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ORIGINAL ARTICLE

Techno-economic viability analysis of gasification technology as a sustainable alternative for electric power generation from municipal solid waste

Análise de viabilidade técnica e econômica da tecnologia de gaseificação como alternativa para geração de energia elétrica a partir de resíduos sólidos urbanos

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Abstract: The present study has analyzed the techno-economic feasibility of applying gasification technology to the energy use of Municipal Solid Waste in an industrial plant. In that case, the obtained gas shall be used as an alternative source for electric energy generation. The technical feasibility analysis took into account the waste suitability to the gasification process, as well as the gasification process efficiency, through tests carried out in a testing plant, and an estimation of electric power was obtained. The economic viability studied the indicators Net Present Value, Internal Rate of Return and Discounted Payback considering the cash flow estimation from plant installation and operation. A univariate sensitivity analysis of Net Present Value has considered the variables with influence on the cash flow, such as the Minimum Attractiveness Return Rate, energy tariff, installed power, operating and maintenance costs and the undertaking unitary cost. The results suggested the technical feasibility considering both the suitability of the waste for the process and its efficiency, which reached values of 62% allowing to reach an estimated electric power of 1.46 MW. The economic viability was verified under the studied conditions. The sensitivity analysis showed that the economic viability was sensitive to the variation of some parameters estimated on cash flow, which in turn leads to an understanding of the need for subsidies as an incentive to the technology effective viability. This study provides decisions makers with data and information on how to adopt the gasification technology in Brazil.

Keywords: Economic viability study; Energy use; Gasification; Municipal solid waste.

Resumo: Este estudo analisou a viabilidade técnica e econômica de aplicação da tecnologia de gaseificação no aproveitamento energético de Resíduos Sólidos Urbanos em planta industrial,

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na qual o gás obtido é fonte alternativa para geração de energia elétrica. A viabilidade técnica consistiu das análises de adequabilidade do resíduo ao processo, eficiência do processo de gaseificação, realizado em planta piloto, e estimativa de potência elétrica obtida. A análise de viabilidade econômica investigou os indicadores Valor Presente Líquido, Taxa Interna de Retorno e Payback Descontado, levando-se em consideração o fluxo de caixa da planta ao longo de sua vida útil. Realizou-se análise de sensibilidade univariada considerando os parâmetros chave que afetam o Valor Presente Líquido do projeto: taxa mínima de atratividade; tarifa de energia elétrica; potência instalada; custo de operação e manutenção; e custo unitário. Os resultados apontaram para a viabilidade técnica considerando a adequação do resíduo e a eficiência do processo de gaseificação, que alcançou taxa de 62%, permitindo, dadas as características e disponibilidade do resíduo, chegar a uma potência elétrica de cerca de 1,46 MW. Foi constatada a viabilidade econômica do projeto para as condições estudadas. A análise de sensibilidade mostrou que a viabilidade econômica é muito sensível à variação dos parâmetros considerados neste estudo. Tais parâmetros podem ser influenciados por fatores internos ou externos, levando ao entendimento da necessidade de subsídios como incentivo para efetiva viabilização da tecnologia. Este estudo fornece informações que auxiliam os tomadores de decisão sobre como agir para impulsionar a adoção dessa tecnologia no Brasil.

Palavras-chave: Análise de viabilidade econômica; Aproveitamento energético; Gaseificação; Resíduos sólidos urbanos.

1 Introduction

The generation, collection and final disposal of municipal solid waste (MSW), those originated from domestic waste and public cleaning (*Lei* n. 12.305, Brasil, 2010) are part of the serious problems in urban metabolism, raising concerns not only regarding the amount generated, but also of the methods used in its neutralization (Mesjasz-Lech, 2014).

The inadequate destination of MSW is accountable for pollution and environmental degradation, Greenhouse Gas emissions, disease spread and social vulnerability (Azevedo et al., 2015). However, according to Mesjasz-Lech (2014), these negative effects can be minimized through waste management systems, which, in addition to environmental gains, can cause economic and social advantages.

Around the world, the main forms of MSW final disposal are landfills, composting and incineration (Sontag et al., 2014). In Brazil, landfills, the most widely used (58.4%), show that waste disposal systems are overloaded. Even more worrisome data show that in the country the other 41.6% of collected waste, or 29.7 million tons of MSW, are still deposited in dumps. These dumps don't rely on adequate measures to protect the environment against damage and degradation, causing environmental pollution and health problems (*Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais* [ABRELPE], 2019).

Although selective garbage collection initiatives are registered in 69.6% of the Brazilian cities, recycling rates have remained stagnant for years. The country still has no consolidated initiatives for the usage and recovery of the organic fraction (ABRELPE, 2019). According to data from Generation Information Bank, there are 25 operating thermoelectric plants that exploit MSW, mainly biogas energy from landfills. Those represent installed capacity of approximately 187 MW, corresponding to 0.1% of the generation capacity of the country (*Agência Nacional de Energia Elétrica* - ANEEL, 2020). None of these factories are based on biomass gasification.

