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ENERGY VALORIZATION OF BIOGAS IN THE STATE OF SANTA CATARINA, BRAZIL: ALTERNATIVES OF IMPLEMENTATION

Julian Esteban Barrera
Marco Antonio Casarin
Edson Bazzo
Laboratory of Combustion and Thermal Systems Engineering, Federal University of Santa Catarina, Florianópolis, SC –Brazil.
julian@labcet.ufsc.br
eng.aut.mac@gmail.com
e.bazzo@ufsc.br

Paulo Belli
Hugo Gossman
Department of Sanitary and Environmental Engineering, Federal University of Santa Catarina, Florianópolis, SC –Brazil.
paulo.belli@ufsc.br
gosmann.ha@hotmail.com

Abstract. *Based on the current status of the harnessing and exploitation of the biogas in the state of Santa Catarina, this paper analyzes various strategies for taking full advantage of its energy potential. The Municipal Solid Waste (MSW) and the swine waste appear as the sources with the greatest biogas availability, representing a current production of about 4.2 millions of cubic meters per day. Three currently accessible technologies for electricity generation were compared with the biomethane production and exportation, taking into account the typical compositions for the landfill biogas and the swine waste-derived biogas. Given the different nature and processing level for these options, the analysis was carried out on an exergy basis with the aim of determining the most efficient alternative for the biogas energy valorization in each case. The results indicated the electricity generation as the best choice when compared with biomethane exportation, due mainly by the large exergy consumption of the compression stage necessary for gas transportation. Analogously, among the generation alternatives, it was found that biogas engines are the most convenient choice in both cases, mainly because of its low exergy destruction rate when compared with biogas microturbines and steam turbines. By other side, the waste heat exergy coming from the engines can be recovered more easily, enabling the implementation of cogeneration schemes. Scaling these results to the whole state biogas production, it results in the empowerment of about 1.7 GW that were not previously exploited and an annual electricity generation potential of up to 6,6 TWh.*

Keywords: *Biogas, Energy Valorization, Exergy Analysis, Biomethane, Thermodynamic cycles.*

1. INTRODUCTION

In the last decade, the harnessing and exploitation of biogas as an energy source have caught the attention of diverse companies and academic entities around the world, motivated mainly by environmental and sustainability concerns (REN21, 2014). In that way, one of the most important advantages of the use of biogas as fuel is the provision of useful and valuable energy from environmentally-harmful gases, simultaneously reducing the impact inherent to their emission. Nevertheless, the lack of transport infrastructure, the level of refinement of biogas treatment processes and the size of a biogas source can limit its practical and economical utilization, reducing consequently the feasibility of being availed (Wellinger *et al.*, 2013). Considering that these aspects can rarely be modified since the biogas commonly is considered as a sub-product of other activities (e.g. Municipal waste management, agroindustry, etc.), it is important to select adequately its energy conversion method in order to take full advantage of it.

The proper selection of the biogas conversion technology is especially important in emergent markets –like the Brazilian market, which has a great biogas production potential due to its great biomass availability and the dynamics encouraged by its current MSW (Municipal Solid Waste) disposal legislation (ABRELPE, 2012), but has an incipient infrastructure and a relatively poor biogas-specific technology accessibility. In spite of that, until early 2015, ten biogas production plants generate around 65 MW, three more are under construction with a total capacity of 58 MW and three new projects were approved by the Brazilian energy agency (ANEEL) with a total capacity of 32 MW (ANEEL, 2015). Particularly, in the state of Santa Catarina (South of Brazil), various biogas-related projects were inaugurated during the last two years. Among them, the LFG (Landfill Gas) electricity generation plant in the city of Itajaí (Dresser-Rand, 2014), the biogas-dedicated laboratory in the city of Concordia (GIZ GmbH, 2013) and the swine waste biomethane plant in the city of Pomerode (Brasil Clean Energy, 2014) are the most notable projects, demonstrating a growing interest of public and private entities in the biogas exploitation chain.

Various studies related with the general production, harnessing and exploitation of the biogas in Brazil has been developed (*e.g.* Zanette (2009); Gusmão (2008); Salomon and Silva Lora (2009)), including studies focused in small and energy-autonomous condominiums (Coimbra-Araújo *et al.*, 2014) as well as in large-scale applications as fuel substitute for urban bus fleet (Nadaletti *et al.*, 2015). However, the most part of these publications has reported the energy potential of the biogas directly associated with its methane content, and sometimes estimating a general electricity conversion efficiency, without taking into account the different available technologies that could be used for the energy biogas valorization chain.

