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Application of Exergoeconomic and Exergoenvironmental Analysis to an SOFC System with an Allothermal Biomass Gasifier

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Abstract

In the future, energy conversion systems will be needed that reduce the environmental impact and costs of energy supply when fossil fuels are employed. An alternative is using biomass as a renewable energy resource to achieve both effects. For this reason, interest in biomass gasification processes resurged considerably in the past years. In particular, combination of allothermal biomass gasification with a high-temperature solid oxide fuel cell (SOFC) has met with great interest as an attractive option for electricity generation. To objectively evaluate this new biomass conversion process, the newly developed exergoenvironmental analysis and the established exergoeconomic analysis are applied. The basic idea of both methods is that in energy conversion systems, exergy represents the only rational basis for assigning environmental impacts and costs to the energy carriers and to the inefficiencies within the system. The present article identifies the most relevant system components from the environmental and economic points of view and provides information about possibilities of design improvements. Comparison of the results of both methods reveals that the most relevant process components are the SOFC, the heat exchanger for preheating the air, and the allothermal fluidized-bed gasifier. A special focus will be placed on differences between both analysis methods.

Keywords: *Exergoenvironmental analysis, exergoeconomic analysis, biomass conversion.*

1. Introduction

The exergoeconomic methodology is used in the design of energy conversion systems to calculate the costs of final products as well as the costs of the exergy destroyed within each system component. This information is essential to detect cost-ineffective processes and identify technical options which could improve the cost effectiveness of the overall energy conversion system.

Besides the efficient use of energy sources and profitability, the environmental consequences of a power plant must be predicted for a sustainable development, because potential environmental problems must be foreseen and addressed at an early stage in project planning and design. All energy sectors have undertaken efforts to reduce their environmental impacts, in particular by introducing new technologies which increase thermal efficiency and decrease specific fuel consumption and related greenhouse gas emissions.

These technical improvements may imply modifications of the design of plant components and result in less or more environmental damage, but to what an extent and at what expense? Which substances are emitted most of all? Which part of the system is responsible for the environmental impacts? How many materials and how much energy are needed for the fabrication, operation, and dismantling of the associated facilities? What is their resulting impact on the environment?

To address these questions, optimization of an energy conversion system should be supported by analysis tools that reveal the environmental impacts associated with each component and any energy and material stream of the plant. This article presents the exergoenvironmental methodology (Meyer et al., 2007&2009) as a design tool which, in conjunction with an exergoeconomic analysis, permits to identify those system components that have the highest need for further economic and ecological optimization.

2. Methodology

The most important criterion in improving the performance of an energy conversion process is thermodynamic efficiency. The source of thermodynamic inefficiencies in an energy conversion system is quantified and identified by an exergy analysis over 50 years (Rant, 1956; Szargut and Petela, 1965). The increase in inefficiencies always leads to a higher consumption of fuel, resulting in increasing environmental impacts and costs. On the other hand, minimization of inefficiencies could increase the materials and energy needed for the construction of a component, for example, the area of a heat exchanger. These life cycle-related effects of components and the resulting impact on the costs and environment should be taken into account by systems analysis for design optimization.

For this purpose, exergy analysis is combined with a cost analysis to an exergoeconomic analysis to provide

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information crucial to the design of cost-effective conversion systems. Various names have already been given to various exergoeconomic approaches proposed in the past (Tsatsaronis, 1984; Bejan, 1996; Tsatsaronis and Cziesla, 2002; Frangopoulos, 1983, 1987; Gaggioli and Wepfer, 1980; Erlach et al., 2001; Lazzaretto and Tsatsaronis, 2006; Tsatsaronis and Lin, 1990; Tsatsaronis and Winhold, 1985; Valero et al., 1992; Von Spakovsky and Evans, 1993):

- Exergy Economics Approach (EEA)
- First Exergoeconomic Approach (FEA)
- Thermoeconomic Functional Analysis (TFA)
- Exergetic Cost Theory (ECT)
- Engineering Functional Analysis (EFA)
- Last-In-First-Out Approach (LIFOA)
- Structural Analysis Approach (SAA)
- SPECO Method (SPECOM)

Methodological work for an environmentally friendly design, the combination of an exergy analysis with an environmental assessment, started later. Szargut suggested the cumulative exergy consumption (CExC) as an environmental indicator (Szargut, 1978). Based on this approach, he suggested the indicator "ecological cost" (Szargut et al., 2002) and developed a method (Szargut, 2004) for the ecological analysis and optimization of processes (Szargut and Stanek, 2005). Exergoecological analysis (Valero et al., 1986; Valero, 1998) and extended exergy accounting (Sciubba, 1999&2001) are also based on the calculation of CExC, but take additional aspects into consideration. Another example of the combination of exergetic and environmental analysis is the environomic method (Frangopoulos, 1992&1997), which is an extension of an exergoeconomic approach considering environmental aspects by internalizing external costs caused by pollutants. None of these methods, however, takes the life cycle of components as described above into account.