The energy use of MSW through gasification technology is an innovative technological solution that enables to turn urban waste, once considered an environmental liability, into an environmentally and socially responsible asset. From the technology of energy exploitation, it is possible to obtain biogas, electricity, and heat, with a varied possibility of commercial applications (ABRELPE, 2015).

This technology is in line with the current environmental needs of cities, especially those concerning MSW management. It contributes to give solid waste a new role in energy generation, thus contributing to the diversification of the Brazilian energy matrix.

Gasification applied to MSW currently amounts to a total of 100 plants around the world. In spite of this number, these plants operate in undercommercial conditions and its main challenge is the solution of technical and economic problems related to the high MSW heterogeneity (Intharathirat & Salam, 2016). For Matsakas et al. (2017), gasification involves more complex conversion processes and is still in the stage of technical development.

In Brazil, a single initiative in implementation phase, in the city of *Boa Esperança*, *Minas Gerais* State, is carried out by the power company *Furnas Centrais Elétricas* (*Furnas*) in the scope of Research and Development (R&D) projects regulated by the National Electrical Energy Agency (from Portuguese, ANEEL).

The R&D project entitled "Energy Utilization and Generation of Electric Energy from Municipal Solid Waste from Thermo-Chemical Reactor", (ANEEL Code PD-0394-1602/2016), proposes to use the technology of gasification based on circulating fluidized bed thermo-chemical reactor for generation of a gas. The gas should be used afterwards in a boiler for burning and generation of steam, which will drive a turbine to generate electric energy in Rankine cycle.

This study analyses the development of this pilot unit and explores the hypothesis of technological innovation with a commercial application perspective, using MSW as source to produce alternative and sustainable electricity. The general objective is to study the technical and economic feasibility of applying this technology, analyzing the case of implantation at *Boa Esperança* power plant.

2 Gasification in circulating fluidised bed

It is possible to obtain a combustible gas with thermochemical gasification through the partial oxidation of carbonaceous solids or carbonaceous liquids. The transformation of the material occurs by the provision of heat in the presence of an oxidizing agent, in a quantity less than the stoichiometric amount so that not all carbon of the fuel is oxidized (Lora et al., 2012; Sanches et al., 2011; Wenzel, 2013).

The gasifier is the reactor in which occurs the thermochemical transformation of the biomass into gas (Lora et al., 2012). A variety of gasifiers is used in gasification processes and due to their characteristics, they can be grouped into different categories according to the working pressure and bed type (Melo, 2008).

The fluidized bed gasifier, the main subject of this study, was developed prior to World War II for application in coal gasification and was subsequently adapted for the chemical and petrochemical industries (*Centro Nacional de Referência em Biomassa* [CENBIO], 2002).

The technology provides an environment in which solid material – when in contact with the gasification fluid, the heat, and a slight increase in pressure – takes the behavior of a fluid, while the transformation reactions take place (Mendoza, 2009).

In this type of gasifier, the fuel particles are kept suspended in a bed of inert particles, which may be sand, ash or alumina, creating better conditions for heat transfer and homogeneity of temperature in the reaction chamber (CENBIO, 2002).

According to Mendoza (2009), the supporting base of a fluidized bed is usually made of sand, which is responsible for the composition of a thermal reservoir, which attenuates great humidity variations for longer periods. The bed is isothermal, operating at temperatures between 700 and 900 °C (Lora et al., 2012; Rodrigues, 2008).

These gasifiers can be either of bubbling or circulating type. These two types of gasifiers are basically distinguished by the speed the material crosses the bed, which is 1 m/s in case of bubbling fluidized bed (BFB) and 7 to 10 m/s in a circulating fluidized bed (CFB), according to CENBIO (2002).

The BFB gasifier has lower carbon conversion and lower process efficiency compared to CFB. CFB is more efficient due to the recirculation of the solid particles inside the reactor, allowing for a longer residence time of these particles in the reactor and, therefore, for a higher rate of carbon conversion (Melo, 2008). In this type of bed, the gas velocity is high enough to transport all the solids, reaching a higher degree of mixing and heat transfer (La Villetta et al., 2017). A cyclone withdraws from the gas all the unconverted carbon, which flows back through the bed, increasing the efficiency of the carbon conversion process, which exceeds 95% (Gómez, 1996).

In CFB, a greater variety of raw material can be applied. However, as the operating temperatures are lower, more reactive loads are preferred (Quitete & Souza, 2014). As MSW is a more complex raw material for heat treatment processes associated to energy recovery, its use can lead to operational problems and poor final product quality (Intharathirat & Salam, 2016).

As an alternative to MSW high complexity and its effects on gasification systems, refuse-derived fuel (RDF) is used as raw material because of the advantages of having a higher calorific value, being easy to handle, to store and to transport (Intharathirat & Salam, 2016; Massarini & Muraro, 2015).

