Calculating the overall efficiency of polygeneration plants – introducing an integrated thermodynamic decision tool for biomass gasification

S. Vakalis [a]* and M. Baratieri [a]

[a] Free University of Bolzano, Faculty of Science and Technology, Piazza Università 5 – 39100 Bolzano, Italy
* Corresponding author, e-mail: stergios.vakalis@natec.unibz.it, Tel: +39 0471 017635; fax: +39 0471 017009.
Co-authors' e-mail: marco.baratieri@unibz.it

Abstract

The increased demand for energy efficiency and environmental assessment of the energy production units has raised the attention to polygeneration plants. As polygeneration plants could be defined the plants that combine the generation of electricity with cooling and heating applications. In addition, it is the case that alongside the production of electricity and heat, valuable or waste materials streams are generated. Therefore a more integrated approach needs to be developed in order to assess the full range of products. In the framework of this paper a thermodynamic approach for assessing comprehensively polygeneration plants is introduced, where a qualitative assessment of the streams is done by means of thermodynamic concepts defined as exergy, entransy and statistical entropy. The ultimate aim of this method is to provide a comprehensive tool capable to compare energy production units with each other, even if these plants couldn't be compared on a straightforward way, because they produce a different spectrum of products and have different operating parameters and conditions. A numerical example of this efficiency index is projected by utilizing measurements that were implemented in a small scale gasification plant in Northern Italy. The application of this second-law index provides a clearer and more straightforward projection of the quality of the products and their potential. This may assist the decision-making both in the policy and the industrial sector because it can project which type of investment will perform better on an integrated thermodynamic way.

Keywords: exergy, entransy, statistical entropy, cogeneration, biomass gasification

1. Introduction

Energy efficiency has been a significant parameter in the development of policy tools but also for decision making purposes. The standard approach is that energy efficiency is projected by a simple ratio of the 'useful output' in comparison to the total input [1]. Moreover the utilization of indicators is a rather common practice in order to integrate complex parameters that go beyond the simple scenario of an energy balance. Four major categories could be identified: Thermodynamic, physical/thermodynamic, economic /thermodynamic and economic [1, 2]. Thus more complex issues can be tackled and quantified like the environmental impact or issues of economic nature. Nevertheless, except from the pure thermodynamic approaches, in all the other cases hybrid indicators are utilized. These hybrid indicators transform the input – which usually has thermodynamic units- into physical or economical units. As a result we come across efficiency factors that transform energy units into carbon dioxide equivalent units (CO2-eq.) or even monetary units when parameters like the Gross Domestic Product (i.e. GDP) are introduced. The issue that is stated by Patterson (1996) is "how to precisely define the useful output and the energy input, which in turn gives rise to a number of important methodological considerations which are often ignored in the literature."

The political aspects of energy efficiency have mainly the scope to denote the necessity of reducing CO2 emissions due to the fact that climate change is on the agenda of the political dialogues of all the industrialized countries. As a result various policy tools have been deployed, i.e. subsidies, taxation schemes and labelling, in order to enhance the objective of higher energy efficiency. At the same time, although these tools have the same scope, they should not be considered functionally equivalent and therefore a way to estimate, quantify and compare them objectively is an issue of high importance [3].

While the concept of energy efficiency is rather familiar, the various implementation methods and techniques produce a vague and sometimes confusing outcome. The complexity of modern industrial and manufacturing processes usually involve a variety of flows and products of different nature. The application of conversion factors may connect units and physical quantities in ways that do not necessarily produce a meaningful outcome. Therefore the adoption of a specific and objective framework needs to be developed in order to precisely measure energy efficiency. It is an essential step in order to optimize our technological decisions that will eventually affect the costs, the environmental impact and finally the way that policy is implemented [4].

