Electricity and Hydrogen Generation from Food and Vegetable Wastes – Technical and Economic Analysis

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Abstract. The city of Guaratinguetá, Brazil, produces 104 tons of MSW daily, 45.3% of which is its organic fraction, and the rest is divided between recyclable material and waste without use. This study proposes the calculation of the biogas production potential from the anaerobic digestion of the Organic Fraction of Municipal Solid Waste (OFMSW). This fraction is mainly composed of food residues, such as fruits and vegetables, as well as paper and cardboard, among others, being a compound able to be processed in a biodigester. A production potential of 3,1 Nm^3 of biogas per day, or 3,6 kg/day, was calculated. An electricity generation potential of 6.3 MWh/day was calculated. Considering the use of all this electrical potential in a water electrolysis process, a production potential of 107 kg/day of electrolytic hydrogen was calculated. An economic analysis of electricity generation is carried out, resulting in a cost of electricity between 34.7 and 41.2 USD/MWh, depending on the interest rate applied. The payback of the investment in electricity generation was calculated between 3 and 4 years, considering the local electricity tariff of 74 USD/MWh.

Keywords: municipal solid waste · food wastes · biogas · power generation · hydrogen

1 Introduction

In 2018 in Brazil, about 40% of MSW collected in 2018 was disposed of inappropriately in open air dumpsites, with 53% of municipalities disposing of their MSW in open air dumpsites or controlled landfills, while 46.1% disposed of it in sanitary landfills [1].

Anaerobic Digestion (AD) of organic material in dedicated anaerobic reactors results in the production of biogas, with a high concentration of methane, which can be used as a fuel in the generation of electricity, mechanical work or heat. Thus, this process is

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an attractive way to treat organic waste, since it allows the energy use of its biomass contained and therefore a renewable energy resource.

The present work analyzes the possibility of using all the organic waste contained in the MSW generated in the city of Guaratinguetá, Brazil, aiming at the production of biogas through anaerobic digestion. In this city 104 tons of MSW are produced daily.

According to data from the Brazilian Association of Public Cleaning Companies and Special Waste (ABRELPE) [2], 45.3% of the MSW mass in Brazil is composed of organic material, 28.6% of recyclable materials (paper, metals, glass, wood, plastics) and 26.1% of others (cloths, rags, rubbers and other materials).

Assuming that the complete sorting of MSW generated in Guaratinguetá is done, the organic material is separated from the others by mechanical processing, and is then called Organic Fraction of Municipal Solid Waste (OFMSW). Household food scraps, leftovers from pruning and open fairs, and horticultural discards are the main components of OFMSW. For this specific type of waste, the results of the physical-chemical characterization performed by [3] with samples of MSW composed of 35% fruit, 35% other vegetables, 20% cardboard and 10% plastic are used.

The potentials for biogas production from the anaerobic digestion of OFMSW, as well as for electricity generation through the combustion of this gas in generator sets with Brayton cycle Gas Turbines (GT) will be calculated using the Eqs and relationships given. The potential for hydrogen production is then calculated with the full use of this electricity in an electrolysis process.

2 Methodology

2.1 Technical Analysis

Biogas Production. Considering the composition given by ABRELPE [2], 45.3% are apt to compose a digestible material, here called OFMSW. It is assumed that all this material will be processed for the typical conditions of anaerobic digestion in reactors developed specifically for this purpose. The potential biogas production can be calculated, as shown below, with Equations adapted from [4]. Equation 1 gives the amount of available OFMSW after sorting and treatment of MSW:

$$OFMSW_T = MSW_T - MSW_{LF} - MSW_{rec} \tag{1}$$

where MSW_T is the total colected MSW (t/day), MSW_{LF} is the total part of MSW sent to the landfill (t/day) and MSW_{rec} is the total MSW sent to recycling (t/day). Equation 2 gives the amount of OFMSW available after MSW sorting and treatment:

$$OFMSW_{SV} = OFMSW_T \times \eta_{VS} \tag{2}$$

where $OFMSW_{SV}$ is the total (t/day) Volatile Solids (VS) contained in the organic fraction of the waste and η_{MV} is percentage of volatile matter (% VS / VT). The biogas generation potential is given by Eq. [3]:

$$m_{Bio} = OFMSW_{SV} \times \eta_{Bio} \tag{3}$$

where m_{Bio} (kg/dia) is the daily biogas produced, η_{Bio} (kg_{biogas}/tSV) is the conversion ratio of SV into biogas. The biogas is assumed to have a volumetric composition of 65% CH_4 and 35% CO_2, as verified by [5].