Based on the idea that exergy represents the only rational basis not only for assigning costs, but also for environmental impacts to the energy carriers and to the inefficiencies within the system a methodological approach, the so-called exergoenvironmental analysis, has been developed (Meyer et al., 2007&2009). Figure 1 shows the analog structures of both exergoeconomic and exergo-environmental analysis.

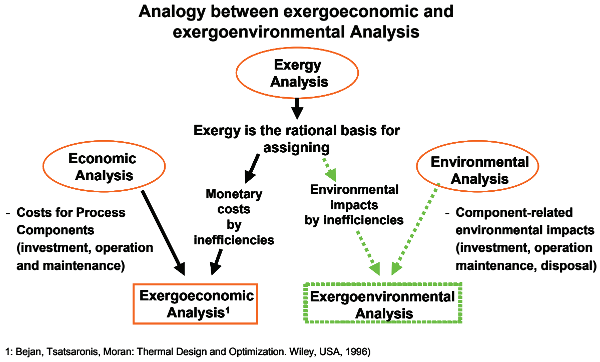

Figure 1. Analogy between Exergoeconomic and Exergoenvironmental Analysis.

2.1 Exergoenvironmental Analysis

The exergoenvironmental analysis mainly consists of three steps. The first step is an exergy analysis of the energy conversion process. In the second step environmental impacts are determined by applying the method of life cycle assessment (LCA) (ISO, 2006). In the third step the environmental impacts are assigned to the exergy streams in the process. Subsequently, exergoenvironmental variables are calculated and the exergoenvironmental evaluation is carried out. Based on the evaluation of the process and its components, possibilities for an improvement with respect to environmental performance can be developed.

First, the boundaries of the system to be analyzed and the components involved must be defined for exergy analysis. All relevant system sub-units that have a productive purpose should be regarded as separate components (Bejan, et al., 1996; Lazzaretto and Tsatsaronis, 2006). Next, the exergy values of all material and energy streams within the system must be determined. The exergy of the material streams can be calculated as the sum of their chemical and physical exergy values, while kinetic and potential exergies can be neglected. The calculation of exergy values is discussed, for example, in (Bejan, et al., 1996; Tsatsaronis and Cziesla, 2004-2007).

An LCA of the total system must include the supply of the input flows, especially fuel, and cover the full life cycle of components. Following the guidelines of international standard approaches, inventories of elementary flows (i.e., consumption of natural resources and energy carriers as well as emissions) are compiled (ISO, 2006). The inventory result calculated for the life cycle processes investigated is based on the general physical laws of conservation of energy and mass. The accuracy of this procedure depends on the assumptions made for each modeled process and the entire system defined.

In the next step based on the life cycle inventory (LCI) result, the environmental impacts are calculated for various impact categories by a quantitative impact assessment method. An impact category describes the impact pathway between the LCI results and their environmental endpoint(s) or so-called areas of protection, i.e. the receptors that are damaged. It includes a cause-effect chain (environmental mechanism) by using quantitative characterization indicators based on an environmental model. For the methodological development of exergoenvironmental analysis, a single-score life cycle impact assessment method, Eco-indicator 99, is chosen (in line with the economic assessment using the single-score indicator costs) (Goedkoop and Spriensma, 2000). It is an impact assessment method to support decision-making in a design for the environment. The structure and the considered environmental aspects are displayed in Figure 2.

In resource analysis, land use analysis, or fate analysis inventory data of each component of the overall system are assigned to compartments (e.g., water, soil, air) in which they could cause environmental problems. Within the following exposure and effect analysis, a classification into categories of environmental problems is made. The impact categories cover the width of environmental aspects and model environmental damage of three damage categories: Human health, ecosystem quality, and natural resources. The characterization model for each impact category is determined in detail elsewhere (Goedkoop and Spriensma, 2000). In the last step, the three damage categories are normalized and weighted, with the result being expressed as Eco-indicator points (pts), where higher damage is reflected by a higher Eco-indicator value. To improve understanding, some examples of Eco-indicator values for certain air emissions, e.g., 1 kg of CO_2, Hg and generation of 1 kWh of electricity in the EU (medium voltage at grid from the Union for the Coordination of Transmission of Electricity, UCTE in 2000) are given in Table 1.

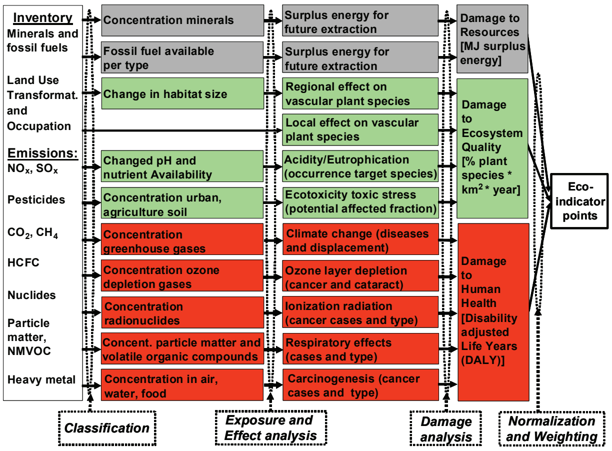

Figure 2. General Structure of the Life Cycle Impact Assessment Method Eco-indicator 99.

