



## Article Opportunities and Challenges of Gasification of Municipal Solid Waste (MSW) in Brazil

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Abstract: The growth of the economy in urban centers is invariably accompanied by an increase in human activities and environmental interference, mainly related to waste generation. Due to the nature of these activities, large volumes of varied waste are generated daily without the establishment of compatible and adequate collection, logistics, and final disposal systems, bringing relevant impacts to society on health, the environment, and the economy itself. In Brazil, in 2019 alone, almost 30 million tons of MSW were not collected and the total collected, of approximately 44 million tons, went to landfills, with little or no energy use. There is therefore a great opportunity for energy use using this source, aiming not only to adapt to current legislation, but also to reduce GHG emissions, reduce the population's exposure to sanitary landfills and open air, and use the energy contained in these wastes. The purpose of this study is to analyze the main conditions and challenges of current technologies for harnessing the energy potential of biomass from urban solid waste (USW) to enable the insertion of mini thermal plants connected to distributed generation.

Keywords: gasification; municipal solid waste; syngas; waste to energy; distributed generation



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### 1. Introduction

The population growth of large urban centers in Brazil imposes several adjustments on the energy supply system. Besides the requirement of new energy conversion plants, there is also the need for an improved regulatory apparatus, together with the understanding of public perception and society behavior regarding such technologies. If access to improved technologies is related to economic and financial factors, it depends on the movement of society to provide legislation adhering to new scenarios. According to some analyses [1] part of the current difficulty in the Brazilian electric energy system is due to the existing infrastructure mainly based on the use of large electric plants (almost 60% of the total electricity generated) coming from huge hydroelectric power plants, from which near 40% are installed more than a thousand miles from the main load centers (according to the Brazilian Electric Matrix, Available at https://www.gov.br/aneel/pt-br) (Accessed on 5 March 2022). The so-called SIN—National Interconnected System, named in 1998, is the Brazilian integrated electricity system, formed by a large group of interconnected generation power plants, substations, transmission lines, and other apparatus. Its history dates to the beginning of the 20th century (1920) and it has since been through a series of transformations, adjustments, and interconnections following the economic and social development of the country. At the end of the century, the Brazilian government established new regulatory measures, enabling the concession of public electricity services to private entities (Law N° 8987, of 1995 and Law N° 12,783, of 2013), the opening of the consumer market (Law Nº 9074, of 1995 and Law Nº 10,848, of 2004), and the development of alternative sources of electric energy and their insertion in the local supply system. The opening of the energy market provided a wide set of opportunities for the development

and implementation of new technologies, allowing exploration of different energy sources. It allowed new unexplored potentials, either because of regulatory and technological difficulties, or because of the inertia in rethinking the generation, transmission, and wholesale distribution model. The insertion of new energy sources in a decentralized manner, in places close to consumption, was increased with the establishment of basic legislation through Law N° 10,848 and Decree N° 5163 of 2004, and normative resolutions (REN) issued by ANEEL—Agência Nacional de Energia Elétrica—National Agency of Electric Energy, in particular, REN 482/2012 and REN 687/2015. The concept of net metering for distributed generation (DG) was introduced, allowing small-scale (up to 5 MW) generation units to guarantee self-consumption. The main drivers for the DG are the reduction of technical losses (due to the generation being close to the load centers) and the reduction or postponement of investments in transmission, allowing lower environmental impact, rapid implementation, and increasing security of supply. This is mainly since the energy supplier allows an independence from the distributor's supply, diversification of the energy matrix, and job creation. These policies are necessary since there is still the scenario of large-scale electricity production, with its transmission across the country. Despite its increase, DG-installed power in Brazil is only 9.3 GW [2]; while centralized generation is responsible for 182.2 GW, DG represents just 5.1% of the total installed electrical power in the country [2]. The market for distributed generation in Brazil is quite new, considering the short term elapsed since its effective regulation. However, it offers growth opportunities for the technologies implemented until now, and expansion through new technologies for use sources already known under research and development. This is the case of waste generated by populous urban centers, the so-called RSU—Resíduos Sólidos Urbanos—or Municipal Solid Waste (MSW). In Brazil, in 2019, approximately 29.4 million tons of MSW were not collected or were disposed in an inadequate way (in open dumps or in controlled landfills, which correspond to dumps just adapted to reduce environmental impact), equivalent to 40.5% of the total waste generated in the year, with energy potential reaching over 20 GWh [3]. The complementary portion collected, approximately 43.3 million tons of MSW, was destined to the registered landfills by environmental agencies, most of them without any apparatus or system to use the energetic potential. According to EPE [4], the share of energy generation in 2018 that came from "other sources", which, in this study, included coke oven gas, other secondary sources, other non-renewable sources, other renewable and solar, including generation of electricity from biomass of landfills, was 18,281 GWh. This study aims to analyze the perspectives for the use of this energy resource in a decentralized way, increasing the supply of electricity in the DG. In this context, the present paper has the objective of discussing perspectives of efficient waste to energy conversion systems to contribute to the adequate disposal of MSW. The goal of this paper is to present the current scenario of urban solid waste generation in Brazil, the opportunities, and the main barriers, as well as the potential available for the energy use of MSW in Brazil. This paper brings, in Section 2, an overview of MSW in Brazil, from generation and collection through to destination, showing the amount of biomass that can be explored. Section 3 brings the advantages of gasification over the other WtE technologies, and the main kind of gasifiers that can be applied in relation to the available biomass. Section 4 explores the challenges for utilizing gasification of MSW in electric power plants for injection in distribution grid near consumption centers, covering the main barriers and, mostly, the opportunities to solve environmental issues through the use of gasification technology of MSW. Section 5 brings conclusions and purposes of new studies to improve energy production in gasification processes.

