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Exergetic evaluation of a biomethane production route from biogas

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Abstract:

The rising demand for sustainable energy and the challenge of managing urban solid waste have led to the use of anaerobic digestion as an alternative for producing biogas, a renewable fuel rich in methane. However, unprocessed biogas contains impurities that compromise it for more sophisticated applications, such as fuel for vehicles, thus requiring a purification process to produce biomethane. Within this context, this study presents an exergetic evaluation of a biogas processing route using municipal solid waste, focusing on the analysis of irreversibilities associated with the involved processes, as well as their energy consumption, to determine whether the processing is exergetically viable. The route analyzed corresponds to the biogas production plant at the Institute of Energy and Environment of the University of São Paulo (IEE-USP) in Brazil, consisting of a direct contact cooling system, a desulfurization unit, multistage compressors, a membrane separation system, a chiller, and a final compression stage. The thermodynamic modeling was performed using the Engineering Equation Solver (EES) software, considering mass, energy, and exergy balances, with calculations of the physical, chemical, and mixing exergy fractions in line with the Second Law of Thermodynamics, thereby enabling the quantification of exergy loss in each component, energy consumption, and exergy efficiency. The results indicate that the main sources of exergy loss in the process are those directly associated with methane separation, while the purification and storage processes account for a smaller portion of the loss. The energy requirement of the upgrading process is 41.3 kW, while the effective exergy gain in the purified biomethane is only 8.3 kW, resulting in an overall exergy efficiency of 20.2%. Moreover, for the system to operate self-sufficiently, approximately 23,6% of the biogas produced must be directed toward electricity generation. Thus, from an exergetic perspective, this route is not the most efficient for maximizing the production of useful work, since it leads to the loss of exergy by concentrating the fuel. However, from an economic and mobility perspective, biogas processing is significant, as it enables the production of highly pure biomethane, suitable for vehicle use, contributing to waste recovery and emission reduction through the replacement of fossil fuels.

Keywords:

Thermodynamics; Energy; Exergy; Sustainability; Biomethane.

1. Introduction

The growing challenge of managing urban solid waste, coupled with the increasing demand for sustainable energy, has driven efforts to valorize wastes by recovering energy through anaerobic digestion. Moreover, the conversion of organic matter into biogas and biofertilizer promotes a circular, sustainable energy cycle [1,2]. The biogas derived from anaerobic digestion consists mainly of methane (~60% in mol) and carbon dioxide (~40% in mol), as well as other gases that appear in residual concentrations [3]. This process not only offers a renewable alternative to fossil fuels but also contributes to reducing greenhouse gas emissions and to the upcycling of organic waste [4,5].

However, biogas contains impurities such as H_2S, H_2O, NH_3, and other gases, which can compromise equipment efficiency and the final product's quality. Therefore, for this biofuel to be used in applications such as vehicle biofuel, or injection into the methane gas grid, it requires a process of purification, dehumidification, compression, and membrane separation. These processes consume energy and must therefore be evaluated thermodynamically, as they can result in exergy loss [6-8].

The passage of biogas through a dehumidifier is crucial, as it is a cooling and condensation system that removes the excessive moisture present in the biogas, which can cause corrosion and operational problems in equipment, as well as particulate impurities [9-11]. Additionally, the removal of ammonia (NH_3) is essential in biogas purification, as it is corrosive and toxic, potentially causing damage to equipment and compromising the final quality of biomethane [12]. Furthermore, it is important that biogas passes through a desulfurizer, where hydrogen sulfide (H_2S) is removed; this is a corrosive and toxic gas that can damage system components and is also an atmospheric pollutant [13]. Finally, it is essential that the biogas also pass through membranes that allow for the selective separation of methane (CH_4), carbon dioxide (CO_2), and other residual gases [14].

The article by Pinheiro et al. [15] presents an exergy analysis of an actual biogas plant located at the Institute of Energy and Environment of the University of São Paulo (IEE-USP), focusing on the food waste digestion process. The study examines the irreversibilities of the facility based on the exergy of the substrate and the final products (biogas, digestate, electrical energy, and heat). However, the subsequent processes of biogas purification, compression, and separation, which are essential for obtaining high-quality biomethane, were not explored. This study is a logical continuation of the separation of biogas into biomethane and carbon dioxide.

