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Thermodynamics Based Sustainability Concept[*]

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Abstract

The main objective is to minimize the influence of subjective arguments in the determination of an indicator for sustainability. Current methods are often based on the results of an environmental oriented Life Cycle Assessment. By using the laws of thermodynamics it is possible to calculate the amount of the apparent non-renewable exergy necessary for the life cycle of a certain product or process. The new concept is mainly based on dividing the exergetic cost of a flow into a *renewable* exergetic cost flow and a *non-renewable* exergetic cost flow, resulting in a so-called rate of sustainability.

Key words: exergy, sustainability, exergetic cost, eco-efficiency

1. Introduction

The main goal of this article is to develop a method, based on thermodynamics, to determine the rate of sustainability of a process. If a thermodynamics based definition of sustainability is possible, then the conclusions drawn will be more objective. The current methods are often based on an environmental oriented Life Cycle Assessment (LCA). The result is a profile consisting of different environmental effects, such as ozone-layer depletion and greenhouse potential. The way these effects contribute to the total impact on the environment, determined by weighting-factors, is often open to discussion. However, a thermodynamics based indicator could avert this kind of discussion. It is often seen that an environmental profile is significantly influenced by the use of (fossil) energy. Because the amount of energy used cannot change, by the 1st law of thermodynamics, the quality of energy, exergy, of a flow is taken as an indicator. The discussion of a thermodynamics based comparison of two or more processes relies on a few common definitions, as given in section 2. In section 3 the combination of thermodynamics and potential impact on the environment is more thoroughly discussed. The allocation of the exergetic costs of a more complex system can be calculated using an expanded method of Valero et al. (1986). The integration of the concept and Valero's method is presented in section 4. This is followed by an example (section 5) and finally some conclusions are drawn (section 6).

2. Common Definitions

The definitions can be divided into two types: general process definitions and method related definitions. The following definitions are used and referred to in the coming sections.

General definitions:

Exergy sources: Useful exergy, which is a potential process feed (F).
Two types of exergy feed can be distinguished:
Renewable exergy feed (F_r): The renewable exergy feed can be replenished within the considered period in which the studied 'process' takes place. This means that the total amount of renewable exergy feed is recovered over the life span of the process. By definition renewable sources cannot decrease. For instance, the exergy

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feed related to *wind or solar energy* is 100% renewable.

Non-renewable exergy feed ($F_{n\text{-}r}$): The non-renewable exergy feed cannot be replenished or recovered within the considered period. This means that the use of non-renewable feed will decrease the exergy sources. Actual depletion of resources is a frequent topic of discussion. Some *fossil* sources are exploited at such a slow rate that the *depletion* is not noticeable. However, it is generally assumed that non-renewable sources can finally be depleted. For instance, forest fires are non-renewable exploitation of *biomass.*

Exergy product (P): The exergy product of a process is stated in terms of the total useful output of the considered process.

Exergy losses (E+I): The exergy losses of the studied process include the exergy waste (E) and the irreversible exergy destruction (I). The exergy waste flow is actually an output, however it is not used and is therefore considered to be lost. Two types of exergy losses can be defined: exergy losses associated to renewable exergy feed ($[E+I]_r$) and losses associated to non-renewable exergy feed ($[E+I]_{n\text{-}r}$).

Exergetic efficiency: The exergetic efficiency of a process is defined by the total useful output over the total exergy feed. ($\eta = P/[F_r+F_{n\text{-}r}]$)

Method related definitions:

Harmful exergy loss: The exergy loss associated with the non-renewable exergy feed is considered to be the ‘harmful’ exergy loss. It is assumed that the exergy loss related to the renewable exergy feed does not indicate any harmful effect since it is stated that the renewable exergy sources can be recovered. This assumption is further discussed in section 3.

Thermodynamic sustainability: Although the relationship between exergy losses and the environmental effects is not strictly given, the following is postulated.

Proposition 1

> The less harmful exergy loss occurs, the more sustainable the process is. A process is called completely (thermodynamic) sustainable if no harmful exergy loss takes place.

If a process is judged by its sustainability and proposition 1 is taken into account, then the following can be postulated.

Proposition 2

> The exergy losses due to the use of renewable exergy may be disregarded if a process is judged by its sustainability.

Energy process: An energy process is a process with a positive exergetic efficiency ($\eta > 0$) and thus the exergy product is positive.