European Community legislation defines RDF as a solid fuel produced from non-hazardous waste, which can be used in incineration or co-incineration plants (Massarini & Muraro, 2015). RDF typically consists of paper, plastic, textiles, wood and organic matter (Brás et al., 2017; Zhao et al., 2016).

In the scope of the R&D project carried out by Furnas the CFB gasifier is the technology adopted for the construction of the gasification and power generation plant from RDF obtained from MSW processing.

3 Description of the gasification and generation of electric power plant

The power plant will be installed in the municipality of *Boa Esperança*, Brazilian city located in the southwest of the State of *Minas Gerais*, on the banks of Lake *Furnas*.

The estimated population of 40,219 inhabitants (Instituto Brasileiro de Geografia e Estatística - IBGE, 2020) has now an open-air spillway, popularly known as a dump, for the final disposal of MSW collected in the city. The collection takes place on Mondays, Tuesdays, Wednesdays, Fridays and Saturdays, according to official information.

Figure 1 records the current scenario of MSW allocation in the municipality as well as the place for future installation of the plant.

Figure 1. Images of the open-air spillway, or dump, and of the area where the plant shall be built (by the author, 2017).

Figure 2 presents the entire plant where the MSW will be treated. The plant for gasification and electric power generation from MSW consists of: (i) a plant for MSW processing, composed of a unit to receive and treat waste generated in the city for the production of RDF; (ii) a gasification plant, in which the RDF produced will be converted into gas through means of a CFB thermochemical reactor; and (iii) an energy generation plant, in which the produced gas is burned for electricity generation in Rankine cycle.

Figure 2. General layout of the plant (Furnas, 2016, adapted by the author).

The plant operates from class II inert and non-inert, non-hazardous waste, which may exhibit biodegradability, combustibility or water solubility properties (*Associação Brasileira de Normas Técnicas* – ABNT, 2004a).

The technical characteristics of the plant are presented in Table 1 and are based on the proposed design dimension for the project, calculated by the designers and suppliers of the equipment and executed according to a mass and energy balance.

Table 1. Characteristics of the MSW thermochemical treatment plant.

Parameter	Value	Unit
i. MSW processing line		
Hours of operation	10	h
Inlet flow	5,500.0	kg/h
MSW input particle size	*In natura*	
MSW input humidity	50.0	% weight
Output flow	3,005.6	kg/h
RDF final granulometry	25.0	mm
RDF final humidity	15.0	% weight
RDF density	250.0	kg/m^3
ii. Thermochemical reactor		
RDF daily coinsumption	30,055.9	kg
Hours of operation	24	h
RDF mass flow	1,252.3	kg/h
Gasification fluid flow	2,300.9	kg/h
Limestone consumption	5.2	kg/h
Produced gas volume	2,736.4	Nm^3/h
Produced gas mass	3,218.3	kg/h
Ash + particulate + limestone	340.0	kg/h
iii. Electric energy generation		
Installed capacity	1,000.0	MW
Capacity Factor	95.0	%

4 Methodology

In this paper, the assessment of the gasification technology applied to the energy use of MSW is made from a technical and economic viability perspective.

The technical feasibility is analyzed based on the characteristics of the residue, on the efficiency of the gasification process – through tests carried out in a pilot plant and on the estimation of electric power generation in Rankine cycle referenced in the literature. For this estimation, the availability and characteristics of the MSW are considered. It is assumed that these characteristics, as well as the composition of the gas produced, will remain constant throughout the plant operation life.

The economic viability study of the plant implementation was based on the analysis of economic viability indicators: Net Present Value (NPV), Internal Rate of Return (IRR) and Discounted Payback, according to a deterministic study. Subsequently, a univariate sensitivity analysis was carried out on the parameters that have greater influence on the NPV: (i) Minimum Attractiveness Return Rate (MARR); (ii) energy tariff; (iii) installed power; (iv) operating and maintenance costs; and (v) the undertaking unitary cost. This analyze identifies which parameters are more sensitive and therefore require more attention.

In order to carry out these studies, sequential stages of collection, preparation and characterization of the RDF produced from MSW and the gas produced in a pilot gasification plant were required. The objective was to identify the properties of each of these materials, in order to allow an assessment of the gasification process, as well as to determine the potential and the arrangement of the plant, through a mass and energy balance.

Table 2 shows the triggering and description of the methodology execution. The results are the specific objectives through which it is possible to determine the viability of the case studied.

Table 2. Execution of the proposed methodology.

Evaluation	Step	Description	Subsequent step
Technical	A	MSW sampling	B
	B	RDF preparation	C, D
	C	Gasification test	D, E
	D	Characterization analysis	E, F
	E	Obtaining the gasification process efficiency	Result 1
	F	Obtaining the estimated electrical power	Result 2, G
Economical	G	Cash flow modeling	H
	H	Obtaining economic viability indicators	Result 3, I
	I	Sensitivity Analysis	Result 4

Initially, MSW samples were collected either at the landfill currently used by the city or from the street collection activities according to Brazilian Standard ABNT NBR 10007 - Solid Waste Sampling (ABNT, 2004b).