An exergetic analysis is necessary to quantify the irreversibilities of producing biomethane for transportation or direct use of biogas for electrical energy. Since it allows the identification of the sources and magnitudes of irreversibilities, which are losses of work potential, highlighting opportunities for optimization and reduction of energy consumption [16]. One of the advantages of studying exergy is the ability to identify which processes have more irreversibilities and use better the quality of the energy of any input, for instance the ethanol from sugarcane that is decarbonized as well as the bioenergy [17], although the exergy content of solar radiation could be better used if used for direct energy supply [18].

Therefore, in the context of the Sustainable Development Goals (SDGs), by addressing issues such as clean energy generation (SDG 7), reduction of greenhouse gas emissions (SDG 13), sustainable waste management (SDG 11), and sustainable agriculture through the production of biofertilizers (SDG 2), this analysis aims to determine the energy and exergetic efficiency of the complete biogas purification and compression system [19]. This study aims to evaluate, from the perspective of the First and Second Laws of Thermodynamics, the processes involved in the processing of biogas produced at the biodigestion plant for urban solid waste (USW) at the Institute of Energy and Environment at USP. This plant aims to process biogas, a mixture of methane and other gases, into biomethane stored at high pressure, thereby enabling its direct use in automobiles. These analyses allow us to understand which stages involve the greatest exergy losses and, therefore, offer the greatest potential for optimization, as well as the energy requirements of the compression and separation system. The answers to these questions can assist in technical decisions for implementing more efficient systems with lower environmental impact and higher energy return.

2. Materials and methods

This study continues the analyses conducted by Pinheiro et al. [15], who performed an exergetic analysis of a biodigester system that produces biogas, which is then used as fuel for a generator to produce electricity. Using USW to produce electricity is a sustainable and exergetically attractive solution, given that this waste is typically disposed of in dumps or landfills [15]. Figure 1 illustrates in detail the process flow analyzed in [15]. Thus, the exergy contained in this waste is concentrated in fuels, reducing the loss of this energy source's capacity to generate work.

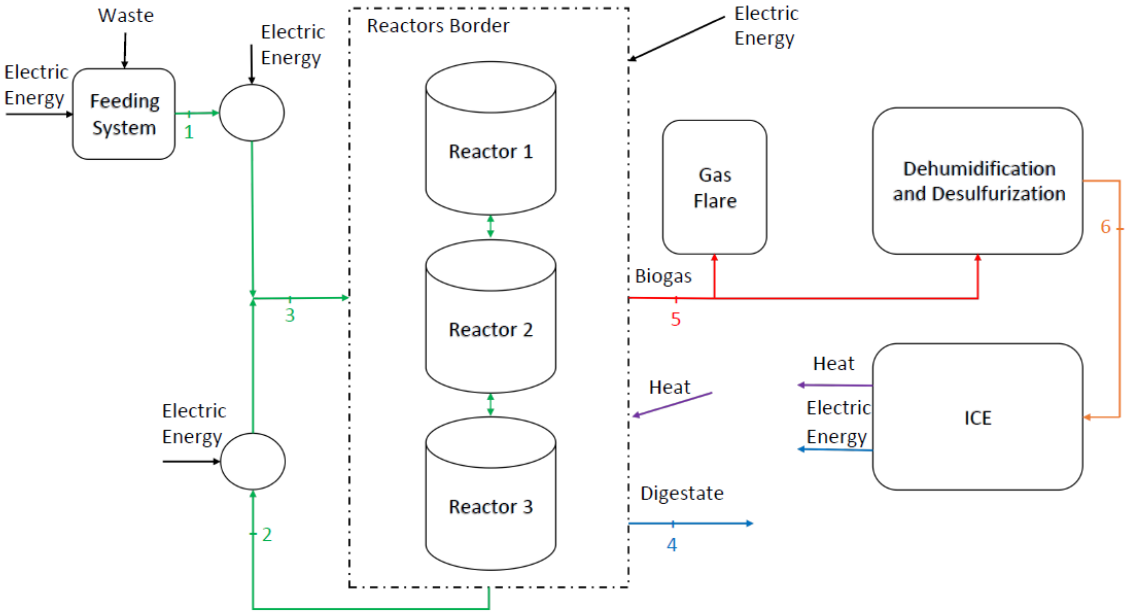

Figure 1. Process flowchart of the Biodigester. Source [15]

