# Exergoenvironmental analysis - A combination of exergy analysis and LCA to support the design for environment of energy conversion processes

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**Abstract** The design of environmental-effective energy conversion processes can be provided by an exergoenviromental analysis which is a new method supporting design for environment. It combines an exergy analysis with a LCA to determine thermodynamic efficiency and the formation of environmental impacts on plant components. The exergoenvironmental approach is used to assign environmental impacts to all energy and material flows as well as thermodynamic inefficiencies within each process component. The analysis reveals the interdependencies between thermodynamic behaviour and environmental impacts and between process components. Presenting the example of electricity production using a high-temperature solid oxide fuel cell (SOFC) with integrated allothermal biomass gasification process, exergoenvironmental analysis is described, and the environmentally most relevant process components are identified.

## 1 Introduction

Design for environment (DfE) aims at minimizing the environmental impacts of a process which can be designed in a preliminary phase [1,2]. LCA is mainly applied to compare various products and processes but it can also be used as a tool to analyze environmental impacts in the life cycle or process chain. As a result, a designer will be able to identify the most relevant steps in the process chain and are supported in producing promising design alternatives. For a given process design to be improved, the key issues are identified by applying LCA. “Key issues” or “hot spots” of a system in this context mean those parts of a system e.g. a component, a process step or an elementary flow that contribute most to the entire environmental impacts. Various definitions of the term “key issue” is published in [3]. The groundwork of the calculation of environmental impacts in a

LCA is a life cycle inventory analysis which is based on a material and energy flow analysis of the entire predesigned process considering the first law of thermodynamics. Normally the entire predesigned process is modular build up by unit processes the smallest element considered in the inventory analysis for which input and output data are quantified [4]. But ISO 14044 is not declared the level of detail to which these unit processes shall be studied. For this reason a unit process is normally modeled as black-box. This means a linear mathematic function between input and output flows and a lack of knowledge about inside the process. Therefore it is not possible to calculate the inefficiencies of a unit process which is based on the thermodynamic laws are occurred especially in the case of energy conversion processees. These thermodynamic inefficiencies of plant components in energy conversion processes (as unit process) can be analyzed with an exergy analysis. In other words the exergy analysis is an application of the second thermodynamic law in order to identify the generated entropy in a plant component. An exergy analysis in combination with a LCA, which is called exergoenvironmental analysis in literature [5,6], is a powerful tool in order to support a design for environment of energy conversion processes. The novel methodological concept of exergoenvironmental analysis for energy conversion processes and its benefit of knowledge for design improvements are presented.

## 2 Methodology of the exergoenvironmental analysis

The concept of exergoenvironmental analysis consist mainly of the following three steps [5,6]: (i) exergy analysis of the investigated system; (ii) LCA of each system component and of each input flow; (iii) assignment of environmental impacts to each exergy flow. Subsequently exergoenvironmental variables are calculated and an exergoenvironmental evaluation is carried out. With the aid of the system evaluation, the most important components with the highest environmental impact can be identified.

### *2.1 Exergy analysis*

The exergy of a system is the maximum theoretical useful work obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts only with this environment [7-10]. This means that energy that has a high convertibility potential is said to contain a high share of exergy. In other words, exergy is characterised as a property describing the quality of energy.

First for exergy analysis, the boundaries of the system to be analyzed and the components involved must be defined. All relevant system sub-units that have a productive purpose should be regarded as separate components [10,11]. Next, the exergy values of all material and energy flows within the system must be determined. The exergy of the material flows 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 in [12].

In exergy analysis, each component k is characterized by the definition of its exergy of product, $\dot{E}_{P,k}$ and fuel $\dot{E}_{F,k}$ shown in Fig. 1.

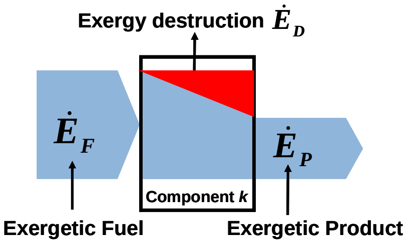


**Fig.1: Exergy balance of component k**

Calculation of fuel and product is carried out according to the exergetic and economic purposes of the kth component and is based on the SPECO approach [11]. After calculating the exergy of fuel and the exergy of product, the remaining exergetic variables can be calculated for each system component [10]. These include exergetic efficiency and exergy destruction. The exergetic efficiency of the kth component is defined as the ratio between the exergies of product and fuel. It was introduced earlier by Grassmann in the fifties [13].