The increased demand for energy efficiency and environmental assessment of the energy production units has raised the attention to polygeneration plants. As polygeneration plants could be defined the plants that combine the generation of electricity with cooling and heating applications. Along with electricity and heat, valuable or waste materials are produced which can have various utilizations [5]. In the case of biomass gasification, various by-products like tars, are not utilized for either electricity or heat production but could have an environmental impact. The variety of products has raised the necessity to evaluate the performance of cogeneration /polygeneration plants on an integrated basis by means of a more integrated approach and additional thermodynamic concepts should be introduced in order to assess their efficiency and their performance [6]. Implementing mass and energy balances can be a first but still very crucial step to the estimation of the efficiency of a process with various streams. In particular, it has been observed that conventional CHP efficiency analysis is not sufficient if used alone to reflect the overall potential of a gasification plant. Moreover until now there has been not a solid and robust way to evaluate the quality of the materials [6, 7].

2. Background and scope

2.1. The process of gasification

As gasification we could define the thermochemical conversion of a carbon-rich fuel under sub-stoichiometric conditions into mainly a gaseous product commonly known as syngas or producer gas. The syngas has heating value therefore it is a fuel, due to the energy that is packed into chemical bonds during the conversion process. This fuel is usually combusted in a Combined Heat and Power engine, i.e. CHP, in order to produce electricity and heat.

As projected in Fig. 1, gasification has also other output streams. Char can be the main co-product of gasification, it has a structure similar to graphite and a significant heating value. Additionally there are other output streams, i.e. tars, soot, dust and ash that their energetic value is relatively low but they could have a significant environmental impact [8]. Thus, the quantification of the impact is a factor that should be taken into consideration.

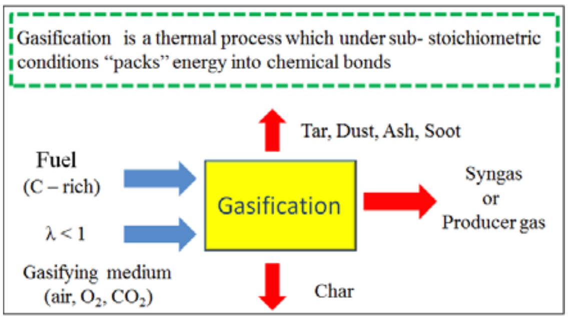

Figure 1. The process and the streams in gasification.

2.2. Assessment of energetic streams

The standard approach in assessing energy production units is the calculation of the CHP efficiency. This is a thermodynamic ratio where numerator is the sum of the electrical power and the enthalpy of the heat (thermal energy) and the denominator is the total (lower) heating value of the input. In addition other indicators like available thermal energy have been introduced [9]. These approaches have been widely applied and have been the standard practice, nonetheless the necessity for the assessment of the quality of the products have made CHP efficiency obsolete.

In this framework the application of second law analysis became handy. Exergy can be defined as a thermodynamic indicator for the quality of the energy. It represents the maximum work that could theoretically been obtained from a system [10]. A more comprehensive explanation of the physical unit exergy will be done in a next chapter. What becomes evident from an exergy analysis is that the functions of state of a system, like temperature and the pressure, are crucial for the amount exergy. In example, the same amount of steam would have a higher exergic value the hotter and the more pressurized it is. The concept of exergy has been very useful in the energy industry due to the wide utilization of steam turbines.

2.3. Analysis of Material Flows

As it has already been mentioned, gasification plants similarly to other polygeneration facilities have also material output streams which can be quantified with onsite measurements and the implementation of mass balances [6]. Material Flow Analysis, i.e. MFA, is very useful tool to assess the sustainability of a process. Usually this happens by means of assessing the environmental degradation due to accumulation of pollutants [11]. By means of MFA we have the quantitative representation of the input and output flows along with accumulated stocks in the different steps of the process. Thus, the tool enhances our ability to identify potential environmental threats.

This assists not only the efficiency of the monitoring but also the ability to develop precautionary measures. The MFA can take into consideration the economic aspect because the flow of materials is correlated to economic activity. Therefore, MFA can be a great tool for decision making. On the other hand, the quality and the accuracy of the provided data are crucial to the result. This requires global standardized methods that could take place only if MFA is adopted on a global scale [12].