### 2. Current Scenario for MSW

Currently, the issue of the MSW energy conversion (the so-called waste-to-energy processes) has been the subject of several studies by the academic community, due to the broad drivers such as the reduction of greenhouse gas (GHG) emissions from MSW management and disposal. In addition, it offers the opportunity for valorization of an

abundant energy resource in urban communities around the world and the application of technology that allows the use of energy in a decentralized manner, reducing energy losses in intermediate processes of energy conversion and transport, and postponing investments in extensive power transmission lines to interconnect large generators to consumer centers. In Brazil, Law 12,305/2010, the current legislation imposes to municipalities the obligation of guaranteeing collection and disposal. It is also considered public health and safety and the well-being of the population. Due to the high amount of MSW produced daily and several socioeconomic factors (including lack of capacity building and funds), many municipalities are unable to comply with those obligations. As a result, inefficient collection and disposal systems and underutilization of these energy resources are observed. There are more than 4897 (88% of the total) cities in Brazil with less than 50,000 inhabitants [5]. It is not clear how many of them have suitable and legalized landfills, but it was known that many of them do not have adequate collection and disposal instruments. Table 1 shows MSW collection in each state of Brazil in 2019 and the respective CCI (collection coverage index), representing the percentage of RSU collected in relation to the amount generated, and the estimated volume of MSW not collected by the municipal public administration. Despite the high MSW amount collected and the equally high collection rates in most Brazilian regions, there is still a significant volume of uncollected MSW. The lack of mechanisms allowing its collection and use in a safe and decentralized way, near its sources, is a major cause of the current scenario, in which only the MSW management entity could be responsible for energy generation. It is important to note that there are thousands of Brazilian municipalities with population below 50,000 inhabitants, which do not allow the use of large-scale waste-to-energy systems, mainly incineration (mass burning processes); this is because there are not commercial plants worldwide with such technology, since it is not economically feasible for systems below 500–600 t/d, which is equivalent to the Brazilian municipality collection of a 50,000–60,000-inhabitants city, considering an average production of 1 kg/hab/d. Considering this, incineration is not a suitable waste-to-energy technology; in this case, it appears that MSW gasification (thermochemical process) systems could be an interesting option. However, it is not yet verified in the country any unit of MSW gasification, although pilot plants seem to point out technical and economic feasibility for its applications in various technologies, not only covering gasifiers but also prime movers for electric power generation, whether ICEs-internal combustion engines, GTs—gas turbines, MGTs—micro gas turbines, and STs—steam turbines, with electrical efficiency trespassing 60% [6].

Region	State	Total MSW Colected in 2019 (t/y)	Collection Cover Index (%)	Total Estimated Generation (t/y)	Total Estimated Uncollected (t/y)
NORTH	ACRE	198,925	83.10	239,380	40,455
	AMAPÁ	239,075	93.30	256,243	17,168
	AMAZONAS	1,385,905	86.60	1,600,352	214,447
	PARÁ	2,028,670	76.70	2,644,941	616,271
	RONDÔNIA	402,960	78.90	510,722	107,762
	RORAIMA	139,430	84.10	165,791	26,361
	TOCANTINS	375,220	83.40	449,904	74,684
NORTH EAST	ALAGOAS	915,785	83.80	1,092,822	177,037
	BAHIA	4,266,120	84.10	5,072,675	806,555
	CEARÁ	2,830,210	80.10	3,533,346	703,136
	MARANHÃO	1,605,270	63.90	2,512,160	906,890
	PARAÍBA	1,111,425	86.70	1,281,920	170,495
	PERNAMBUCO	2,856,855	86.90	3,287,520	430,665