The samples collected in the landfill were obtained from five different random points at a depth of 1.50 m. The street samples were selected in a collection course that covers several neighborhoods, including residential and commercial areas, in order to obtain a representation of the diversity of residues and patterns of consumption and disposal in the city.

Afterwards, MSW samples were treated to suit the laboratory physicochemical characterization analysis and the gasification tests through its conversion into RDF. For this purpose, samples were crushed in a Shredder type crusher to reach 60 mm grain size and were submitted to three sequential grinding stages, due to the high heterogeneity of the residues in terms of grain size.

In order to be suitable for laboratory tests, the samples were again subjected to grinding in a monoaxial knife type crusher, to reach the final granulometry of 10 mm.

The gasification test was performed at an average temperature of approximately 825 °C, in a 1 MW thermal power test plant, located in the municipality of *Guarulhos*, State of *São Paulo*, and owned by Carbogas, the equipment supplier and executor of the plant installation project. See Infiesta (2015) for further details on the gasification test plant.

For the pilot plant gasification tests, the RDF, in bags of approximately 200 kg, were hoisted and inserted by a feed system composed of three feed threads and an infinite screw inside the CFB gasifier.

For 37 hours, over four days, approximately 9 hours of operation per day, the gasification tests were carried out processing 4,109 kg of RDF. The tests' parameters are presented in Table 3.

Table 3. Testing parameters.

Parameter	Value	Unit
RDF average discharge	111.0	kg/h
Processa air average discharge	111.0	kg/h
Moist product gas average discharge	221.0	kg/h
Moist product gas average flow	180.0	Nm^3/h
Average bed temperature	825.0	ºC

The analysis of technical feasibility is verified by determining the suitability of the residue to the gasification process according to its: (i) physicochemical characterization and to how it responds to the gasification test; (ii) by the efficiency of the gasification process, through tests carried out in a pilot plant; and (iii) by the estimation of electric power generation.

The residue and product gas composition is given by elemental analysis, which is an important parameter for the determination of the mass and energy balance of the thermochemical conversion processes (José & Bork, 2011). This analysis identifies the concentration of carbon (C), hydrogen (H), nitrogen (N), sulfur (S) and oxygen (O).

The RDF is subjected to physicochemical and thermogravimetric analysis to determine the calorific value, the elemental composition, as well as ash and humidity content.

The chemical composition of the gas is determined by gas chromatography, with a thermal conductivity detector, and continuous analysis, performed by non-dispersed infrared. It aimed at the determination of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and other chemical substances, as well as thermal conductivity for determination of hydrogen gas (H_2) and calorific value.

The efficiency of a gasifier is defined by its ability to convert solid material, and the energy it contains, into gas (Zhang et al., 2018). Known as the cold gas efficiency (CGE), the gasification process efficiency is assumed by the ratio between the chemical energy of the gas and the chemical energy of the fuel (Syed et al., 2012), given by Equation (1) as described by La Villetta (2017):

$$\eta_{CGE} = 100 \cdot \frac{\left(\upsilon_{gas} \cdot LHV_{gas}\right)}{\left(\upsilon_{RDF} \cdot LHV_{RDF}\right)} \tag{1}$$

Where, η_{CGE} is the cold gas efficiency, in %; υ_{gas} is the moist product gas medium discharge, in kg.h-1; LHV_{gas} is the moist product gas lower heating value, in MJ.kg-1; υ_{RDF} is the RDF medium discharge, in kg.h-1; and LHV_{RDF} is the RDF lower heating value, in MJ.kg-1.

The estimation of the generated electric power aims to extrapolate the data from the experimental analyses to the operating conditions of the plant, in order to evaluate the efficiency of the real plant operation – from the energy point of view. That is, to verify whether the energy produced is greater than the energy required for maintaining all stages of operation, which involve the MSW receiving and its processing, the RDF gasification and, finally, the generation of electric energy.

The electric power in Rankine cycle is estimated based on the thermal power available in the gas and is limited by the design efficiency of the power cycle and the efficiency of the generator set given by Equation (2) as in Carvalhaes (2013):

$$W_{electric} = \eta_{Rankine} \cdot \eta_{generator} \cdot \upsilon_{gas} \cdot LHV_{gas} \quad (2)$$

Where, $W_{electric}$ is the electric power, in kW; $\eta_{Rankine}$ is the efficiency of Rankine cycle; $\eta_{generator}$ is the generator efficiency; υ_{gas} is the moist product gas medium discharge designed for the plant, in kg.h-1; and LHV_{gas} is the moist product gas lower heating value.

In this study, the efficiency of 35% is adopted for the Rankine cycle and, for the generator, an average efficiency of 95%, similar to those adopted by Carvalhaes (2013).

The deterministic economic analysis for the plant implementation is based on the estimated electric energy generation found in the technical study and in the operational aspects of the industrial plant, taking into account a planning horizon of 20 years, term of operation of the plant.