Table 1. Examples of the Impact Assessment of Some Emissions and of Electricity Generated in the EU Grid with the Eco-indicator 99 Method.

Emission, resource or product	Eco-indicator 99 points
1 kg CO_2 emitted into air	0.00545
1 kg Hg emitted into air	64.6000
1 kg Fe ore (25 % in raw ore)	0.00121
1 kWh electricity, medium voltage in EU grid (UCTE 2000) (Frischknecht et al., 2007)	0.02118

Besides the selected Eco-indicator 99 lifecycle impact assessment method, other LCIA methods exist in literature (Udo de Haes H.A. et al., 2002; Jolliet et al., 2004). Today, the best LCIA method available is not known, because measuring and modeling of environmental impacts is a young multidisciplinary scientific area which will lead to further developments in the future.

The LCA results (expressed in Eco-indicator 99 points) are assigned to the corresponding exergy streams is realized by calculating the specific environmental impact rate of each material and energy stream b_j (expressed in Eco-indicator points per exergy unit). It depends on the environmental impact rate $\dot{B}_j$ and the exergy rate $\dot{E}_j$ of the j^{th} stream:

$$b_j = \frac{\dot{B}_j}{\dot{E}_j} \tag{1}$$

The environmental impacts associated with the supply of an input stream (e.g. the impacts of cultivation, harvest, and transport of biomass) can be calculated directly. To calculate the values for internal as well as output streams, functional relations among the system components have to be considered. This is done by formulating environmental impact balances for all components k of the system.

$$\sum \dot{B}_{j,k,in} + \dot{Y}_k = \sum \dot{B}_{j,k,out} \tag{2}$$

The basis is that all environmental impacts entering a component have to leave the component in relation to its outputs. Consequently, there is not only an exergy flow through the system, but also a flow of environmental impacts. Besides the environmental impacts associated with incoming exergy streams, also component-related environmental impacts $\dot{Y}_k$ associated with the k^{th} component are considered. The environmental impacts that occur during the three life cycle phases of construction $\dot{Y}_k^{CO}$, operation and maintenance $\dot{Y}_k^{OM}$, and disposal $\dot{Y}_k^{DI}$ are the component-related environmental impacts and obtained by LCA:

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + Y_k^{DI} \tag{3}$$

On the basis of the exergy and environmental impact rates and the specific environmental impacts of every exergy stream in the process, the exergoenvironmental variables can be calculated for every process component. The variables are developed in analogy to the exergoeconomic variables as defined in (Bejan et al., 1996) and (Tsatsaronis and Cziesla, 2002).

Within exergy analysis, exergy destruction of each component is calculated. Exergoenvironmental analysis allows to calculate the environmental impact rate $\dot{B}_{D,k}$ associated with the exergy destruction $\dot{E}_{D,k}$ in the kth component by applying the following equation:

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{E}_{D,k} \tag{4}$$

The exergy destruction rate is multiplied by the average specific environmental impacts of the exergetic fuel of k^{th} component $b_{F,k}$. This value is calculated based on the definition of exergetic fuel and product within exergy analysis (Lazzaretto and Tsatsaronis, 2006).

The relative difference r_b between the average specific environmental impact of the exergetic product $b_{P,k}$ and the fuel $b_{F,k}$ is given by:

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \tag{5}$$

This exergoenvironmental variable is an indicator of the potential for reducing the environmental impact associated with a component.

Sources for the formation of an environmental impact in a component are compared with the aid of the exergoenvironmental factor $f_{b,k}$, which expresses the relative contribution of the component-related environmental impact $\dot{Y}_k$ to the sum of environmental impacts associated with the k^{th} component:

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}} \tag{6}$$

2.2 Exergoeconomic Analysis

In analogy to the exergoenvironmental analysis, an exergoeconomic analysis also starts with an exergy analysis of the energy conversion system. It is followed by an economic analysis based on the method of total revenue requirements (TRR) which considers the entire life cycle of the energy conversion system in the same way as the LCA method (Bejan et al., 1996; Tsatsaronis and Cziesla, 2004-2007). The method of total revenue requirements consists of the following steps:

- Estimation of the total capital investment
- Calculation of total revenue requirement (operation, maintenance, and disposal)
- Calculation of leveled product costs

The investment costs are treated differently from fuel and operation and maintenance (O&M) expenses, because they are non-recurring costs.

The total capital investment (TCI) is defined as the sum of the fixed-capital investment (FCI) and other outlays. Here, the FCI includes the capital needed to purchase land, build all facilities, and install all machinery and equipment for an energy conversion system. The FCI represents the total system costs, assuming that no time is required for design and construction as so-called overnight construction. The estimation of FCI is differentiated according to two cost elements: direct and indirect costs. Direct costs are the costs of all permanent materials, equipment, labor, and other resources involved in the fabrication, erection, and installation of the permanent facilities. The indirect costs are defined as non-permanent parts of the facilities. They are required for the proper completion of the project.

Other outlays consist of the working capital, start-up costs, costs of licensing, research, and development, and allowance for funds used during construction. More detailed information is provided in (Bejan et al., 1996; Tsatsaronis and Cziesla, 2004-2007; Peters and Timmerhaus, 1991).