In contrast, Figure 2 presents the exergy flow using a Grassmann diagram, illustrating the irreversibilities and the transformations of each process analyzed in [15]. This figure complements the results obtained in the study, providing an analysis of the discharge to the tank.

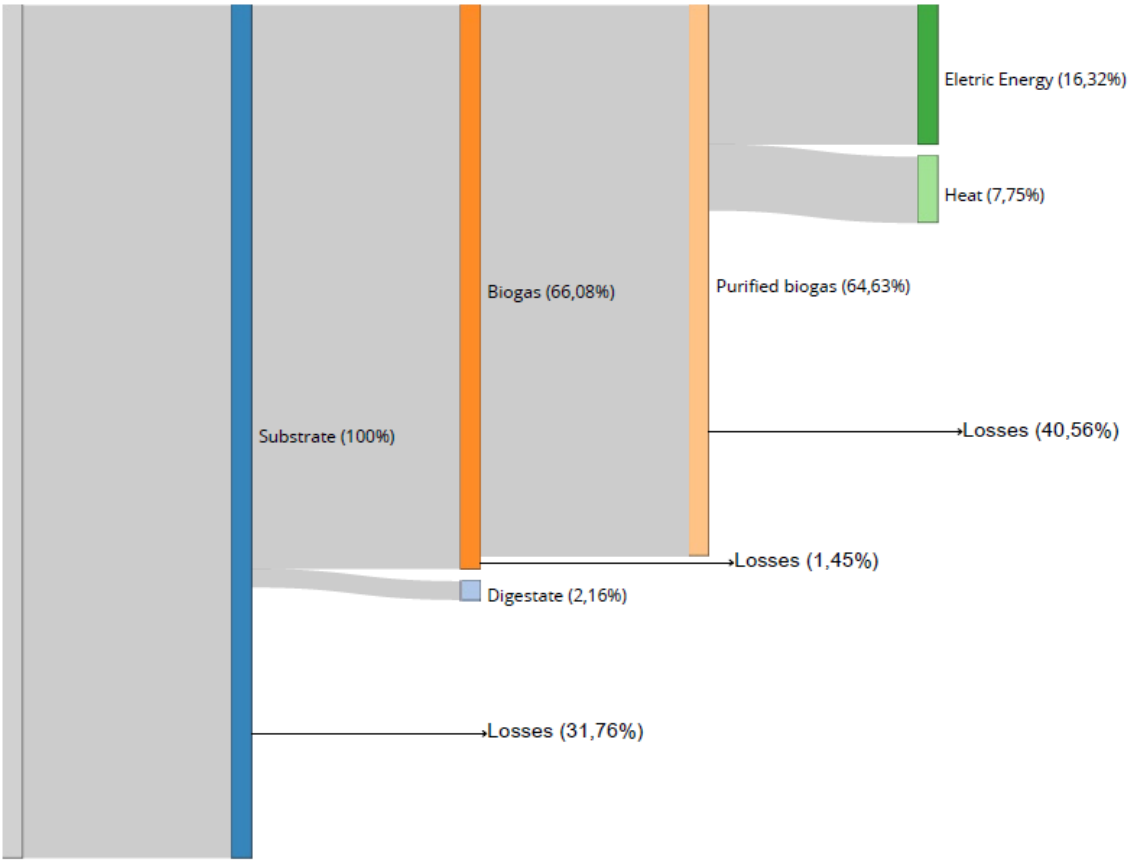

Figure 2. Grassmann diagram of the anaerobic digestion process. Source [15]