Within this context, this paper presents an exergy comparison of three already-demonstrated biogas technologies for electricity generation, with the aim of assisting the selection of a proper valorization method. The alternatives chosen are: 1) use of gas generator sets (internal combustion engines), 2) use of gas turbines and 3) use of Rankine cycles. On the other hand, based on the operation scheme of the plants already installed in the state, two biogas pre-treatment methods are covered: 1) biogas humidity removal by cooling/condensation and 2) biomethane purification using water scrubbing.

2. METHODOLOGY

2.1 Exergy Analysis

The exergy analysis has demonstrated to be a suitable approach when assessing electricity generation plants, since it enables the identification of the most inefficient processes or components within these systems, as well as the quantification of their maximum recoverable energy when interacting with their surroundings. The formulation for this analysis is based on the methodology presented by Bejan *et al.* (1996), but considering the specific exergy of a multicomponent stream (b) formed by three addends, as proposed previously by Hinderink *et al.* (1996) (see Eq. 1). The use of this approach facilitates the exergy calculation when separation processes of multicomponent mixtures are involved.

$$b = b_{ph} + b_{ch} + \Delta_{mix} b \tag{1}$$

Where b_{ph}, b_{ch}, and $\Delta_{mix} b$ are the specific physical exergy, the specific chemical exergy and the specific exergy of mixing, respectively. In addition, the exergy consumption was defined as the electricity taken from the grid for the equipment operation in each plant. Analogously, the exergy efficiency (η_{II}) of the generation plants was defined as the degree of thermodynamic perfection (see Eq. 2) as proposed by Szargut *et al.* (1988).

$$\eta_{II} = \frac{B_p}{B_{in}} \tag{2}$$

Here, B_p corresponds to the exergy flow of the product of the plant (*i.e.* electricity) and B_{in} is the exergy fed to the plant. In order to establish a comparison frame for the different cases, the calculation basis was set at 1 MW (exergetic basis) of raw biogas fed into each plant.

2.2 Biogas composition

The composition of the biogas depends mainly on the type of source, the method and the conditions used for its extraction. However, the biogas dedicated literature shows various typical composition ranges for the most common sources of biogas (*i.e.* LFG, swine manure biogas and swage biogas). Since the methane content of the biogas is one of the most important parameters when evaluating its energy potential, this work considers three different biogas compositions, resembling a poor methane content biogas, a medium methane content biogas and a rich methane content biogas (see Tab. 1). The molar fractions were set arbitrarily, based on the biogas composition ranges presented by Deublein and Steinhauser (2008). The chosen compositions are presented in dry basis, however for the exergy calculations, the raw biogas is considered saturated with water at the inlet conditions of the pre-treatment plant.

2.3 Biogas pre-treatment options

There are several biogas pre-treatment options, whose main purpose is to remove the humidity and other impurities that can alter the proper operation of the generation systems, mainly the hydrogen sulfide and the siloxanes (Wellinger *et al.*, 2013). On the other hand, if the purpose of the plant is to obtain biomethane to inject into a natural gas grid (or as vehicle fuel), the carbon dioxide must be removed in order to meet the methane content requirement for natural gas (regularly >96%). The method of biogas treatment evidently depends on its composition, the conditions of its production and the objective of the plant. The report presented by Bauer *et al.* (2013) summarizes various commercially available technologies for the biogas treatment and purification, as well as a list of various biogas upgrading plants suppliers. For

Table 1. Biogas Molar Compositions (Dry Basis)

Component	Composition 1	Composition 2	Composition 3
Methane	0.45	0.52*	0.70
Carbon Dioxide	0.35	0.28*	0.25
Nitrogen	0.18	0.15	0.03
Oxygen	0.02	0.05*	0.02
Hydrogen Sulfide	8000 ppm	8000 ppm	8000 ppm

**Data acquired from Itajaí city landfill in August 2014*

this study, the chosen technologies are those previously installed in the state of Santa Catarina, because it is expected that these technologies have a rapid employment in the region due to the fact that are already demonstrated.

