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# **Título:** ANALYSIS OF URBAN SUSTAINABILITY OF ARARANGUÁ-SC-BRAZIL APPLYING THERMODYNAMIC CONCEPTS TO MUNICIPAL SOLID WASTE INDEXES

Araranguá - SC
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Trabalho de Conclusão do Curso de Graduação em Engenharia de Energia do Centro de Ciências, Tecnologias e Saúde da Universidade Federal de Santa Catarina, como requisito para a obtenção do título de Engenheiro/a de Energia.
Orientador: Prof. Thiago Dutra, Dr.
Coorientador (se houver): Prof. Ricardo Morel Hartmann, Dr.

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O presente Trabalho de Conclusão de Curso, do Curso de Engenharia de Energia, foi avaliado e aprovado pela banca examinadora composta pelos seguintes membros:

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# ANALYSIS OF URBAN SUSTAINABILITY OF ARARANGUÁ-SC-BRAZIL APPLYING THERMODYNAMIC CONCEPTS TO MUNICIPAL SOLID WASTE INDEXES

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## ABSTRACT

Each day, humankind adds more and more products into the earth' life cycle, mostly made out of virgin materials and not accounting how much out there can be reused and reinserted in the chain. The world produces over 2 billion tons of Municipal Solid Waste (MSW) every year and Brazil contributes with 80 million tons to this amount, of which only 3% is recycled. Strategies like Reducing/Reusing/Recycling/Recover (4R's) must be attached to our thoughts and actions. Also, maximizing exergetic efficiency and minimizing entropy generation can lead to more powerful solutions to this global problem, once the world can be seen as a living organism, where matter and energy are consumed as well as waste, heat and entropy are rejected. In this work, the MSW management system of Araranguá – Santa Catarina State, Brazil is evaluated in terms of exergy and a control volume around the city's urban center was defined. Streams of fuels such as gasoline, natural gas, liquefied petroleum gas, diesel oil, ethanol and also electricity into the city's control volume were considered as exergetic inflow. The outlet solid mass flow was calculated by the passage of solid waste across the control volume boundary, on its way to the landfill. Two scenarios were considered: (i) the current one with no solid waste segregation, inconsiderable recycling rate and transportation by trucks; (ii) the ideal one, but feasible scenario, which considers a proper waste separation with the highest material recycling and waste-to-energy generation. The analysis has shown that a correct waste separation can lead to an increase of 1.4% in the exergetic efficiency, which represents 47,137 GJ of exergy potentially recovered and around US $ 300,000 saved in a year, related to less diesel oil consumption and to MSW management system enhancement. The results show that waste-to-energy solutions can be very powerful and effective regarding the world's solid waste treatment, for cities like Araranguá.

## 1 INTRODUCTION

As the global population reaches around 8 billion people in 2020, there is an expressive increase in the Municipal Solid Waste (MSW) production. Annually, the world produces over 2 billion tons of MSW, and that number is expected to grow to 3.4 billion tons by 2050, as reported by the World Bank [1].

In 2010, Brazil has taken a step ahead on the solid waste issue progress (which includes environmental, social and economic problems), establishing the National Policy on Solid Waste (NPSW - PNRS, in Portuguese) [6]. The policy provides principles, goals and instruments for the solid waste issue, guiding the actions for more sustainable habits, such as recycling, material reuse and correct destination of the non-recyclables.

Even though there is a national policy on solid waste, Brazil produces annually 80 million tons of MSW, of which only 3% is recycled. The south region of Brazil contributes with 11% of all the MSW produced in the country, of which only 28% is destinated to landfills [21].

There are many studies proposing solutions to this global and national MSW problem, and one of the alternatives is the waste-to-energy technologies, which have a high potential to enhance the national and international energy matrix, as well as to decrease the environmental impacts of the human being.

Lopes *et al.* [4] evaluated the energy gain in gasification processes with and without the segregation of the organic fraction from the rest of the municipal solid waste of a Brazilian city called Mafra, located in Santa Catarina State. It was mentioned that highly industrialized countries that do not have enough land for landfills tend to apply waste-to-energy methods, such as gasification, to manage their MSW. They found out that the heating value available doubled when 90% of segregation of the organic fraction was obtained.

Zaman [3] discussed and presented results of an analysis of the municipal solid waste system of Adelaide, Australia. This author observed that a zero-waste management is a holistic concept that looks at waste not as an end-of-life product, but as a resource and as an index for (in)efficiency of an urban environment. Zaman [3] also described what a zero-waste product is, defining it as a product that is created based on cradle-to-cradle principles, which is the opposite of those commonly made today, the so-called cradle-to-grave products. The study also indicated a diversion rate (which determines the amount of waste diverted from landfill to recycling and/or composting) of 72% and a Zero Waste Index (ZWI) of 0.41 in 2010, and projected a diversion rate of 85% and a ZWI of 0.45 by 2020, applying zero waste strategies. Finally, it was discussed (i) the possibility of reaching a 100% diversion rate by raising environmental consciousness and appropriated infrastructure, and (ii) the fact that a greater ZWI implicates in a virgin materials substitution and resource recovery.

One of the approaches to understand the potential of an ideal MSW management system is the thermodynamics. Hartmann *et al.* [2] presented an analysis on the exergy efficiency of Florianópolis, Santa Catarina, Brazil. The analysis has shown that a correct waste segregation can lead to a zero mixing entropy of the MSW management system and also increase the exergetic efficiency related to the waste management system by 1.5%.

The present paper was built on the idea of Hartmann *et al.* [2], but applied to a smaller and socio-economically distinct city, called Araranguá, also located in Santa Catarina. The main objective was to assess quantitatively and qualitatively the environmental and exergetic impacts of a correct MSW management system, applying thermodynamic concepts to a specific city and analyzing two opposite scenarios.