The biogas purification plant consists of a direct contact cooling (DCC) tower, which removes moisture and ammonia from the biogas; this equipment uses chilled water from a chiller. The biogas is then ventilated (C1) to the desulfurizer, which contains activated carbon and captures hydrogen sulfide. Once free of contaminants, the biogas is compressed by C2, a two-stage compressor, with the first stage cooled by atmospheric air and the second stage cooled by water from the chiller. This is necessary because, in the next stage, the biogas must be at the appropriate temperature for the process. Therefore, the compressed and cooled biogas is sent to a membrane separation system, which extracts the biomethane from the biogas; this step releases the separated CO_2, as well as O_2, into the atmosphere, and sends the biomethane to a high-pressure compressor, which raises the fuel's pressure to 250 bar, making it suitable for automotive use; this compressor has three stages and uses atmospheric air to facilitate cooling between stages. This process can be divided into three groups: the first is the biogas purification process, the second is the CO_2 separation process, and the third is the biomethane storage process. Figure 3 illustrates this process, with each group of processes highlighted: the purification process is shown in purple, the separation process in blue, and the storage process in green.

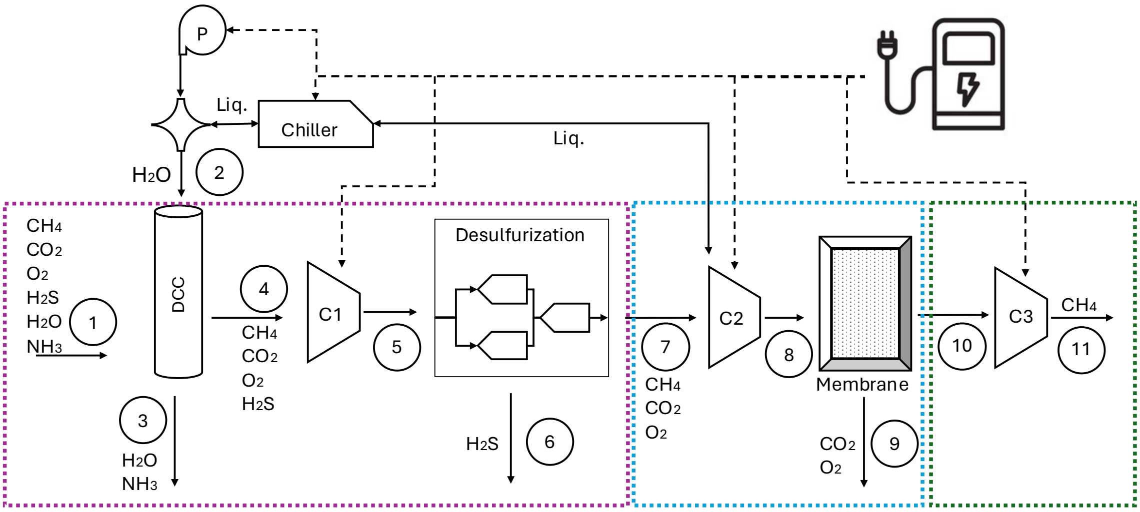

Figure 3. *Diagram of methane upgrading*

Figure 3 shows a diagram of the processing route, which requires an external energy source to power the chiller, compressors, and pumps. In this regard, some questions arise regarding the system's energy viability: does the route consume more energy than can be produced from the processed fuel? How much of this fuel must be diverted to the generator to meet electrical demands? And what are the irreversibilities of this process?

To answer these questions, the First and Second Laws of Thermodynamics are applied in this study; therefore, the mathematical model used respects the conservation of mass and energy. Since this involves a mixture of gases that will be separated, the equations and the tables by Morris and Szargut [20] are used to compute physical and chemical exergy. The total exergy of the flow is given by the sum of the physical exergy and the chemical exergy, plus the mixing factor, according to the equations below.