The cash flow for the plant operation period is obtained from the estimation of cost and revenue arising from its implementation, and it allows to see the results of the proposal analyzed through deterministic indicators of economic viability: NPV, IRR and Discounted Payback. In the study, both the cash flow and the MARR do not consider inflation effect.

The cash flow model adopted follows the methodology applied in Probiogás (2016) and is presented in Equation (3).

$$CF = -CAPEX - OPEX + \text{Avoided Cost} \quad (3)$$

In which, CF is the Cash Flow, in R$; CAPEX is the capital expenditure or the initial investment, in R$; and OPEX is the operational expenditure or operation cost, in R$. The avoided cost is equivalent to savings obtained from the energy generated by the plant which is no longer purchased from the electricity grid.

CAPEX comprises: (i) Engineering project with technical specification of the equipment and executive project; (ii) preparation and analysis of the RSU of the region; (iii) acquisition and implantation of the industrial plant; (iv) civil and infrastructure works; (v) commissioning of the industrial plant; (vi) cost of connection to the grid; (vii) training of the workforce for plant operation and assisted operation.

OPEX includes operating expenses which are: (i) MSW processing line O&M costs; (ii) gasification and electric power generation plant O&M costs; (iii) plant insurance; and (iv) sector duties. O&M takes the following into account: expenses with operational and administrative labor, contemplating charges, benefits and other expenses; maintenance costs; indirect costs; and consumables according to Infiesta (2015).

This study considers that there is no electric energy consumption from the power Distribution Company, or sale of the generated energy. Once all the generated energy is consumed by the prefecture, there is no incidence of taxes.

To determine the annual avoided cost it has been considered that the plant operates for 24 hours daily, except for the scheduled maintenance stops, making it up to a total of 8,000 hours of operation per year. The annual avoided cost is given by Equation (4).

$$\text{Avoided Cost} = T_a \; . \; W_{available} \; . \; 8000 \tag{4}$$

When, T_a is the weighted average electricity tariff, in R$/kWh; $W_{available}$ is the electric power available for exporting to the power grid after consumption of the plant. The industrial plant power consumption is calculated in 259.66 kW according to the consumption of each equipment.

The weighted average electricity tariff is determined according to Equation (5), following the methodology adopted in Probiogás (2016).

$$T_a = \frac{780.T_P + 7980.T_{OP}}{8760} \tag{5}$$

When, T_P is the peak tariff, day interval when there is a higher energy demand, therefore, more expensive tariff, in R$/kWh; and T_{OP} is the off-peak tariff, when there is lower energy demand, in R$/kWh.

Univariate sensitivity analysis were performed considering variations in MARR, electricity tariff, available electric power, O&M costs and the unit cost and its effects on the NPV indicator. For this purpose, it has been established that these parameters vary as it follows:

- The MARR varies in a range between 0 e 20%;
- The electricity tariff varies in a range from R$ 0.20/kWh to R$ 0.90/kWh;
- The power varies from 600 kW to the value scaled in the study;
- The cost of O&M varies from R$ 0.17/kWh to R$ 0.27/kWh (Intharathirat & Salam, 2016);
- The unit cost varies in a range from R$ 12 million/MW to R$ 22 million/MW.

5 Results e discussions

According to Zhao et al. (2016), the residue is theoretically feasible for combustion without any auxiliary fuel when: (i) its humidity is less than 50%; (ii) its ash content is less than 60%; and (iii) the carbon content is greater than 25%. These parameters can be understood and used here for a theoretical evaluation of the application of the residue under study in the gasification process, in which partial combustion of the material occurs.

The results of the characterization of the residue are shown in Table 4.

Table 4. RDF characterization.

Parameter	Value	Unit
Carbon	48.7	% weight
Hydrogen	5.7	% weight
Oxygen	30.4	% weight
Nitrogen	0.87	% weight
Humidity	4.7	% weight
Ashes	8.4	% weight
Higher heating value	17.0	MJ/kg
Lower heating value	15.8	MJ/kg

Carbon content gives an idea of the possibility of energy recovery from RDF and shows the potential of the material to produce CO when gasified (Syed et al., 2012). The high carbon content (48.7%) indicates a potential of the material to generate a gas that can be burned to obtain energy, according to (Zhao et al., 2016). In their study, Zhao et al. (2016) consider the carbon content to be high in samples of residues whose composition presents values between 32% and 92%. In addition to the moderate content of hydrogen, between 4% and 14%, according to the same study, the high carbon content denotes a good energy potential. The characterization analyses have also indicated moderate content of hydrogen (5.7%), which demonstrates, according to the criteria of Zhao et al. (2016), the viability of the energy potential observed in the samples.

The lower heating value reinforces this conclusion (15.8 MJ/kg), according to the reference literature, which suggests values not less than 15 MJ/kg (Intharathirat & Salam, 2016).

As for the gas produced, the characterization is presented in Table 5.

Table 5. Produced gas characterization.