## 2 MATERIALS AND METHODS

The thermodynamic analysis was based on a premise in which there is a correlation between the exergy destruction, caused by combustion of fuels and misuse of the inherent waste-to-energy availability of a city and the entropy of mixing, caused by the production and collection of the MSW. The analysis was based on existing data, from different sources, and adopting a thermodynamic approach. Calculations were performed with the software Engineering Equation Solver, Professional Version V10.836-3D (EES) [22].

### 2.1. PROPOSED SCENARIOS

To better understand how effective can be a proper MSW management system, this study took into account two scenarios [2]:

- Scenario 1: no adequate management and destination of the MSW, which is fully destinated to a landfill. Unfortunately, this is also the actual situation of the analyzed city. There is a possibility to capture the landfill biogas and generate electricity;
- Scenario 2: This is the best scenario in terms of sustainability and circular economy and, although it is an idealization, it is feasible. In this context, all the recyclables are recycled, the organic fraction is destinated to biodigesters and only the non-recyclable fraction is taken to a gasifier.

Regarding scenario 2, one could argue why not composting the organic fraction or, at least, part of it. The choice between composting and biodigestion in this work was made based on the energy potential. However, in a feasible and pragmatic way, it is interesting to manage the organic material in both ways, once those methods are complementary.

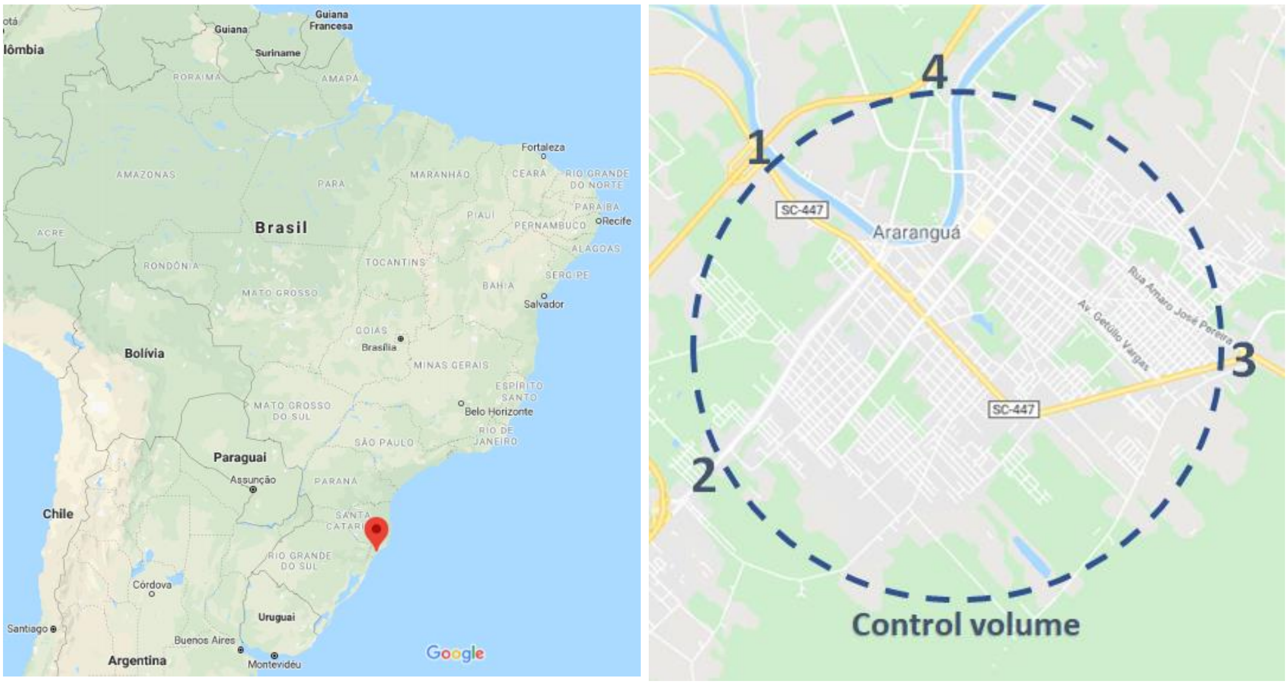
### 2.2. CITY AND CONTROL VOLUME

The city analyzed in this work is called Araranguá and is located in the state of Santa Catarina, Brazil. According to the Brazilian Geography and Statistic Institute (IBGE, in Portuguese) [7], the total territorial area of the city is 301.8 km$^2$. Araranguá has an estimated population of 68,228 inhabitants, a Municipal Human Development Index (MHDI) of 0.76 [7] and, also, the city is a touristic spot in the summer, bringing tourists from different nationalities. According to Sebrae [8], 46% of the companies established in the city are from the commercial sector, 15% are converting industries and 7% are classified as administrative activities.

The MSW collection and transportation is operationalized 65-70% by a private company and 30-35% by municipal employees. All of the waste collected is destinated to a landfill located in Içara, 25 km away from Araranguá. The landfill is managed by a private company too.

The control volume established in this work is presented in Figure 1. The four main entrance/exit are highlighted, where all input of mass, fuels, transportation of car and bus and goods deliveries are made through.

Figure 1: Localization of Araranguá and the control volume established in the work.



Source: adapted from Google Maps

## 2.3. MUNICIPAL SOLID WASTE PRODUCTION IN ARARANGUÁ

According to the city hall of Araranguá, 1,200 tons of MSW are generated monthly in the city, which corresponds to around 14,400 tons on an annual basis, which is a similar value to that found by Gluzezak (2018). Currently, the MSW is collected as one, without any segregation and is destinated to the landfill. The most recent results for Araranguá MSW gravimetric composition were obtained in 2011 [23] and since then, the city has passed through considerable changes. Comparing data from 2010 and 2018, Araranguá presented a 10% growth of the population, 30% growth of formal jobs and 37% growth of the GDP per capita [7]. Due to that, Ararangua MSW gravimetric composition was approached by the MSW gravimetric composition of another city with similar socioeconomic aspects, as will be explained further, in section 3.