There have been various methods to evaluate the quality and the environmental impact of the material flows. Mainly the approaches utilize hybrid indicators with the most characteristic ones to be: material intensity per service unit (MIPS), sustainable process index (SPI), the Swiss ecopoints (SEP) approach and the most familiar concepts of Cost-Benefit Analysis (CBA) and Life Cycle Assessment (LCA). The idea behind utilizing these approaches and not objective thermodynamic quantities is mainly based on two pillars; the willingness to rationalize the results and give them meaning and on the other hand the inability of the pure thermodynamic concepts to provide an integrated index [11].

Although the implementations of well-established evaluation methods, like LCA, have very precise execution rules, the consistency and reliability of the data but also of the realistic impact are matters of objective concern [13]. Therefore more fundamental thermodynamic concepts are increasingly utilized for the evaluation of material flows like chemical exergy and statistical entropy [11, 14]. Finally, combining second law evaluation tools with other assessment tools is a topic that gains momentum. Characteristic is the development of hybrid combinations of LCA with statistical entropy and exergy [15, 16].

2.4. Assessing flows from a gasification plant

In Fig. 2 are projected, the energy and exergy flows of a small scale gasification plant. The results were obtained during the implementation of GAST project, which is a project that aims to monitor and assess small scale biomass gasification plants in the region of South Tyrol (Italy). The abbreviation GAST simply means GAsification in South Tyrol and it was developed due to the rapid growth of small scale biomass gasification plants in the area. The high interest of local entrepreneurs to invest in gasification technology is mainly justified due to the high economic incentives and the fact that biomass is a pillar of the local economy [17].

Analyzing the exergy flow in gasification processes is an accepted and well-established method in order to provide integrated results that reflect the quality of the output streams and quantifies the irreversabilities [18, 19].

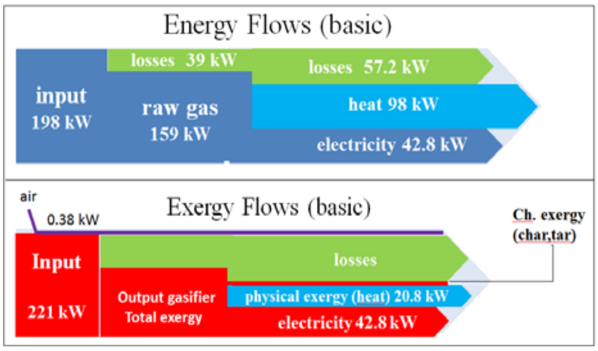

Figure 2. Energy and exergy flows of a small scale downdraft gasifier in kW [6].

From the analysis of the energy and exergy flows along with the evaluation of the material flows some very important outcomes became evident. Although the CHP efficiency is almost 75%, the exergic efficiency varies significantly. Heat has much lower exergic content than energetic value. This reflects the low quality of the thermal energy. Nonetheless what should be pointed out is that the streams with thermal energy are not intended to provide work but to transfer heat, i.e. heating or cooling applications. Thus the concept of exergy becomes obsolete in the assessment of the heat streams and additional thermodynamic concepts should be applied. In addition the integration of indexes containing energy and material streams remains an issue that has only been tackled with indirect- non thermodynamic methods [11].

2.5. Scope of developing a new efficiency tool

The issues described above denote the fact that a more integrated and fundamental approach needs to be developed in order to assess the full scale of products. In the framework of this paper a thermodynamic approach for assessing comprehensively polygeneration plants is introduced. The efficiency index combines the measure of the maximum amount of work that can theoretically be obtained, the ability of the system to transfer the produced heat and the potential of the process to concentrate or dilute substances. An initial approach to make a qualitative assessment of the streams is done by means of thermodynamic concepts defined as exergy, entransy and statistical entropy. The goal is the qualitative assessment of the whole spectrum of output streams, i.e. electricity, heat, emissions, liquid and solid residues (e.g. NOx, tar, char, heavy metals). The approach uses different expressions that are derived from the second law of thermodynamics.

The example of this efficiency index is projected by utilizing measurements that were implemented from a small scale gasification plant in Northern Italy.