Service process: A service process is a process without a general exergetic efficiency ($\eta = 0$) and thus the exergy product is negligible.

3. Thermodynamics and Sustainability

Basically it can be said that the use of fossil sources is no more than a decrease in the potential power of the earth. However it has been discovered by the evaluation of some LC-analyses that the loss of non-renewable exergy is a good indicator of the environmental impact of a process. The use of renewable sources creates no harmful effects because the emissions related to the renewable exergy feed have short cycles. It is clear that in some cases the relationship is confusing. For example, the way in which toxic substances harm the environment is not shown by its use of non-renewable exergy. Therefore it is assumed that the Exergetic Life Cycle Assessment (ELCA) can only give a first indication of the potential impact on the environment. In the next section a new exergetic based process indicator will be introduced: *the eco-efficiency*[1] (η_{eco}). This value represents the ability of the process to achieve complete thermodynamic sustainability, so this number has a range of 0 to 100%.

3.1 Calculation of the eco-efficiency

The eco-efficiency can be determined for the so-called *energy processes*. This new process parameter can serve as a base of comparison between two or more similar processes. The calculation of the eco-efficiency is fully based on proposition 2, which means that the rate of sustainability is based on the non-renewable exergy losses. A general energy process can be presented as in *Figure 1.*

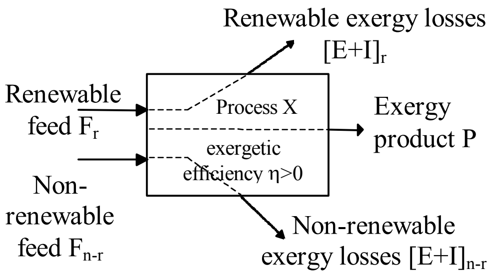

Figure 1. A general presentation of an energy process

If proposition 2 is taken into account and the process is presented more symbolically then the energy process can be illustrated as shown in *Figure 2.*

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[1] Eco-efficiency in connection with this concept has been introduced by Cornelissen (1995)

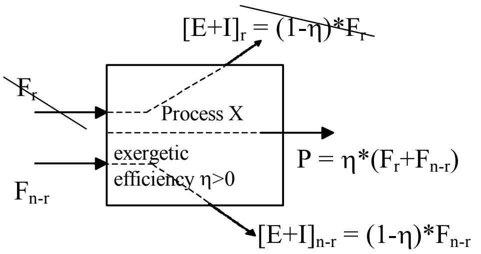

Figure 2. The impact related presentation of an energy process

The process, as shown in *Figure 2,* does not satisfy the First Law of Thermodynamics as a consequence of disregarding the renewable flows. In order to correct the dissatisfaction, a correction factor of $\eta \cdot F_r$ is assumed. This factor appears in the exergy feed of the process and therefore an *apparent* exergy feed (F_{app}) can be introduced, see also *Figure 3.*

$$F_{app} = [E + I]_{n\text{-}r} + P = F_{n\text{-}r} + \eta \cdot F_r \qquad (1)$$

In fact the presentation of *Figure 3* depicts an imaginary process with the same non-renewable exergy losses and exergy product as in *Figure 1*, but which satisfies the First Law of Thermodynamics. The efficiency of the process, as presented in *Figure 3*, is the so-called eco-efficiency. This efficiency is the recalculated original efficiency, as presented in *Figure 1* and can be defined by:

$$\eta_{eco} = \frac{P}{F_{app}} = \frac{\eta \cdot (F_{n-r} + F_r)}{F_{n-r} + \eta \cdot F_r} \qquad \text{and}$$

$$\frac{1}{\eta_{eco}} = \frac{F_{app}}{P} = \frac{F_{n-r} + \eta \cdot F_r}{\eta \cdot (F_{n-r} + F_r)} \qquad (2)$$

Along the approach of Valero (1986) the eco-efficiency appears often also in its reciprocal form.

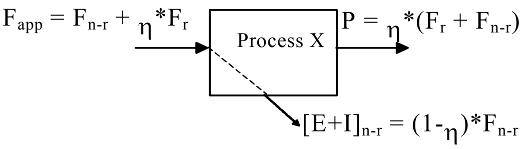

Figure 3. The rebalanced presentation of an energy process

3.2 The sustainability concept and service processes

The sustainability concept as the new indicator can be adopted for service processes in a way basically consistent with the calculations of the former section. According to the definition of a service process the new indicator cannot be an efficiency, but it is the fossil exergetic unit consumption (C_{fos}).