In the case of the landfill gas with a low hydrogen sulfide content, the process is rather simple and consist in the removal of the humidity from the biogas by decreasing its temperature for promoting the condensation and further separation of the water droplets. Its operation scheme is presented in Fig. 1. First, the biogas is fed to the vessel V-201 where the liquid and other impurities drawn by the biogas within the gathering system are removed. Thereafter, the biogas stream is cooled through the heat exchanger E-201 by the circulation of a water-glycol mixture (streams 31 and 32), and the condensed water is then separated in vessel V-202. Next, the biogas stream is compressed by K-201 to meet the pressure requirements for its exportation, prior a temperature adjustment in the exchanger E-202. By other side, the flare F-201 is used for contingencies and to burn properly the biogas that is not used/exported by the plant.

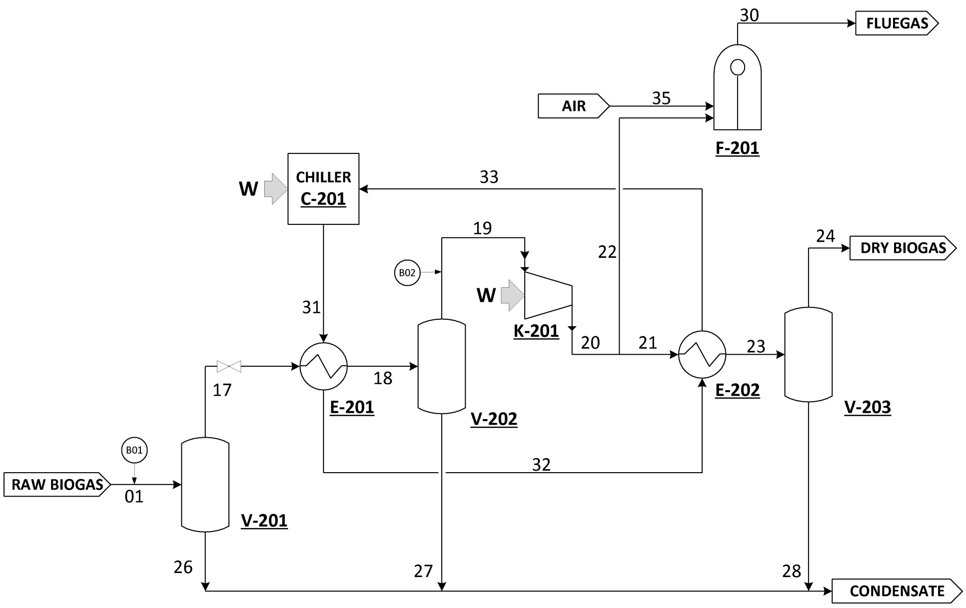

Figure 1. Operation scheme of a biogas dehumidification plant.

On the other hand, Fig. 2 illustrates a water scrubbing plant for biomethane production. This arrangement includes a packed adsorption column (T-101) to remove the hydrogen sulfide present in a typical swine manure biogas. The humid biogas coming from the manure digester is compressed by K-101 and directed trough the column T-101, where the hydrogen sulfide is striped from the gas by adsorption on an iron-oxide-impregnated matrix. The detailed description of this adsorption process can be found in (Becker, 2013). Next, the biogas (free of hydrogen sulfide) is cooled through the air cooler E-101 and conducted through the absorption column T-102, where a great portion of the carbon dioxide content is removed from the biogas. The separation of the carbon dioxide and the methane is driven by the difference between their solubilities in water. The operation parameters of this column were stablished according the Henry's law, following the formulation presented by Bauer *et al.* (2013). Thereafter, the water-saturated biomethane is directed to a compressed gas dryer, where its humidity is removed. Finally, the dry biomethane is compressed (K-102) and its temperature is adjusted (E-102) for its exportation.