**Table 1.** MSW collection in Brazilian states by region and collection coverage rate ([3], adapted by the author).

Region	State	Total MSW Colected in 2019 (t/y)	Collection Cover Index (%)	Total Estimated Generation (t/y)	Total Estimated Uncollected (t/y)
	PIAUÍ	789,495	69.20	1,140,889	351,394
MIDDLE WEST	RIO GRANDE DO NORTE	992,070	89.00	1,114685	122,615
	SERGIPE	606,265	91.40	663,310	57,045
	DISTRITO FEDERAL	1,049,740	95.00	1,104,989	55,249
	GOIÁS	2,430,900	96.10	2,529,553	98,653
	MATO GROSSO	1,069,450	88.60	1,207,054	137,604
	MATO GROSSO DO SUL	903,375	92.70	974,515	71,140
SOUTH EAST	ESPÍRITO SANTO	1,131,500	93.70	1,207,577	76,077
SOUTH	MINAS GERAIS	6,383,485	92.00	6,938,571	555,086
	<b>RIO DE JANEIRO</b>	8,182,570	99.50	8,223,688	41,118
	SÃO PAULO	22,984,050	99.60	23,076,355	92,305
	PARANÁ	3,074,395	95.00	3,236,205	161,810
	RIO GRANDE DO SUL	3,004,315	95.50	3,145,880	141,565
	SANTA CATARINA	1,791,055	96.20	1,861,804	70,749
	TOTAL	72,748,515		79,072,853	6,324,338

Table 1. Cont.

### 3. MSW Gasification Process

There are already studies [6–8] and pilot plants [9,10] that are being developed, aiming to solve the question of small-scale MSW conversion into energy, and MSW gasification systems appear to be a significant option. Gasification is a process that consists of the thermochemical conversion of the processed MSW (RDF—residual derived fuel), under substoichiometric conditions; this means that the process is developed in the presence of oxygen for combustion, but in an amount below the stoichiometric (which would produce the complete combustion of all MSW components). Under the gasification process, carbon and hydrogen are converted from chemical structures (in an incomplete combustion process, or gasification) by transforming the residues into a gas called synthesis gas, or "syngas". A typical composition of syngas that can be obtained through MSW gasification process considering the gravimetry found in Brazilian society [11] is basically carbon monoxide (CO) in a concentration ranging from 8% to 25%, hydrogen ( $H_2$ ) from 13% to 15%, methane  $(CH_4)$  from 3% to 9%, carbon dioxide  $(CO_2)$  from 5% to 10%, nitrogen  $(N_2)$  from 45% to 54%, and water steam (H<sub>2</sub>O) from 10% to 15% (Coelho et al., 2020, p. 85). Syngas can be used in heating boilers or direct heating in industrial processes. It can also be used as a raw material to produce methanol in an economically viable way, and as a raw material in industrial applications. In this case study, syngas is considered to produce electrical energy (in CHP—combined heat and power systems) and in the Rankine cycle, through the thermal use of syngas burning for feeding steam turbines coupled with electrical generators (turbogenerator set).

The production process of syngas in the gasifier can occur continuously or in batch, and the oxidizing agent may be pure oxygen, atmospheric air (more economic option), or steam, however, maintaining the sub stoichiometry in the reaction. Gasifiers can be classified according to certain characteristics such as syngas LHV—lower heat value, type of oxidizer, type of bed (the lower structure of the gasifier equipment that supports the MSW or RDF to be processed) operation, and type of biomass. In co-current (downdraft) fixed-bed gasifiers, the biomass is fed from the top, as well as the oxidizing agent, which can also be inserted from the sides, forming a kind of "throat", through which the biomass under combustion passes. This allows the accumulation of the residues (carbonaceous and ashes) produced, through which the syngas must pass (reaction zone), ensuring high quality of the gas, with low tar and particulate content, which leaves the base of the gasifier, with the ash being collected under the grate (fixed bed). The low volume of the syngas production (from 15% to 20%), the difficulty in handling the feedstock (manual feeding),

and the ash generated in the process are disadvantages observed in this type of gasifier construction. In countercurrent (updraft) fixed-bed gasifiers, biomass is fed from the top. Both types of gasifiers are shown in Figure 1.



Figure 1. Fixed-bed gasifiers ([12], 2020, adapted by the author).

