

Exergy analysis of a biomass-based multi-energy system

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Abstract. This paper focuses on a biofuel-based Multi-Energy System generating electricity, heat and hydrogen. The proposed system, that is conceived as refit option for an existing anaerobic digester plant in which the biomass is converted to biogas, consists of: i) a fuel processing unit, ii) a power production unit based on the SOFC (Solid Oxide Fuel Cell) technology, iii) a hydrogen separation, compression and storage unit. The aim of this study is to define the operating conditions that allow optimizing the plant performances by applying the exergy analysis that is an appropriate technique to assess and rank the irreversibility sources in energy processes. Thus, the exergy analysis has been performed for both the overall plant and main plant components and the main contributors to the overall losses have been evaluated. Moreover, the first principle efficiency and the second principle efficiency have been estimated. Results have highlighted that the fuel processor (the Auto-Thermal Reforming reactor) is the main contributor to the global exergy destruction (9.74% of the input biogas exergy). In terms of overall system performance the plant has an exergetic efficiency of 53.1% (it is equal to 37.7% for the H₂ production).

1 Introduction

Energy systems designed to produce useful multiple energy output (e.g. hydrogen, heat and electricity) from one or more kinds of energy inputs represent a possible sustainable solution for the transition to low-carbon future energy systems thanks to the enhancement of the overall efficiency. Moreover, a further step to reach the zero-carbon energy systems can be done by using renewables as primary sources. In particular, the biomass utilization could contribute to the mitigation of greenhouse gas emissions, while enhancing energy security and promoting the economic development of rural regions [1]. Thus, the combination of multi-generation with biomass conversion seems to satisfy the current requirements of high overall energy efficiency and renewable sources implementation in the energy production.

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Several studies on multi-generation systems for various applications are available in the technical literature. Soltani et al. [2] presented energy and exergy analyses on an integrated energy system fed primarily by a sawdust burner biomass. The system proposed by the authors produced five commodities: electricity, steam, hot water, district heating and timber drying, and served a wood factory and the neighborhood via district heating. The thermodynamic analysis identified two parameters that affected significantly system performance, and parametric studies were utilized for an optimization purpose. The calculated energy and exergy efficiencies were found to be around 60% and 25%, respectively, while the corresponding energy and exergy efficiencies of a biomass system with only electricity generation are 11% and 13%, respectively.

Dincer and Zamfirescu [3] evaluated the advantages of multi-generation energy systems powered by renewable energy and compared several options from energy and economic points of view. Results of their study highlighted that the multigeneration can help to increase both energy and exergy efficiencies, to reduce the costs and the environmental impact, and to increase the energy generation sustainability.

Ahmadi et al. [4] presented a paper in which the thermodynamic analysis of a multi-generation system, based on a biomass combustor, an organic Rankine cycle (ORC), an absorption chiller and a PEM electrolyzer, was carried out. The modeling of the plant was performed and the exergy destruction and exergy efficiency of each component were calculated by varying some design parameters.

In [5], a novel multigeneration system (heating, cooling, electricity, hydrogen, water) fed by biogas and geothermal heat source, was studied by applying the first and second laws analyses that result to be an effective tools for the performance assessment.

Cruz et al. [6] proposed a bio-hydrogen energy system integrated with a combined-cycle plant and analyzed its performance through an exergy analysis. The hydrogen production section consists of a dry reforming of methane (DRM) unit, high and low temperature water gas shift (WGS) reactors and a pressure swing adsorption (PSA) unit. The combined cycle satisfies the electricity and steam requirements of the process. Results highlighted that the system had an exergetic efficiency of 55%, with the DRM and the power generation unit arising as the main sources of irreversibility.

Bellotti et al. [7] proposed a power to fuel system integrated with CCS Coal power plant producing electricity methanol, and oxygen as main output and performing also the economic assessment.

In this study a biomass-based Multi-Energy System (MES) for the combined hydrogen, heat and electricity was analyzed under the exergy point of view. The MES, that is conceived as retrofit option for an existing anaerobic digester plant in which the biomass is converted to biogas, consists of: i) a fuel processing unit, ii) a power production unit based on the SOFC (Solid Oxide Fuel Cell) technology, iii) a hydrogen separation, compression and storage unit. In previous papers [8,9], the authors designed this plant and evaluated its performances from energy and economic points of view by applying a sensitivity analysis based on the SOFC load variation and, as a consequence, on the production of the two main energy vectors, hydrogen and electricity. Results of the economic assessment [9], highlighted that the main contributor to the plant economic sustainability was the hydrogen production, due to the low prices of electricity in the day ahead market compared with the current hydrogen market price.