After the estimation of the TCI, the annual total revenue requirement or total product costs are calculated. This means the revenue that has to be collected in a given year through the sale of all products to compensate the operating company for all expenditures incurred in the same year and to ensure sound economic plant operation. The major cost categories included for the calculation of the TRR are shown in Figure 3.

The expenses are defined to be the sum of fuel costs and operating and maintenance costs. Expenses include goods and services that are used in a short period of time. In contrast to carrying charges, expenses are paid directly from revenue. Hence, they are not capitalized. The carrying charges illustrate the liabilities associated with an investment. The liability remains until the energy conversion system is taken out of operation at the end of its estimated economic life. For the calculation of carrying charges, a lot of economic parameters are needed, while for the accounting of expenses, specific technical parameters are necessary.

Afterwards, the revenue requirements (product costs) are leveled for all cost categories, because fuel and O&M costs generally increase, while carrying charges decrease with increasing years of operation. Leveled means a transformation to an equivalent series of constant payments, called annuities. In the next step the costs are assigned to the exergy streams in the process. It is also called exergy costing. In the end, the exergoeconomic evaluation is carried out.

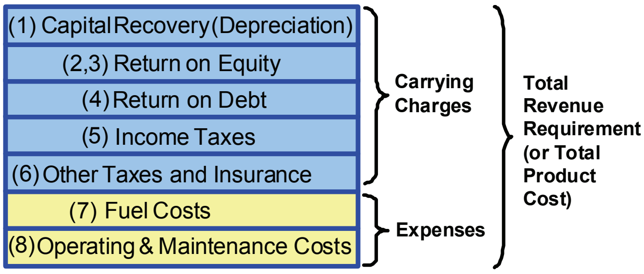

Figure 3. Revenue Cost Categories for the Total Revenue Requirement (TRR) Method (Bejan et al., 1996).

On basis of the evaluation of the process and its components, possibilities for an improvement with respect to the cost effectiveness can be developed.As the exergoeconomic analysis is well-known, the needed formulas only are presented in Table 2 in comparison to the exergoenvironmental analysis.

Table 2. Variables used by Exergoeconomic and Exergoenvironmental Analyses .

Exergoeconomic Analysis	**Exergoenvironmental Analysis**
Exergy cost rate: $\dot{C}_j = c_j \cdot \dot{E}_j$	Exergoenvironmental impact rate: $\dot{B}_j = b_j \cdot \dot{E}_j$
Cost balance: $\sum \dot{C}_{j,k,in} + \dot{Z}_k = \sum \dot{C}_{j,k,out}$	Environmental impact balance: $\sum \dot{B}_{j,k,in} + \dot{Y}_k = \sum \dot{B}_{j,k,out}$
Component-related cost rate: $\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM}$	Component-related environmental impact rate: $\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI}$
Relative cost difference: $r_k = \frac{c_{P,k} + c_{F,k}}{c_{F,k}}$	Relative environmental impact difference: $r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}}$
Exergoeconomic factor: $f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}$	Exergoenvironmental factor: $f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}}$

3. Application of the Analyses

For the application of exergoeconomic and exergoenvironmental analyses, a novel thermochemical process for the conversion of biomass to electricity was selected. The flowchart of the process is shown in Figure 4. The system was modelled using AspenPlus™ process simulation software (Aspen, 2004).

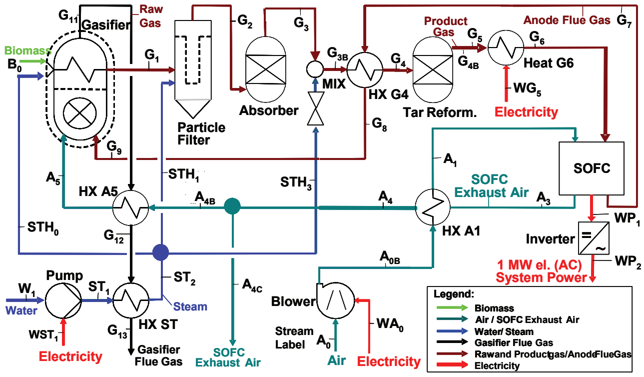

Figure 4. Flowchart of Power Generation by SOFC with Allothermal Biomass Gasification.

The temperatures, pressures, molar flow rates, and exergy rates of material flows are presented in Table 3.

Table 3. Temperatures, Pressures, Molar Flow Rates, and Exergy Rates of Material Streams.

