MSW-TO-ELECTRICITY FOR MICROGRIDS: ANALYSIS OF TWO BRAYTON CYCLE TECHNOLOGICAL ROUTES

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RESUMO

À luz do amplo foco nas mudanças climáticas e na conservação ambiental, há um imperativo crítico para transformar os métodos de consumo e produção, especialmente na geração e distribuição de eletricidade. As microrredes têm atraído uma atenção significativa da pesquisa devido aos seus impactos técnicos, econômicos e, principalmente, ambientais, pois essas redes geralmente combinam fontes renováveis e não renováveis para a geração de energia - por meio de diversas rotas tecnológicas -, possibilitando um amplo espectro de combinações. Este artigo explora a utilização de Resíduos Sólidos Urbanos (RSU) produzidos no Estado do Espírito Santo - Brasil, para a geração de eletricidade por duas rotas tecnológicas, ambas utilizando ciclos Brayton, assim denominadas: incineração e gaseificação. Essas rotas foram simuladas com o software de simulação IPSEPro e classificadas com base em sua eficiência, fixando os mesmos parâmetros e a disponibilidade de RSU em todas as simulações. Os resultados mostraram que, com o mesmo fluxo mássico de 33,80kg/s de biomassa com um Poder Calorífico Inferior de 10505kJ/kg, a rota tecnológica de incineração produziu 94,08MW com uma eficiência de 26,50% e a rota tecnológica de gaseificação produziu 67,39MW com uma eficiência de 18,98%, sendo a primeira considerada a rota mais eficiente.

Palavras-chave: microrredes; geração distribuída; gaseificação; incineração; Resíduos Sólidos Urbanos.

ABSTRACT

In light of the extensive focus on climate change and environmental conservation, there is a critical imperative to transform consumption and production methods, especially in electricity generation and distribution. Microgrids have attracted significant research attention due to their technical, economic, and, mostly, environmental impacts for these networks commonly combine renewable and non-renewable sources for power generation – through diverse technological routes –, enabling a large spectrum of combinations for it. This paper explores the usage of Municipal Solid Waste (MSW) produced in the State of Espírito Santo - Brazil, for generating electricity by two technological pathways, all using Brayton cycles, so called: incineration and gasification. These routes were simulated with IPSEPro Simulation Software and ranked based on their efficiency, fixing the same parameters and MSW availability in all simulations. The results showed that, with the same mass flow of 33,80kg/s of biomass with

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a Low Heat Value (LHV) of 10505kJ/kg, the incineration technological route produced 94.08MW with an overall efficiency of 26.50% and the gasification technological route produced 67.39MW with an overall efficiency of 18.98%, with the first being the most efficient.

Keywords: microgrids; distributed generation; gasification; incineration; municipal solid waste.

1. INTRODUCTION

The microgrid concept of decentralised power generation - or generation closer to the consumer - has the potential to positively impact consumers, energy utilities, and the overall electrical system by reducing the burden on centralised power systems, representing an incentive for integrating environmentally friendly generation technologies into the grid - such as solar, wind, and biomass energy - while monitoring the usage of the generated energy, in order to minimise losses and enhance reliability.

An efficient and environmentally approach to incorporating a cleaner energy mix into the power generation system is through the usage of society's waste production. This involves diverting the waste generated by large cities, agricultural and livestock area and others from being disposed of in landfills and stay there. These waste materials have significant calorific value and can be used to generate energy, either where they are produced or in dedicated landfill facilities.

The primary focus of this paper revolves around the usage of Municipal Solid Waste (MSW) produced in the State of Espírito Santo - Brazil, for electricity generation in landfills for self-catering or closer distribution. Two Brayton cycle technological routes for converting waste into energy were compared: incineration and gasification. These routes were assessed and classified based on their efficiency, comparing the amount of energy that can be produced relative to a fixed amount of biomass available, the same for each route.