## 2.4 EXERGETIC ASSESSMENT

The exergetic analysis takes into account all the inputs and outputs of mass and energy through the control volume. The chemical exergy of a fuel can be calculated as the following formula:

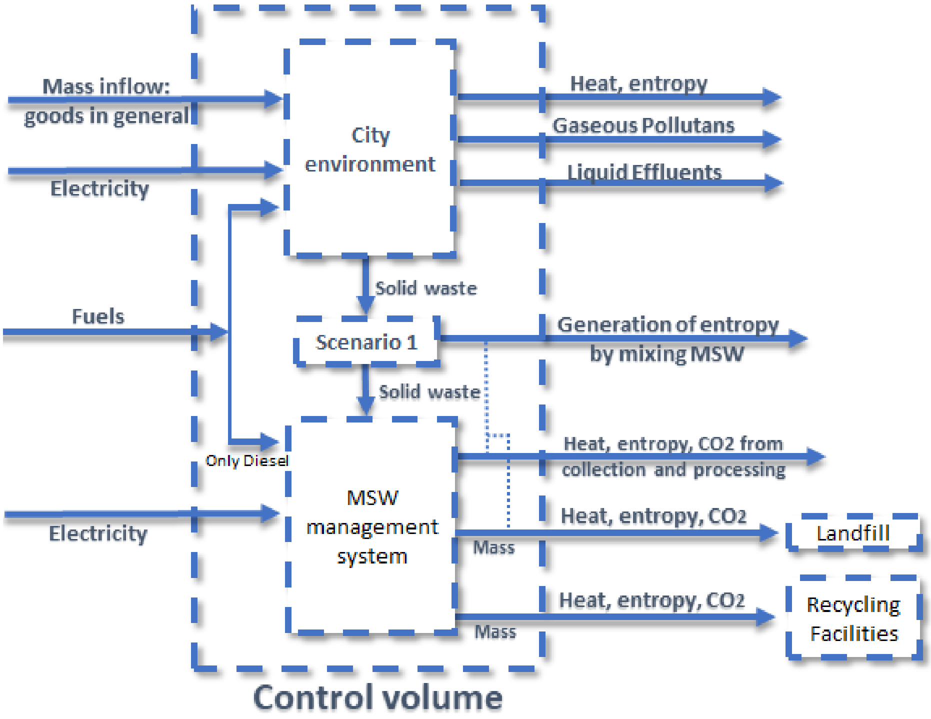
$$e^{ch} = \beta \cdot LHV_{Fuel} \qquad (1)$$

where $LHV_{Fuel}$ represents the lower heating value of a fuel in kJ/kg and $\beta$ is the ratio of chemical exergy to the $LHV_{Fuel}$, which is based on the amount of hydrogen and carbon in the fuel [10]. $\beta$ was calculated following the correlation proposed by Szargut *et al* [10] which consists in two equations: one for liquid hydrocarbons and the other for gaseous hydrocarbons. As a consequence, the total exergy for a time interval can be calculated, in GJ, as:

$$E_{Total} = e_{gasoline}^{ch} \cdot m_{gasoline}^{total} + e_{LPG}^{ch} \cdot m_{LPG}^{total} + e_{ethanol}^{ch} \cdot m_{ethanol}^{total} + e_{NG}^{ch} \cdot m_{NG}^{total} + e_{DO}^{ch}.m_{DO}^{total} + E_{elect_{TT}} \tag{2}$$

where LPG means Liquefied Petroleum Gas, NG stands for Natural Gas, DO is Diesel Oil, $E_{elect_{TT}}$ is the total electricity consumed in the time interval (TT) and $m^{total}$ can be calculated multiplying the mass flow rate by the total time. In exergy analyses and, more specifically, regarding exergy destruction, the difference between the input and output exergy, by itself, is really relevant [20]. Thus, it is very important to observe that the exergy destruction is caused by mixing processes related to the MSW management system, by combustion [2] and by heat transfer [3,4]. Figure 2 shows the analyzed control volume and its inflows and outflows.

Figure 2: Detailed control volume of Araranguá - SC



Source: adapted from [2]

As depicted in Fig. 2, the main control volume can be divided in two others: one for the city environment and another for the MSW management system. Note that in scenario 1, besides the fact that the waste generates heat, entropy and $CO_2$ from collection, processing and landfilling, it also generates entropy by mixing the MSW, which, in scenario 2, would not happen.

When an analysis and quantification of the exergy destructed in combustion processes is made, it is essential to notice that those processes are frequently involved in our nowadays lives. Trucks are fueled with diesel oil, whereas cars are fueled with natural gas, ethanol and gasoline, and LPG is often used in cooking and for heating purposes. In this work, to avoid the effects of the type of engine used, it was used a general approach that analyzes only the combustion process on the entropy generation [2]. In this context, Hartmann *et al.* [11] made a thermodynamic approach to improve accuracy of laminar flame speed measurements and presented results of exergy destruction in fuels with isooctane, Jet A-1, methane and n-heptane. They found out that, on average, all fuels assessed presented an exergy destruction of 30% and that was the percentage used in this work.

### 2.4.1 Exergetic Efficiency

According to Çengel *et* al [9], the exergetic efficiency can be calculated as:

$$\eta_E = 1 - \left(\frac{\sum E_{Dest}}{E_i}\right) \tag{3}$$

where $\eta_E$ is the exergetic efficiency, $E_i$ is total exergy that inflows the control volume, which can be calculated using (2), and $\sum E_{Dest}$ is the summation of all exergy destroyed, all of which, in this analysis, is related to combustion processes and due to mixing of MSW. Moreover, as suggested by Hartmann *et al.* [2], it was assumed that all the exergy that enters the control volume is consumed, i.e., all fuels, electricity and material are consumed.