Stream Label	Temp. [°C]	Pressure [bar]	Mole Flow [kmol/h]	Exergy rate [MJ/s]
A_0	25	1.0	316.9	0.008
A_{0B}	31	1.05	316.9	0.019
A_1	800	1.04	316.9	1.112
A_3	1001	1.04	301.9	1.484
A_4	220	1.03	301.9	0.127
A_{4B}	220	1.03	90.6	0.038
A_{4C}	220	1.03	211.3	0.089
A_5	531	1.02	90.6	0.166
B_0	25	1.0	28.3	2.804
G_1	650	1.07	40.9	2.929
G_2	550	1.07	40.9	2.898
G_3	450	1.06	40.9	2.871
G_{3B}	470	1.06	70.4	2.978
G_4	900	1.05	70.4	3.212
G_{4B}, G_5	759	1.04	71.6	3.144
G_6	800	1.03	71.6	3.168
G_7	1000	1.03	79.6	1.582
G_8, G_9	641	1.02	79.6	1.333
G_{11}	754	1.02	163.4	0.755
G_{12}	615	1.01	163.4	0.588
G_{13}	235	1.0	163.4	0.240
W_1	25	1.0	36.4	0.009
ST_1	25	5.0	36.4	0.009
ST_2	501	4.90	36.4	0.205
STH_0	501	4.90	6.9	0.039
STH_1	501	4.90	0.0	0.166
STH_3	501	4.90	29.5	0.166

In the process, H_2 and CO are the main products generated by allothermal biomass gasification, followed by electricity generation in a high-temperature fuel cell. Wood chips are fed into an allothermal fluidized-bed gasifier that is heated by an integrated burner.

The flue gas of the solid oxide fuel cell (SOFC) which contains non-depleted fuel represents the feedstock for the burner.

The gasification agent is steam which is generated within the process. At 750°C, the biomass is converted into a raw gas which mainly consists of H_2, CO, CO_2, and CH_4. The service life of all components is set to 100,000 h or 15 years. Only the SOFC stack has to be exchanged every 40,000 h.

3.1 Exergy Analysis

The exergy analysis of the process determines the exergy flows as a basis for the following analysis and exergetic variables (Table 5) for a thermodynamic evaluation.

Calculation of the exergetic efficiencies is based on the definitions of exergetic fuel and product (Table 4). For dissipative components like the particle filter, absorber, and inverter, exergetic product and fuel cannot be defined (Lazzaretto and Tsatsaronis, 2006).

Table 4. Definitions of Exergetic Fuel and Product of System Components.

System Comp.	Exergetic Product $\dot{E}_P$	Exergetic Fuel $\dot{E}_F$
GASIFIER	$\dot{E}_{G1}-\dot{E}_{B0}-\dot{E}_{STH0}$	$\dot{E}_{G9}+\dot{E}_{A5}-\dot{E}_{G11}$
HX G4	$\dot{E}_{G4}-\dot{E}_{G3B}$	$\dot{E}_{G7}-\dot{E}_{G8}$
TAR REFORM.	$\dot{E}^{CH}_{G4B}-\dot{E}^{CH}_{G4}$	$\dot{E}^{PH}_{G4}-\dot{E}^{PH}_{G4B}$
HEAT G6	$\dot{E}_{G6}-\dot{E}_{G5}$	$\dot{E}_{WG5}$
HX A1	$\dot{E}_{A1}-\dot{E}_{A0B}$	$\dot{E}_{A3}-\dot{E}_{A4}$
SOFC (incl. INVERTER)	$\dot{E}_{WP2}+(\dot{E}^{PH}_{A3}-\dot{E}^{PH}_{A1})$ $+(\dot{E}^{PH}_{G7}-\dot{E}^{PH}_{G6})$	$(\dot{E}^{CH}_{A1}-\dot{E}^{CH}_{A3})$ $+(\dot{E}^{CH}_{G6}-\dot{E}^{CH}_{G7})$
HX A5	$\dot{E}_{A5}-\dot{E}_{A4B}$	$\dot{E}_{G11}-\dot{E}_{G12}$
HX ST	$\dot{E}_{ST2}-\dot{E}_{ST1}$	$\dot{E}_{G12}-\dot{E}_{G13}$
Total Process	$\dot{E}_{WP2}-$ $\left(\dot{E}_{WST1}+\dot{E}_{WA0}+\dot{E}_{WG5}\right)$	$\dot{E}_{B0}+\dot{E}_{A0}$

The exergetic efficiency of the entire process is 33.7 %. A high amount of exergy is destroyed within the process and, in addition, a significant amount of 0.329 MW is released into the environment with the exhaust air and flue gas (streams A_{4C}, G_{13}).

Table 5. Exergetic Variables.

System Component	Exerget. Eff. [%]	Exergy Destruction [MW]	Exergy Destruction Ratio $y_{D,k}$ [%]	Rel. Exergy Destruction Coeff. $y^*_{D,k}$ [%]
GASIFIER	11.6	0.658	23.3	42.6
HX G4	94.0	0.015	0.5	1.0
TAR REFORM.	23.9	0.068	2.4	4.4
HEAT G6	70.3	0.010	0.6	0.6
HX A1	80.5	0.265	9.4	17.2
SOFC (incl. INVERTER)	93.1	0.126	4.5	8.2
HX A5	76.5	0.039	1.4	2.5
HX ST	56.2	0.153	5.4	9.9
PUMP	24.7	0.0	0.0	0.0
BLOWER	65.2	0.006	0.2	0.4
Total Process	33.7	1.543	55	100

The exergy destruction ratios (y) and relative exergy destruction coefficient (y^*) show that the gasifier, the heat exchangers HX A1 and HX ST, and the SOFC are responsible for almost 80 % of exergy destruction within the process. The gasifier alone reduces the overall efficiency of the process by 23.3 %. Other components with low exergetic efficiencies contribute to a very small extent to the thermodynamic inefficiencies of the process only.