Parameter	Continuous	Chromatography	Average	Unit
Methane	6.58	5.09	5.84	% volume
Hydrogen gas	3.38	4.68	4.03	% volume
Carbon monoxide	11.68	9.54	10.61	% volume
Carbon dioxide	11.68	12.23	11.96	% volume
Ethane	-	0.24	0.24	% volume
Ethylene	-	2.14	2.14	% volume
Propane	-	0.74	0.74	% volume
Butane	-	0.08	0.08	% volume
Water	7.98	-	7.98	% volume
Nitrogen gas	58.71	57.28	57.99	% volume
Lower heating value	6.38	5.70	6.04	MJ/Nm^3
Lower heating value	5.19	4.65	4.92	MJ/kg
Molar mass	27.6	27.5	27.5	Kg/mol

According to Begum et al. (2014), through gasification processes it is feasible to obtain a gas with LHV from 4 to 10 MJ/Nm^3, with the possibility of generating electric power.

Sanches et al. (2011) classify gases as follows: (i) low heating value, up to 5 MJ/Nm^3; (ii) medium heating value, from 5 to 10 MJ/Nm^3; and (iii) high heating value, over 10 MJ/Nm^3 and below 40 MJ/Nm^3.

Based on table 4, considering the literature of reference, it is possible to affirm that the produced gas presents medium calorific value and it is able to burn, as verified in the flare during the gasification tests. The observed LHV (6.04 MJ/Nm^3) is consistent with that indicated by the literature, taking into account the gasification fluid used in the process, i.e. atmospheric air. According to Intharathirat & Salam (2016), LHV is allowed between 4 and 7 MJ/Nm^3, for gases obtained from processes that use atmospheric air as gasification fluid.

The chemical composition also shows the presence of a series of combustible gases, such as methane, hydrogen, carbon monoxide and other organic gases, showing that it is possible to obtain a mixture of gases with the possibility of energy exploitation.

The percentage of nitrogen gas in the sample (57.99%) - an inert gas that negatively influences the final gas LHV - can be explained by the use of atmospheric air as the gasification fluid. This percentage could be altered by increasing the calorific value of the gas with the application of different gasification fluids such as water vapor and oxygen gas, for example (Intharathirat & Salam, 2016). However, it is necessary to consider the economic impacts related to the use of these alternatives.

Based on the characterization data of RDF and gas produced (Tables 4 and 5), and gasification test parameters (Table 3), it is possible to determine the efficiency of the gasification process by applying Equation (1).

The CGE resulted in an average value of 62%, within the range estimated in the literature for gasification processes; or between 60 and 90%, according to Reed & Das (1981). Quitete & Souza (2014) indicate a more restrictive value, between 60 and 70%, still served by the study sample, which classifies the process as highly efficient.

The electric power generated in Rankine cycle, given by Equation (2), was estimated in 1,462.45 kW, which is, discounting the power needed to operate the plant, equal 259.66 kW, enough to guarantee the operation of the entire plant and also to provide a net power of 1,202.79 kW for injection in the power distribution network.

From the estimation of energy generation, an economic evaluation of the investment option in the project was carried out. The technical and economic assumptions for deterministic evaluation are presented in Table 6:

Table 6. Parameters used to obtain cash flow (base case).

Parameter	Value	Unit
Available electric power	1,202.79	kW
Useful life of the plant	20	years
Investment	26,372,683.76	R$
Electric energy tariff	0.55	R$/kWh
MARR	9.63	% p.a.
MSW processing line O&M cost	13.49	% of investment in the processing line
Gasification and power generation plant O&M cost	5.57	% of investment in the gasification and electric power generation plant
Plant insurance	0.30	% of investment
Distribution System Use Fee	6.61	R$/kW

The life span follows the equipment supplier specification. The initial investment was obtained through a public call notice. The energy tariff adopted was the seasonal weighted average - green A4, for the voltage range of 2.3 to 25 kV, according to the Energetic Company of Minas Gerais (CEMIG) (2018), following calculations presented in Equation (5). TUSD was also obtained from the same energetic company (CEMIG, 2018). The value of MARR was defined as the resource application rate obtained from methodology of ANEEL (2014). The O&M costs of the MSW processing line and the gasification and power generation plant were determined based on the work of Infiesta (2015). And the insurance of the plant adopted according to the study of Pinheiro (2017) for other plants from alternative sources.

The economic feasibility indicators synthesize the cash flow performance of the option studied, considering the assumptions adopted in the development of this work, and are presented in Table 7, for a MARR of 9.63% p.a. considered in this study.

Table 7. Economic feasibility indicators.

Parameter	Value	Unit
NPV	1,300,838.77	R$
IRR	10.36	% p.a.
Discounted Payback	17.7	years

Results from the Table 7 suggest the economic viability of the project, since: (i) NPV is greater than zero (R$ 1,300,838.77); (ii) The IRR (10.36%p.a.) is higher than the adopted MARR (9.63% p.a.); and (ii) the Discounted payback (approximately 17 years and 8 months) is less than the useful life of the plant (20 years).