Based on these assumptions, the equation (3) can be rewritten as follows:

$$\eta_E = 1 - \left(\frac{E_{Dest}^{ethanol} + E_{Dest}^{DO} + E_{Dest}^{LPG} + E_{Dest}^{NG} + E_{Dest}^{gasoline} + E_{Dest}^{elect} + E_{Dest}^{mix}}{E_i^{ethanol} + E_i^{DO} + E_i^{LPG} + E_i^{NG} + E_i^{gasoline} + E_i^{elect}}\right) \tag{4}$$

For a practical approach, based on the analysis of Liu *et al.* [12], it was considered herein that Araranguá electric exergetic efficiency is 35%, which is the same value adopted by Hartmann *et al.* [2] in their study regarding Florianópolis with data from 2014. Additionally, it is important to note that Florianópolis has a Gross Domestic Product (GDP) 64% higher than Araranguá's [7], and it is assumed that the higher the GDP is, the more modern and efficient the electronic devices are, so the 2014 data may be a good estimative for Araranguá in 2020.

The exergy destructed by combustion processes can be calculated as [9,13]:

$$E_{Dest}^{Fuel} = m_{total}^{Fuel} \cdot e_{ch}^{Fuel} \cdot \%E_{Dest}^{Fuel} = m_{total}^{Fuel} \cdot \beta_{Fuel} \cdot LHV_{Fuel} \cdot \%E_{Dest}^{Fuel} \tag{5}$$

where $E_{Dest}^{Fuel}$ is the total exergy destructed by combustion for each fuel, $m_{total}^{Fuel}$ is its total mass consumed in a year and $\%E_{Dest}^{Fuel}$ is the percentage of exergy destructed during the combustion process. The exergy destruction associated with the mixing process of MSW ($E_{Dest}^{mix}$) will be defined in the next section.

### 2.4.2 Exergetic Analysis of the MSW Management System

The exergetic assessment of the MSW management system was made considering two scenarios previously described and repeated here for clarity; (i) scenario 1: this is the actual situation with no adequate management nor correct destination of the MSW. All MSW is disposed off in a landfill with the possibility to capture biogas; (ii) scenario 2: this is a hypothetical situation where recyclables are recycled, organic fraction is destinated to biodigesters and only non-recyclable fraction is taken to a gasifier.

Only in 2010, Brazil has taken a step ahead on the solid waste issue progress (which includes environmental, social and economic problems), establishing the National Policy on Solid Waste (NPSW - PNRS, in Portuguese) [6]. The policy provides principles, goals and instruments for the solid waste issue, guiding the actions for more sustainable habits, such as recycling, material reuse and correct destination of the non-recyclables. In this context, the NPSW reinforces scenario 2, including its energy recovery consequences.

Considering scenario 2, although there are many ways to reach the idealized situation, it was considered in this work that the waste would be segregated at source, which is understood to be the heart of the waste management solution. The separation is made using 6 different bins: yellow for metal, red for plastic, green for glass, blue for paper and cardboard, brown for the organic fraction and a silver for the non-recyclables. It was assumed in this work that the segregation at source facilitates the next recycling steps, saving time and effort of the people who work in waste sorting centers and, besides that, increases collective consciousness on this issue, once people, in general, do not know the difference between the types of waste that is produced nor its final destination.

In the context of waste-to-energy technologies, it was considered that the best energy solution for the organic fraction is biogas production using anaerobic biodigestion (AB) and the non-recyclables should be taken to gasifiers, once it may reduce emission of some pollutants, such as polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/PCDF) and $NO_x$, when compared to incineration [2,5]. Then, the exergy that can potentially be recovered in this case was computed as [2]:

$$EPR_{scen2} = m_{organic} \cdot \beta_{Biogas,AB} \cdot LHV_{Biogas,AB} \cdot \gamma_{ab} + m_{nr} \cdot \beta_{syngas} \cdot LHV_{syngas} \cdot \gamma_{gasf} \tag{6}$$

where $m_{organic}$ is the total organic mass that is collected, $LHV_{Biogas,AB}$ is the lower heating value of the biogas generated in the anaerobic biodigestion reactor, $\gamma_{ab}$ is the relation between the biogas produced and the organic waste feeded to the AB reactor, $m_{nr}$ is the total mass of the non-recyclables, $LHV_{syngas}$ is the lower heating value of the syngas produced by the gasifier, $\gamma_{gasf}$ is the relation between the syngas produced and the non-recyclable waste fed to the gasifier and $\beta_{Biogas,AB}$ and $\beta_{syngas}$ are related to the biogas and the syngas produced . Both $\gamma_{ab}$ and $\gamma_{gasf}$ are values obtained empirically and were provided by the companies that own those types of technologies. Hence, the better the technology, the more exergy that can be recovered.

In scenario 1, the exergy that can potentially be recovered is:

$$EPR_{scen1} = m_{landfill} \cdot \beta_{Biogas,landfill} \cdot LHV_{Biogas,landfill} \cdot \gamma_{landfill} \tag{7}$$

where $LHV_{Biogas,landfill}$ is the lower heating value of the biogas captured in the landfill and $\gamma_{landfill}$ is the relation between the biogas produced and the MSW destinated to the landfill, which has a default value of 50 $Nm^3$ biogas/ton MSW. [19].

In between scenarios 1 and 2 there is a lot to be done regarding education of the population and improvements in the MSW management system. It is controversial to talk about developed or modern cities without looking at which scenario is the city related to. Although it is a duty of the government to provide basic services and correct destination of the MSW, it is not something common to see in Brazil and, more specifically, in Araranguá – SC. In this context, the difference between $EPR_{scen2}$ and $EPR_{scen1}$ values can be useful to provide a good view of the problem, both in a quantitative and qualitative way. So, the delta of exergy that could potentially be recovered was calculated as:

$$\Delta EPR = EPR_{scen2} - EPR_{scen1} \tag{8}$$

The $\Delta EPR$ value is related to the mixing entropy associated with scenario 1. The higher the mixing of the MSW is, the less exergy can be recovered and the closer the city is to scenario 1.