Therefore, the presented exergy analysis focuses on a MES designed to produce the amount of hydrogen as required by small refueling stations (100 kg/day); in this case the power production unit (the SOFC power unit) is sized to satisfy the electric energy consumption required for the MES operation and in particular for the hydrogen separation, compression and storage unit.

2 The Multi-Energy System Description

The multi-energy system proposed is conceived to be integrated in an existing anaerobic digestion plant, so that the biochemical conversion of the biomass into biogas is not analysed. The biogas composition is assumed equal to 60% CH₄ and 40% CO₂; this is the composition expected by using the BEKON Dry Fermentation technology [10], which has been chosen as the Best Available Technology for the anaerobic digestion process.

Figure 1 shows the layout of the plant. Biogas, air and water are heated in the heat exchangers HE2 (320°C), HE3 (580°C) and HE1 (550°C), respectively, before entering the ATR (Autothermal Reforming) reactor.

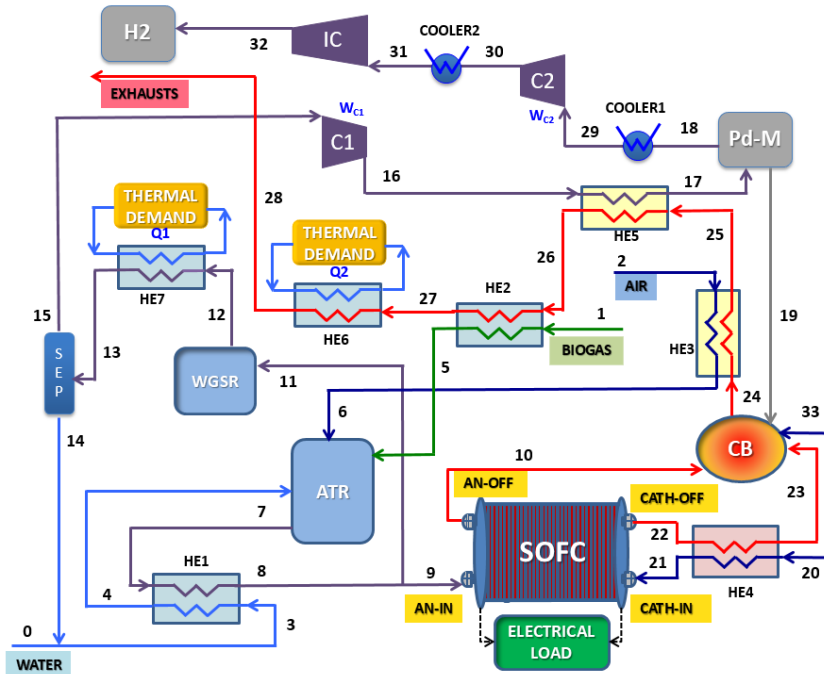


Fig. 1. Layout of the polygeneration system, optimized for compressed H₂ production

The ATR combines the partial oxidation reforming and the steam reforming in a single process in which the thermal energy, needed to sustain the endothermic reforming reactions, is internally supplied by the oxidation of a portion of processed fuel with a controlled amount of oxidant. Thus, the operating parameters of the process are the pressure, the temperature (or the oxidant to carbon ratio, here defined as the air to biogas ratio, A/B) and the steam to carbon ratio (here defined as the steam to biogas ratio, S/B) [11]. High reforming temperatures assure higher hydrocarbon conversion as suggested in [12,13].