The oxidizing agent is inserted from below, so that syngas will be extracted from the top, causing the flow of gas and biomass to move in opposite directions. As it is converted, the biomass provides heat and the methane. The resulting gas, rich in tar, is extracted from the top of the gasifier. Air and steam can be introduced to keep the ash below its melting temperature, facilitating the conversion of biomass. The ashes will fall under the grate (fixed bed), from where they will be removed. Fixed-bed gasifiers have limitations in terms of dimensions, since, with the material deposited in the bed, the accumulation of residues processed on the bed would harm the combustion process, causing thermal losses in the process and even with the constant extraction of residues. Fluidized-bed gasifiers use inert particulate material that is kept in suspension (usually sand, ash, or alumina) by the flow of the oxidizing agent that drags the biomass. Fluidized-bed gasifiers are normally used for energy production greater than 200 kW, but they can be used in smaller scale applications, being able to work with biomass of lower density and higher moisture content. Fluidized-bed gasifiers can further be classified as pressurized or atmospheric depending on the working pressure. They are also classified as circulating (Figure 2) or bubbling (Figure 3) fluidized-bed according to the speed of the sand flow that composes the bed, which affects the contact of the oxidizing agent with the biomass. In bubbling fluidized bed gasifiers, the bed, composed of a thin layer of inert material, is crossed by the flow of the oxidizing agent (oxygen, air, or steam) in a vertical direction, contrary to the direction of the biomass, which is inserted through the side of the gasifier, causing the movement of the inert bed. This flow is inserted at a speed sufficient to keep the inert material (sand) in suspension together with the biomass, normally from 1 to 3 m/s [12].

Circulating fluidized-bed gasifiers work similarly, also with the injection of the oxidizing agent through the bottom of the gasifier and the biomass being fed from the side. They react thermally in suspension due to the flow of the oxidizing agent (air or  $O_2$ ), in this case, at a higher speed, between 5 and 10 m/s, allowing a better mixture of the fuel and the oxidizing agent. The produced syngas is separated from the particulates in suspension through a cyclone system, which causes the syngas to be extracted from the top and the particulates return to the gasifier chamber [12].



Figure 2. Bubbling fluidized-bed gasifier ([12], adapted by the author).

Fluidized-bed gasification is composed of a reactor with a bed made of inert material, in general sand. It is a quite well-known process, but it requires some regular monitoring. After producing a certain amount of gas and processing the biomass, the bed starts to become thick and with lower efficiency, due to the accumulation of ash. This material must then be purged, which may be performed continuously or by batch. Figure 3 illustrates the situation. This type of gasifier is the most suitable for larger quantities of biomass, from 10 to 20 t/h, and is more flexible regarding the characteristics of the biomass to be processed (gravimetric composition and consequently LHV of the MSW) [12]. Table 2 presents the characteristics of each type of gasifier according to the properties.



Figure 3. Circulating fluidized-bed gasifier ([12], 2020, adapted by the author).

Existing studies indicate that the gasification process does not pose technical barriers to projects, even with the processing of small quantities of MSW, which can be confirmed in the literature. [6] used a fixed-bed, co-current gasifier able to generate up to 5 kW, using a 10 kW ICE and 15 m<sup>3</sup>/h of syngas continuous flow, with LHV between 4–6 MJ/Nm<sup>3</sup>. Ref. [10] used a 500 kWt gasifier driving 30 kWe MGT, obtaining satisfactory results in terms of stability and emissions within European standards, with syngas LHV between 8–15 MJ/Nm<sup>3</sup> at high flow. Another study that presented satisfactory results was conducted by Infiesta (2015) [11], in which a countercurrent fluidized-bed gasifier produced 741 Nm<sup>3</sup>/h of syngas with LHV of 4.85 MJ/Nm<sup>3</sup>, consuming up to 325 kg/h of MSW with LHV of 14.6 MJ/kg. This study was conducted trough the observations and measures on a pilot gasifier built in Maua city, in Sao Paulo State, Brazil, and observed electric power installed of 1 MWe. After certified by CETESB, the governmental environmental company of Sao Paulo State, run by a group of researchers of Sao Paulo University, and by

Societé Générale of Surveillance, the Carbogas Company, the producer of the gasifier was authorized to implement a gasifier in real size. The project is running in Boa Esperança city, in the State of Minas Gerais, Brazil, with a population of 40,308 inhabitants according to IBGE (2020) [5]. The municipality manages the collection and disposal of MSW in an open-air dump, near the city. The power plant building started in 2018 and it is composed of a processing MSW unit (in which RDF is produced), a gasification unit (in which the reactor is being built), and a generation unit (in which the electric power will be generated). This plant, when finished, will process 30 T/day of RDF, and will have 1 MWe of power installed, operating with 95% of capacity factor [13].

