EXERGOENVIRONMENTAL ANALYSIS IS A NEW TOOL FOR EVALUATION OF AN ENERGY CONVERSION SYSTEM

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Exergy-based methods (exergetic, exergoeconomic and exergo-environmental analyses) are powerful tools for developing, evaluating and improving an energy conversion system. Exergoenvironmental analysis is a unique combination of exergy analysis and life cycle assessment conducted at the component level to identify the location, the magnitude and the causes of environmental impact.

Introduction. An *exergoenvironmental analysis*, as a new exergy-based method, has been proposed in the year 2009 in Germany [1]. *Exergoenvironmental analysis* rests on the notion that exergy is the only rational basis for assigning values of environmental impact to the transport of energy and to the thermodynamic inefficiencies within the components. This principle is called *exergoenvironmental costing*. An *exergoenvironmental analysis* consists of: (a) an exergy analysis, (b) a Life Cycle Assessment (LCA) conducted for each relevant system component, and for all relevant input streams to the overall system, and (c) a calculation of the environmental impact associated with each exergy stream in the system, and with the exergy destruction within each system component.

Many other approaches also deal with the combination of an exergetic and an ecological (environmental) analysis, for example, *cumulative exergy consumption* by Szargut (Poland) [2], *exergoecological analysis* by Valero (Spain) [3], *extended exergy accounting* by Sciubba (Italy) [4], *environomic analysis* by Frangopoulos (Greece) [5]. These methods have been applied to energy conversion systems, and some can be applied to a country too, i.e., cumulative exergy consumption [6] and extended exergy accounting [7].

Exergy analysis. Today an exergetic analysis is recognized as the most effective method for evaluating (a) the quality of energy carriers and energy-conversion processes, and (b) the rational use of energy [8-11]. It can be applied to any energy-conversion system or chemical process. Exergy principles can also be used to develop new processes that use energy resources more effectively [12]. The analysis of the real thermodynamic inefficiencies in a system and its components is valuable for improving an energy-intensive operation.

The exergetic analysis identifies the location, the magnitude and the causes of thermodynamic inefficiencies, assists in better understanding the operations in an energy conversion process, and enhances the creativity of engineers dealing with the improvement of such systems and processes.

The exergy of the system E_{sys} consists of four main components: physical exergy, chemical exergy, kinetic exergy, and potential exergy

$$E_{sys} = E_{sys}^{PH} + E^{CH} + E^{KN} + E^{PT}$$

Usually, the potential (E^{PT}) and kinetic (E^{KN}) exergy changes can be neglected. For compression refrigeration machines, the chemical exergy can also be neglected. The physical exergy is the maximum theoretical useful work obtainable as the system passes from its initial state (*T, p, x*) to the restricted dead state (T_0, p_0, *x*) while heat transfer takes place only between the system and the environment. The physical exergy for a material stream is

$$E^{PH} = \dot{m} \cdot e^{PH} = \dot{m}\left[\left(h - h_0\right) - T_0\left(s - s_0\right)\right]$$

However, for refrigeration machines, the physical exergy of material streams can be further split into a thermal part and a mechanical part [13]

$$e^{PH} = e^{T} + e^{M}$$

Early developments of an exergetic analysis were based on the concepts of *input exergy* and *output exergy* [8,9], and the exergetic efficiency of component *k* was defined as the ratio between these two variables

$$\varepsilon_k = \frac{\dot{E}_{out,k}}{\dot{E}_{in,k}} \tag{1}$$

This definition of exergetic efficiency is, however, not consistent with the general definition of efficiency

$$Efficiency = \frac{Desired\ \ result}{Re\,sources\ \ spent\ \ to\ \ generate\ \ this\ \ result} \tag{2}$$

because not all incoming streams to the k-th component are associated with *resources,* neither do all outgoing streams belong to the *desired result*. This deficiency was corrected by the general concept of *exergy of product* (the desired result achieved by the k-th component expressed in exergy terms) and *exergy of fuel* (exergetic resources expended to provide the exergy of product) [10]. The exergetic efficiency is now the ratio between the exergy of product and the exergy of fuel

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \quad \text{and} \quad \varepsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}} = 1 - \frac{\dot{E}_{D,tot} + \dot{E}_{L,tot}}{\dot{E}_{F,tot}} \tag{3}$$