The produced syngas exiting the ATR reactor at 767°C, is cooled up to 328°C (HE1) and then is separated in two fluxes: the stream (11) is sent to the WGSR (water gas shift reactor) and the stream (9) is used for feeding the SOFC power unit. The air for the cathode side (20) of the SOFC is pre-heated before entering it (21) at about 368 °C. The SOFC power unit has been sized for supplying the electrical power required by the hydrogen separation and storage sections. Thus, its configuration, in terms of stacks number and cells number per stack, has been defined by taking into account the characteristics of a single cell analyzed by means of experimental and numerical activities presented in a previous paper [14]. By fixing the cell operating temperature equal to 800°C, the SOFC operating conditions (the average cell

voltage 0.725 V, the current density 0.508 A/cm²) have been chosen because they permit to obtain a good compromise between the stack efficiency (0.45 referred to the LHV of syngas) and the average cell power density (0.33 W/cm²). Finally, the stack cooling has been performed by assigning the anode and cathode flow rates and temperatures. The stream exiting the WGSR (12) is cooled in the heat exchanger HE7 and dried in the separator, SEP, before to be compressed by C1 to 8 bar, that is the operating pressure of the membrane separation unit in the feeding side. Then, the stream (16) is heated (HE5) to reach the operating conditions of the membrane separation unit (Pd-M), where the product hydrogen is recovered at 1.1 bar. Thus, the pure hydrogen (18) is cooled (Cooler1) at 20 °C and pre-compressed at 5 bar by the compressor C2. The stream (30) coming out from the C2 is cooled in the Cooler2 and compressed (Ionic Compressor, IC) at 820 bars, in accordance to the requirements of an high pressure hydrogen refilling station. The purge gas (19) from the membrane separation unit is oxidized in a catalytic burner (CB) together with the cathode off-gas (23), the anode off-gas (10) and the fresh air (33). The combustor effluent exchanges heat with more streams (heat exchangers HE3, HE5, HE2, HE6), before being exhausted (28) at 156 °C. The heat exchangers devoted to the thermal demand are HE6 and HE7. Table 1 summarizes the main operating parameters and the energy balance of the plant.

Table 1. MES system: main operating parameters

Power production area	
SOFC power unit (kW) DC/AC	38/36.4
Stacks number/ Cells number x stack	4/52
Active area (cm ²)	500
Average stack voltage/Current density (V/A cm ²)	0.725/0.508
Stacks Temperature (°C)	800
U _F	0.790
Chemical process area	
<i>Fuel processing unit</i>	
ATR/WGS reactors temperature (°C)	767/400
A/B;S/B (mol/mol)	1.7;0.62
H₂ separation area	
<i>Pb-Membrane Separation Unit</i>	
Hydrogen Recovery Factor, HRF	0.747
Feed/Permeate sides pressure (bar)	8.0/1.1
Operating Temperature (°C)	400
Modules Number/ Module Tubes Number	9/18
Tube area (m ²)	0.0385
<i>Compressor C1</i>	
Pressure ratio	7.3
Polytropic efficiency	0.75
Electric power (kW)	18.4
Hydrogen compression area	
<i>Compressor C2</i>	
Pressure ratio	5
Electric power (kW)	4.0
Polytropic efficiency	0.75
<i>Ionic compressor IC</i>	
Stage Pressure ratio	2.77
Stage Polytropic efficiency	0.91
Stage Heat removed (%)	90
Electric Power	11.0
Auxiliaries consumption (kW)	3.0

3 Exergetic Analysis Results

Exergy analysis seems to be an appropriate technique to assess and rank the irreversibility sources in chemical processes [15].

The exergy analysis is here performed for both the overall plant and main plant components. The total exergy of a multicomponent material stream is given by the sum of the chemical exergy of the species and the physical exergy:

$$Ex = Ex_{Chem} + Ex_{Phys} \tag{1}$$

The value of the chemical exergy is derived from [16], taking into account the two physical states of the water and the effect of the gas mixing on the chemical potential. The physical exergy is estimated with respect to the enthalpy and entropy, calculated in polynomial form and assuming as reference conditions 25°C and 1 bar [17]. The exergy balance was performed by the means of a calculation spreadsheet.

The general exergy balance, referred to the global control volume “g”, is defined by eq. (2). The sum of the exergy input and the reversible work exchanged is equal to the sum of the output exergy stream, the exergy lost (i.e. dispersed to the ambient in the *i*th component) and the irreversibility (Irr) that represents the exergy destruction rate occurring at the *i*th component level.

$$Ex_{input,g} + \sum W_{rev,i} = Ex_{output,g} + \sum Ex_{lost,i} + \sum Irr_i \tag{2}$$

Figure 2 shows the overall system exergy balance. The main exergy input is due to the biogas chemical content, Ex_{biogas} , (the physical exergy of water, air and biogas are quite negligible, because their temperatures, 20°C, slightly differs from the state reference condition). The term Ex_{lost} , in the global balance consists of the exergy of effluents (i.e. low temperature flue gas and heat rejected by the coolers to the ambient) and summarizes all the low exergy streams that leave the process without yield a product. This term, directly calculated at component level, was added to evaluate correctly the exergy balance of the system. At MES level, the power production balance, represented by the term $W_{rev,i}$ is null, since the system is not designed for power production, but to sustain the process energy needs. The Grassmann diagram represents the global exergy balance with the irreversibilities destroying the 32.1% of the exergy in input, while the exergy lost is the 14.8 %.