Electricity Generation. Figure 1 shows the components of the plant to generate electric power and biohydrogen from the biogas produced in the biodigester with the AD of OFMSW. The desulfurization of biogas is performed in the component indicated with the letter "L", following to the combustion chamber (CC) of the gas turbine, with mechanical shaft power P_{TG} (kW). The generator converts this mechanical power into daily E_{el} generation (MWh).

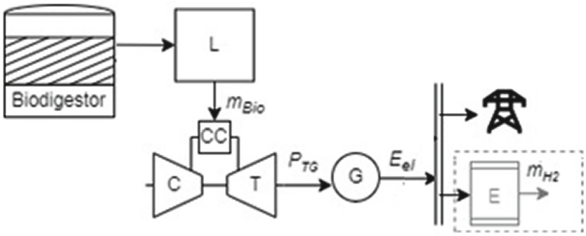

Fig. 1. Electricity generation and hydrogen production plant (elaborated by the author).

Adapting equations from [6], the energy generation is calculated with Eqs. 4 to 6:

$$E_{el} = P_{el} * t_{op} \tag{4}$$

$$P_{el} = \eta_{ge} * P_{GT} \tag{5}$$

$$P_{TG} = \eta_{T,GT} * m'_{Bio} * LHV_{Bio} \tag{6}$$

where P_{TG} is the mechanical shaft power of TG [kW], LHV_{Bio} Lower Heating Value of biogas [kJ/kg], m_{Bio} the mass flow of biogas [kg/s], $\eta_{T,TG}$ the thermal efficiency of GT [%] and η_{ge} conversion efficiency into electric power of the power generator [%].

Hydrogen Production. The case study for electrolytic hydrogen production considers the electrolyzer connected to the generator output bus, consuming the electrical energy generated by the plant. Figure 2 shows the electrolyzer (E), in which electric energy E_{el} (MWh) is consumed, originating quantities of hydrogen (m_{H2}) and oxygen (m_{O2}) from an input mass of water (m_{H2O}). The electrolysis reaction is described as a stoichiometric equation ($H_2O \rightarrow H_2 + ½ O_2$). Considering an efficiency of 57%, the hydrogen potential can be calculated with Eq. 7 [7]:

$$\eta_{ele} = \frac{\dot{m}_{H_2}.LHV_{H_2}}{P_{el,eletr}} \tag{7}$$

where m_{H2} is the massic flow of hydrogen from the electrolyzer (kg/s), LHV_{H2} is the hydrogen Lower Heating Value (120 MJ/kg) and $P_{el,eletr}$ is the electric power of the electrolyzer (MW).

2.2 Economic Analysis for Bioelectricity Generation

Using the methodology proposed by Silveira, Tuna and Lamas and Lamas [8] the cost of electric power generated by a generating plant is calculated with Eq. 8:

$$C_{el} = \left(\left(I_{pl} \times f\right) / \left(365 \times t_{Op} \times P_{el}\right)\right) + CO\&M \tag{8}$$

where I_{pl} is the total investment [US$], f is the annuity factor [1/year], t_{Op} is the daily operating time [h/day], P_{el} is the electric power [kW], and $C_{O\&M}$ is the operating cost [US$/kWh], assumed as 3% of the investment. The annuity factor is the value of a cash flow that produces profit in a given period, the annuity factor is given by Eqs. [7] and [8]:

$$f = \left(q^k \times (q - 1)\right) / \left(q^k - 1\right) \tag{9}$$

$$q = 1 + r/100 \tag{10}$$

where f is the annuity factor [1/year], k is the number of years [years], and r is the annual rate of interest [%].