The concept of *fuel* and *product* is also applicable to the definition of energetic efficiencies. In this way, energetic and exergetic efficiencies can be compared. Using the terms *exergy of fuel* and *exergy of product*, the exergetic balances for the k-th component and for the overall system are written as [10]

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \quad \text{and} \quad \dot{E}_{F,tot} = \dot{E}_{P,tot} + \dot{E}_{D,tot} + \dot{E}_{L,tot} \tag{4}$$

The *exergy destruction* (or *internal exergy loss*) is the exergy destroyed due to the irreversibility ($\dot{S}_{gen}$) within the k-th component or within a system

$$\dot{E}_{D,k} = T_0 \dot{S}_{gen,k} = T_0\, \dot{m}_k\, s_{gen,k} \quad \text{and} \quad \dot{E}_{D,tot} = \sum \dot{E}_{D,k} = T_0 \sum \dot{m}_k\, s_{gen,k} \tag{5}$$

The *exergy loss* (or *external exergy loss*) is the exergy transfer from the system to its surroundings. This exergy is not further used in the overall system being considered or in another system. At the component level, all exiting material streams are generally either associated with fuel or with the product of the component. Thus, the only exergy loss in a component is associated with the transfer of thermal exergy to the environment (heat loss). When the boundaries for the component analysis are drawn at the ambient temperature T_0, the exergy loss is zero and the thermodynamic inefficiencies consist exclusively of exergy destruction. In this case, exergy losses may only be associated with the overall system, but not with any of its components.

For practical applications of the exergy concept for the improvement of energy conversion systems, it is of particular importance to know how to interpret the values of the exergetic variables, and how to systematically use the information provided by a detailed exergy analysis, in order to improve the design or operation of the overall system.

L C A. Life cycle assessment (LCA) is a method used to evaluate the mass balance of inputs and outputs of systems and to organize and convert those inputs and outputs into environmental impacts relative to resource use, human health and ecological areas. The quantification of inputs and outputs of a system is called Life Cycle Inventory (LCI). At this stage, all emissions are reported on a volume or mass basis. Life Cycle Impact Assessment (LCIA) converts these flows into simpler indicators. The Eco-indicator of a material or process is a number that indicates the environmental impact of a material or process, based on data from a life cycle assessment. The higher the indicator, the greater the environmental impact.

During the last 15 years many LCIA methods have developed, for example, Eco-indicator 95 [14] and Eco-indicator 99 [15], EDIP 97 [16] and EDIP 2003 [17], EPS 2000d [18], Impact (2002)+ [19], JEPIX [20], LIME [21], Swiss Ecoscarcity [22]. However, only few of them are applied to an energy conversion system (because of the availability of data that can be used for this purpose, for example, Eco-indicator 95, Eco-indicator 99, and Swiss Ecoscarcity), but almost all these methods have already been applied to estimate environmental impacts of land, processes in agriculture, transport, buildings, etc.

Exergoenvironmental analysis and evaluation. In analogy to the assignment of costs to exergy streams in exergoeconomics [10], an environmental impact rate $\dot{B}_j$ and an environmental impact per unit of exergy b_j are assigned to exergy streams in an exergoenvironmental analysis [1].

The environmental impact balance applied to the *k*-th system component can be written as

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k \qquad \text{or} \qquad b_{P,k}\dot{E}_{P,k} = b_{F,k}\dot{E}_{F,k} + \dot{Y}_k \tag{6}$$

The environmental impacts that occur during the three life-cycle phases construction (including manufacturing, transport and installation), $\dot{Y}_k^{CO}$, operation and maintenance, $\dot{Y}_k^{OM}$, and disposal $\dot{Y}_k^{DI}$ constitute the component-related environmental impact associated with the *k*-th component $\dot{Y}_k$:

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \tag{7}$$

An impact assessment is performed using an environmental indicator (e.g., the Eco-indicator 99, which is based on the definition of three damage categories, human health, ecosystem quality and natural resources. The result is expressed as *Eco-indicator points* (Pts).

The *environmental impact rate* $\dot{B}_{D,k}$ associated with the exergy destruction $\dot{E}_{D,k}$ within the *k*-th component is calculated by

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{E}_{D,k} \tag{8}$$

Here $b_{F,k}$ is the environmental impact per unit of exergy of fuel.

