	54.32	12.05
Unit cost (US$.$kW^{-1}$)*	3,010.37	5,562.06	4,200.49
Energy (GWh.$year^{-1}$)*	24.11	68.44	20.10
Potencial (kW)*	3,440	9,766	2,867
Technology readiness level	CE: US, LA, EU, EA	CE: EU, US, EA ECD: LA; Africa, Australia	CE: EU, US, EA ECD: LA, Africa
Land use	High	Low	Low
Odors	High	Low	Low
Environmental impact	High	Mid/High	Low
Technical difficulty	Low	High	Mid

*Study conducted by SANTOS et al. (2019) for the city of São José dos Campos, located in the state of São Paulo--BR, with population exceeds the 500,000 inhabitants. CE: Commercially Established; ECD: Early Commercial Deployment; EU: European Union; US: United States of America; EA: East Asia; LA: Latin America.

It should be also mentioned that the choice of the technology must consider economic, environmental or energy potential aspects. For example, developing countries still have landfills as the main form of MSW disposal due to the low-cost (MARGALLO et al., 2019). Although not the best option, LFG for electricity is an alternative to generate revenue and mitigate GHG emissions in these countries. However, some countries, mainly in Europe and China applied public policies to consolidate landfills as the last disposal option and to promote AD and incineration, instead. These policies involve the establishment of goals and landfill taxes, as well as an introduction of subsidies, tax incentives, and tax relief (BAENA-MORENO et al., 2020; WANG et al., 2020b; ZHAO et al., 2016).

5. CONCLUSIONS

The most used MSW energy recovery technologies are energy recovery from LFG, AD and mass burn incineration. LFG can be an alternative for developing countries that are still transitioning from unlicensed landfills and dumps to sanitary landfills, due to its low cost, compared to other technologies. Thus, the investment and operating costs in landfills are estimated to be 10-30 US$.t 1.year^{-1} and 1-3 US$.t^{-1}.year^{-1}, respectively. This represents only 20% of AD costs and about 3% of incineration costs. However, AD can become an economically viable alternative if the effluents are used as fertilizers and not only from the return of the electricity generation. Likewise, incineration becomes viable if the gravimetric composition of the waste is known and an energy analysis of the operational process is performed to identify the technological components harmed by corrosion and abrasion, due to pollutant gas emissions.

However, regarding production potential, the landfill is the worst alternative, producing only between 0.1 and 0.2 MWh·t^{-1}. Conversely, AD produces around 0.3 MWh.t^{-1} and incineration between 0.3-0.7 MWh.t^{-1}, depending on MSW composition. Thus, incineration would be the most efficient way to supply the power electricity consumption in a city. According to one study reported here, the landfill would serve only 6.3% of a city's needs, while incineration would serve about 48.9%. However, it should be noted that, although incineration is technically and economically viable, some operational aspects should be considered, such as the biowaste content of the MSW, applying technologies suitable for waste with high moisture content.

About environmental aspects, properly controlled incineration, with emission control equipment, has less impact than landfills (with or without power generation). This is because landfills are great GHG sources (mainly because of the fugitive methane emissions), occupy large areas, emit odors, pollute the soil and water, among other negative social and environmental aspects. Conversely, AD is classified in diverse LCA studies as the most environmentally viable energy recovery technology, which can only apply to biowaste.

To conclude, depending on the location and waste composition, the different technologies could complement each other instead of competing: for example, the organic fraction that would lower the LHV of the waste that is incinerated can be treated separately through AD, only sending for incineration the refuse from intermediate treatments. This way, greater environmental benefits would be achieved, while incineration would potentially generate more power, therefore economically compensating for the higher costs of these technologies.

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