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \quad (1)$$

Exergy destruction $\dot{E}_{D,k}$ in the kth component is a direct measure of thermodynamic inefficiencies. It is calculated:

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \quad (2)$$

Exergy analysis gives answers to the question of where thermodynamic inefficiencies occur in the system. In addition, it reveals their rates and causes. Moreover, exergy analysis puts all process components on the same physical basis to determine the functional interrelationship between components.

## 2.2 Environmental analysis

An LCA of the total system must include the supply of the input flows, especially fuel, and cover the full life cycle of components. It is necessary to extend the exergy process model with the pre-chain of each input flow and the entire life cycle of each component. Based on the LCI result, the environmental impacts are calculated for various impact categories by a quantitative impact assessment method. For the methodological development of exergoenvironmental analysis, a single-score life cycle impact assessment (LCIA) method, Eco-indicator 99, is chosen [14]. It is an LCIA method to support decision-making in a design for environment. Besides the selected Eco-indicator 99, other LCIA methods exist, which are discussed in literature [15,16]. A comparative investigation of exergoenvironmental analysis using Eco-indicator 99, CML 2001 and Impact 2002 as LCIA method is presented in [17].

## 2.3 Exergoenvironmental variables and evaluation

In the third step the LCA results (expressed in Eco-indicator points) are assigned to the corresponding exergy flows.

### 2.3.1 Definitions

The environmental impact rate $\dot{B}_j$ is the environmental impact expressed in Eco-indicator points per time unit (Pts/s or mPts/s). The specific (exergy-based) environmental impact $b_j$ he average environmental impact associated with the production of the jth flow per exergy unit of the same flow (Pts or mPts/GJ exergy). The environmental impact rate $\dot{B}_j$ of the material flow j is the product of its exergy rate $\dot{E}_j$ and the specific environmental impact $b_j$:

$$\dot{B}_j = \dot{E}_j \cdot b_j \tag{3}$$

The environmental impact rate $\dot{B}_j$ can also be calculated using the specific exergy $e_j$ and the mass flow rate $\dot{m}_j$:

$$\dot{B}_j = \dot{m}_j \cdot e_j \cdot b_j \tag{4}$$

Depending on the system or component being analyzed, it may be useful to distinguish between physical and chemical exergy. In this case, a specific environmental impact for each exergy component must be known in order to calculate the environmental impact rate $\dot{B}_j$ or the average specific environmental impact $b_j$:

$$\dot{B}_j = \dot{B}_j^{CH} + \dot{B}_j^{PH} = b_j^{CH}\,\dot{E}_j^{CH} + b_j^{PH}\,\dot{E}_j^{PH} = b_j\,\dot{E}_j \qquad (5a)$$

where

$$\dot{E}_j = \dot{E}^{PH} + \dot{E}^{CH} \qquad (5b)$$

The environmental impact rate associated with heat $\dot{Q}$ and work $\dot{W}$ are calculated as follows:

$$\dot{B}_q = b_q \cdot \dot{E}_q \qquad (6)$$

$$\dot{B}_w = b_w \cdot \dot{W} \qquad (7)$$

The exergy rate associated with a heat transfer is calculated using the following equation:

$$\dot{E}_q = \left(1 - \frac{T_0}{T_j}\right)\dot{Q} \qquad (8)$$

Here T0 is the surrounding temperature and Tj the temperature at which the heat transfer crosses the boundary of the system. For the exergy analysis of the case study, it was assumed that all heat transfers to the environment take place at T0 = Tj. Otherwise the temperature Tj is calculated through simulation software. It could also be the thermodynamic average temperature.