To complement this analysis, a sensitivity study was performed on the NPV considering the effect of the variation of the main parameters used in the cash flow modeling. This analysis is done by varying one key parameter at a time, keeping the others constant. In this study, the following key parameters were considered: (i) MARR; (ii) electricity tariff; (iii) installed electric power; (iv) O&M cost; and (v) unit cost of the project.

The NPV behavior as a function of MARR variations is shown in the graph of Figure 3. It can be observed that: (i) the NPV of the project decreases as the discount rate increases, that is, the project profitability decreases; (ii) the project is viable for MARR values less than IRR values (10.63%); and (iii) NPV is very sensitive to MARR changes, so MARR should be well estimated in order to avoid losses in the project profitability.

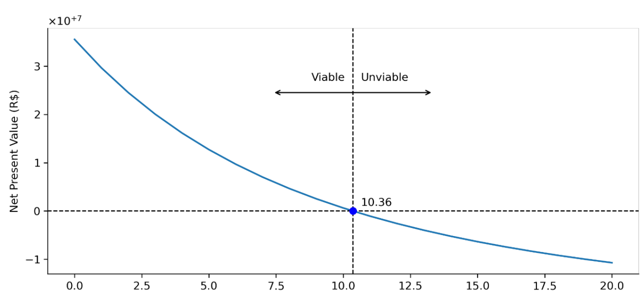

Figure 3. Sensitivity analysis: NPV as a function of MARR.

Figure 4 shows that, regarding the sensitivity to the electricity tariff: (i) NPV tends to increase as the weighted average electricity tariff increases; and (ii) NPV is very sensitive to potential variations in the energy tariff practiced. A variation of 3.6% is enough to make the project unfeasible with tariffs lower than R$ 0,53/kWh. This analysis demonstrates that, both in a more optimistic hypothesis and in a more pessimistic one, a variation of 64% in the value of the tariff causes a variation of 2,256% in the NPV.

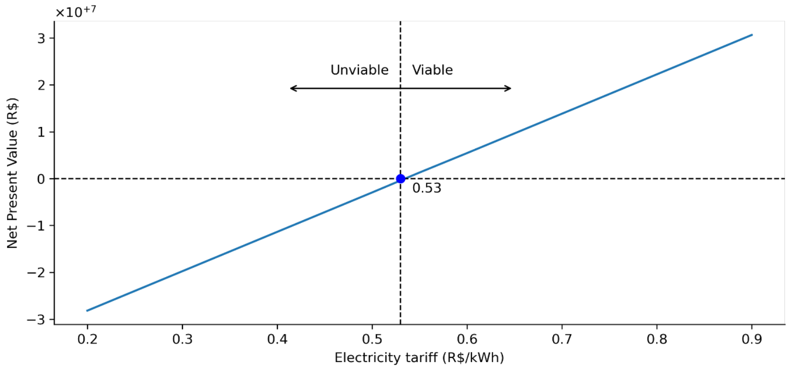

Figure 4. Sensitivity analysis: NPV as a function of electricity tariff variations.

The electric power was also varied in order to analyze its impacts on economic viability. The effects felt in the NPV are shown in Figure 5. From Figure 5 it is possible to see that: (i) The NPV increases as the available power also increases, improving the economic outcome of the project; and (ii) the viability occurs in the case of electric power above 1,169 kW. An alarming fact, since it allows small variations of power in relation to the base case (1,202.79 kW), in order of 3%, without altering the viability of the project.

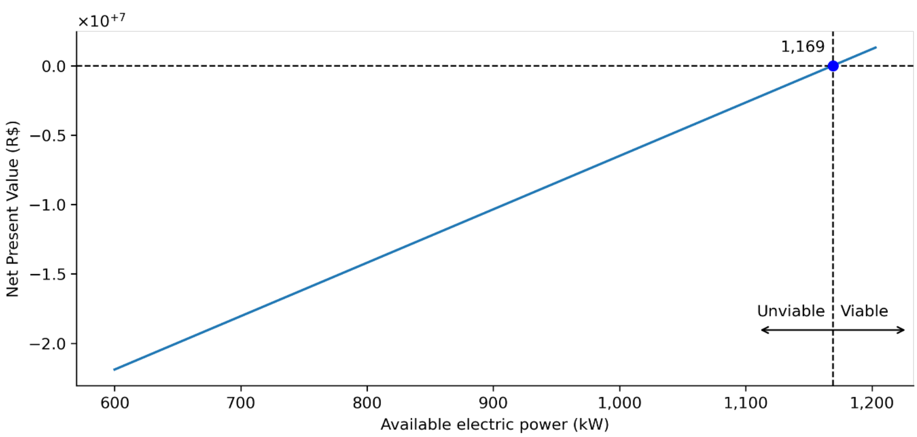

Figure 5. Sensitivity analysis: NPV as a function of electric power variations.

Figure 6 shows the variations in NPV as changes are made at O&M values within the study range. Figure 6 suggests that: (i) the NPV decreases as O&M costs increase, that is, reducing project profitability; and (ii) the project is not feasible when small variations are simulated in O&M costs, making it unfeasible with O&M values higher than R$ 0,18/kWh; that is, a variation of 10.0% in relation to the base case.