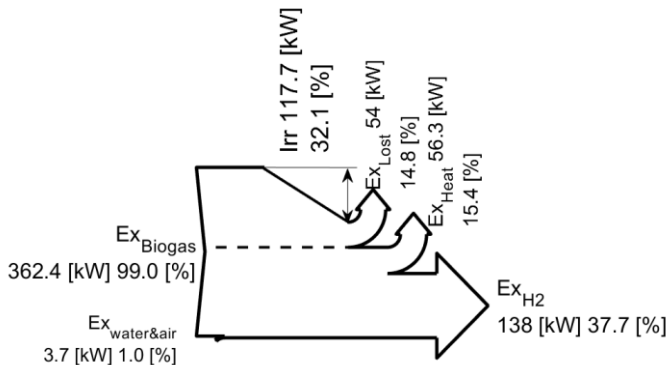


Fig. 2. Global MES Exergy Balance (Grassmann Diagram)

The two products, hydrogen and heat, represents the 37.7% and the 15.4% of the input exergy, respectively. The Biogas to hydrogen mass flow rate ratio is 16.6:1, resulting in a production of 4.2 kg/h of H₂.

Moreover it is possible to assess the overall MES performance defining a first principle efficiency, η , and a second principle efficiency (or rational efficiency), ε , referring to the generic “x” control volume, as in equation (3).

$$\eta_x = \frac{E_{output,x}}{E_{input,x}} \qquad \varepsilon_x = \frac{EX_{output,x}}{EX_{input,x}} \qquad (3)$$

In both case the balance for the “g” control volume, can be summed up as the ratio between the output and the input stream to the system, basing on energy for the first principle efficiency and to the exergy for the rational efficiency. Table 2 presents the comparison of the two efficiencies taking into account the separate production of hydrogen and the combined hydrogen and heat production. In these two cases, the MES has an efficiency of 40.71% and 77.28% and an overall rational efficiency of 37.7% and 53.1%. It can be noticed how the exergy approach reduces the heat production weight with respect to the first principle evaluation.

Table 2. Global Balance of the MES system: efficiency and rational efficiency

	Efficiency (η_g)	Rational Efficiency (ε_g)
H ₂ Production	40.71	37.71
H ₂ and Heat Production	77.28	53.09

The same approach can be used at single component level, taking into account in the efficiency definition also the effect of $W_{rev,i}$ that must be added to the output exergy if extracted by the system, i.e. produced by the system, and added, as absolute value, to the input exergy if introduced into the system. Moreover, the exergy destruction ratio (Irr_i), that represents the part of the overall input exergy that is destroyed in the *i*th component [6], can be calculated as:

$$y_{Irr,i} = \frac{Irr_i}{EX_{input,g}} \qquad (4)$$

Table 3 presents the balance of the single components of the MES: the main contributor to the global exergy destruction is the combustion process which occurs in both ATR ($y_{Irr,i}$ 9.74%) and the Catalytic Burner (6.68%). High values of exergy destruction can be founded at HE1 (5.09%) where the irreversibility is due to heat transfer through a finite temperature difference, which is enhanced by the phase change of the water. The HE4, that is the regenerative cathode air heat exchanger, presents the lowest exergy efficiency (70.2%) due to the high temperature difference between the hot and cold fluid.

It is worth noting that the syngas compression to 8 bar (after the WGSR) by means of the intercooled compressor C1 necessary for the Hydrogen separation requires more power with respect to subsequent compression phase. The compression up to 820 bar is performed by the C2 compressor and after the cooler 2 by the ionic compressor, IC, which performs a quasi-isothermal compression of the hydrogen up to 820 bar, leading to a large impact of the C1 exergy destruction (1.6%).