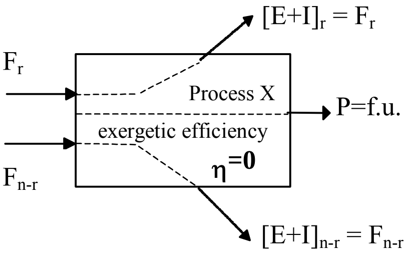

Figure 4. The presentation of a general service process

A general service process can be presented as shown in *Figure 4.*

By definition the exergy product is negligible. However the product of a service process is defined in a functional unit[2] (f.u.). If proposition 2 and the calculations in the former section are taken into account, then the results for C_{fos} can be presented as:

$$C_{fos} = \frac{F_{n-r}}{P} = \frac{F_{n-r}}{f.u.} \qquad \text{and}$$

$$\frac{1}{C_{fos}} = \frac{P}{F_{n-r}} = \frac{f.u.}{F_{n-r}} \qquad (3)$$

Although the fossil exergetic unit consumption is not dimensionless, this number can still serve as a basis for comparison, given that both processes should be compared on the same f.u.

3.3 Exergetic life cycle assessment (ELCA)

ELCA is an exergetic based life cycle assessment. This assessment is a method to obtain an objective (exergy-) indicator for evaluating products or processes. The reader unfamiliar with life cycle assessment in general is referred to Heijungs (1995). This kind of study can often be executed with life cycle oriented software. One commonly used program is *Simapro* by Pré (1999). The authors have developed an exergy database compatible with this program. It is now possible to execute an ELCA-analysis on an existing Simapro model.

4. The Eco-efficiency and Valero's Exergetic Cost Method

In this section the calculation of the eco-efficiency is made compatible with Valero's

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[2] According to Heijungs (1995) a functional unit is the basis for comparison between two or more processes. It defines the function of the process and is a useful calculation unit.

exergetic cost method (1986). The importance of this method stems from the fact that it can analyze complex energy processes containing sequential processes with several subsystems. And thus the method supplies a better understanding of the exergetic relationships within the system and therefore the allocation of the exergy losses. The main idea is that every single exergy flow has an exergetic cost flow. These costs are actually used by the process to produce the main exergy flow. With the aid of these exergetic costs it is possible to calculate the individual efficiency of each flow. The additions made to the method are defined to be consistent with the symbols already used in this method. The method can be extended to calculate the eco-efficiencies. The additions are presented below, then some extra propositions are submitted.

Additions to Valero's method:
The exergy flows are split in a renewable and a non-renewable flow; this yields:

$F_{n\text{-}r}$: the non-renewable exergy feed
F_r : the renewable exergy feed
$B_{n\text{-}r}^*$: the non-renewable exergy cost
B_r^* : the renewable exergy cost
$\kappa_{n\text{-}r}^*$: the non-renewable exergetic unit cost of a flow ($=B_{n\text{-}r}^*/B^*$)
κ_r^* : the renewable exergetic unit cost of a flow ($=B_r^*/B^*$)
$\kappa_{n\text{-}r}$: the non-renewable exergetic unit consumption of a (sub)system ($=F_{n\text{-}r}/P$)
κ_r : the renewable exergetic unit consumption of a (sub)system ($=F_r/P$)

These definitions yield the following equations:

$$F = F_{n\text{-}r}+F_r \tag{4}$$

$$B^*= B_{n\text{-}r}^*+B_r^* \tag{5}$$

$$\kappa^*= \kappa_{n\text{-}r}^*+ \kappa_r^* \tag{6}$$

$$\kappa= \kappa_{n\text{-}r}+\kappa_r \tag{7}$$

It must be noted that either $\kappa_{n\text{-}r}^*$ or κ_r^* or $\kappa_{n\text{-}r}$ or κ_r can be smaller than one. However κ^* and κ are always greater than or equal to one since they are the sum of the non-renewable and renewable unit costs (or unit consumptions). If they would be smaller than one, it would mean exergy production within a flow (or subsystem). This is thermodynamically not possible.