2. CONCEPTS AND BACKGROUND

2.1. Municipal Solid Waste (MSW) definition

According to Silva (2008) framework, waste is defined as the residual product of human activities, commonly regarded as unwanted by its producers. Solid waste, because of human endeavours, possesses special characteristics that makes it capable of inflicting detrimental effects to both humanity and the environment, particularly when improperly discarded.

MSW includes the following main categories of waste: household waste, public waste (from urban cleaning services such as sweeping, cleaning of public areas and streets), and commercial waste. The generation of MSW is directly linked to the place where human activities are developed, as the generation of waste is directly correlated with the acquisition and consumption of various goods and products (OKAMURA, 2013).

2.2. Environment impact

The massive amount of waste generated by the global population highlights the significant environmental impact associated with the release of Greenhouse Gases (GHG) into the atmosphere through the decomposition of organic waste.

According to the Intergovernmental Panel on Climate Change (IPCC) (2021), Methane (CH_4) has a global warming potential approximately 28 times greater than that of Carbon Dioxide (CO_2), which is considered the primary GHG. This means that emitting just 1 kilogram of CH_4 would have the same impact as emitting 28 kilograms of CO_2 into the atmosphere.

However, not only being a pollutant, Methane also have a relatively High Heating Value (HHV). According to Okamura et al. (2013), the Methane HHV can reach up to 13,249.00 kcal/kg (55,433.81 kJ/kg), which is approximately six times higher than the CO_2 HHV, turning Methane a great fuel for power generation. Currently, most landfills do not harness the produced CH_4 in any form, simply burning the gas in flares, in order to mitigate the environmental impact of the gas.

2.3. Composition and Properties of Municipal Solid Waste

Generally MSW is composed of organic materials (degradable and non-degradable) and inorganic materials. If these inorganic materials are disposed of in the environment, they can take hundreds of years to decompose, and their accumulation contributes to the reduction of landfill lifespan (OKAMURA, 2013).

In order to determine the energy potential of a biomass as a fuel and to be able to thermodynamically assess its utilisation, it is necessary to know its fundamental characteristics, since it is these that help determine the choice of conversion processes.

Among the properties of interest, some stand out depending on the conversion process. If the process is thermochemical, the calorific Heat Value and content of ash and other residues are fundamental characteristics in analysing the conversion. In bioconversion processes, such as anaerobic biodigestion, for example, the moisture content and chemical composition of the material must be properly assessed, as it is a wetter biomass (SAIDUR, 2011).

The routes assessed in the paper are thermochemical conversions, so the Heat Value is a topic to be considerate, since the efficiency of the routes are calculated based on the Heat Value extracted from the composition of the biomass.

The Heat value is expressed in two different forms: High Heat Value (HHV) and Low Heat Value (LHV). HHV represents the total amount of energy contained in the fuel when all forms of moisture, including water resulting from the hydrogen reaction during combustion, are completely condensed. On the other hand, LHV corresponds to the actual amount of energy available in a fuel, disregarding the heat from the condensation of water vapour present in the gases resulting from combustion (DERMIBAS, 2004).

For the presented paper, the LHV was obtained trough the simulations and was the one used for the overall efficiency calculations.

2.4. Brazil's Municipal Solid Waste Production

The composition of waste generated can vary depending on the population and level of industrialisation in each region. According to ABRELPE (short in Portuguese for: Brazilian Association of Public Cleaning and Special Waste Companies) (2023), around 45.3% of the Brazilian MSW composition is organic matter, followed by plastic (16.8%), paper and cardboard (10.4%) and other materials.

ABRELPE recently published the latest revised report, "Overview of Solid Waste in Brazil," which includes data from the year 2022. The previous survey (base-year 2021) indicated that during the two years of the pandemic, 2020 and 2021, household waste generation in the country increased by approximately 4%, reaching an average of 1.07 kg per inhabitant per day. In 2022 survey, the waste panorama showed some improvement, with a slight reduction in per inhabitant waste production to 1.04 kg per person per day. This translates to approximately 81.9 million tons of waste generated throughout the year.