### 2.3.2 Environmental impact balances

From the results of the exergetic analysis and LCA, the specific environmental impact $b_j$ an be calculated directly for input flows (i.e. fuel flows) entering the overall system. Applying equation (4), where $\dot{B}_j$ is the result of LCA for the fuel (jth flow) and $\dot{E}_j$ is the exergy rate of the jth input flow, $b_j$ is calculated as follows:

$$b_{j,in} = \frac{\dot{B}_{j,in}}{\dot{E}_{j,in}} \qquad (9)$$

The values for internal and output flows can only be obtained by considering the functional relations among system components. This is done by formulating environmental impact balances and auxiliary equations. The environmental impact balance for the k-th component states that the sum of environmental impact rates associated with all input flows plus the component environmental impact rate is equal to the sum of the environmental impact rates associated with all output flows shown in Fig. 2. The equation is

$$\sum_{j=1}^{n} \dot{B}_{j,k,in} + \dot{Y}_k = \sum_{j=1}^{m} \dot{B}_{j,k,out} \tag{10}$$

or

$$\sum_{j=1}^{n} \left(b_j \dot{E}_j\right)_{k,in} + \dot{Y}_k = \sum_{j=1}^{m} \left(b_j \dot{E}_j\right)_{k,out} \tag{11}$$

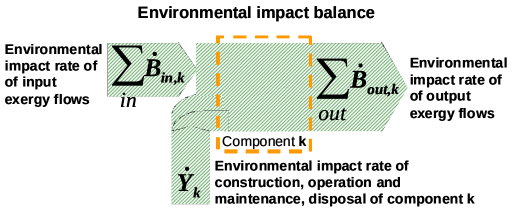


**Fig. 2: Environmental impact balance of component k**

The LCA provide the environmental impact for each component itself is made up of the three life cycle phases construction (CO), operation and maintenance (OM), and disposal (DI). The sum of all component-related environmental impacts is $\dot{Y}_k$ as shown in equation 12:

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \tag{12}$$

Within the analyzed system, the direct emissions from a component are assigned to the operation and maintenance phase. The construction phase includes manufacturing, transport and installation of a component. The equation 10 or 11 of the environmental impact balance of a component cannot be solved if the number of output flows, and therefore the number of unknown variables, is greater than one. To solve this problem, additional auxiliary equations are required by the exergy analysis. In exergoenvironmental analysis, auxiliary equations are developed in analogy to exergoeconomics by using environmental impact rates instead of cost rates and applying the F and P principles, which refer to the definition of the exergies of fuel and product for a component [11,18].

### 2.3.3 Treatment of dissipative components

Often components without a productive or exergetic purpose are part of a system. Examples for this type of components, which are called dissipative components

(DCs), are coolers, gas cleaning units, or throttling valves operating entirely or partially above surrounding temperature. These components decrease the exergy content of a flow without generating an immediate useful effect. A product from the thermodynamic viewpoint cannot be defined for these components, which serve either other so-called productive components or the overall system directly [9]. The environmental impact due to thermodynamic inefficiencies within a DC and the component-related environmental impact should be charged to the productive components or to the product of the overall system, if this system is being served directly by the DC. The approach for the calculation is given in [11].

#### 2.3.4 Calculation of exergoenvironmental variables

On the basis of the exergy and environmental impact rates and the specific environmental impacts of each exergy flow in the process the exergoenvironmental variables can be calculated for every process component. Only two exergoenvironmental variables will be discussed here.
Within exergy analysis, the exergy destruction of each component is calculated. The 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:

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{E}_{D,k} \quad (13)$$

The exergy destruction rate is multiplied by average specific environmental impacts of the exergetic fuel of the kth component $b_{F,k}$ This value is calculated based on the definition of exergetic fuel and product within exergy analysis. The sum of the environmental impacts $\dot{B}_{TOT,k}$ of the kth component is calculated by adding the environmental impacts of exergy destruction $\dot{B}_{D,k}$ and the component-related environmental impacts $\dot{Y}_k$:

$$\dot{B}_{TOT,k} = \dot{B}_{D,k} + \dot{Y}_k \quad (14)$$

This exergoenvironmental variable reveals the environmental relevance of each component. The exergoenvironmental evaluation is carried out applying the exergoenvironmental variables. Based on the evaluation of the process and its components possibilities for an improvement with respect to the environmental performance can be developed. The exergoenvironmental analysis is shown in detail in [5,19].