Nonetheless the method can be used also to assess any other cogeneration plant with multiple outputs. Furthermore, the aim of this method is to provide a comprehensive tool capable to compare energy production units even if these plants couldn’t be compared on a straightforward way, because they produce a different spectrum of products and have different operating parameters and conditions. This direct comparison of different technologies may assist the decision-making both in the policy and the industrial sector because it can project which type of investment will perform better on an integrated thermodynamic way.

3. Development of methodology

3.1. Theoretical background

The concepts that will be analyzed and explained are *exergy, entransy* and *statistical entropy.*

Exergy, as mentioned before, can be defined as a thermodynamic indicator for the quality of the energy. It is a function of the ambient conditions, i.e. pressure, temperature and the internal energy of the system and represents the *maximum potential* of the system to provide work if the system went reversibly into equilibrium with its surroundings. This thermodynamic quantity has been called with various ways, but mainly the terms that were used have been ‘available energy’ and ‘maximum available work’. In 1956 the term ‘ekthalpy’ was introduced and in the same year, the term ‘exergy’ was introduced by Rant [19, 20].

Nonetheless, exergy should not be confused with Gibbs free energy (or the more correctly, the Free Enthalpy) which is the isobaric and isothermal thermodynamic potential. Although conceptually similar, Gibbs free energy is independent from the system surroundings and it strictly refers to the maximum non-expansion work that can be obtained from a closed system.

Exergy is generally defined with the equation

$$\mathrm{B} = \mathrm{h} - \mathrm{h}_0 - \mathrm{T}_0(\mathrm{s} - \mathrm{s}_0) \qquad (1)$$

but may have different aspects that can correspond to a system according to specific characteristics. The main types of exergy are physical and chemical exergy and in rare cases kinetic and potential exergy may also be a factor. Physical exergy, i.e. B_{ph}, is highly dependent not only on the relative temperature and pressure of a stream, but also on the physical state of matter. It is defined as the maximum work that can be done when the system comes reversibly to equilibrium with the surroundings, i.e. to the restricted reference state. Accordingly, chemical exergy is the maximum work that can be performed by a system when it is taken from the restricted reference state to a complete thermodynamic equilibrium where the system is in total thermal, mechanical and chemical equilibrium with the surroundings. Chemical exergy, i.e. B_{ch}, is dependent on the composition but also to the specific type of bonds that are developed inside a compound [21]. Straightforward correlations have been developed which relate the substances and their heating value by a factor, known as β factor: $B_{ch} = \beta * LHV$ (2)

For biomass the β factor is:

$$\beta = \frac{1.0414 + 0.0177\left[\frac{H}{C}\right] - 0.3328\left[\frac{O}{C}\right]\left(1 + 0.0537\left[\frac{H}{C}\right]\right)}{1 - 0.4041\left[\frac{O}{C}\right]}$$

Chemical exergy may assist the evaluation of material flows and provide insight for possible utilization of material for production of work.

Entransy is a physical quantity that projects the ability of a system to transfer heat, thus it could be described as the transfer heat potential [22]. It is developed within the framework of the thermomass theory and can be derived directly from the special theory of relativity [23]. Entransy, i.e. G, is for the system in terms of the analogy what the electrical potential energy represents for a capacitor [24] and is defined as:

$$G = \frac{1}{2} MCvT^2 \qquad (3)$$

where T is the temperature, M is the mass and Cv is the constant volume specific heat capacity. Entransy is a useful concept due to the fact that the produced thermal energy is not utilized to provide work but mainly to provide heat. In such cases, where the thermal energy is solely utilized for heating (or cooling) purposes, entransy and the optimization of its dissipation rate provides a different (and more optimal) result than the application of the minimum entropy generation principle [24]. Finally, for the cases of open systems expressions for the efficiency of entransy and exergy have been developed, where it became evident that the concepts of entransy dissipation and entropy generation are linked [25].