Despite the produced amount, the actual volume of waste collected reaches 76.1 million tons per year, representing a coverage of approximately 93%. The remaining waste, which amounts to around 5.8 million tons per year - equivalent to almost 3,000 Olympic-sized swimming pools - is not removed from households and is instead disposed of in vacant lots, rivers, lakes, or simply incinerated in open-air settings (ABRELPE, 2023).

Also according to the survey, Brazil's Southeast region stands out in terms of urban waste collection rates, reaching an average of 98.6%. From this collected waste, the majority amount (61%) continues to be sent to registered sanitary landfills, with 46.4 million tons disposed of in an environmentally appropriate manner in 2022. In the Southeast region, the percentage is above the national average, reaching approximately 74.3% (ABRELPE, 2023).

2.5. Production of MSW on the State of Espírito Santo

According to the latest census data from the Brazilian Institute of Geography and Statistics (IBGE, in Portuguese) (2022), released in June 2023, with data from the 2022 base-year, the state of Espírito Santo has a population of 3,833,486 inhabitants.

Considering the population just mentioned and the average MSW production presented in section II-D, we can estimate a daily average waste generation of 3,986.82 tons for the year 2022. Taking into account the collection rates of 98.6% and the percentage of 74.3% for correct destination of the collected waste, both mentioned in section II-D for the Brazilian's Southeast region, where Espírito Santo state is located, we can estimate that approximately 2,920,740.34 tons of MSW produced were collected and sent to landfills in 2022.

For the purpose of this paper, it was assumed that all waste collected in the state is centralized in a single location, which poses logistical challenges. In the state of Espírito Santo, only five municipalities have licensed landfills (either public or private): Aracruz, Colatina, Cariacica, Vila Velha, and Cachoeiro de Itapemirim. After analyzing the logistical connections between these municipalities, considering factors like population and daily waste volumes received at each landfill, it is suggested that areas such as Cariacica and Aracruz hold greater potential for implementing the technological energy conversion methods discussed in this article. This is because, even if a larger quantity of waste is taken into account in the calculations, the efficiency of the methods remains proportional to energy generation. Therefore, the efficiency will remain consistent, even with a smaller quantity of waste, as the energy generation will decrease, ensuring the proportionality of the calculations conducted.

2.6. Technological Routes (TR)

As mentioned above, it is necessary to know the energy characteristics of biomass in order to know the best energy conversion route. Other factors, such as the amount of biomass available, environmental and location restrictions, as well as the desired form of energy, are fundamental characteristics for a good performance of the conversion system.

According to Goldemberg (2009), there are various TRs to which waste can be subjected to harness and generate electricity, and, in some cases, process heat as well. This paper addresses and analyses two routes via Brayton cycles: incineration and gasification, for energy generation in landfills.

2.6.1. Incineration TR

The Incineration TR involves burning biomass in combustion chambers, using the heat produced to heat ambient air through a heat exchanger, used to activate a gas turbine connected to an electric generator to produce energy, in a process so called EFGT Cycle - External Fire Gas Turbine Cycle (LEMOS, 1997).

In general, solid biomass combustion systems have a generating capacity of around 50MW, which, combined with the low combustion temperature, are the main reasons why the overall efficiency of these systems is between 15% and 30%. These values are considered low when compared to those that can be obtained in power stations using coal, where the total efficiency of the system can be around 40% (SAIDUR, 2011).

For this TR, the biomass is fed into a combustion chamber and is burned, producing heat that is directed to a heat exchanger, where it meets the ambient air that passes through a compressor to increase the pressure. After being heated, the air flows into a gas turbine, where expansion occurs, resulting in power generation. This power drives a shaft connected to an electric generator, which converts mechanical power into electrical power. The exhaust gases from the turbine are sent back to the combustion chamber to assist in the biomass burning process.

2.6.2. Gasification TR

The Gasification TR involves placing dried organic matter in a device called Gasifier and carrying out a process of controlled combustion, which generates synthesis gas or simply syngas. The syngas can be used in gas turbine cycles or internal combustion engines, provided it is purified, as this process generates a certain amount of tar, depending on the type of gasifier used (ANDRADE, 2007).