Currently, both pre-treatment schemes are good alternatives for improving the quality of biogas and mitigate simultaneously the environmental impact of its atmospheric venting or flaring. From the exergy point of view, these disposal methods were compared with the chosen pre-treatment plants in order to illustrate the biogas valorization effect. This

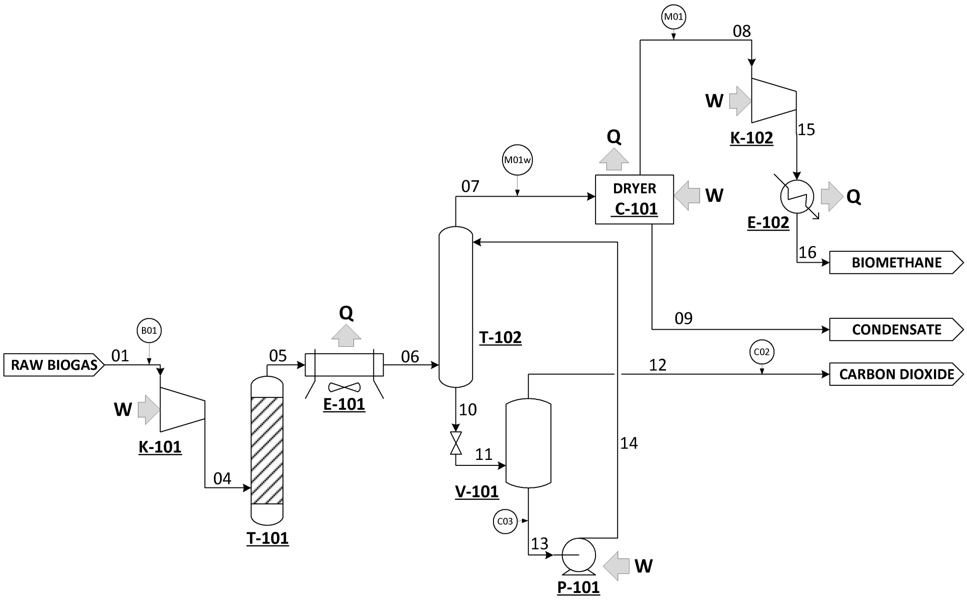

Figure 2. Operation scheme of a biomethane purification plant.

analysis was carried out considering the variation of the biogas composition (see Sec. 2.2) in four cases described as follows:

- *Case 1: Biogas atmospheric venting.* This case reflects the conditions of landfills and farms that have incipient or poor biogas gathering systems, and permit the uncontrolled emission of biogas to the atmosphere via field sparse drainpipes (landfill case) or directly from the agricultural waste.
- *Case 2: Biogas atmospheric flaring.* This case simulates the conditions of landfills and farms that gather the biogas and burn it properly using flares. This operation was considered adiabatic (by using encapsulated flares), following the requirements for carbon credits attribution (Conestoga-Rovers & Associates, 2004).
- *Case 3: Biogas dehumidification plant.* This case analyzes the treatment of a low hydrogen sulfide content biogas following the scheme of Fig. 1. The main operation conditions were stablished according the actual operation of the generation plant at the Itajaí city landfill.
- *Case 4: Biomethane purification plant.* This case simulates the treatment of a high hydrogen sulfide content biogas, commonly encountered at swine manure digestion plants. The model was developed following the scheme displayed in Fig. 2 using typical operation conditions as reported by Bauer *et al.* (2013).

2.4 Electricity production systems

Taking into account the scope and the focus of this paper, the chosen technologies are those that are or could be available in the state of Santa Catarina. In that way, the technologies covered by this study are: 1) gas engines, 2) gas turbines, 3) Rankine cycles. Considering the options for biogas pre-treatment as well as the current biogas production circumstances, the exergy analysis was developed using the composition of the medium methane content biogas (see Tab. 1 – Composition 2) and taking into account the energy efficiency for three different sizes of equipment according to available data. The proposed cases for electricity production are described as follows:

- *Case 5: Use of generator sets (internal combustion engines) fabricated/modified by suppliers to work directly with dry biogas (about 50% methane).* This option are currently applied for small-to-medium projects (up to 3 MWe) and uses the dehumidification plant (see Fig. 2) to supply the biogas to the engine.
- *Case 6: Use of microturbines fabricated/modified by suppliers to work with dry biogas.* This option appears to be a suitable option for small projects (up to 1 MWe). In the same way of case 5, this option uses the biogas coming from a dehumidification plant.
- *Case 7: Use of an ORC (Organic Rankine Cycle).* This option conceives the direct combustion of the raw biogas in the burner of a thermal oil heater with the aim of transferring the required heat for activating an ORC. This option was conceived for isolated locations with small biogas availability, since this type of system are accessible in small

sizes and unattended operation is possible (Siemens Energy, 2014). The analyzed range was from 70 kWe up to 300 kWe.