<b>Gasifier Characteristics</b>	Properties		
Syngas LHV	Low: Up to 4.2 MJ/kg Medium: From 4167 to 8.3 MJ/kg High: From 8.3 to 33.3 MJ/kg		
Oxidizing	Air Oxygen Steam		
Type of Bed	Fixed (Co-Current or Countercurrent Flow) Fluidized (Circling Or Bubbling)		
Operating Pressure	Atmospheric up to 6 MPa		
Biomass	Farm/Industrial Residues/MSW Raw Material, Pelletized or Sprayed		

Table 2. Gasifier characteristics (FEAM, 2010 apud [12], p. 84).

### 3.1. Prime Movers

Studies [6] have demonstrated the good perspectives for MSW conversion into energy using ICE—internal combustion engines, GT—gas turbines and MGT—gas microturbines, and FC—fuel cells, fed by synthesis gas (syngas) produced from MSW gasification at temperatures between 500 °C and 1400 °C, with minimal adjustments to its components. However, it is important to note that some prime movers such as GT, MGT, and FC used as drivers for power plants in syngas applications are still in the early stages of development. Despite all these prime movers observing simplicity of implementation, with no major modifications, low CAPEX values, low control system complexity, compactness, low sensitivity to syngas composition and high ramp-up/ramp-down (equipment capacity to adapt to a new power generation point, measured in W/s), they need to be more deeply analyzed, considering thermal-electrical efficiency and financially, in integrated applications with MSW gasifiers and operating on industrial scale. They present different efficiencies for electricity generation: 20% to 35% in ICE, 42% 61% in GT, 26% to 33% in MGT, and 45% to 60% in FC, according to Indrawan et al. (2020) [6]. Rabou et al. (2008) [9] conducted studies with a 500 kWt fluidized-bed gasifier, operating close to atmospheric pressure at 850 °C, and in a system with syngas cooling up to 400 °C, which fed an unmodified 30 kWe MGT. Infiesta (2015) [11] obtained good results running a gasifier that feeds syngas to be converted by a 180 kWe engine-generator set, consuming 325 kg/h of MSW.