The entropy of mixing of the MSW, which was analyzed from its collection to its disposal in landfills, was given by the following formula, which is an analogy of entropy of mixing for ideal gases:

$$S_{Mix}^{MSW} = -k^{MSW} \sum_{i=1}^{n} y_i \ln{(y_i)} \tag{9}$$

where $k^{MSW}$ is a particular constant for the mixing process of MSW and $y_i$ is the molar fraction of the *ith* component of the MSW.

The exergy destructed by mixing the MSW is given by the product of $\Delta EPR$ and the mixing entropy index $S_{Index}^{Mix}$, as follows:

$$E_{Dest}^{mix} = \Delta EPR \cdot S_{index}^{Mix} \tag{10}$$

where

$$S_{index}^{Mix} = {S_{mix}^{MSW}} \Big/ {S_{mix}^{scen1}} \tag{11}$$

in which $S_{mix}^{scen1}$ is the mixing entropy in scenario 1. The entropy index ($S_{index}^{Mix}$) was called mixing index in this work and its use facilitates equation (9), once the constant $k^{MSW}$ is cancelled, as shown in section 3.1.1. Finally, it is interesting to note that when the city is classified in scenario 1, its mixing index is highest (= 1) and, hence, the exergy destruction reaches its maximum rate as well. On the other hand, when there is a correct waste segregation, as proposed in scenario 2, the mixing index of the city is zero and the exergy destruction by mixing the MSW is also zero.

## 3 RESULTS AND DISCUSSION

The last results available for gravimetric composition of the MSW of Araranguá - SC are from 2011 [23], which is very outdated, since the city has shown a considerable socio-economic change in the past few years, as shown in section 2.3, and, therewith, the gravimetric composition is supposed to be different as well.

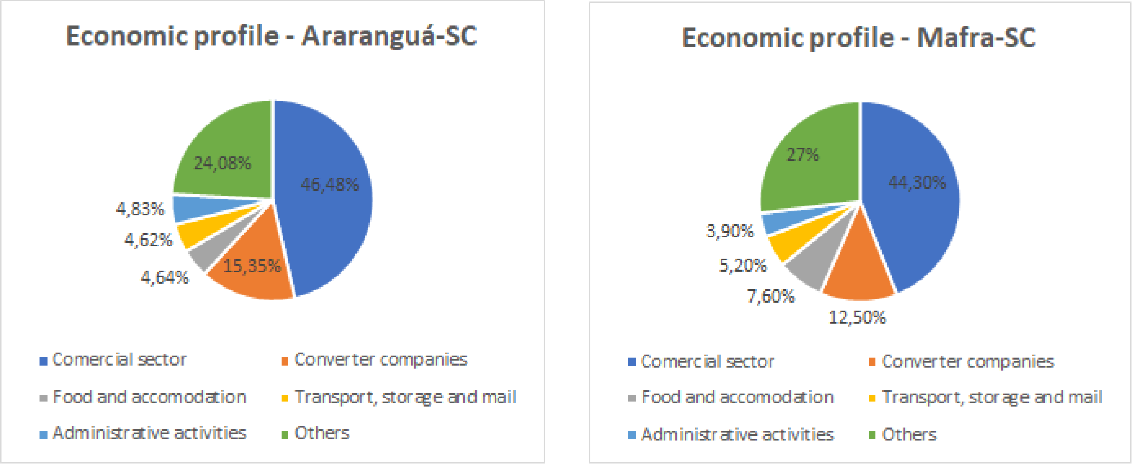
Based on that, a research was made to find similar cities to Araranguá, with common or close socio-economic aspects, in order to find an approximation for the actual gravimetric composition. Among Blumenau, Lages, Criciúma, Florianópolis, Garopaba and Mafra, all located in the state of Santa Catarina, Mafra has shown to be the most similar city to Araranguá. Table 1 and Figure 3 present an overview of the economic landscape for both cities:

Table 1: Socio-economic aspects of Araranguá – SC and Mafra - SC

| | **Araranguá** | **Mafra** |
|---|---|---|
| Estimated population [2019] | 68,228 | 56,292 |
| Urban population [2010] | 82.4% | 78.1% |
| Average wage [2010] | 2.2 minimum wages | 2.3 minimum wages |
| GDP per capita [2017] | US $ 5,000 | US $ 5,740 |
| Municipal HDI [2010] | 0.76 | 0.78 |
| Schooling rate (age: 6-14 years old) [2010] | 98.4% | 98.9% |

Source: Brazilian Geography and Statistic Institute (IBGE, in Portuguese) [7]
*minimum wage in Brazil, for the year of 2020, is around US $ 200, considering BRL /USD=5

Figure 3: Economic profile of Araranguá -SC and Mafra-SC



Source: SEBRAE [8]

According to the city hall of Araranguá, all the solid waste collected is destinated to a landfill located 24 km away from the city, which yields a diversion rate of 0%. In Florianópolis [2], the diversion rate is about 5%, and in Adelaide (Australia), the diversion rate is 85% [3].

In Araranguá, 87% of the population is benefited with MSW collection service. Each ton of solid waste collected costs around 68 US dollars, which represents 82% of all the costs related to the MSW management system [14]. As a result, the city spends around US $ 69,600 per month to manage and destinate the MSW to a landfill.

Lopes *et al.* [4] discussed the energy gain from the segregation of the organic fraction from the MSW of Mafra. They obtained samples of residues from the responsible company for the landfill located in the city and the percentage of each component in the MSW was determined. The gravimetric composition of the MSW found by Lopes *et al.* [4] in 2018, which was considered similar to Araranguá's in 2020, is shown in Table 2. In this work, since the non-recyclable fraction was not mentioned in [4], it was assumed to correspond to 18%, which is the fraction of diapers and absorbents, leather, textiles and wood, rubber and tires, and a fraction of the recyclables without potential to be recycled.