- *Case 8: Use of conventional NG (natural gas) generator sets.* This alternative is conceived together with biomethane purification plants (see Fig. 2) and considers the performance characteristics of greater engines than those considered in case 5 (2 - 4.5 MWe).

- *Case 9: Use of conventional NG turbines.* Similarly to the case 8, this alternative is accomplish by a biomethane purification plant and considers the performance characteristics of greater turbines than those considered in case 6 (2.5 - 6.5 MWe).

- *Case 10: Use of conventional Rankine cycle.* This option contemplates the direct raw biogas burning at a proper steam boiler with the aim of generating between 2 and 7.5 MWe using conventional steam turbines.

2.5 Operation parameters and assumptions

The cases escribed previously were modeled using the computer software EES®. The general assumptions are listed below:

- Steady state operation.

- Comparison basis: 1 MW of biogas supplied to the plants (exergy basis).

- The performance data of the electricity production equipment corresponds to the information supplied by various manufactures at nominal capacity conditions. These parameters can be found in Annex 1.

- The extensive characteristics of selected equipment (*e.g.* air flow, fuel flow, etc.) were scaled relative to the equivalent fuel heat flow entering each system.

- Environmental conditions: 25°C and 101.325 kPa.

- Biogas supply conditions: 50°C and 101.325 kPa.

- Air molar composition: 20.9% O_2, 78.1% N_2 and 1% Ar.

- Exhaust gases formed by the following components: O_2, N_2, Ar, CH_4, CO, CO_2, H_2 and H_2O.

- Compressors isentropic efficiency (mean): 65%.

- Pumps isentropic efficiency (mean): 75%.

- Pressure drop through piping and equipment is neglected.

For each case, different assumptions and parameters were adopted properly with the aim of modeling the operation of the plant within reasonable conditions. These assumptions are listed as follows:

- *Case 2 (biogas flaring):* 1) the combustion of the biogas takes place adiabatically and stoichiometrically, 2) chemical equilibrium is reached, 3) the excess of air is calculated in such a way that the exhaust gases final temperature is about 330 °C (this figure corresponds to the temperature reported for the encapsulated flare in the LFG plant at Itajaí city landfill).

- *Case 3 (biogas dehumidification):* 1) the water dew point of the biogas is adjusted to 8.7 °C, 2) water-glycol mixture supplied at 0°C, 3) outlet biogas temperature: 20°C and 4) outlet biogas pressure: 113.5 kPa (122 mbar). These figures were reported in the Itajaí landfill plant.

- *Case 4 (biomethane purification):* 1) biogas compressed up to 10 bar, 2) pressure drop at T-101: 2 bar, 3) pressure drop at T-102: 3 bar, 4) outlet biomethane pressure: 60 bar, 5) water dew point of the biomethane is adjusted to 3 °C, 6) outlet biomethane temperature: 40 °C and 7) biogas intermediate temperature: 35°C.

- *Cases 5 and 8 (biogas/biomethane gen. set):* 1) biogas/biomethane pressure at engine intake: 113.5 kPa (in case 8, an expansion valve was included upstream the engine) and 2) the composition of the exhaust gases was calculated assuming that the combustion takes place adiabatically and isochorically after an isentropic compression of the air-fuel mixture. Chemical equilibrium is reached.

- *Cases 6 and 9 (biogas/biomethane turbines):* 1) biogas/biomethane pressure at turbine intake is adjusted according with manufacturers data and 2) Exhaust gases composition is calculated assuming a non-adiabatic combustion at constant pressure. Chemical equilibrium is reached.
- *Case 7 (Heater and ORC):* 1) The combustion of the biogas takes place adiabatically and stoichiometrically, 2) chemical equilibrium is reached, 3) the excess of air is calculated in such a way that the exhaust gases reach a temperature of about 500 °C and 4) the outlet temperature of exhaust gases was set to 150 °C.
- *Case 10 (steam Rankine cycle):* 1) Boiler adiabatic efficiency: 91%, 2) Turbine inlet pressure 45 bar, 3) Turbine outlet pressure: 110 kPa, 4) Turbine output: 7.5 MW.