If, for example, κ_r is smaller than one, it means that the main part of the exergy product leaving the subsystem is a result of the non-renewable exergy feed (P is larger than F_r). And therefore $F_{n\text{-}r}$ has to be larger than P and thus $\kappa_{n\text{-}r}$ will be larger than one. This will result in a κ larger than one. This is also valid for or κ_r^* or $\kappa_{n\text{-}r}^*$ and κ^*. Note that κ=1 means a subsystem with an exergetic efficiency of 100% and thus completely reversible.

It can be seen that the exergetic unit consumption is the reciprocal of the exergetic efficiency. Therefore the reciprocal of the eco-efficiency is the so-called apparent[3] exergetic unit consumption. Two types of apparent exergetic unit consumption can be distinguished:

κ_{app}^* : The apparent exergetic unit cost of a flow
κ_{app} : The apparent exergetic unit consumption of a (sub)system

and thus two types of eco-efficiency can be defined:

The eco-efficiency of an exergy flow:

$$\eta_{eco}^* = 1/\kappa_{app}^* \tag{8}$$

The eco-efficiency of a (sub)-system:

$$\eta_{eco} = 1/\kappa_{app} \tag{9}$$

It can be proven that:

$$\kappa_{app} = 1 + \kappa_{n-r} - \frac{\kappa_{n-r}}{\kappa} \qquad \text{and}$$

$$\kappa_{app}^* = 1 + \kappa_{n-r}^* - \frac{\kappa_{n-r}^*}{\kappa^*} \tag{10}$$

because

$$\kappa_{app} = 1 + \kappa_{n-r} - \frac{\kappa_{n-r}}{\kappa} \quad \Rightarrow$$

$$1 + \frac{F_{n-r}}{P} - \frac{F_{n-r}\cdot P^{-1}}{\left(F_{n-r}+F_r\right)\cdot P^{-1}} \quad \Rightarrow$$

$$\frac{F_{n-r}+F_r}{F_{n-r}+F_r} + \frac{F_{n-r}}{\eta\left(F_{n-r}+F_r\right)} - \frac{F_{n-r}}{F_{n-r}+F_r} \quad \Rightarrow$$

$$\frac{F_r}{\left(F_{n-r}+F_r\right)} + \frac{F_{n-r}}{\eta\left(F_{n-r}+F_r\right)} \quad \Rightarrow$$

$$\frac{F_{n-r}+\eta\cdot F_r}{\eta\left(F_{n-r}+F_r\right)} = \frac{1}{\eta_{eco}}$$

In order to calculate these additional parameters the following propositions are postulated.

Additional propositions to Valero's method:
The renewable and non-renewable parts of the exergy product of a subsystem can be calculated by:

$$P_{n-r} = \frac{F_{n-r}}{\kappa} \qquad \text{and} \qquad P_r = \frac{F_r}{\kappa} \tag{11}$$

The rate of two non-renewable product flows of one subsystem equals the rate of the total product flows:

$$\frac{P_{n-r,i}}{P_{n-r,j}} = \frac{P_i}{P_j} \qquad \text{also} \qquad \frac{B_{n-r,i}^*}{B_{n-r,j}^*} = \frac{B_i^*}{B_j^*}$$

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[3] The fact that this exergetic unit consumption is called *apparent* is consistent with the definition of an apparent exergy feed.

moreover $$\frac{B_i^*}{B_i} = \frac{B_{n-r,i}^*}{B_{n-r,i}} \qquad (12)$$

In conformity with proposition 2F[4] in Valero (1986), the rate of the non-renewable exergy feed of a doublet feed F_J equals the rate of the made up flows, f_i and f_j:

$$\frac{f_{n-r,i}}{f_{n-r,j}} = \frac{f_i}{f_j}$$ moreover for a doublet product

$$\frac{p_{n-r,i}}{p_{n-r,j}} = \frac{p_i}{p_j} \qquad (13)$$

5. Eco-efficiency and the Production of Electricity

Lately a major discussion has been going on in the Netherlands as to what extent the electricity produced by a Waste Incinerating Plant (WIP) is sustainable. As a contribution to this discussion a thermodynamics based point of view is given by using the eco-efficiency. It will be clear in the coming sections that the eco-efficiency here defined could also be used as a tool by decision-makers. Before any comparison is made, the scheme of the waste incinerating process is presented and discussed. The scheme, presented in *Figure 5*, is calculated using the expanded Valero method. In section 5.2 a comparison is made with the production of electricity by a natural gas-fired power plant (NGP).