The relative difference $r_{b,k}$ defined by:

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \tag{9}$$

The sources for the formation of environmental impact in a component are compared using 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

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}} \tag{10}$$

Example. A vapor-compression refrigeration machine with a closed compressor (Figure 1) is used as an example to demonstrate the application of the exergoenvironmental analysis.

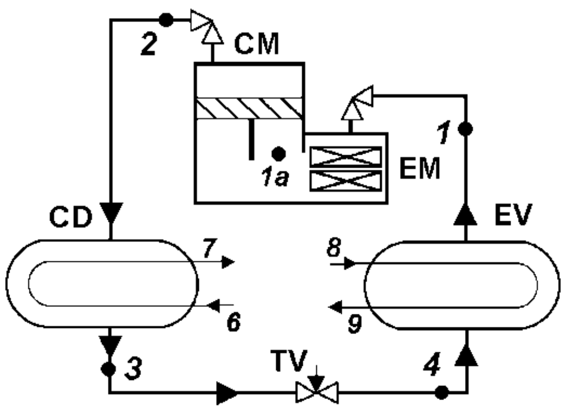

Fig 1. Vapor-compression refrigeration machine with a closed compressor:

CD – condenser; EM – electrical motor; EV – evaporator; CM – compressor; TV – throttling valve.

Table 1

Thermodynamic and exergoeconomic data for the refrigeration machine shown in Figure 1.

Stream	Working fluid	$\dot{m}$ (kg/s)	T (ºC)	p (bar)	e^T (kJ/kg)	e^M (kJ/kg)	e (kJ/kg)
1	R134a	0.325	0	2.93	0.63	24.67	25.3
1a			4	2.93	0.39	24.67	25.06
2			44	8.16	7.44	39.63	47.07
3			32	8.16	0	39.63	39.63
4			0	2.93	11.90	24.67	36.57
6	Water	2.848	20	1.5	0	0.05	0.05
7			25	1.5	0.18	0.05	0.23
8	Water	1.704	12	1.5	0.46	0.05	0.51
9			5	1.5	1.66	0.05	1.71

This machine consists of a compressor with electrical motor (CM and EM), a condenser (CD), a throttling valve (TV) and an evaporator (EV). R 134a is the primary working fluid for the refrigeration machine, whereas water is used as the secondary working fluid in the condenser and the evaporator.

The product from the overall system is the cold rate $\dot{Q}_{cold}$=50kW, the exergy rate of which is kept constant in the analysis: $\dot{E}_{P,tot} = \dot{E}_9 - \dot{E}_8 = const$. The isentropic efficiency of the compressor and the electrical motor is assumed to be $\eta_{CM} = 0.85$ and $\eta_{EM} = 0.85$, respectively.

Table 1 shows the working fluid, mass flow rate, temperature, pressure and specific physical exergy (and the splitting of physical exergy into its thermal and mechanical parts) for all streams of matter shown in Figure 1. Table 2 shows the definition of the exergy of product and exergy of fuel for each component. Table 3 shows the exergy rates associated with fuel, product and exergy destruction as well as the exergetic efficiency and the exergy destruction ratio for each component.

Table 4 summarizes the main results obtained from LCA as well as Table 5 shows the results obtained from the exergoenvironmental analysis. The value of b_{el} is equal to 27 mPts/kWh (average for Europe) [15].

Table 2

The definition of the exergy of product and exergy of fuel (for the exergetic analysis) and of the environmental impacts associated with them.