# 3 Case study of electricty production

For application of the exergoenvironmental analysis, a thermochemical process for the conversion of biomass to electricity was selected. The flowchart of the process design is shown in Fig. 3.

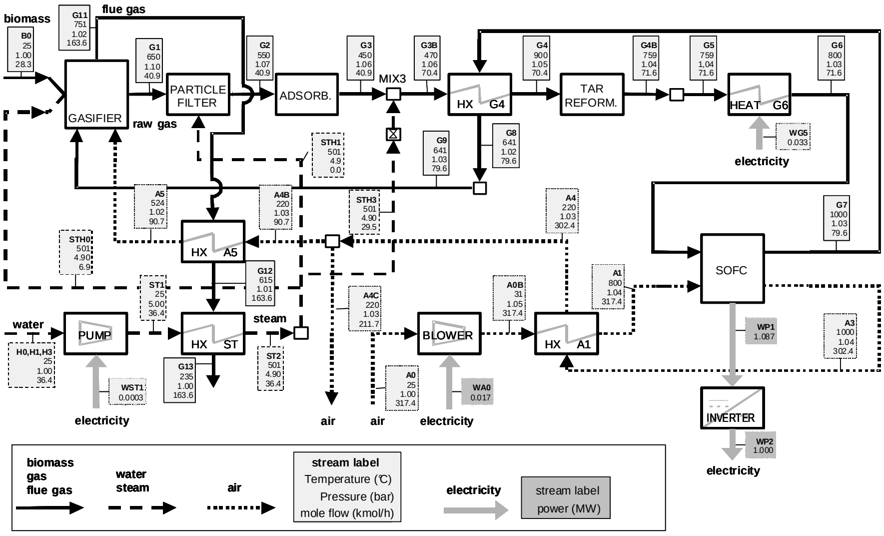


**Fig. 3: Flow chart of electricity production by means of biomass conversion process**

Wood chips are fed to an allothermal fluidized-bed gasifier that is heated using 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 to a raw gas which mainly consists of H2, CO, CO2 and CH4 are generated as main products by allothermal biomass gasification, followed after the product gas cleaning components by electricity generation in a high-temperature SOFC. The details of the process can be found in [19]. The life-time of all components is fixed at 100,000 h. The SOFC stack has to be exchanged every 40,000 h.

## *3.1 Result of exergy analysis*

The process consists of the components shown in Fig. 3, each one of which is considered separately in the exergy analysis and exergoenvironmental analysis. An exception is the inverter integrated into the SOFC. The calculation of the exergetic efficiencies is based on the definitions of exergetic fuel and exergetic product shown in Tab. 1. The cleaning components (particle filter, adsorber) and the inverter are dissipative components. The particle filter is assigned to the gasifier just like the adsorber and inverter are assigned to the SOFC.

**Tab. 1: Definitions of exergetic fuel and product of system components.**

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

The main exergetic variables of the system components are presented in following Tab. 2.

**Tab. 2: Exergetic variables of system components.**

| System Component | Exergetic Efficiency [%] | Exergy Destruction[MW] |
|---|---|---|
| Gasifier (incl. diss. comp.) | 11.6 | 0.658 |
| HX G4 | 94.0 | 0.015 |
| Tar Reform. | 23.9 | 0.068 |
| HEAT G6 | 70.3 | 0.010 |
| HX A1 | 80.5 | 0.265 |
| SOFC (incl. diss. comp.) | 93.1 | 0.126 |
| HX A5 | 76.5 | 0.039 |
| HX ST | 56.2 | 0.153 |
| Pump | 24.7 | 0.000 |
| Blower | 65.2 | 0.006 |

The result shows that the gasifier, the two heat exchangers (HX A1, HX ST) and the SOFC including the inverter are responsible for almost 80 % of the destroyed

exergy within the process. Other components with low exergetic efficiencies contribute only to a very small extent to the inefficiencies of the process.
An amount of 1.543 MW exergy is destroyed within the process and, in addition, a significant amount of 0.24 MW exergy is released into the environment with the gasifier flue gas (A4C) and 0.089 MW exergy with the SOFC exhaust air (G13).