Table 2: Estimated gravimetric composition of Araranguá in 2020

| **Components** | **Mass percentage** |
|---|---|
| Organic fraction | 47.9% |
| Paper and cardboard | 16.6% |
| Carton packings | 1.9% |
| Plastics: | 16.1% |
| *PET* | *1.7%* |
| *HDPE* | *0.7%* |
| *LDPE* | *8.6%* |
| *Other plastics* | *5.1%* |
| Diapers and absorbents | 5.4% |
| Leather, textiles and wood | 4.7% |
| Rubber and tires | 0.6% |
| Total of waste as potential fuel | 93.2% |
| Total inorganic (non-fuel) waste | 6.8% |

Source: Lopes *et al*. [4]

Even though there is a National Policy on Solid Waste (NPSW - PNRS, in Portuguese) [6], which provides principles, goals and instruments for the solid waste issue, there is no campaign or plan from Araranguá city hall to improve the segregation, collection and destination of the MSW. On the other hand, there are some actions from the private enterprise sector that tries to solve this problem. One of them is the initiative of four students from the Federal University of Santa Catarina that run a start-up called Selectum [15], whose main purpose is to manage the reverse logistics of the recyclables and organics. They connect the clients with waste pickers that have their only income from recyclables, teaching the clients how to properly separate the waste. This type of segregation turns the work of those people easier and more hygienic, since they often have to search in waste bins and dumpsters, where all the waste is mixed, what is valuable for them.

## 3.1 RESULTS OF EXERGETIC ANALYSIS FOR ARARANGUÁ

Table 3, bellow, presents the input exergy in Araranguá, which is the exergy that inflows the control volume.

Table 3: Input exergy into the control volume of Araranguá

| | **Amount** | **$\beta$** | **Input exergy [GJ/year]** | **Percentage of input exergy [%]** |
|---|---|---|---|---|
| Gasoline– ANP type C[liters/year] | 29,202,169 | 1.066 | 923,263.52 | 45.17% |
| Diesel Oil [liters/year] | 10,294,964 | 1.053 | 384,646.71 | 18.82% |
| Ethanol–ANP type Hydrated [liters/year] | 654,528 | 1.077 | 15,026.69 | 0.74% |
| LPG [kg/year] | 2,449,251 | 1.070 | 121,734.28 | 5.96% |
| Natural Gas [Nm$^3$/year] | 4,514,733 | 1.023 | 149,912.26 | 7.33% |
| Electricity [GWh/year] | 124.78 | N/A | 449,238.84 | 21.98% |
| Total | | | 2,043,822.31 | 100.00% |

Source: adapted from [16], CELESC and SCGAS

All the fuel data was provided, via e-mail, by the Brazilian Petroleum and Biofuels Regulatory Agency (ANP, in Portuguese) [16], data for natural gas was provided by SCGAS, the Gas Company of Santa Catarina and the electricity data was provided by CELESC, the Electricity Company of Santa Catarina. One notices that there is a high amount of input exergy from gasoline. According to the data provided by IBGE [7], Santa Catarina has the highest ratio of individual car for each 1,000 inhabitants in Brazil. While the average in Brazil is 261 cars for each 1,000 inhabitants, Santa Catarina has a 409 ratio and Ararangué 447. Also, Ararangué has a ratio of 21 trucks for each 1,000 inhabitants, while Florianópolis has a ratio of 7. This can explain the high percentage of input exergy due to diesel oil consumption. According to Hartmann *et al.* [2], this last percentage for Florianópolis is 9.19%.

### 3.2.1 Exergy Destruction in the MSW Management System

To calculate the exergy destruction due to an inefficient MSW management system, it was necessary to compute the exergy that can potentially be recovered (EPR) considering scenarios 2 and 1. Tables 4 and 5 show the values of the constants in equations (6) and (7) adopted for estimating EPR.

Table 4: constants for equation (6)

| **Anaerobic Biodigestion** | |
|---|---|
| $m_{organic}$ [kg/year] | 47.9% * 12*1,200*10³ = 6,897,600 |
| $\beta_{Biogas,AB}$ | 0.9986 |
| $LHV_{Biogas,AB}$ (60% of methane) [kJ/Nm$^3$] | 21,000 |
| $\gamma_{ab}$ | 0.35 Nm$^3$ biogas/kg organic waste |
| **Gasification of non-recyclables** | |
| $m_{nr}$ [kg/year] | 18% * 12*1,200*10³ = 2,592,000 |
| $\beta_{syngas}$ | 0.7217 |
| $LHV_{syngas}$ [kJ/Nm$^3$] | 8,500 |
| $\gamma_{gasf}$ | 0.5 Nm$^3$ syngas/kg non-recyclable waste |

Source: adapted from [2,4,17]

Table 5: constants for equation (7)

| **Anaerobic Biodigestion for Landfills** | |
|---|---|
| $m_{landfill}$ [ton/year] | 12*1,200 = 14,400 |
| $\beta_{Biogas,landfill}$ | 0.9928 |
| $LHV_{Biogas,landfill}$ (50% of methane) [kJ/Nm$^3$] | 16,000 |
| $\gamma_{landfill}$ | 50 Nm$^3$ biogas/ton MSW |

Source: adapted from [2,18,19]

Substituting those values in equations (7) and (6) yields:

$$EPR_{scen1} = 14{,}400 \cdot 0.9928 \cdot 16{,}000 \cdot 50 = 11{,}437 \text{ [GJ/year]} \tag{12}$$

$$EPR_{scen2} = 6{,}897 \cdot 10^3 \cdot 0.9986 \cdot 21{,}000 \cdot 0.35 + 2{,}592 \cdot 10^3 \cdot 0.7217 \cdot 8{,}500 \cdot 0.5 = 58{,}576 \text{ [GJ/year]} \tag{13}$$

and the delta of exergy potentially recovered is:

$$\Delta EPR = EPR_{scen2} - EPR_{scen1} = 47{,}140 \text{ [GJ/year]} \tag{14}$$

which is an expressive number. It is three times the input exergy of ethanol and approximately a third of the exergy from LPG. The entropy generated by mixing of the MSW is computed with equation (9), taking into account n = 11 types of waste and using mass fraction $y_i$ from Table 2:

$$S_{Mix}^{scen1} = -k^{MSW} \sum_{i=1}^{n} y_i \ln(y_i) = k^{MSW} \cdot 1.708 \tag{15}$$