A thermodynamic improvement of the process should focus on the components and streams mentioned.

3.2 Exergoenvironmental Analysis

Figure 5 shows the environmental impact rates of components associated with component related impacts $\dot{Y}_k$ and impacts due to exergy destruction $\dot{B}_{D,k}$. The sum of both impact rates are the total environmental impacts $\dot{B}_{TOT,k}$.

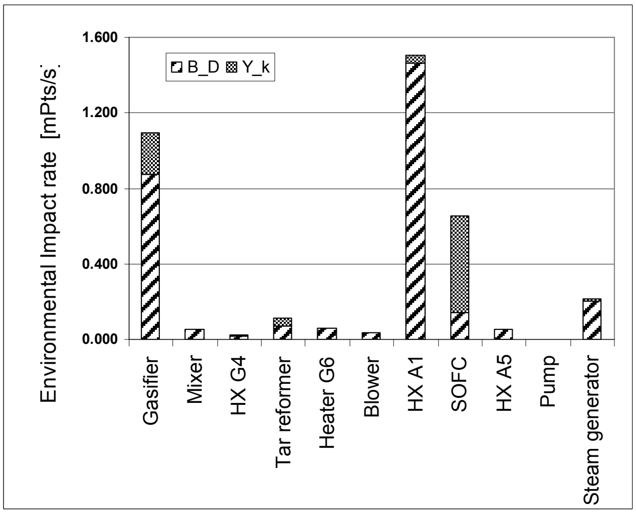

Figure 5: Sum of Environmental Impacts $\dot{B}_{TOT,k}$ for System Components.

It is obvious that the heat exchanger HX A1, the gasifier, and the solid oxide fuel cell are the main components responsible for the formation of environmental impacts.

An interpretation in detail is given by the exergoenvironmental factor f_b in Table 6. The SOFC alone has a value clearly above 50 %, because the component-related environmental impacts are dominant. For all other components, the factor shows that the environmental impact caused by exergy destruction is the main source.

Table 6. Exergoenvironmental Variables of System Components

System component	$\dot{Y}_k$ [mPts/s]	$\dot{B}_{D,k}$ [mPts/s]	$r_{b,k}$ [%]	$f_{b,k}$ [%]
GASIFIER	0.222	0.875	955.4	20.0
HX G4	0.008	0.017	9.1	30.1
TAR REFORM.	0.044	0.070	519.9	38.9
HEAT G6	0.001	0.058	42.9	1.3
HX A1	0.042	1.461	24.9	2.8
SOFC (incl. INVERTER)	0.514	0.140	34.8	78.6
HX A5	0.003	0.052	32.7	6.2
HX ST	0.011	0.203	82.2	5.3
PUMP	0.0	0.001	358.6	15.0
BLOWER	0.002	0.033	55.7	4.2

In any case, design improvements should be directed to the dominant source of environmental impacts.

The relative increase of environmental impacts within a component from its fuel to its product is represented by r_b, the relative difference of environmental impacts (Table 6). When looking at the five most important components with respect to environmental impacts only, the tar reformer, the heat exchanger HX ST, and especially the gasifier have a high potential for reducing the environmental impacts with a relatively small effort.

3.3 Exergoeconomic Analysis

The relevance of the components to cost formation is represented by the sum of the component-related cost rate $\dot{Z}_k$ and the cost of exergy destruction $\dot{C}_{D,k}$, which is equal to the total cost rate of a component $\dot{C}_{TOT,k}$ (Fig. 6).

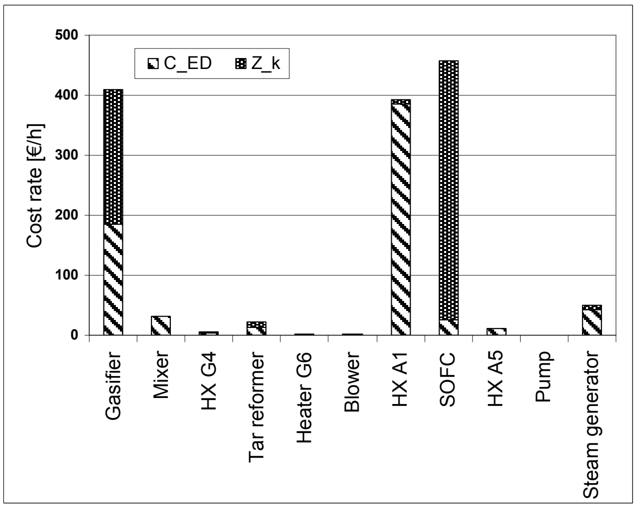

Figure 6. Sum of Costs $\dot{C}_{TOT,k}$ for System Components.

The SOFC, the gasifier, and the heat exchanger HX A1 play the main role for cost formation within the process. The additional exergoeconomic variables help to develop options for cost reduction (Table 7).

Table 7. Exergoeconomic Variables of System Components.