The fuel generated can be used to generate heat, by burning it directly, or to produce electricity in more complex systems, when injected into Otto cycle engines and/or gas turbines (WETTERLUND, 2010). If gasification employs steam cycles for power production, the overall efficiency typically ranges from 9% to 20%. When a gas engine is utilized, the overall efficiency hovers around 13% to 24%, which still falls short of achieving higher efficiencies compared to direct incineration. It's only with the implementation of a Combined Cycle Gas Turbine (CCGT) that better results can be achieved, ranging from approximately 22% to 26% (PANEPINTO, 2014).

For this TR, generaly the biomass is fed into the gasifier through an inlet, while oxygen or ambient air is introduced through other. The process of controlled combustion is initiated, resulting in the production of syngas. After undergoing desulfurization and the removal of particulates and ashes, the syngas is sent to a combustion chamber, where it meets the pressurised ambient air from the compressor and is burned. Following combustion, the exhaust gases pass through the gas turbine, driving the shaft and activating the electric generator. After passing through the gas turbine, the remain air is released back into the environment.

3. METHODOLOGY

Based on the data obtained regarding MSW generation in Espírito Santo state and its composition, simulations were conducted for each route using the IPSEpro Simulation Software in order to evaluate the best TR for the implementation of efficient microgrids for non-centralised energy generation, considering the following parameters.

3.1. IPSEPro Software

IPSEpro serves as a comprehensive software solution designed for the computation of heat and mass balances, along with process simulation. It encompasses an array of software modules that facilitate the development of process models suitable for a diverse spectrum of applications, offering seamless utilization of these models across the entire lifecycle of process plants. These models are categorized into libraries such as concentrating solar power, refrigeration processes, desalinization processes, low-temperature processes, and the Advanced Power Plant library, which is specifically employed in this research.

3.2. Simulation inputs

For both simulations, the same composition of MSW were used. The values of mass fraction of Carbon (C), Oxygen (O), Hydrogen (H), Nitrogen (N), Sulphur (S), Water and Ash were calculated based on the MSW composition, resulting in the following data: C: 0.21kg/kg, O: 0.25kg/kg, H: 0.07kg/kg, N: 0.01kg/kg, S: 0.01kg/kg, Water: 0.30kg/kg and Ash: 0.15kg/kg.

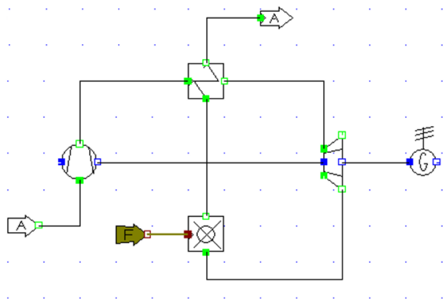
Some pressures, temperatures, and mass flow, as well as equipment mechanical, isentropic and electrical efficiencies were set the same for all the simulations, to provide an equal environment for the results, as follows:

- The input of ambient air is set at pressure of one bar and temperature of 25°C.
- The fuel (biomass) mass flow is set at 33.80 kg/s, calculated by section II-E.
- The isentropic efficiency of the compressor is set at 85%.
- The isentropic efficiency of the gas turbine is set at 90%.
- Both mechanical and electrical efficiencies of the generator are set at 98%.
- The combustor output temperature is set at 1,100°C.
- The pressure of output air is set at one bar.

3.3. Simulation models

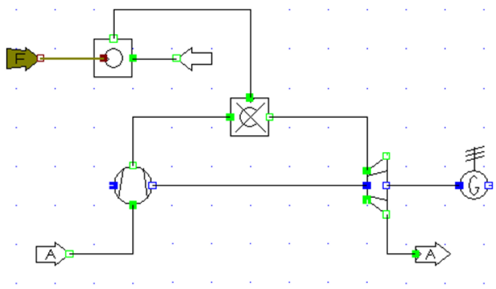
For the incination TR, the following model (figure 1) was used to simulated and obtain the data used on the calculations.