$$\dot{B}_{ph} = \dot{m} \cdot \left((h - h_0) - T_0 \cdot (s - s_0)\right). \tag{1}$$

$$\dot{B}_{ch} = \dot{B}^{\circ}{}_{ch} + \frac{\dot{m}}{M} \cdot R \cdot T_0 \cdot y \cdot ln(y). \tag{2}$$

$$\dot{B} = \dot{B}_{ph} + \dot{B}_{ch}. \tag{3}$$

For heat, as observed in the condensers and the chiller, the following equation is used:

$$\dot{B}_q = \dot{Q} \cdot \left(1 - \frac{T_f}{T_q}\right). \tag{4}$$

The EES software is used to perform this analysis. Certain assumptions must be made to simplify the analysis and focus only on the most significant results. The efficiency of the compressors and pumps is assumed to be 60%. The effects of the chiller are calculated using a control volume that considers the exergy from the heat removed from the process and the exergy released in the chiller's condenser, without accounting for the internal irreversibilities of this equipment. Moreover, the separation processes are considered fully effective, meaning that the molecule to be removed in each process is completely removed. The profile of the biogas to be processed is described in Table 1.

Table 1. Biogas inflow conditions.

Condition	Value
Pressure	1.034 bar
Temperature	36°C
Flow Rate	0.03484 kg/s
Concentration of CH_4	51%

Concentration of CO_2	39.1%
Concentration of H_2O	4.2%
Concentration of H_2S	0.0379%
Concentration of NH_3	4.29%
Concentration of O_2	1.37%

Source: [15]

Some important considerations regarding the evaluated processes also need to be highlighted. Water cooled by the chiller enters the DCC at 20°C and 10 bar, exiting it at 25°C and 1 bar. Compressor C1 increases the pressure of the gases leaving the DCC from 1 bar to 1.314 bar. The desulfurizer reduces the pressure of the gases to 1 bar. Compressor C2 raises the pressure from 1 bar to 16 bar. The membrane reduces the gas pressure to 1 bar. Compressor C3 raises the gas pressure to 250 bar. Also, since the system is not fully commissioned, there is no precise data to calibrate the mathematical model; therefore, separation efficiencies will be assumed to be ideal. Mechanical and energy efficiencies, however, will be estimated as previously mentioned.

3. Results and discussion

After compiling the equations representing the process flows for this route in the EES software, some interesting results were observed. The operating conditions, as well as the exergies for each process flow, identified in Figure 3, are detailed in Table 2.

Table 2. *Operation conditions of flow diagrams*

#	P [bar]	T [K]	m [kg/s]	B [kW]	Bch [kW]	Bph [kW]	Bmis [kW]
1	1.0	309	0.035	569.20	569.10	0.11	-1.046
2	2.6	293	0.556	27.94	27.75	0.19	0.000
3	1.0	295	0.558	46.24	46.15	0.09	-0.137
4	1.0	295	0.033	550.20	550.10	0.06	-0.977
5	1.3	323	0.033	550.90	550.10	0.79	-0.977
6	1.0	323	0.000	0.39	0.39	0.00	0.000
7	1.0	323	0.033	549.80	549.70	0.04	-0.995
8	16.0	314	0.033	557.40	549.70	7.70	-0.995
9	1.0	298	0.023	9.93	9.93	0.00	-0.043
10	9.0	298	0.010	544.30	540.80	3.50	0.000
11	250.0	313	0.010	549.10	540.80	8.38	0.000

In this table, besides the pressures, temperature, and mass flow rates of each of the process streams described in the diagram in Figure 3, four exergy components are also calculated. The first “B” is the total exergy of the stream, calculated using Equation 3; “Bch” is the chemical exergy, calculated using Equation 2; and “Bph” is the physical exergy, calculated using Equation 1. Finally, there is also “Bmis,” which represents the effect of mixing the compounds in each stream; this value is highlighted to allow for the analysis of the impacts of the mixtures, since the objective of this route is to separate biomethane from the other biogas compounds.

Using the exergetic variations of the fluid along the route, it was possible to calculate the exergy destruction of each process, as described in Table 3.