System component	$\dot{Z}_k$ [€/h]	$\dot{C}_{D,k}$ [€/h]	r_k [%]	f_k [%]
GASIFIER	224	185.1	1945	55
HX G4	1.8	3.6	10	34
TAR REFORM.	9.15	13.2	723	41
HEAT G6	1.3	0.8	113	63
HX A1	8.4	384.9	25	2
SOFC (incl. INVERTER)	432.0	25.2	132	94
HX A5	0.9	11	0.33	8
HX ST	6.3	42.9	89	13
PUMP	0.2	0	4065	93
BLOWER	1.5	0.5	224	76

An improvement of the SOFC should focus on a reduction of capital investment costs, as the exergoeconomic factor f is rather high. As the SOFC still is in an early development stage, cost reductions can be expected, which do not decrease the efficiency of the component.

The allothermal gasifier is associated with both high exergy destruction costs and high capital investment costs. It should be considered to increase its efficiency as well as to lower the investment costs. This might be possible, as the technology is not yet mature.

The heat exchanger HX A1 shows the highest exergy destruction costs and the lowest exergoeconomic factor. This means that investment costs have a slight influence on the total costs caused by the component only. For an improvement, the efficiency should be increased, even if this leads to higher capital investment.

The relative increase of costs from the fuel to the product side is represented by r_k, the relative cost difference of a component k. The high values for the gasifier, tar reformer, and SOFC show that these economically important components have a high cost reduction potential.

4. Comparative Analysis of the Results

The sum of environmental impact rates $\dot{B}_{TOT,k}$ and the sum of cost rates $\dot{C}_{TOT,k}$ related to a component k reveal the absolute relevance of the component to the formation of environmental impacts and economic costs, respectively. Comparison of the results of both methods shows that the same components are of highest relevance. These are the SOFC, the heat exchanger HX A1 for preheating the air, and the gasifier, as shown in Table 8.

Table 8. Economic and Environmental Relevance of Components.

System Component	Exergoenviron-mental Analysis $\dot{B}_{TOT,k}$ [mPts/s]	Exergoeconomic Analysis $\dot{C}_{TOT,k}$ [€/h]
HX A1	1.503 (1)	393 (3)
GASIFIER	1.097 (2)	409 (2)
SOFC (incl. INVERTER)	0.654 (3)	457 (1)

Due to the similar methodological approach, exergy destruction plays an important role for the results. This leads to high values for the gasifier and the heat exchanger HX A1 regarding environmental impacts and costs.

On the other hand, the similar high relevance of the SOFC cannot be explained in the same way, because the component-related aspects are dominant for this component. There is no direct relationship between component-related costs and environmental impacts. But it is expected that a greater effort for producing and building a component leads to higher capital investment costs $\dot{Z}_k^{CI}$ as well as to higher environmental impacts during construction $\dot{Y}_k^{CO}$.

From various exergoeconomic analyses of components, the relationship between investment costs and exergy destruction per unit of product exergy for the k-th component of an energy conversion system is known (Tsatsaronis, 2007). A hyperbola curve as single line is presented in figure 7 on the left side.

The hyperbola is limited by two asymptotic lines, the specific unavoidable exergy destruction $\left[\frac{\dot{E}_D}{\dot{E}_P}\right]_k^{UN}$ and the specific unavoidable investment costs $\left[\frac{\dot{Z}^{CI}}{\dot{E}_P}\right]_k^{UN}$. Both terms are evident, because the production of a component always leads to a minimum economic effort and each component has inefficiencies which always include a minimum of exergy destruction.

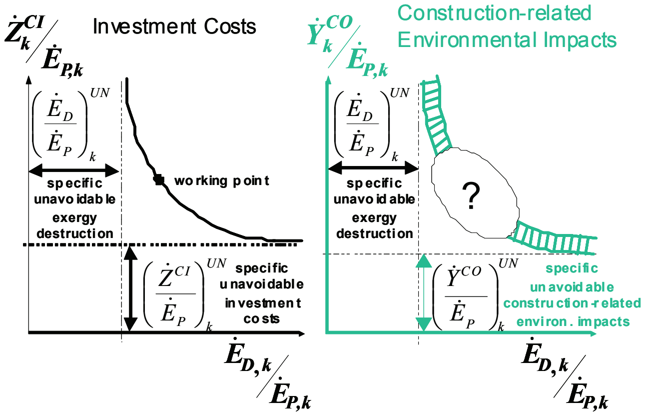

Figure 7. Expected Relationship between Investment Costs and Environmental Impact of Construction as a Function of Exergy Destruction for the k[th] Component of an Energy Conversion System.

A similar hyperbola is expected for the construction-related environmental impacts versus exergy destruction shown in figure 5 on the right side. Due to the same approach, the asymptotic lines of specific unavoidable exergy destruction are the same. The other asymptotic line declared as specific unavoidable construction-related environmental impacts $\left[\frac{\dot{Y}^{CO}}{\dot{E}_P}\right]_k^{UN}$ evidently is associated with a production of a component, because a minimum of material and energy is needed for each component. Of particular interest is the relationship between capital investment costs and construction-related environmental impacts of a component for the area of possible working points marked by a question mark. Hence, more comparable exergoeconomic and exergoenvironmental analyses of different components are needed.