3. RESULTS

Evidently, the treatment of the biogas has significance only if used subsequently. Given the current status of most landfills and farms in the state of Santa Catarina, where the biogas that is produced or accumulated is simply vented of flared without any practical use, a comparison with the proposed treatment options is presented in Fig. 3. As mentioned above, one of the main advantages of using the exergy analysis approach is that it enables the distinction of the sources of irreversibility in a process and the work potential that is wasted because of the rejection of heat and material streams. In that way, for the case of direct biogas venting, all its potential is discarded to the atmosphere and therefore it is considered as an exergy loss.

3.1 Biogas pre-treatment options

Analogously, for the case of the biogas flaring, a portion (about 17-30%) of the exergy of the biogas is destroyed (shown as solid gray portion) in the combustion process, the rest is rejected to the atmosphere as hot exhaust gases. From the energy point of view, these disposal methods have no efficiency nor consequence. However, the gas burning is preferable from the environmental point of view (EPA, 2012) and enables the use of the heat released by the combustion.

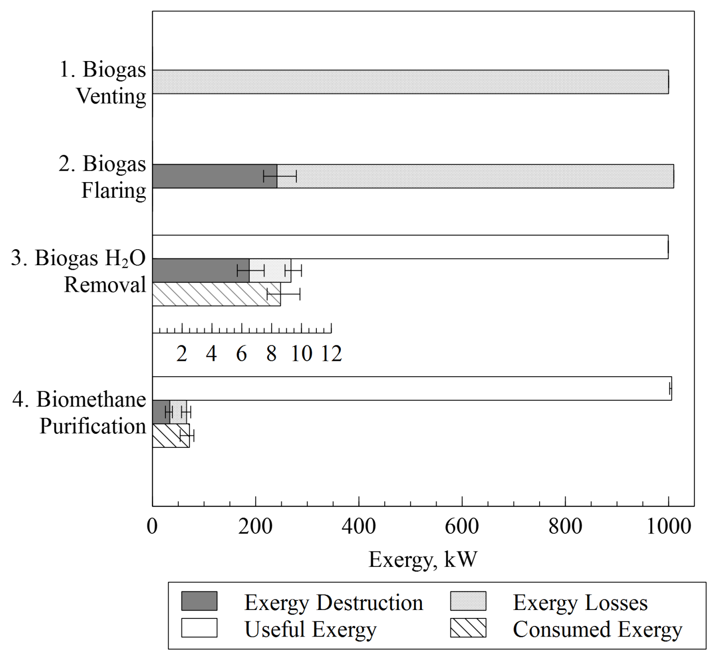

Figure 3. Exergy parameters comparison for the biogas pre-treatment options.

On the other hand, the biogas pre-treatment processes denote a further utilization of the biogas, for that reason the treated biogas coming out from the plants is considered as useful product of each pre-treatment system. Given that most of the exergy of biogas stream corresponds to the chemical exergy of methane, the exergy of treated biogas is practically equivalent to the raw gas entering the plant. Evidently, the quality improvement of the biogas implies an electricity (work) consumption that is displayed as consumed exergy. The results indicate that the exergy consumption for a biomethane plant is approximately 5-6 times greater than the consumption of a dehumidification plant. This great difference is caused mainly by the work necessary to compress the biogas, first up to 10 bar for promoting the carbon dioxide absorption and then up to 60 bar, which is the minimum pressure necessary to inject the biogas into the natural gas grid (pressure drop through connecting pipeline is neglected). The compression work represents approx. 72% of the total demand for the biomethane plant and about 20% for dehumidification plant.

The incidence of the methane content of the raw biogas is represented by the bar ranges, the greater the biogas methane fraction, the lesser the exergy consumption. This behavior is related with the calculation basis imposed to the model, the greater the specific exergy of the biogas (*i.e.* its methane content), the lesser the mass flow necessary to meet the exergy flow of 1 MW.

3.2 Electricity production alternatives

Regarding the selection of the most adequate biogas-to-electricity conversion technology, often the decision is restricted by the commercial availability of equipment and the lack of operating facilities that demonstrate the convenience or profitability of these plants. In addition, given that new biogas facilities commonly imply great investments and important adaptations at biogas source location in order to guarantee a sustainable operation, it is important to choose the most adequate technology that can take full energy advantage of biogas and presents a better convenience.