After finding expressions that can reflect the potential of the system to produce work or to transfer heat, a thermodynamic expression should be utilized in order to describe the behavior of the material that undergoes a specific process. *Statistical entropy* in material flow analysis could be defined as the potential of a system or a process to concentrate or dilute substances [14]. This quantity utilizes the equation that was developed by Claude Shannon and is utilized in Information Theory to quantify the amount of missing information (MI). Although the equation is very similar to the expression that Max Planck derived from Ludwig Boltzmann's original statistical entropy equation, this specific quantity is missing Boltzmann's constant and thus it is unitless [26]. Nonetheless it is valid, under specific restrictions, to make the transition from the information entropy to the thermodynamic entropy [27]. In Fig.3 is projected an example of statistical entropy calculation.

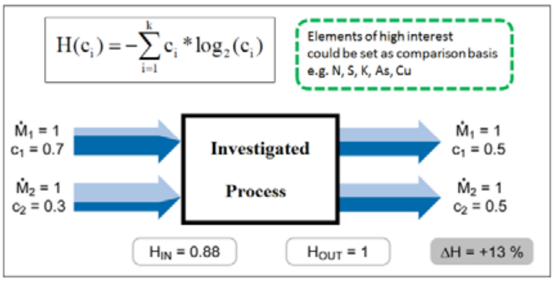

Figure 3. Example of calculating the statistical entropy [14].

It is interesting to point out that there has been a very vivid debate about the nature of entropy and the possibility that the units of entropy cancel each other. The explanation is that entropy was introduced by Clausius before James Maxwell introduced the dynamic theory of gases and established the connection between the average kinetic energy of the molecules and the absolute temperature. Therefore entropy's units, which are energy divided by temperature, would cancel out due to the fact that temperature is a unit of energy [27]. On the other hand this approach implies that the Boltzmann's constant is nothing more than a correction factor in order to make his statistical entropy compliant with the thermodynamics of his era. Nonetheless the presence of Boltzmann's constant solves the issue of entropic degeneracy, a quantity which would be relatively high in various compounds like carbon monoxide if not for the diminishing presence of Boltzmann's constant.

3.2. Integrated balance

The three previous concepts defined as exergy, entransy and statistical entropy are therefore combined in order to create an overall efficiency index that would include all the input and output steams and their potential whether they are energetic or material flows. The concept of this comprehensive tool is projected on Fig.4. The goal is not to replace existing factors like the CHP efficiency which are widely used and familiar to the majority of the people but to enhance existing indexes that do not sufficiently represent the quality of the streams and the potential of the process with second law thermodynamic concepts.

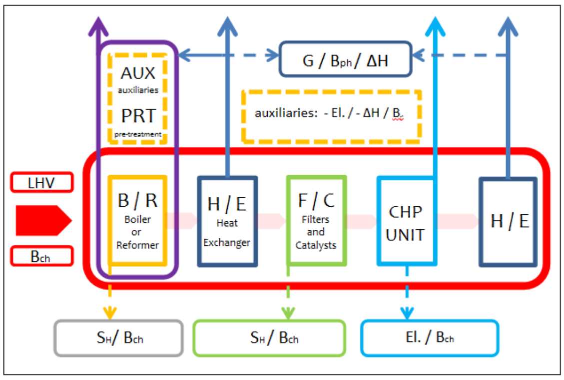

Figure 4. Integrated balances - Comprehensive assessment tool

This integrated tool takes into consideration all the different possible parts/ processes of a gasification plant. Therefore drying, filtering and the recovering of heat through heat exchangers have various irreversabilities that should be taken into consideration. Individual balances can be developed for the different thermodynamic expressions. Thus for every step of the process, one can observe how much the exergy or the entransy are dissipated or which part of the process chain dilutes or concentrates more substances.

Alongside the development of this comprehensive tool the scope was also the development of an overall index that would project the efficiency of the whole process. It is the case that exergy, entransy and statistical entropy do not share the same units and thus they cannot be directly summed. Nonetheless each of the individual efficiencies for every different expression can be calculated, which are unitless indexes. Therefore the overall index may consist from the combination of the efficiencies as projected in the next equation:

$$OE= (Eff_B + Eff_G + Eff_H) / 3 \qquad (4)$$

with OE representing overall efficiency and Eff_B, Eff_G and Eff_H being the efficiencies for exergy, entransy and statistical entropy respectively.