Table 3. *Exergy destruction in each route’s process*

Processes	Destroyed Exergy [kW]
Compressor C1	0.440
Compressor C2	9.607
Compressor C3	7.921
Pump B	0.001
DCC	0.675

Desulfurizer	0.765
Membrane	3.244
Chiller	10.85
Total	33.50

The chiller was modeled as a control volume considering only the heat absorbed by the refrigerant, the electrical energy consumption, and the heat rejected through its condenser. In this way, the significant exergy variations occurring within this complex system are accounted for, although not explicitly detailed. The chiller is understood to add exergy to the water entering the DCC, as its temperature decreases from ambient to lower values. Conversely, at compressor C2, the chiller absorbs exergy by reducing the temperature of the compressed gas to near ambient conditions. Therefore, all irreversibilities associated with this cooling system are directly attributed to the chiller.

It is evident that the C2 and C3 compressor units are major sources of exergy destruction, due to the fact that they cool the compressed fluid using atmospheric air, resulting in exergy loss. The membrane also proves to be a major source of exergy destruction, due to the pressure drop caused by its operation. Finally, the chiller is the second largest destroyer of exergy; this is mainly due to the condenser temperature, which was set at 40°C. If we consider that this heat from the condenser is released into the atmosphere without being utilized, the exergy destroyed by this equipment will increase.

Looking at the results for each process group, including the division of the chiller's effects between compressor C2 and water cooling in flow 2, it is observed that CH_4 separation is the process with the greatest exergetic destruction, accounting for more than half of the irreversibilities, followed by the process of compressing biomethane to high pressures. These results are summarized in Table 4.

Table 4. *Destroyed exergy in each process group of the route*

Process groups	Destroyed Exergy [kW]	Percentage
Pre-treatment	6.13	18%
Separation of CH_4	19.45	58%
Compression	7.92	24%
Total	35.50	100%

The CH_4 separation system is the most critical stage in this methane upgrading route, as it is responsible for achieving the desired effect of separating methane from CO_2. It is observed that this system consumes approximately 21.8 kW, including electrical energy for compression and the chiller used for cooling prior to membrane operation. In addition, it accounts for 19.45 kW of system irreversibility. This entire energy expenditure is associated with eliminating the negative exergy effects of methane mixing with other biogas components, as well as increasing the physical exergy of methane at the membrane outlet. These results clearly indicate that the process is energetically and exergetically intensive.

Figure 4 organizes the exergy flows and the irreversibilities of each process in a Grassmann diagram, facilitating the exergy-based understanding of the system. Unidentified exergy flows entering the process correspond to the consumed electrical energy, while unidentified exergy flows leaving the processes correspond to the rejected heat.