Since there is no segregation of the MSW in Araranguá, the actual mixing entropy corresponds to that of scenario 1:

$$S_{Mix}^{MSW} = -k^{MSW} \sum_{i=1}^{n} y_i \ln(y_i) = k^{MSW} \cdot 1.708 \tag{16}$$

and therefore:

$$S_{index}^{Mix} = {S_{mix}^{MSW}} \Big/ {S_{mix}^{scen1}} = {k^{MSW} \cdot 1.708} \Big/ {k^{MSW} \cdot 1.708} = 1 \tag{17}$$

Finally, the exergy destruction associated with the MSW mixing was determined via equation (11):

$$E_{Dest}^{mix} = \Delta EPR \cdot S_{index}^{Mix} = 47{,}140 \cdot 1 = 47{,}140 \text{ [GJ/year]} \tag{18}$$

It is worth mentioning that the result of the calculation (18) was not accounted as input exergy, once the MSW is mixed and no waste-to-energy solution is used in the actual scenario of Araranguá. Additionally, if the energy calculated in (18) was applied to the control volume, certainly the exergetic efficiency would be greater, as explained further in this paper.

### 3.2.2 Exergy Destruction as a result of the combustion processes

Table 6 shows the exergy destructed in combustion processes associated with the control volume under analysis. It was considered a fixed exergy destruction of 30% for all fuels, based on Hartmann *et al.* [11]. It is noticeable that the exergy destructed by combustion of gasoline represents more than 50% of the total exergy destructed by combustion, possibly because of high ratio of individual car for each 1,000 inhabitants of Araranguá.

Table 6: Compiled data of exergy destruction due to combustion

| | Input Exergy [GJ/year] | Exergy Destroyed by Combustion [GJ/year] | Percentage of the Total Destroyed by Combustion |
|---|---|---|---|
| Gasoline | 923,263.52 | 276,979.05 | 57.90% |
| Natural Gas | 384,646.71 | 115,394.01 | 24.12% |
| LPG | 15,026.69 | 4,508.01 | 0.94% |
| Diesel oil | 121,734.28 | 36,520.28 | 7.63% |
| Ethanol | 149,912.26 | 44,973.68 | 9.40% |
| Total | 1,594,583.46 | 478,375.04 | 100% |

Source: Adapted from [11]

### 3.2.3 Evaluation of Exergetic Efficiency for the Actual Scenario

To calculate the exergetic efficiency for the actual scenario, the exergy destructed was previously evaluated as follows:

$$\sum E_{Dest} = E_{Dest}^{mix} + E_{Dest}^{comb} + E_{Dest}^{elect} = 47{,}137 + 478{,}375 + 292{,}005 = 817{,}504 \text{ [GJ/year]} \tag{19}$$

where $E_{Dest}^{comb}$ is the total exergy destructed in combustion processes as presented in Table 6, and $E_{Dest}^{elect}$ is the exergy destructed due to electricity consumption, considered herein as 65%, as explained in section 2.4.1 Accordingly, the exergetic efficiency for the actual scenario is:

$$\eta_E = 1 - \left(\frac{\sum E_{Dest}}{E_i}\right) = 1 - \left(\frac{817{,}504}{2{,}043{,}738}\right) = 0.600 \tag{20}$$

### 3.2.4 Calculation of Exergetic Efficiency for the Idealized Scenario

The evaluation of the exergetic efficiency for the idealized scenario took into account two main differences with respect to the actual scenario. The exergy potentially recovered from the MSW, besides not being accounted as exergy destructed, can reduce LPG and Diesel Oil consumption and, as a consequence, the input exergy in the control volume. Thereby, the calculation of the exergetic efficiency, in this case, became,

$$\eta_E = 1 - \left(\frac{\sum E_{Dest}}{E_i}\right) = 1 - \left(\frac{770{,}867}{1{,}998{,}307}\right) = 0.614 \tag{21}$$

As it can be seen from equation (20) and (21), the exergetic efficiency increased from 60% to 61,4%, which is an enhancement of 1,4%. This may seem little, but it actually means 28,800 liters of diesel oil saved from consumption of the trucks that transport the MSW to the landfill and, hence, avoiding 76.9 tons of $CO_2$ from being emitted to the atmosphere [25]. Furthermore, the economy related to the diesel oil would be around US $ 18,000 in a year. This means that around 960 tons of LPG could be saved in a year, which represents US $ 300,000. Besides that, all the costs related to transportation and disposal in the landfill, that are around US $ 345,000 in a year, would decrease significantly, once in this scenario only a small fraction of the MSW would be destinated to the landfill. This savings would help paying off the costs of implementation of the new facilities needed in scenario 2.

## 4 CONCLUSIONS

It was shown in this work that linking different types of energy in an assessment of urban sustainability applying thermodynamic concepts can help understand a very actual and common problem in many cities in the world: municipal solid waste. It was analyzed two different scenarios in this study and it was shown that a proper MSW management system can save energy and enhance people’s lives.

The city of Araranguá assessed in this work is classified in the worst scenario, in which no solid waste is recycled, taken to an anaerobic biodigester nor gasified, but destinated to a landfill, located 25 km away from the city. This means that 47,137 GJ of potential exergetic recovery is lost each year, which could save around 960 tons of LPG and avoid 76.9 tons of $CO_2$ from being emitted to the atmosphere. In other words, the exergetic efficiency would improve from 60% to 61.4% if Araranguá could be classified in scenario 2. Additionally, around US $ 345,000 that are used to pay transportation and destination to the landfill in a year could be saved and invested in gasifiers and biodigesters equipment. In social aspects, it was also shown that there are many waste pickers in the city that could be benefited from a correct MSW management, besides the fact that people would learn more about the waste, its types and its final destination, creating a more conscious production and consumption within the city.