### 3.2. Technical Issues

The gasification process takes place in four distinct stages: drying, pyrolysis, combustion, and reduction. Although these steps can be considered to overlap, they occur in sequence and in separate and distinct zones where fundamentally different chemical and thermal reactions take place. The first phase, drying, consists of applying heat to the raw biomass or RDF in the absence of air, to decompose it into charcoal and various tar-rich gases and liquids; basically a carbonization process. The biomass then quickly begins to decompose in the heat, as the temperature at this stage rises to close to 240 °C when starting the second phase, the pyrolysis. Biomass begins to be destroyed, being converted into a series of solids, liquids, and gases. The solids produced are called "char". Gases and liquids are collectively called "tar" (or "tars"). These gases and liquids produced at the low temperatures of pyrolysis are simple fragments of the original biomass, which were broken up in the heat. These fragments are the most complex bonds of H, C, and O atoms in biomass that are generally referred to as volatile compounds. As the name suggests, they are reactive. More precisely, they are less strongly "bonded" in biomass than fixed carbons, which are C–C bonds. All organic materials in biomass are composed of atoms of H, C, and O, in a multitude of types of bonds and shapes of molecules. The purpose of gasification is to break this myriad of chains, turning them into combustible gases of H<sub>2</sub> (hydrogen gas) and CO (carbon monoxide). Both are combustible gases and have similar energy densities per volume, and produce a "clean" burning, since both need only 1 atom of O, so that in just one step it reaches the final stage of combustion, in this case,  $CO_2$  and  $H_2O$ . After pyrolysis, both the combustion/cracking phases start, and they run simultaneously. They consist of the process of breaking long and complex molecules, such as tar, into lighter gas molecules when exposed to heat. This process is crucial to produce clean gas that is compatible with an ICE, since tar-rich gases are dense, and during combustion they would condense quickly, forming liquids, making the operation of the chambers unfeasible. Cracking also occurs to ensure proper combustion, as complete combustion only takes place when the combustible gases are completely mixed with oxygen (oxidizing agent). During combustion, the high temperatures produced by exothermic reactions break down the long chains of tar-rich gases that pass into the combustion zone. Finally, the next phase is the reduction, which is the process of extracting oxygen atoms from the products of combustion, the hydrocarbon molecules, to allow those molecules to burn again. Reduction is the direct reverse process of combustion that is the combination of combustible gases with oxygen to release heat, basically producing water steam, carbon dioxide, and other byproducts. In fact, the processes of combustion and reduction are the same and occur in opposite reactions, and in most combustion environments they are both occurring simultaneously in a kind of dynamic equilibrium, with repeated forward and backward movements, alternating between the two processes. Reduction in the aerator is achieved by causing carbon dioxide  $(CO_2)$  or water vapor  $(H_2O)$  to cross the bed of red-hot charcoal (C). The carbon present in red-hot charcoal is highly reactive with oxygen. It has such a high affinity for oxygen that it takes oxygen out of water vapor and carbon dioxide and redistributes it to as many sites and binding as possible. Oxygen is much more attracted to carbon bonds than to itself. Therefore, no oxygen will remain in its usual diatomic form  $(O_2)$ . All the available oxygen will join bonds with the available carbons until there are no more free oxygen atoms left. When all available oxygen is redistributed as single atoms, reduction ceases. Through this process,  $CO_2$  is reduced to carbon to produce two "consortium" molecules. The (H<sub>2</sub>O) water vapor molecule is broken down by carbon to produce H<sub>2</sub> and the "consortium" these being combustible gases, which can be channeled to be used elsewhere. Combustion is the only liquid exothermic process that takes place in gasification. All the heat that drives drying, pyrolysis, and reduction comes directly from combustion or is recovered from indirect combustion, by heat exchange processes inside the gasifier. Combustion can be fueled by gases rich in tar or by charcoal produced in pyrolysis. Different types of reactors use one or the other, or both. In a co-current gasifier, an attempt is made to burn the tar gases formed in pyrolysis to generate heat to reduce speed, as well as  $CO_2$  and  $H_2O$ , to decrease the reduction. The purpose of combustion, in a countercurrent gasifier, is to obtain a good mixture and high temperatures, so that all tars (liquid or gaseous) are burnt or cracked, and therefore do not remain present in syngas. The charcoal bed and reduction contribute relatively little to syngas's tar conversion. The solution to the problem of tar lies essentially in its cracking in the combustion zone. As it was described, drying is the process that removes moisture from the biomass before entering pyrolysis. All moisture will be removed from the fuel before processes above 100 °C occur. All the water in the biomass will be vaporized from the fuel at some point in the high-temperature processes. Where and how this happens is one of the main questions that needs to be resolved for successful

gasification. Fuel with high moisture content or improper handling of moisture internally is one of the most common reasons for syngas production failure. To mitigate this risk, the use of RDF biomass is indicated, imposing, however, higher production costs, which must be considered beforehand. Both the composition of syngas and the production of solid fuel (charcoal) and of condensable liquids depend on the type of gasifier, the composition of the MSW, the retention time, and the type of oxidant (air, O<sub>2</sub>, steam, or combinations of the same). In fact, the main operating parameters that need to be precisely controlled are the residence time, the gasifying agents (they are related to MSW's gravimetric composition), the air–fuel ratio, the reaction temperatures, and operating pressures [14–21]. Currently, most installations use air as an oxidizing agent, operate at atmospheric pressure, and produce medium LHV syngas. The type of gasifier to be chosen depends on the composition of available biomass. Fixed-bed aerators are suitable in applications where particulate biomass is available, with 25% moisture content. For less dense biomass, such as "pelleted", fluidized-bed gasifiers are indicated, which also show good efficiency with biomass with higher moisture content.

# 4. Possibilities and Challenges for Increasing the Energy Supply in DG with MSW Gasification

Considering the characteristics of the Brazilian's electricity system, mainly constituted by large-scale power plants and long-distance transmission lines to the major demand centers, there is a clear need to increase energy production in a decentralized manner, close to the consumption centers (where load is concentrated). This energy conversion process is the so-called distributed generation—DG. Despite the several definitions of DG existing, there is a consensus that its biggest advantage is the fact that energy is produced close to the site where it will be consumed; this is because power storage in large quantities is still incipient in Brazil. DG also contributes to reduce the pressure on the transmission lines of the National Interconnected System, as it reduces the amount of energy to be transferred from large power plants (hydroelectric and other power plants) to the load center, which is located very far from it.