It is also obvious from the comparison of the relevant components that the order of the components is different and that there are relative differences (Tab. 7). The air preheater HX A1 has the highest environmental impacts, followed by the gasifier and, with a greater distance, the fuel cell. In contrast to this, the SOFC has a slightly higher relevance to cost formation than the other two components.

In addition to the absolute values of environmental impact rates or cost rates, the relative difference of environmental impacts (r_b) or costs (r) is a useful indicator for the potential of improvement of a component (Tab. 9).

The gasifier is the component with the highest values for both methods. This component has the highest potential for an improvement with respect to environmental impacts as well as to costs. The improvement leads to a win-win situation between the environmental impacts and the costs.

Table 9. Relative Differences of Environmental Impacts and Costs of Components.

System component	**Relative differences of environmental impacts r_b [%]**	**Relative differences of costs r_k [%]**
GASIFIER	955.4	1945.0
TAR REFORM.	519.9	723.0
PUMP	358.6	4065.0
HX ST	82.2	89.0
HX A1	24.9	25.0

The results of the two methods show that environmental and economic improvement of the analyzed process should focus on the same relevant components. However, to decrease the environmental impacts, the focus should be on the reduction of exergy destruction. To reduce the overall costs of the process, the reduction of investment costs seems to have a higher potential.

5. Conclusion

The methods discussed in this paper are useful for supporting the optimization of energy conversion processes. The exergoeconomic analysis is an established method for reducing the overall costs of energy conversion and the exergoenvironmental method a new one for reducing environmental impacts. The application of both methods to the same process may be expected that in many cases the same process components were identified for improvement, but the results are not equivalent in general.

The following two aspects substantiate similar results of both methods during analogous methodological approach.

First, exergy destruction within a component leads to an increase of the specific costs exergy unit and environmental impacts respectively. Therefore components with high exergetic inefficiencies are relevant for economic as well as ecological optimization.

The second aspect is that there is often an interrelation between investment costs and component-related environmental impacts. If the investment costs are high due to high consumption of energy and materials during the production of a component then the environmental impacts are high as well. But this interrelation between investment costs and environmental impacts is not valid in any case. If for example a production of components is rather cost efficient due to low environmental standards that are in force the emissions will be rather high and the environmental impacts accordingly. But on the other hand the calculation of fixed-capital investment includes a part of indirect costs (engineering or constructors profit for example) which have not any environmental impact.

An other case are generated emissions during the operation of the process which released directly (without any cleaning component) to the environment. These lead also to different results of exergoeconomic and exergoenvironmental method. The latter one considers environmental impacts due to these emissions, for example CO_2, while they have usually no economic impact.

The internalization of all external environmental costs is a very challenging task that might be realized in the far future but is not yet reality. Therefore at the moment, a reliable improvement of a process with respect to ecological and economic aspects can only be achieved by applying both methods. During an improvement process, it is important to keep both aspects in mind. An environmental optimization should not lead to a process that is not economic any more and vice versa. Future analysis is needed to show under which circumstances a relationship can be determined between the capital investment costs and construction-related environmental impacts of a component for the area of possible working points.

Nomenclature

$\dot{B}_j$ environmental impact rate of the jth material stream, (Eco-indicator 99 mPoints/s)

b_j specific environmental impact of the production of the jth material per exergy unit of the same stream, (Eco-indicator 99 mPoints/GJ)

$\dot{C}_j$ cost rate of the jth material stream (€/h)

c_j specific costs of the production of the jth material stream per exergy unit of the same stream, (€/GJ)

$\dot{E}$ exergy rate (MJ/s)

e specific exergy (MJ/kg)

f exergoeconomic factor which expresses the relative contribution of component-related costs to the sum of costs associated with the component (-)

f_b exergoenvironmental factor which expresses the relative contribution of component-related environmental impacts to the sum of environmental impacts associated with the component (-)

r relative difference of exergy-related costs (-)

r_b relative difference of exergy-related environmental impacts (-)

$\dot{Y}$ component-related environmental impact rate associated with the life cycle of the component, (Eco-indicator 99 Points/s)

y_D exergy destruction ratio which relates the exergy destruction within a component to the exergy of fuel of the overall system (%)

y_D^* relative exergy destruction coefficient which compares the exergy destruction within a component with the exergy destruction within the overall system (%)

$\dot{Z}$ component-related cost rate associated with the life cycle of the component (€/h)

Subscripts

D destruction
F fuel
in input
j j-th stream or material stream of the energy conversion system
k k-th component of the energy conversion system
out output
P product
TOT total (with reference to the component)

Superscripts

CI capital investment
CO construction
DI disposal
OM operation, maintenance

Abbrevations

AC	alternating current
BIOMASS	wood chips produced from industrial residual soft wood
BLOWER	electrically driven blower
GASIFIER	fluidized-bed gasifier
HEAT	electric heater
HX	heat exchanger
INVERTER	converter of direct current to alternating current
LCA	life cycle assessment
MIX	mixer
PUMP	electrically driven pump
SOFC	solid oxide fuel cell
ST	steam generator
TAR REFORM.	catalytic tar reformer

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