4. Results and discussion

In order to make a numerical example, the exergy and the entransy efficiency will be extrapolated by the monitoring campaign of the GAST [6] and have been also partially projected on Fig.2. The statistical entropy efficiency will be extracted from Fig. 3. Also the hot water was distributed to the network at a temperature of 90 °C and the environmental temperature was 25°C). Therefore the exergic efficiency was 29,8%, the entransy efficiency was 75,7% and the statistical entropy efficiency 13%. The OE would be in this case 39,5%.

The electrical efficiency of the plant was 22%. In the case that the electrical efficiency was 30%, and the losses were less, the OE would be 41,7%. Accordingly, the OE would increase if e.g. more substances were concentrated or on the other hand would decrease if the temperature of the distributed heat was higher.

An issue of high concern is the development of a precise framework of the substances that should be taken into consideration during the implementation of the statistical entropy analysis. Different types of inputs have different types of pollutants that can potentially be emitted.

The OE factor becomes really useful when the same input can be processed with various technologies or at different scales. Thus in the case of organic waste, anaerobic digestion can be directly compared with gasification or in the case of municipal solid waste landfill gas can be compared with waste incineration. Also different scales of operation may perform differently or may project a small increase in the overall efficiency of the process.

Finally higher or lower overall efficiencies do not rely only at the process itself but also at the decisions made by the operator, i.e. as it was mentioned before the temperature of the distributed heat has a direct effect on the dissipation of entransy. Therefore this is a tool that can not only compare different processes or systems but also can indicate the optimal conditions for the operation of a specific technology.

A possible development is the categorization of the plants not according to their specific technologies but according to the input that they process. In this case, e.g. the facilities that process biomass would be category A, the facilities that process municipal solid waste would be category B etc. Thus each different plant would have a characteristic number/ code that would reflect its overall efficiency in the processing-utilization of a specific type of input. For example, our small scale gasification plant would be A-39,5.

An interesting pathway would be the development of a Multi-criteria Analysis tool that would integrate limits that are acceptable for efficient energy production or limited environmental impact. This would be also important in the case that we would like to compare energy plants with reforming facilities. Nonetheless, this would require significant changes in the approach that is presented in this paper.

5. Conclusions

Energy efficiency is very useful method that assists policy development and decision making. Nonetheless, the conventional efficiency indexes are not sufficient in order to represent the potential of the processes that take place and the quality of the streams that are produced in a polygeneration plant. A new comprehensive assessment tool has been introduced where different expressions of the second law of thermodynamics are combined. These are exergy, entransy and statistical entropy. Due to the fact that these physical quantities do not share the same units, their efficiencies are combined in order to create one integrated index. This index can compare how a specific input is processed between different technological options or even how the same performs in different scales. Originally the tool was developed in order to assess biomass gasification plants but it can be utilized also for the assessment of various energy production facilities.

6. References

[1] Patterson, M.G, : What is energy efficiency - Concepts, indicators and methodological issues. Energy Policy. Vol. 24, No. 5, pp. 377-390. (1996)

[2] Wilson, B, Trieu, L H and Bowen, B : 'Energy efficiency trends in Australia' *Energy Policy* 22 (4) 287-295. (1994)

[3] Varone, F., Aebischer, B.: Energy efficiency: the challenges of policy design. Energy Policy 29. pp. 615 – 629 (2001)

[4] Giacone,E., Mancò, S.: Energy efficiency measurement in industrial processes. Energy 38, pp. 331 – 345 (2012)

[5] Carpenter, A.: Polygeneration from coal. Clean Coal Center, Report No 139, ISBN 978-92-9029-458-0, pp. 96 (2008)

[6] Vakalis, S., Prando, D., Patuzzi, F. and Baratieri, M.: Measuring the performance of biomass small scale gasification plants by implementing mass and energy balances. Proceedings for the 4th Central European Biomass Conference, Graz, January 15-18 (2014)