Figure 4 presents the results of the exergy analysis applied to the available technologies using dehumidified biogas directly. Vertical bars are used for delimiting the thermal efficiency range (nominal) for available equipment, according with their size. In this manner, for biogas generator sets, the size range was established between 72 kW and 1.38 MW with efficiencies ranging from 31% up to 41% for the larger sets. Analogously for biogas microturbines, available sizes range from 30 kW up to 1 MW with efficiencies between 26% and 33%. For the case of the ORCs, the minimum size selected was 70 kW with a thermal efficiency of 17% and the maximum size was 300 kW with a thermal efficiency of 22%; the combustion of biogas in the furnace was modeled following the same procedure for the encapsulated flare.

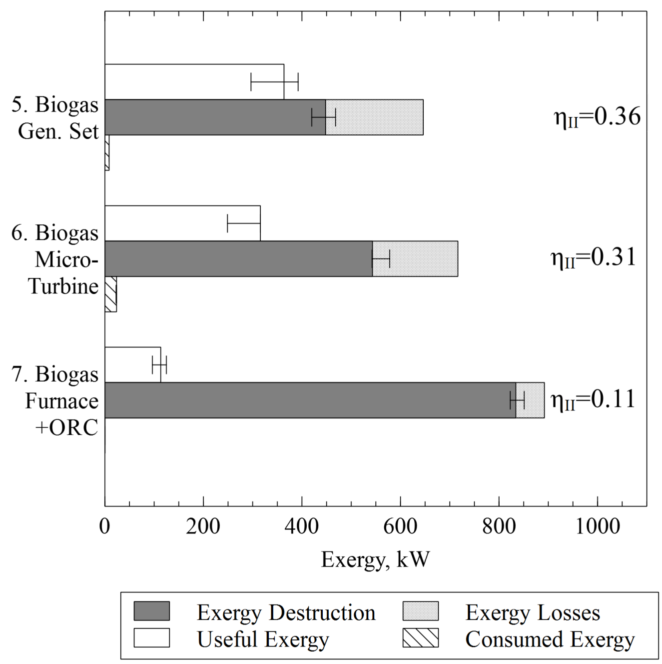

Figure 4. Exergy parameters comparison for the biogas equipment options.

As it can be seen, the alternative with the best exergy performance is the use of generator sets. This option reports the highest electricity production and the lowest exergy destruction with the given exergy input constraint. In addition, it has the lowest electricity consumption when compared with the biogas microturbines. The exergy losses of both alternatives are comparable, however the engines commonly have one or more refrigeration circuits that can facilitate the integration of additional systems for exergy recovering. On the other hand, the poorest efficiency was reported for the ORC. This behavior is related to the high exergy destruction due by large temperature difference between the heat source (combustion chamber in the furnace) and the ORC. The main vantage of this system is the fact that it is compact and can be installed in autonomous mode (not water nor other auxiliaries needed), without direct consumption from the grid. The specific electricity output using ORC is lesser than the half of that produced using generator sets or turbines, while its exergy losses are reduced due to the low temperature at which the residual heat is rejected (150°for exhaust gases and about 40°for the air-coooled condenser).

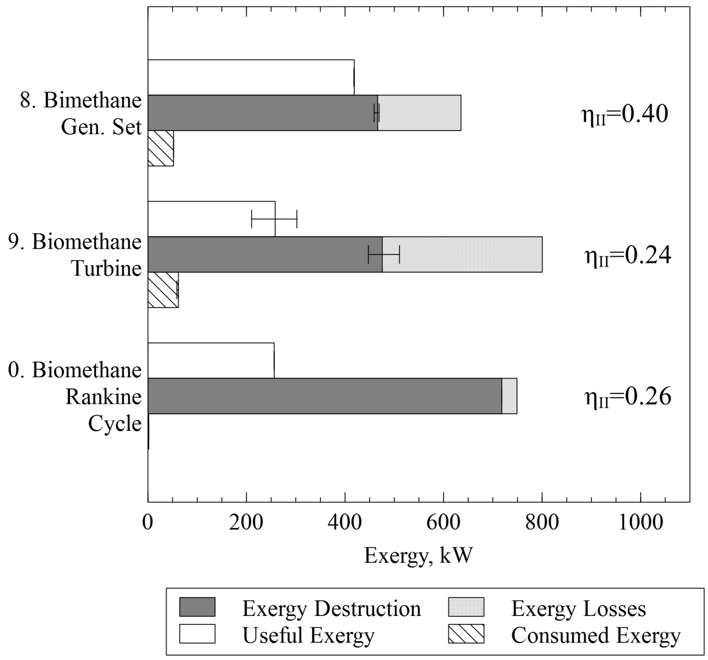

Figure 5. Exergy parameters comparison for the biomethane (natural gas) options.