Figure 1. Schematic Model – Incineration



For the gasification TR, the following model (figure 2) was used to simulated and obtain the data used on the calculations.

Figure 2. Schematic Model – Gasification



4. RESULTS

4.1. Incineration

Trough the simulation, the mass flow of biomass cited in section III-D can generate 94,082kW (94.08MW) of power. The LHV of the biomass were collected by the simulation with a value of 10,505kJ/kg. Multipling the LHV by the biomass mass flow ($\dot{m} = 33{,}80\ kg/s$), the input heat results in $Q_{in} = 355{,}069\ kJ/s$.

With the data cited before, it is possible to calculate the efficiency of the TR by dividing the produced power (W_{out}) for the input heat (Q_{in}), then multiplying the result for 100 to turn it into percentage, as shown in (I):

$$\eta = \frac{W_{out}}{Q_{in}} \times 100 = \frac{94{,}082\ kW}{355{,}069\ kJ/s} \times 100 = \mathbf{26,50}\% \qquad \textbf{(I)}$$

4.2. Gasification

Trough the gasification simulation it is possible to generate 67387kW (67.39MW) of power. The input heat is the same as before, as the simulation uses the same MSW composition and parameters in both cases.

With this data it is possible to calculate the efficiency of the TR, the same way as the previous TR, as shown in (II):

$$\eta = \frac{W_{out}}{Q_{in}} \times 100 = \frac{67{,}387 kW}{355{,}069\ kJ/s} \times 100 = \mathbf{18.98}\% \qquad \textbf{(II)}$$

4.3. Comparison of Results

The results are displayed below (Table 1):

Table 1. Results comparison

METHOD	MSW AVAILABILITY (kg/s)	POWER GENERATION (MW)	OVERALL EFFICIENCY (%)
Incineration	33.80	94.08	26.50
Gasification	33.80	67.39	18.98

When comparing the efficiency of both TR, based on the same availability of biomass, incineration shows a notable advantage in terms of efficiency and energy generation capacity, demonstrating that it is able to extract a significantly higher percentage of the energy contained in the fuel, resulting in a substantially higher production of electricity for the same amount of input.

The overall efficiencies observed align well with established ranges in the literature. As mentioned in section 2.6.1, the typical overall efficiency of incineration systems ranges from 15% to 30%. The findings presented in this paper demonstrate an overall efficiency of

26.50%, aligning closely with similar studies within the same evaluation. Similarly, in section 2.6.2, the average overall efficiency for gasification, employing a gas engine, can range from 13% to 24%. The outcomes reported in this paper indicate an overall efficiency of nearly 19%, which also falls within the scope of other studies evaluating the same technological approach.

5. CONCLUSION

Based on the data and calculations performed, it can be observed that, among the analysed routes, the incineration route exhibits the highest efficiency and energy production considering the same conditions and biomass availability. Other power cycles could be used to improve even more the efficiency of the incineration, such as burning in boilers or using the exit gas for re powering.

Despite being a technology that is still in its early stages and relatively costly, gasification also showed satisfactory results, indicating a potential path to follow as this technology matures. This emphasises the importance of developing technologies that are more efficient for energy generation, with gasification coming as a promising option for promoting a more sustainable energy transition.

In both cases, the waste can be used at local landfills and the energy produced can be used as a microgrid for self-catering or it can be transmitted for close locations. For enhancing power generation, a co-generation system could be used to avail the remain heat, since it is released to the ambient over 500°C - a significantly high temperature.

In conclusion, this article has provided a comprehensive comparison of different technological routes for energy generation and has shed light on their respective strengths and limitations. Incineration emerged as the most promising route, displaying its efficiency in terms of energy production per unit of biomass, but gasification also showed its potential.

The findings of this study contribute to the ongoing efforts in finding sustainable solutions for non-centralised energy generation, emphasising the importance of considering not only energy output, but also environmental considerations and resource efficiency in the energy systems.

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