### *3.2 Result of the life cycle assessment*

It was assumed to use wood chips made of industrial residual soft wood as feedstock with an average transport distance of 50 km to the plant which is situated in central Europe. During the operation of the process the same amount of CO2, which was previously consumed from the air for the production of biomass, is released as direct emissions to the atmosphere. These direct emissions are generated as part of the raw gas in the gasifier and are conveyed through the entire system back to the burner of the gasifier. For this reason the environmental impacts of these direct CO2 emissions could not be assigned to one component of the system. Therefore the impacts associated with the CO2 emissions are assigned to the biomass supply, so that the net calculation of CO2 for the biomass growth is zero. Through this the consumption of biomass is directly connected to the emitted CO2 and the processes that are responsible for an increase of biomass can be identified by the exergoenvironmental analysis because there is an interdependence between the exergy destruction and the released CO2 emissions. A sensitive analysis of other allocations of these CO2 emissions are discussed in detail in [19].
The total environmental impact for the production of 100 MWh electricity is 831 Points shown in Fig. 4.

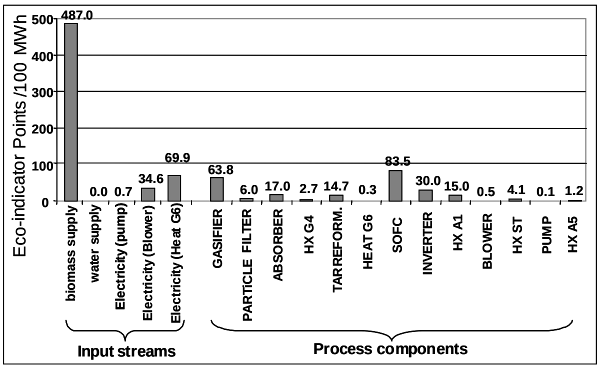


**Fig. 4: Total environmental impacts of input streams and system components**

The highest environmental impact of nearly 58.7 % has the biomass supply because the environmental impact of the direct CO2 emissions are included. Other high contributions to the environmental impact are made by the SOFC, the gasifier and the consumption of electricity for Heat G6.

It clearly shows that the LCA results for the upstream processes of input streams (electricity and biomass supply) and all component-related environmental impacts lead to the sum of environmental impact rates associated with all output streams. The design optimization has to minimize this total amount of environmental impacts. For this purpose it is required the information on the trade-offs between exergy destruction with its hidden environmental impacts by exergetic inefficiencies (equation 13). Therefore, exergoenvironmental variables are needed.

### *3.3 Results of exergoenvironmental analysis*

Exergoenvironmental analysis quantifies both sources of environmental impacts associated with each component of an energy conversion process by calculating the environmental impacts of exergy destruction $\dot{B}_{D,k}$ and the component-related environmental impact rate $\dot{Y}_k$. The sum of both impact rates are the total environmental impacts $\dot{B}_{TOT,k}$. The results of these exergoenvironmental variables are shown in Tab. 3.

**Tab. 3: Exergoenvironmental variables of system components**

| **System Component** | $\dot{Y}_k$ [mPts/s] | $\dot{B}_{D,k}$ [mPts/s] | $\dot{B}_{TOT,k}$ [mPts/s] |
|---|---|---|---|
| Gasifier (incl. dissipative comp.) | **0.222** | **0.875** | **1.097** |
| HX G4 | **0.008** | **0.017** | **0.025** |
| Tar Reform. | **0.044** | **0.070** | **0.114** |
| HEAT G6 | **0.001** | **0.058** | **0.059** |
| HX A1 | **0.042** | **1.461** | **1.503** |
| SOFC (incl. dissipative comp.) | **0.514** | **0.140** | **0.654** |
| HX A5 | **0.003** | **0.052** | **0.055** |
| HX ST | **0.011** | **0.203** | **0.214** |
| Pump | **0.0** | **0.001** | **0.001** |
| Blower | **0.002** | **0.033** | **0.035** |

Besides gasifier and heat exchanger HX A1 also the SOFC can be identified as a component that is mainly relevant for the formation of environmental impacts of the overall system. In contrast to the components mentioned first, the impacts from the fuel cell are due to component-related environmental impacts. These are mainly caused by the manufacturing of the fuel cell and by assigned dissipative components of adsorber and inverter.