Finally, the use of a mixing index has shown to be useful in all of these exergetic understandings, which can be an ally to project effective smart cities and enhance cities where the problem of the MSW management system still persists. It is also understood that solving environmental problems in the current global socioeconomic system is not enough to make change happen, but it must be attached to monetary savings as well, which the present study has shown to contemplate the necessity, demonstrating that more than US $ 600,000 in a year could be saved and invested in gasifiers and biodigesters technologies.

# REFERERENCES

[1] THE WORLD BANK (org.). **Trends in Solid Waste Management**. Disponível em: https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html#:~:text=The%20world%20generates%202.01%20billion,from%200.11%20to%204.54%20kilograms.. Accessed: 01 out. 2020.

[2] HARTMANN, Ricardo Morel *et al.* Assessment of municipal solid waste management system using a mixing index as indicative for urban sustainability analysis. In: INTERNATIONAL CONFERENCE ON EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS, 32., 2019, Wroclaw.

[3] ZAMAN, Atiq Uz. Measuring waste management performance using the 'Zero Waste Index': the case of Adelaide, Australia. **Journal Of Cleaner Production.** Adelaide, Australia, p. 407-419. nov. 2013.

[4] LOPES, E.J. *et al*. Evaluation of energy gain from the segregation of organic materials from municipal solid waste in gasification processes. **Renewable Energy.** Curitiba, p. 623-629. out. 2017.

[5] LUZ, Fábio Codignole *et al*. Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil. **Energy Conversion And Management.** Roma, p. 321-337. jun. 2015.

[6] Brazil. Law n_ 12.305, August 2, 2010a. Establishes the national policy of solid waste; amends the Law n_ 9.605 of February 12, 1998; and provides other measures. Federal Official Newspaper, Brasilia, Brazil, August 3; 2010. <http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm> [accessed 23.07.20 (in Portuguese)].

[7] IBGE, Instituto Brasileiro de Geografia e Estatística. **Cidades e Estados**. Available at: https://www.ibge.gov.br/cidades-e-estados/sc/ararangua.html. Accessed: 24 jul. 2020.

[8] SEBRAE. **Araranguá em Números**. Available at https://www.sebrae.com.br/Sebrae/Relat%C3%B3rio%20Municipal%20-%20Ararangu%C3%A1.pdf. Accessed: 24 jul. 2020

[9] ÇENGEL, Yunus A.; BOLES, Michael A. **Thermodynamics: an engineering approach**. 7. ed. New York: McGraw Hill, 2011.

[10] J. Szargut, D. R. Morris, and F. R. Steward, **Exergy analysis of thermal, chemical, and metallurgical processes**. Hemisphere, 1988.

[11] HARTMANN, R. M.; OLIVEIRA, E. J. de; ROCHA, M. I.; OLIVEIRA JUNIOR, A. A. M. de. Customized Software and Hardware applied to Assessment of Outwardly Spherical Flames Using the Pressure Trace: a Thermodynamic Approach to Improve Accuracy of Laminar Flame Speed Measurements. **International Journal Of Thermodynamics.** [S.I.], p. 121-130. jun. 2017

[12] Y. Liu, Y. Li, D. Wang, and J. Liu, "Energy and exergy utilizations of the Chinese urban residential sector," **Energy Convers. Manag.**, p. 634–643. 2014

[13] A. Bejan, Advanced engineering thermodynamics. John Wiley & Sons, 2006.

[14] SISTEMA NACIONAL DE INFORMAÇÕES SOBRE SANEAMENTO - SNIS. **Diagnóstico do Manejo de Resíduos Sólidos Urbanos**. Ministério do Desenvolvimento Regional, 2018.

[15] SELECTUM. **Quem somos**. Available at: https://selectum.eco.br/. Accessed: 28 jul. 2020.

**[16]** Agência Nacional do Petróleo, Gás Natural e Biocombustíveis- ANP. **Vendas anuais de etanol hidratado e derivados de petróleo por município**. 2018. Disponível em: http://www.anp.gov.br/dados-estatisticos. Accessed: 28 jul. 2020.

[17] SWEDEN. SWEDISH GAS TECHNOLOGY CENTRE. . **Basic Data on Biogas**. Lund: © Sgc, 2012.

[18] G. C. Young, Municipal solid waste to energy conversion processes : economic, technical, and renewable comparisons. Wiley, 2013.

[19] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). IPCC Guidelines for National Greenhouse Gas Inventories**.** 2006

[20] B. PURVIS and Y. MAO, Thermodynamic entropy as an indicator for urban sustainability? **Elsevier.** Nottingham, p. 802-812. set. 2016.

[21] ABRELPE, Associação Brasileira de Empresas de Limpeza Pública e Resíduos. **Panorama**. 2017. Disponível em: https://abrelpe.org.br/pdfs/panorama/panorama_abrelpe_2017.pdf. Acesso em: 01 out. 2020.

[22] Klein SA. Engineering equation solver. Professional Version V10.836-3D(2020-06-10). FChart Software, Madison, WI; 2009.

[23] PRESERVALE. Composição gravimétrica dos resíduos sólidos urbanos do aterro sanitário Preservale. Araranguá: PRESERVALE, 2014.

[24] GLUZEZAK, Maiara Luiza Novello. OPORTUNIDADES E DESAFIOS NA RECUPERAÇÃO ENERGÉTICA DA FRAÇÃO ORGÂNICA DE RESÍDUOS SÓLIDOS URBANOS – O CASO DE ARARANGUÁ/SC. 2018. 38 f. Monografia (Graduação) - Curso de Engenharia de Energia, Universidade Federal de Santa Catarina, Araranguá, 2018.

[25] AGENCY, United States Environmental Protection. Greenhouse Gases Equivalencies Calculator - Calculations and References. Disponível em: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-

references#:~:text=Carbon%20dioxide%20emissions%20per%20barrel,per%20barrel%20(EPA%202019).. Accessed: 16 dez. 2020.