Com-ponent	Heat and work rates (kW)	Exergetic analysis	Environmental impact balances and auxiliary equations
EM	$\dot{W}_{EM}=9.774$ $\dot{Q}_{EM}=1.246$	$\dot{E}_{F,EM}=\dot{W}_{EM}+\dot{E}_1-\dot{E}_{11}$ $\dot{E}_{P,EM}=\dot{W}_{CM}$	$\dot{B}_{F,EM}=\dot{W}_{EM}\cdot b_{el}+\dot{B}_1-\dot{B}_{11}$ $\dot{B}_{P,EM}=\dot{W}_{CM}\cdot b_5$ with $b_{11}=b_1$
CM	$\dot{W}_{CM}=8.308$	$\dot{E}_{F,CM}=\dot{W}_{CM}+\dot{E}_{11}^T$ $\dot{E}_{P,CM}=\dot{E}_2^M-\dot{E}_{11}^M+\dot{E}_2^T$	$\dot{B}_{F,CM}=\dot{W}_{CM}\cdot b_5+\dot{B}_{11}^T$ $\dot{B}_{P,CM}=\dot{B}_2^M-\dot{B}_{11}^M+\dot{B}_2^T$ with $\frac{\dot{B}_2^T}{\dot{E}_2^T}=\frac{\dot{B}_2^M-\dot{B}_{11}^M}{\dot{E}_2^M-\dot{E}_{11}^M}$
CD	$\dot{Q}_{CD}=58.308$	$\dot{E}_{F,CD}=\dot{E}_2-\dot{E}_3+\dot{E}_6^M-\dot{E}_7^M$ $\dot{E}_{P,CD}=\dot{E}_7^T-\dot{E}_6^T$	$\dot{B}_{F,CD}=\dot{B}_2-\dot{B}_3+\dot{B}_6^M-\dot{B}_7^M$ $\dot{B}_{P,CD}=\dot{B}_7^T-\dot{B}_6^T$ with $b_3=b_2$, $b_7^M=b_6^M=b_{el}$ and $b_6^T=0$ (assumption)
TV	–	$\dot{E}_{F,TV}=\dot{E}_3^M-\dot{E}_4^M+\dot{E}_3^T$ $\dot{E}_{P,TV}=\dot{E}_4^T$	$\dot{B}_{F,TV}=\dot{B}_3^M-\dot{B}_4^M+\dot{B}_3^T$ $\dot{B}_{P,TV}=\dot{B}_4^T$ with $b_4^M=b_3^M$
EV	$\dot{Q}_{EV}=50.000$	$\dot{E}_{F,EV}=\dot{E}_4-\dot{E}_1+\dot{E}_8^M-\dot{E}_9^M$ $\dot{E}_{P,EV}=\dot{E}_9^T-\dot{E}_8^T$	$\dot{B}_{F,EV}=\dot{B}_4-\dot{B}_1+\dot{B}_8^M-\dot{B}_9^M$ $\dot{B}_{P,EV}=\dot{B}_9^T-\dot{B}_8^T$ with $b_4=b_1$, $b_9^M=b_8^M=b_{el}$ and $b_8^T=0$ (assumption)
Overall system	$COP=\frac{\dot{Q}_{EV}}{\dot{W}_{EM}}$ = 5.116	$\dot{E}_{F,tot}=\dot{W}_{EM}$ $\dot{E}_{P,tot}=\dot{E}_{P,EV}$ $\dot{E}_{L,tot}=\dot{E}_{P,CD}$	$\dot{B}_{F,tot}=\dot{W}_{EM}\cdot b_{el}$ $\dot{B}_{P,tot}=\dot{B}_{P,EV}$ $\dot{B}_{L,tot}=\dot{B}_{P,CD}$

Table 3

Conventional exergetic analysis of the refrigeration machine shown in Figure 1. ($\dot{E}_{L,tot}$=0.502 kW)

Component	$\dot{E}_{F,k}^{real}$ [kW]	$\dot{E}_{P,k}^{real}$ [kW]	$\dot{E}_{D,k}^{real}$ [kW]	ε_k [%]
EM	9.855	8.308	1.547	84
CM	8.433	7.274	1.160	86
CD	2.416	0.5022	1.914	21
TV	4.857	3.863	0.994	80
EV	3.657	2.045	1.613	56
Overall system	9.774	2.045	7.227	21

Table 4

Data used in the exergoenvironmental analysis

Component	Material	Amount of material (kg)	ECO'99 Indicator (mPts/kg)	Points (mPts)
EM	Steel	34	86	2924
	Steel low alloy	34	110	3740
	Cupper	17	1400	23800
	Total EM	**30464**		
CM	Steel	32	86	2752
	Aluminium	2	420	840
	Steel low alloy	58	110	6380
	Steel high alloy	5	910	4550
	Total CM	**14522**		
CD	Steel	137	86	11782
	Cupper	69	1400	96600
	Total CD	**108382**		
TV	Steel	2	86	172
	10% of EM*)			3046
	Total TV	**3218**		
EV	Steel	120	86	10320
	Cupper	60	1400	84000
	Total EV	**94320**		

*) Throttling valve is in reality a thermostatic valve with a temperature-sensing element and corresponding electric equipment.