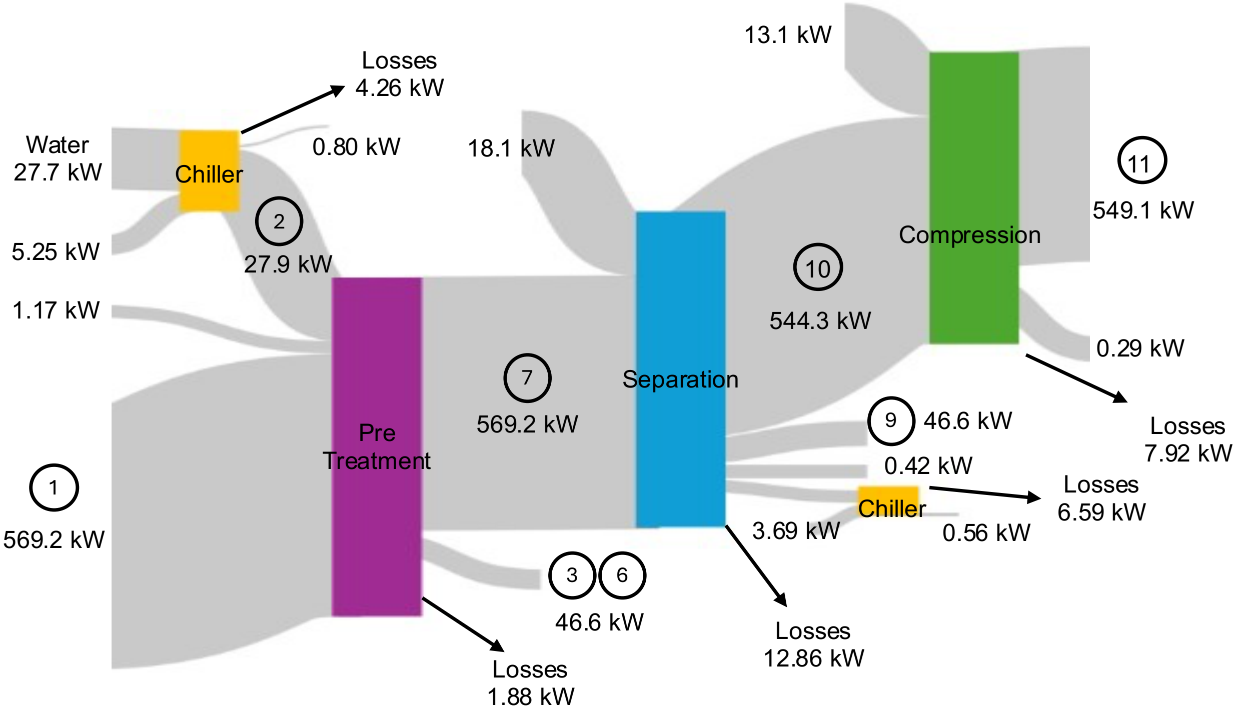

Figure 4. *Grassmann diagram for methane upgrading*

For this process to operate, an electrical consumption of 41.31 kW is required; according to the observed results, this exergy flow was necessary for the conversion of biogas into biomethane. When examining the methane in stream 1, which is still mixed with the other components, it has a chemical exergy of 540.8 kW. By the end of the process, with pure methane at high pressures, the exergy is 549.1 kW; therefore, of the 41.31 kW injected into the route, only 8.3 kW went to the methane. Thus, the process efficiency is 20.2%.

In an analysis conducted by [15], biogas can be fed into a generator with 33.5% efficiency, such that the 521.6 kW of energy flow (lower heating value) of the methane can be converted into 174.7 kW of electrical energy. In this case, for the route to be self-sufficient, approximately 23.6% of the biogas entering the route must be directed to the generator, leaving 76.4% to be processed. Thus, it can be concluded that the route does not consume more energy than is present in the processed biomethane, proving it to be viable. However, one-fifth of the exergy present in the biogas will be used for processing; furthermore, it is likely that vehicles using this biomethane will have lower efficiency than the generator, resulting in lower work output from tank to wheel.

From a strictly work production perspective based on USW utilization, this route is not viable, since it destroys exergy to increase fuel purity, which merely results in a higher exergy concentration per unit volume of fuel from 16.3 MJ/kg of biogas to 52.6 MJ/kg of processed biomethane. However, from a mobility perspective, the route is interesting. By utilizing USW that would otherwise be destined for landfills, the system recovers part of the exergy that would otherwise be destroyed and converts the waste into high-quality fuels for use in vehicles. In a country where the transportation sector emits approximately half of all greenhouse gases, driven by the road transport sector which consumes 80% of the country's diesel [21], the production of biomethane from USW emerges as a highly attractive alternative from both an energy and environmental perspective.

4. Conclusion

This study evaluated the exergetic efficiencies of a biomethane upgrading route; the processes with the highest exergy loss were identified. Also, the exergetic cost of the route and the possibility of using untreated biogas in a generator show that there are several options for biogas utilization, with combustion in a generator being the most attractive from a purely energy-related perspective. It is concluded that the route offers mobility benefits, with high potential to serve as an alternative to diesel. There is a need for future economic analyses to understand and complement the viability analyses of this study, as well as a comparison with the route's operational data, in order to improve the model used.

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Nomenclature

b	specific exergy, kJ/kg
$\dot{B}$	exergy rate, kW
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
M	molar mass, kg/kmol
$\dot{Q}$	heat transfer rate, kW
R	universal gas constant, kJ/(kgK)
s	specific entropy, kJ/(kgK)
T	temperature, K
y	mole fraction

Subscripts and superscripts

0	standard
ch	chemical
ph	physical

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