5.1 A waste incinerating plant

The studied process is a general WIP. The plant can be divided into three parts:

1. The incineration process and the heat transmission to the water-steam cycle, system I
2. The water-steam cycle and the production of electricity, system II
3. The fluegas cleaning plant, system III

However, system III is not a part of this example. The results of all streams are not presented since the minor flows have little bearing on the main results. However, TABLE I shows the complete overview of system I, the exergy data as well as the results of the calculations. The exergy values of the flows of system II are given in TABLE II. These values are necessary to calculate the complete system.

The important results of the exergy product, referred as flows 38 and 39, are given in TABLE III. The last column shows the reciprocal form of the eco-efficiency of each flow. This value is important as far as the environmental impact of the flow is concerned. Calculations pertaining to the waste incinerating system are based on the following assumptions:

- 50% of the input waste stream (1) is of the nature of biomass and hence it is assumed that 50% of flow (1) is renewable[5].

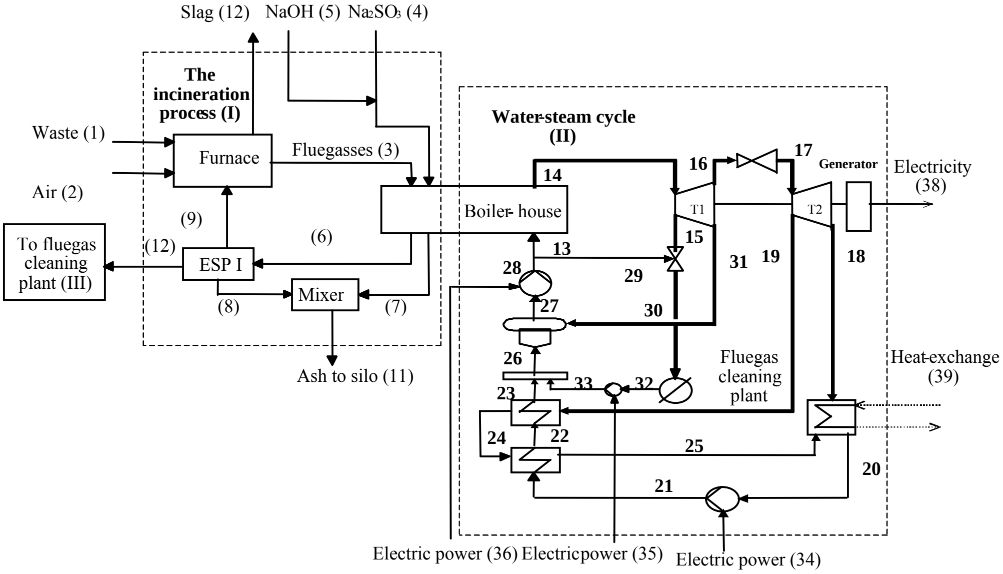

Figure 5. View of a waste incinerating system

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[4] Proposition 2F states that under normal conditions in a generic subsystem, each fuel has a unit exergetic cost greater than or equal to one, and equal to the unit exergetic cost of the currents which make it up.

[5] The companies claim that 50% of the waste stream is of the nature of biomass. Although major discussion is continuing, the Dutch administration currently grants these companies a partial exemption from the tax on fossil based electricity for small consumers as a consequence.

TABLE I. THE RESULTS OF SYSTEM I

Flow #[a]	B (kW)[b]	B^* (kW)	B_{n-r}^* (kW)	B_r^* (kW)	κ^*	κ_{app}^*
1	96500	96500	48250	48250	1.00	1.00
3	44048	99062	49531	49531	2.25	1.62
6	5381	12102	6051	6051	2.25	1.62
9	1139	2562	1281	1281	2.25	1.62
10	4242	9540	4770	4770	2.25	1.62

[a] Flows 2, 4, 5, 7, 8, 11 and 12 are not included(*17) since their exergy flows equal zero.

[b] Data have been taken from Fichtner (1994) and Stavenga (1994).

TABLE II. THE EXERGY OF THE FLOWS IN SYSTEM II

Flow #[a]	B (kW)	Flow #	B (kW)	Flow #	B (kW)
13	2824	22	340	31	1813
14	37609	23	1192	32	19
15	474	24	129	33	19
16	20158	25	41	34	32
17	19244	26	1211	36	224
18	5468	27	2779	38	22512
19	1309	28	2847	39	5205
20	237	29	23	Work T1	13505
21	252	30	433	Work T2	12106

[a] Flow 35 is not included (*18) since its exergy flow equals zero.