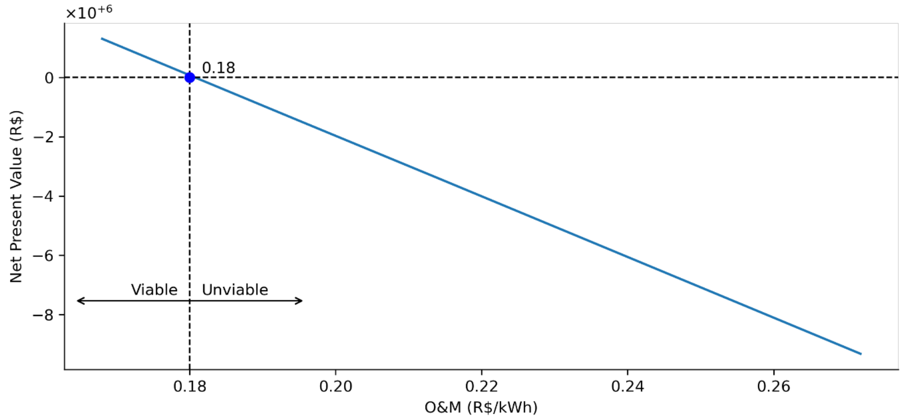

Figure 6. Sensitivity analysis: NPV as a function of O&M cost variations.

The unit cost of the project was estimated at approximately in R$ 18 million/MW. In Figure 7, the sensitivity of the NPV can be examined as a function of unit cost variations, between R$ 12 million/MW and R$ 22 million/MW.

From Figure 7 it can be observed that: (i) The NPV of the project decreases linearly, due to the increase in unit cost; and (ii) NPV assumes values less than zero for a unit cost greater than R$ 18.9 million/MW.

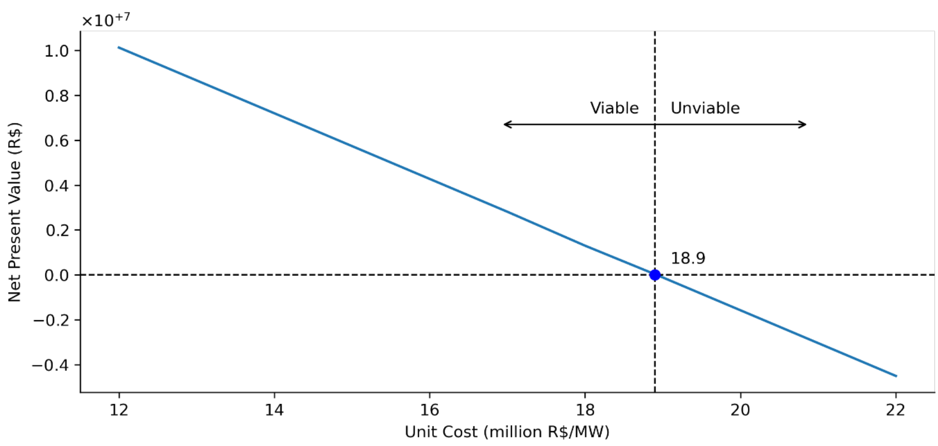

Figure 7. Sensitivity analysis: NPV as a function of unit cost variations.

6 Conclusions

The final disposal of MSW in landfills is still widely applied in Brazil, often without adequate measures to protect both the environment and the population. Energy use through gasification technology is an alternative destination to waste. This technology is capable of providing economic and environmentally adequate usage to waste, as opposed to classic waste final disposal.

This study presented a methodology for technical and economic feasibility analysis of the gasification technology application in the energy use of MSW for the generation of electric energy. In the set of responses to the studies, the technical feasibility of application of the technology was verified both from the perspective of the suitability of the residue to obtaining a gas that can be burned, as well as from the viewpoint of the process efficiency in the conversion of the material into a gas and generation of electric energy.

Although the economic viability of the technology was verified under the conditions studied (base case), it is important to point out that the sensitivity analysis showed that some parameters may affect sensibility of the results more than others. Therefore, in some cases, small variations could make the project unfeasible.

This conclusion is not different from those found in literature, which observe a large number of plants operating in undercommercial conditions. This suggests that in a first moment, the viability of implantation of the technology must be accompanied by incentives, until it reaches the capacity to sustain itself.

From the observation of sensitivity analysis, it is possible to identify some recommendations that can significantly impact the development of this technology in Brazil. Among these recommendations, the following stand out: (i) incentives such as the exemption of taxes for equipment acquisition, reducing unit costs and equipment maintenance costs; (ii) the creation of energy auctions with special tariffs, in order to make sure they can cover the amounts invested; (iii) subsidized interest rates which also guarantee the return on investment; and (iv) actions between public and private entities that encourage the increase in demand enabling scale gains.

This study provides information that can help decision makers and policy makers to make effective and efficient decisions about where resources should be allocated to drive the growth of this type of generation in Brazil.

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