[7] Vakalis,S and Baratieri,M., Measuring biomass gasification plants by means of integrated balances. Proceedings for the International Biomass Conference 2014, Orange County (FL), March 24-26 (2014)

[8] Vakalis, S., Prando, D., Patuzzi, F., Mimmo, T., Gasparella, A., Tirler, W., Dal Savio, S., Chiaramonti, D., Prussi, M., and Baratieri, M.: Experiences in biomass gasification in South-Tyrol: the 'GAST' project. Proceedings for the 21st European Biomass Conference & Exhibition, Copenhagen, June 3-7 (2013)

[9] Thumann, A. and Mehda, P.: Handbook of Energy Engineering – 6th Edition. pp. 247-255, Fairmont Press -Taylor & Francis Group, London (2008)

[10] Perrot, P.: "A to Z of Thermodynamics." Oxford University Press. (1998)

[11] Brunner, P. and Rechberger, H.: Practical Handbook of Material Flow analysis.Lewis Publishers. Vienna (2005)

[12] Daly, H. (2012). The Sustainable Scale Project - Material Flow Analysis. http://www.sustainablescale.org/ (2012), Accessed 11 October, 2012.

[13] Ayres, R.U.: Life cycle analysis: a critique, Resour. Conserv. Recycling (14), pp. 199 (1995)

[14] Rechberger, H., Graedel, T.E.: The contemporary European copper cycle: statistical entropy analysis. Ecological Economics 42, pp. 59–72 (2002)

[15] Kaufman, S., Kwon, E., Krishnan, N., Castaldi, M., Themelis, N.: Use of Statistical Entropy and Life Cycle Analysis to Evaluate Global Warming Potential of Waste Management Systems. Proceedings of NAWTEC16
16th Annual North American Waste-to-Energy Conference, Philadelphia (PA) - USA, (2008)

[16] Bakshi, B.R., Gutowski, T., Seculic, D.: Thermodynamics and the destruction of resources – Chapter 10. Cambridge University Press, New York (NY) –USA (2011).

[17] Vakalis,S and Baratieri,M., Technological advancements in small scale biomass gasification: case study of South Tyrol. Proceedings for the 2nd International Conference on Sustainable Solid Waste Management, Athens (Greece), June 12-14 (2014)

[18] Sues, A., Jurascık, M., Ptasinski, K.: Exergetic evaluation of 5 biowastes-to-biofuels routes via gasification. Energy (35), pp. 996–1007. (2010)

[19] Jurascık, M., Sues, A., Ptasinski, K.: Exergy analysis of synthetic natural gas production method from biomass. Energy (35), pp. 880–888. (2010)

[20] Sato, N.: Chemical Energy and Exergy. Elsevier Science & Technology Books. Japan (2004)

[21] Morris, D., Szargut, J.,(1986)."Standard chemical exergy of some elements and compounds on the planet earth". Energy 11(8):733-755

[22] Guo, Z.Y., Zhu,H.Y., Liang,X.G.: Entransy—A physical quantity describing heat transfer ability. International Journal of Heat and Mass Transfer (50), pp. 2545–2556 (2007)

[23] Cheng, X.T., Liang, X.G.: From thermomass to entransy – Tehnical Note. International Journal of Heat and Mass Transfer (62), pp. 174–177, (2013)

[24] Chen, Q., Liang, X.G., Guo, Z.Y.: Entransy theory for the optimization of heat transfer – A review and update. International Journal of Heat and Mass Transfer (63), pp. 65–81 (2013)

[25] Lucia, U.: Stationary open systems: A brief review on contemporary theories on irreversibility. Physica A (392), pp. 1051–1062 (2013)

[26] Sobańtka, A.P., Zessner, M. and Rechberger, H.: The Extension of Statistical Entropy Analysis to Chemical Compounds. Entropy **(**14), pp. 2413-2426 (2012)

[27] Ben-Naim, A.: A Farewell to entropy: Statistical thermodynamic based on Information