### 4.1. Legislation Compendium

In 2004, Law Nº 10,848 (15 March 2004) established that power plants using renewable energy sources may register in the program called PROINFA (Programa de Incentivo às Fontes de Energia Alternativas)—Alternative Energy Sources Incentive Program. This is a program coordinated by the MME—Ministry of Mines and Energy, with the main objective of diversifying the electric energy matrix in Brazil. It guaranteed a 20-year contract to the energy generator with fixed tariffs. Program participants were producers registered as sellers, while electric utilities, consumers, and self-producers were the buyers of this energy. Decree N° 5163, of 30 July 2004, defines that distributed generation is the production of electricity from power plants connected to the electrical distribution system, except for hydropower plants above 30 MW and thermoelectric, including cogeneration, with energy efficiency below 75%. According to the same decree, the electricity purchase from DG plants would require specific auctions, and utilities should carry out these contracts in a volume of up to 10% of the total load sold in the respective concession regions. Decree Nº 5163 also establishes that the use of hydraulic potentials and the implementation of thermoelectric power plants with power equal to or less than 5 MW are exempt from concession, permission, or authorization, and must only be communicated to the granting authority (wording given by Law 13,360 of 2016). Law 13,203/2015 creates the possibility for utilities to transfer full cost of distributed generation to the consumer's tariff, up to the highest value between the regulated "annual reference value" and the "specific annual reference value". The latter is calculated by EPE—Empresa de Pesquisa Energética, responsible for the energetic studies in Brazil, considering the technical conditions and the source of distributed generation, and must be approved by the MME—Ministry of Mines and Energy. The Decree N° 65, of 27 February 2018, established the "specific annual reference value", which became effective as

of 1 March 2018, and which is applied to generators that are connected to the distribution network through the installation of consumer units and that have an installed capacity less than or equal to the power made available to the consumer (contracted demand), limited to a maximum of 30 MW. This decree established the "specific annual reference value" for MSW at 173.24 USD/MWh at that time. This amount, together with Law N° 13,203, corresponds to an attractive issue for utilities to procure sources to compose their energy supply portfolio, mainly because the generator agent is in the concession area and injects the energy produced in the utility's own distribution network, whether in LV (low voltage) or MV (medium voltage), or in AT (high voltage), into its own sub transmission network. These are the basic conditions for energy sales by an MSW waste-to-energy (WtE) power plant. It offers the advantage of a stable energy supply during the tie of the contract. On the other hand, the decision to purchase this renewable energy is made exclusively by the utility company, so it is not certain to happen.

Another means of energy commercialization would be its use in a compensation regime (net metering), given by the text of REN N° 482/2012, later complemented by REN N° 687/2015 and more recently REN N° 1000/2021, and by the Law N° 14,300, of 6 January 2022 that define the rules of what is called "microgeração ou minigeração distribuída" or micro distributed generation and mini distributed generation. Table 3 presents a summary of the main definitions of each of these normative resolutions. This set of resolutions not only established the rules and limits for project installation and for credit accumulation and use, but also defined the rules for the constitution of business modalities that are currently in operation: DG in the unit itself (basic model), remote self-consumption, shared generation, either through cooperatives or consortia, and multiple consumer units. Each of these models presents a set of established normative rules.

In Brazil, distributed generation currently contributes with an installed power of around 9.3 GW, generated mostly from solar photovoltaic but also from sugarcane bagasse, biogas, rice husk, wind, natural gas, hydro, and forest residues. Yet, there is still no thermochemical MSW power plant in Brazil in commercial operation phase. There are currently financial benefits for enterprises operating in DG, defined by the Federal Government, through the MME and ANEEL, aiming to postpone and reduce investments in expansions of the transmission/distribution and generation network. GD also makes it possible to diversify the country's energy matrix and increase its efficiency, since generation occurs alongside consumption, reduces technical losses, reduces the environmental impacts of large energy generation and transmission projects, allows for rapid deployment, increases security of supply and stability of the distribution network, and increases job creation and economic development. Lease agreements for distributed generation assets are already well established in the Brazilian market, mainly for photovoltaic generation assets. As said, there are few mini-generation projects for distributed electricity that are not from solar sources. However, in the case of large consumption centers, the implementation of solar plants is hampered by the scarcity of large areas without shadows, with high solar irradiation and adequate temperatures. These urban areas provide better conditions for the implementation of energy recovery plants using WtE technology, such as MSW gasification, precisely because of the compactness of the generation system and auxiliary processes. Law N° 14,300 provides basic mechanisms for the operation of these ventures and, unlike previous resolutions, brings greater legal certainty to these ventures, increasing the attractions for potential investors.