Similarly, Fig. 5 shows the exergy flow distribution for equipment using biomethane. In fact, these systems are conventional and are designed for working with natural gas. The purpose of comparing these systems with those using biogas directly is to identify whether the exergy consumed by the pre-treatment processing would be justified by the increase in the size and the performance the equipment or not. In that way, the size range considered for moto-generators was between 2 MW and 4.5 MW with a nominal efficiency of 43.7% and for gas turbines, the sizes were established from 2.4 MW up to 6.4 MW with thermal efficiency ranging from 22% and 31.6%. On the other hand, the conventional Rankine cycle was assessed, taking into account the smaller sizes available in the market, considering that finding a biogas source large enough to provide a commercial-scale plant would be improbable. Thus, the chosen sizes for the steam turbine were from 2 MW up to 7.5 MW and the steam conditions were fixed according with the data supplied by the manufacturer. The results indicate again the gas generator sets as the technology with the greatest exergy efficiency. Moreover, it seems that the integration of a biomethane plant prior to the gas engine improves the overall exergy efficiency, in spite of the greater exergy consumption.

On the other hand, the thermal efficiencies found for available medium-size gas turbines were slightly lower than those found for biogas microturbines and it makes that the overall exergy efficiencies are lower than those reported for smaller plants. For that cases, it seems that a eventual escalation of this technology by treating the biogas to obtain biomethane is not advantageous from the exergy point of view. In addition, that escalation would imply a greater share for exergy losses, suggesting that the use of a combined cycle (Rankine cycle recovering par of the exergy of the gas turbine fluegas) could improve the performance of this system. By contrast, the use of a conventional Rankine cycle seems to be a poor choice given the size and the number of components forming the system, and the fact that the boiler would be fed with biomethane, which results in a great investment for obtaining a large exergy destruction further in the boiler and in the steam turbine. It would be more interesting to produce electricity using commercial-sized Rankine cycles using the raw materials directly for combustion; In other words, to incinerate the RSU or the agriculture residues directly into the boiler (designed for that purpose). This approach does not require any important pre-treatment besides the material selection, and would enable a greater scale production.

From these observations, it can be inferred that if the alternative with the greater efficiency would be applied in the all currently-known biogas sources, a more realistic regional electricity production potential can be estimated. Thus, based on data reported by Gosmann (2014) for the total biogas production in the state of Santa Catarina, which corresponds to approximately 4.2 millions of cubic meters of methane equivalent per day, an electricity production potential between 713 MW and 760 MW is estimated. This figure would represent an annual generation of up to 6.6 TWh.

4. CONCLUSION

Diverse strategies for biogas energy valorization were analyzed using an exergy approach. This analysis was carried out taking into account the typical composition of biogas according to its source, the pre-treatment processes already proven in the state of Santa Catarina, and different equipment commercially-available for electricity generation. The obtained results suggest that local electricity production is more advantageous than biomethane exportation due to the high exergy consumption associated with the compression stage(s) needed for its processing and transportation.

On the other hand, diverse technologies for electricity generation were analyzed aiming to the alternative with the greatest exergy efficiency. Three technologies (Otto cycle, Brayton cycle, and Rankine cycle) were analyzed taking into account the use of dehydrated biogas and biomethane, as well as the common range found for equipment size and efficiency. For both cases, Otto cycle (*i.e.* generator sets) reports the highest exergy performance among these systems, with values of 36% for biogas used in small-to-medium size equipment and 40% for biomethane used in medium size equipment. Moreover, this type of equipment enables the incorporation of heat recovery schemes with more flexibility than the gas turbines due to the existence of the water refrigeration circuits.

Scaling these results to the state biogas production potential, it was estimated an empowerment of 1.7 GW that were not previously exploited (as raw biogas) with an annual electricity generation capacity of 6.6 TWh.

5. ACKNOWLEDGEMENTS

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