Table 5

Exergoenvironmental analysis of the refrigeration machine shown in Figure 1

Component	Y_k (mPts)	$\dot{Y}_k$ (mPts/h)	$\dot{B}_{D,k}$ (mPts /h)	$\dot{Y}_k + \dot{B}_{D,k}$ (mPts /h)	$b_{F,k}$ (mPts /J)	$b_{P,k}$ (mPts /J)	$r_{b,k}$ (%)	$f_{b,k}$ (%)
EM	30464	0.2782	42.02	42.30	7.55	8.96	19	0.66
CM	14522	0.1326	37.68	37.81	9.02	10.47	16	0.35
CD	108382	0.9898	72.13	73.12	10.47	50.91	386	1.35
TV	3218	0.0294	37.45	37.48	10.47	13.16	26	0.08
EV	94320	0.8614	76.41	77.27	13.16	23.66	80	1.11
Overall system	250906	2.2914	234.80	237.09	7.50	23.66	215	0.85

The following conclusions can be obtained from the exergoenvironmental analysis:

- The condenser and the evaporator have highest values of the component-related environmental impact ($\dot{Y}_k$) as well as the environmental impact associated with exergy destruction within these components ($\dot{B}_{D,k}$).

- The values of $\dot{Y}_k$ are very small compared with the values of $\dot{B}_{D,k}$. This means that the environmental impact associated with the exergy destruction is the most important contributor to the total environmental impact associated with a component ($\dot{Y}_k + \dot{B}_{D,k}$). In this way, decreasing the exergy destruction within a component always leads to a decrease in the environmental impact associated with this component.

Since the data given in Table 4 cannot be considered as exact (there is a very high subjectivity in determining size and weight of equipment with corresponding material), a sensitivity analysis was conducted for the values of environmental impact. The purpose of this sensitivity analysis is to determine the effect of $\dot{Y}_k$ and b_{el} on the environmental impact associated with the final product (cold). Three different calculations were used: (a) $\dot{Y}_k$ varied between 0% and 500% while $b_{el} = const$, (b) b_{el} varied between 0% and 500% while $\dot{Y}_k = const$, and (c) both variables $\dot{Y}_k$ and b_{el} were simultaneously varied between 0% and 500%. The data obtained from the sensitivity analysis demonstrate that the value of b_{el} significantly affects the results obtained from the exergoenvironmental analysis, while the effect of $\dot{Y}_k$ is negligible. This conclusion is valid (a) for all energy conversion systems that were evaluated using exergoenvironmental analysis (with Eco-indicator 99), and (b) for all Eco-indicators that were used instead of Eco-indicator 99 for the exergoenvironmental analysis.

Conclusions. An exergoenvironmental analysis is a new exergy-based method [23]. Exergoenvironmental analysis demonstrates the formation of environmental impacts associated with energy conversion systems at the component level, and provides useful information for designing and operating systems with a lower overall environmental impact. The results show that the value of the component-related environmental impact can be neglected during the exergoenvironmental analysis and evaluation and only the value of environmental impact associated with the fuel of the overall system and, therefore, with the exergy destruction should be considered in the analysis.

Nomenclature

b	environmental impact per unit of exergy (Pts /J)
$\dot{B}$	environmental impact rate associated with exergy (Pts /s)
e	specific exergy (J/kg)
$\dot{E}$	exergy rate (W)
f_b	exergoenvironmental factor (%)
k	k -th component
$\dot{m}$	mass flow rate (kg/s)
p	pressure (bar)
$\dot{Q}$	heat rate (W)
r_b	relative environmental impact difference (%)
T	temperature (°C)
$\dot{W}$	power (W)
y	exergy destruction ratio (%)
$\dot{Y}$	environmental impact (Pts/s)

Greek symbols

ε	exergetic efficiency (%)
η	energetic efficiency (%)

Subscripts

Superscripts

● time rate

M	mechanical part of physical exergy
PH	physical exergy
T	thermal part of physical exergy

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