The total environmental impact balance of input and output flows of the analyzed process is shown in schematic sankey diagram in fig. 5. It shows that the exergy destruction of the SOFC exhaust air (A4C) and the gasifier flue gas (G13) lead to a relevant environmental impact of 0.49 mPts/s and 0.32 mPts/s.

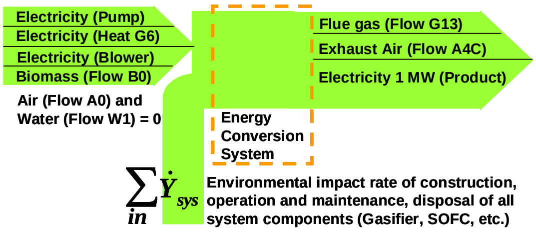


**Fig. 5: Schematic sankey diagram of environmental impacts of system components, input and output flows**

The goal of a design improvement is to minimize the cumulated environmental impacts of product flow (1 MW electricity), SOFC exhaust air (A4C) and the gasifier flue gas (G13). A reliable improvement of the overall energy conversion process with respect to ecological aspects can only be realized if the exergy of the SOFC exhaust air (A4C) and the gasifier flue gas (G13) can be used additionally in a varied heat exchanger network.

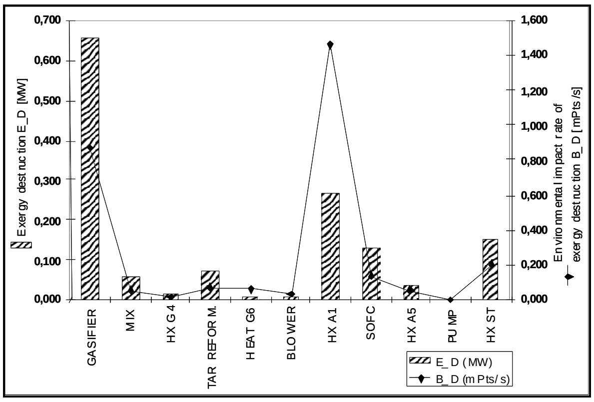


**Fig. 6: Environmental impacts of exergy destruction and exergy destruction of each component**

The exergoenvironmental analysis shows the potentials for optimization more in detail and reveals the influence of the components among themselves than it is possible with a LCA. Especially, the high environmental impact rate of the heat exchanger HX A1 due to the high exergy destruction is revealed.

Although the heat exchanger HX A1 accounts for the highest environmental impacts of exergy destruction, Fig. 6 shows that the highest exergy destruction rate occurs inside the gasifier. This means that the reduction of exergy destruction within the heat exchanger leads to a higher reduction of environmental impacts of the overall system than the same reduction of exergy destruction within the gasifier. The reason for this is the interrelationship between the components and their relative position within the process. The reduction of inefficiencies within the gasifier mainly leads to reduced environmental impacts connected to biomass input. In contrast, a lower exergy destruction within the heat exchanger HX A1 has a positive effect on all upstream components, reducing, e.g. exergy destruction due to smaller exergy streams.

## 4 Conclusion

An exergoenvironmental method has been proposed that investigates the formation of environmental impacts of energy conversion processes regarding components. The environmental impacts are assigned to the exergy flows in the analyzed system. There are two sources of environmental impacts associated with the process components: thermodynamic inefficiencies and impacts associated with the life cycle of the component. The exergoenvironmental analysis of a electricity production process showed that the supply of biomass has the highest environmental impact and that gasifier, heat exchanger HX A1, and SOFC are the most environmental relevant components of the system.

It has become obvious that the effect of exergy destruction within a component on the formation of environmental impacts depends on the position of the component in the process because the exergy rate provides the unified basis of interrelationship between the components. This is the important point why the exergoenvironmental analysis provide more helpful information of the design for environment than a pure LCA.

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