3 Results and Discussion

3.1 Technical Analysis

With Eq. [1] a quantity of 47.3 ton/day of OFMSW was calculated. Considering a η_{SV} of 18%, an amount of 8.51 t/day of volatile matter is obtained, which can be converted into biogas. With Eq. [3], taking a conversion rate of 367 m^3/t_{VS}, a potential of 3,125 Nm^3/day of biogas is calculated.

Through Eq. [6], considering a thermodynamic efficiency of the gas turbine of 33% ($\eta_{T,TG}$) and efficiency of the generator (η_{ge}) of 95% [9], a flow of 0.0556 kg/s of biogas over an operation time (t_{Op}) of 18 h/day, and with the LHV of biogas calculated as 20.2 MJ/kg, a power (P_{TG}) of 352 kW is obtained. With Eqs. [5] and [6], using a 95% efficiency of the generator, a total of 6.34 MWh of daily electric generation potential is obtained.

By the Eq. [8] it is possible to calculate the daily mass of hydrogen produced by electrolysis, considering that all the electricity generated was destined to this process. Considering the electrolyzer's efficiency of 57% [10], was calculated a daily production of 107 kg of hydrogen through the electrolysis of water with electricity generated.

3.2 Economic Analysis of Electricity Production

The costs of the generated electricity were calculated varying amortization periods up to 20 years. An investment cost of 720 USD/kW was used for the TG and 375 USD/ton/day the investment in the biodigester, in relation to its daily processing capacity. The O&M cost of the TG corresponds to 75 USD/kW/year while for the anaerobic reactor this cost is 38 USD/ton/day capacity. Figure 2 shows the electricity costs as a function of the

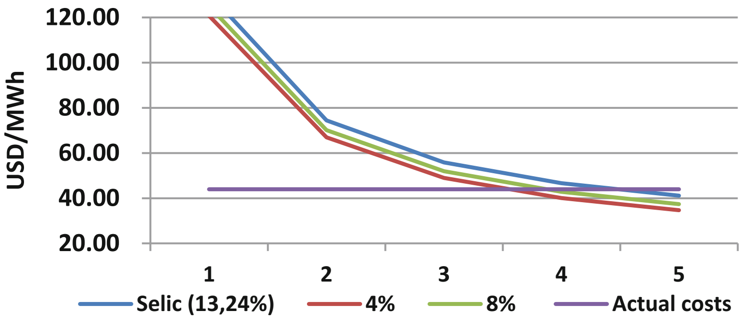

Fig. 2. Electricity costs (USD/MWh) and amortization periods

amortization time, using rates of 4% and 8% per year, and the basic interest rate of the Brazilian economy [11], of 13.24% .

Thus, for 5 years, a cost of 34.68 USD/MWh was reached for an interest rate of 4%, 37.41 USD/MWh for an interest rate of 8% and 41.16 USD/MWh for the SELIC rate of 13.25% y.. Compared to the current local Electric Tariff (ET) of 43.98 USD/MWh [12], the paybacks for the 3 scenarios are between the 4th and 5th year.

4 Conclusions

Considering the daily generation of MSW in the city, it was calculated a potential production of 3,1 Nm^3/day of biogas from the AD of the OFMSW, equivalent to 3,6 ton/day of biogas with a LHV of 20.2 MJ/kg. Considering the burning of this gas in a gas turbine it is possible to generate 6.34 MWh/day, which means a generation of 60.96 kWh per ton of collected MSW.

A total of 107 kg/day of hydrogen can be produced with this electrical potential. In this way, it was possible to estimate the potential for electricity generation from the AD of the OFMSW of a medium-sized municipality, which is of public interest, both in the energy sphere, since it is possible to generate this energy close to the consumer center, and also environmentally, since methane is no longer emitted into the atmosphere.

The cost of generating this electricity was calculated as being between 34.7 and 41.26 USD/MWh. If compared to the local Electricity Tariff, the payback of the investment in electricity generation will occur between the 4th and 5th year.

This is, therefore, a case where the issue of MSW can be addressed not only as a sanitation or public health problem but, on the other hand, as a profitable opportunity to generate renewable electricity, as well as the possibility of enabling the production of an emerging energy vector with broad applications, such as hydrogen.

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