TABLE III. THE MAJOR RESULTS OF SYSTEM II

Flow #	B^* (kW)	B_{n-r}^* (kW)	B_r^* (kW)	κ^*	κ_{app}^*	Comment
38	71911	36039	35872	3.19	2.10	Electricity
39	15305	7670	7635	2.94	1.97	Condenser heat

- Some electrical devices are used in system II. It is assumed that these devices have a 100% non-renewable exergy feed.
- Some device efficiencies are unknown and hence these are assumed

TABLE III shows that the electricity is produced with an exergetic unit cost, $\kappa^* = 3.19$ and an apparent exergetic unit cost, $\kappa_{app}^* = 2.10$. Before any conclusion can be made, a suitable comparable system must be analyzed.

5.2 Comparison

Some conclusions can be drawn specifically from the earlier results, and others are more general in character. The overall exergetic efficiency of the electricity produced by the WIP and the NGP can be calculated as:

WIP: $\eta = 1/\kappa^* = 1/3.19 = 0.313 = 31.3\%$
NGP: $\eta = 1/\kappa^* = 1/2.00 = 0.500 = 50.0\%$

According to the results in section 5.1 and section 5.2, the eco-efficiency of the production of electricity of both systems can be determined by Eq. 8.

WIP: $\eta_{eco} = 1/\kappa_{app}^* = 1/2.10 = 0.48 = 48\%$,
NGP: $\eta_{eco} = 1/\kappa_{app}^* = 1/2.00 = 0.50 = 50\%$

It is clear that both production systems have approximately the same rate of sustainability. However some remarks have to be noted. If the production of electricity by natural gas is reviewed in more detail, the eco-efficiency would probably come up to 55%. Moreover the amount of 50% renewable exergy feed into the WIP can be discussed. The Dutch Department of VROM has determined that 50 wt. % of the WIP's input is renewable. However it is more realistic to consider an approximately 33% of renewable exergy feed from biomass.[6] This means that the eco-efficiency drops to 41%. From this it can be concluded that the production of electricity by a NGP is more sustainable, between 2-14%, than the production of electricity by a WIP. It must be noted that in this comparison the WIP is considered only as an electricity producer. However, basically a WIP should be evaluated as a process for the final disposal of waste since its main function is not producing electricity. The waste-incinerating process should be based on social principles and not on the concept of thermo-dynamical sustainability.

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[6] This can be calculated by the rate of the LHV of biomass and non-biomass and the wt.%. Moreover by pre-separation of household waste the wt.% of the biomass decreases to approximately 30%.

6. Conclusion

Generally it can be concluded that the eco-efficiency can be used as an indicator for the rate of thermodynamic sustainability. This indicator is an objective, quickly obtained and useful parameter that can be estimated for a wide range of processes. Although an ELCA can easily be executed, it will never give a complete overview of the potential environmental impact of the process. For example, in cases of many toxic substances it would even give a wrong picture and thus an environmental oriented LCA is still necessary in order to make the right environmental decisions. It is seen in section 5.2 that the reciprocal form of the eco-efficiency can also be used as a basis of comparison between two or more processes. The fossil exergetic unit consumption of a service process is not a dimensionless number; thus it strongly depends on the magnitude of the functional unit. In these cases it is recommended that the f.u. represents the service process in a correct and useful way. An expanded Valero method, as presented in section 4, can be used for calculating the eco-efficiencies of more complex energetic systems.

Acknowledgements

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Nomenclature

B	flow exergy of a flow (kW)
C	exergetic consumption per unit (kW/unit)
E	exergy emissions of a flow (kW)
F	total exergy feed of a system (kW)
f	exergy feed of a doublet (kW)
f.u.	functional unit
I	irreversible losses of a flow (kW)
NGP	natural gas-fired power plant
P	exergy product of a system (kW)
p	exergy product of a doublet (kW)
WIP	Waste Incinerating Plant
w.t.	weight

Greek symbols

κ	exergetic unit consumption of a (sub)system
η	exergetic efficiency

Superscripts

*	exergetic cost

Subscripts

app	apparent
eco	ecological
fos	fossil
i , j	generic index associated to a flow
n-r	non-renewable
r	renewable

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