	Resolution N° 687/2015	Resolution N° 687/2015	
Micro distributed generation.	Generating plant with installed power less than or equal to 100 kW.	Generating plant with installed power less than or equal to 75 kW.	
Mini distributed generation.	Generating plant with installed power greater than 100 kW and less than or equal to 1 MW.	Generating plant with installed power greater than 75 kW and less than or equal to 3 MW (water sources) or less than or equal to 5 MW (qualified cogeneration, or for other renewable sources).	
Types of sources connected to the distribution network in the consumer unit.	Hydraulic, solar, wind, biomass or qualified cogeneration sources.	Qualified cogeneration or renewable sources of electricity.	
Credit-sharing models.	In the same CU that generated the energy credits, or in other CUs with the same ownership.	Next to the CU; multiple CUs; remote self-consumption, and shared generation.	
Installed power limit.	Limited by the installed load in the case of a UC in the low-voltage group, or by the contracted demand for a UC in the high-voltage group.	Limited by the power made available to the UC where the generating plant will be connected.	
Installation of power above the limit.	Request an increase in the installed load from the concessionaire, in the case of a CU in the low-voltage group, or the contracted demand in the case of a CU in the high-voltage group.	Request an increase in the available power from the concessionaire, with no need to increase the installed load.	
Validity of energy credits.	36 months.	60 months.	
Measurement system costs.	The responsibility of the interested party.	For micro-generation system under the responsibility of the energy distributor, for mini-generation and shared generation system under the responsibility of the interested party.	

Table 3. Rules for micro and mini distributed generation (elaborated by the author).

### 4.2. Economic Aspects

Using seven representative parameters to assess economic feasibility, that is, cost of biomass, sale price of electricity (special tariff for production by renewable source), output power, taxes, fees, and operating costs, Indrawn et al. (2020) [7] concluded that the results are positive for processing 2.5 t/d in a fixed-bed, co-current gasifier, with an output power of 60 kW. Buchholz et al. (2012) [10] experimented a 250 kW wood-based downdraft gasifier system that runs during 12 h/day and 150 kW output power, producing electricity at a cost of 0.18 USD/kWh. [13] concluded that the Boa Esperança WtE Power Plant will present IRR of 10.36% per year and a discounted payback of 17.7 years, with investments close to USD 4.5 million.

### 4.3. Environmental Issues

Among the technologies available for processing MSW and energy recovery through thermochemical processes, gasification presents characteristics throughout the process with greater adherence to Brazilian legislation and ancillary regulations, as they promote the reduction or elimination of environmental liabilities, such as landfills or open-air dumps, and since the MSW extracted from this liability can be considered as "stock" of raw material for energy generation. They also observe good emission characteristics of components harmful to health, such as dioxins and furans, the lowest emissions of toxic particulates and GHG, and the classification of ash and carbonaceous solid materials, resulting from the process, as being class 2 (NBR 10.004: 2004). They are a good solution for most municipalities in Brazil, which have less than 50,000 inhabitants, as these municipalities have a rate of generation of MSW below the minimum viable rate for the implementation of systems with greater processing capacity, such as incineration, and the costs and impacts of implementing a sanitary landfill are currently impracticable, in addition to the fact that the implementation of new sanitary landfills is contrary to the country's current municipal waste policy. In the process emission tests and measurements, when using a fluidized bed gasifier to process 325 kg/h of MSW "in natura", producing syngas with 4.8 MJ/Nm<sup>3</sup> LHV, Infiesta (2015) [11] obtained emissions of dioxins and furans 50 times smaller than those specified in federal legislation (CONAMA Resolution N° 316). The same tests were carried out and compared with the limits established in State Resolution SMA-079, which follow the same atmospheric emission standards established by European norms, which are one of the most rigorous in the world. The sample results were 12 times smaller than the limit imposed by this legislation [12].

### 5. Conclusions

The existing studies analyzing MSW gasification process indicates significant prospects for small and medium-scale applications, with processing ranging from 5 to 50 t/d. Literature offers a diversity of projects with economic feasibility for implementation in systems connected to the electricity grid. The main considerations to be taken in the construction of an MSW gasification system for distributed electric power generation include the analysis of MSW logistics and RDF production locally, the adoption of the gasifier, the electricity generator prime movers, and the treatment, cleaning, and disposal of byproducts system (ash and carbonaceous)—keeping the energy balance of the complete cycle viable. Based on the current challenges for the gasification technology, the development of feasibility studies is proposed for the implementation of a sustainable plant to produce MSW pellets to feed gasifiers, producing thermal and electrical energy for its own consumption, and the manufacture of MSW pellets, for sale as fuel for gasification systems. In the process, it would use pellets for the gasification process and sell the surplus pellet production and electricity. This would contribute to the environment through the general reduction of GHG emissions and provide a circular economy of MSW.

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