Table 3. Component Exergy Balance Results

	$W_{rev,i}$	$Ex_{input,i}$	$Ex_{output,i}$	Irr_i	$Ex_{lost,i}$	ϵ_i	$\gamma_{Irr,i}$
U.M.	[kW]	[kW]	[kW]	[kW]	[kW]	[%]	[%]
FC	36.40	95.47	51.71	7.36	1.98	92.29	2.01
CB	-	126.01	101.54	24.47	-	80.58	6.68
ATR	-	391.63	355.96	35.67	-	90.89	9.74
WGSR	-	228.50	227.77	0.73	-	99.68	0.20
HE1	-	358.61	339.97	18.64	-	94.80	5.09
HE2	-	438.48	435.07	3.40	-	99.22	0.93
HE3	-	102.00	95.99	6.01	-	94.10	1.64
HE4	-	13.23	9.29	3.94	-	70.20	1.08
HE5	-	300.98	297.43	3.55	-	98.82	0.97
C1	-18.40	212.76	214.51	5.82	10.83	92.80	1.59
C2	-4.00	138.02	138.98	3.04	-	97.86	0.83
IC	-11.00	138.02	138.07	0.77	10.18	92.65	0.21
AUX	-3.00	-	-	-	-	-	-
Cooler1	-	140.26	138.02	-	2.24	98.40	-
Cooler2	-	138.98	138.02	-	0.96	99.31	-
Pd-M	-	221.37	221.00	0.37	-	99.83	0.10
Stack	-	27.82	-	-	27.82	-	-

A further step has been made by grouping the MES component into functional segments: i) the energy production area (SOFC, HE1); ii) chemical process area (ATR, WGSR, HE3); iii) the catalytic burner (CB); iv) the H2 separation area (HE7, C1, HE4 Pd-M); v) H2 compression area (C2, IC and the two intercoolers); vi) the heat recovery section (HE2, HE3, HE6 and HE5).

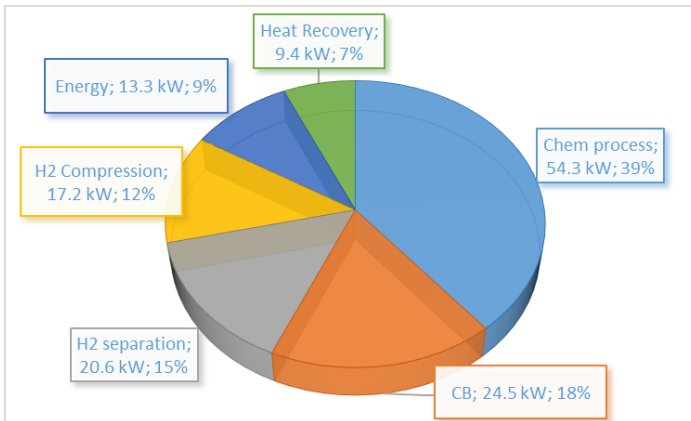


Fig. 3. Irreversibilities and Exergy Losses of the different MES functional section

Figure 3 presents the MES irreversibility contribution divided by functional area; it can be noted that, the chemical process area accounts for the 39% of the overall exergy destruction and loss, while the CB, the H2 separation area and the H2 compression area contribute with 18%, 15% and 12%, respectively.

4 Conclusions

In the proposed system layout, the biogas, produced in an anaerobic digester, is used to feed a poly-generation unit (or a multi-energy system, MES) that consists of a fuel processing unit, an SOFC (Solid Oxide Fuel Cell) power unit and a hydrogen separation and storage unit. The system has been sized taking into account the most common output from an organic fraction of municipal solid waste feeding anaerobic digester (biogas production with a composition of 60%CH₄ and 40% CO₂), and the MES internal power consumption in order to optimize the compressed hydrogen production. The irreversibility of the main components have been taken into account, by identifying the ATR (the Auto-Thermal Reforming reactor) as the main contributor to the global exergy destruction (9.74% of the input biogas exergy) together with the catalytic burner (responsible for the 6.68%). Not negligible irreversibility are introduced by the heat exchangers, which globally destroy the 9.71% of the exergy due to the heat transfer through finite temperature difference; this phenomena is enhanced in case of the water phase changing, as it occurs in the exchanger HE1.

The overall system shows an exergetic efficiency (ϵ) of 53.1% for the combined hydrogen and heat production (37.7%, taking into account just the H₂ production)..

Further efforts should be made in order to enhance the technical performance of the system by testing different chemical reactors options and by optimizing the heat recovery process.

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