

# 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.

## Nomenclature

Capital roman letters.

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)  
I = Irreversible losses of a flow (kW)  
P = Exergy product of a system (kW)  
NGP = Natural Gas fired power Plant  
WIP = Waste Incinerating Plant

Small roman letters.

f = Exergy feed of a doublet (kW)  
f.u. = Functional Unit  
p = Exergy product of a doublet (kW)  
w.t. = weight

Greek letters.

$\kappa$  = Exergetic unit consumption of a (sub)system  
 $\eta$  = 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

## 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 1<sup>st</sup> 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

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

Non-renewable exergy feed ( $F_{n-r}$ ): 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 losses (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 ( $[E+I]_{n-r}$ ).

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

Method related definitions:

Harmful exergy loss: The exergy loss associated to 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 can be found.

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

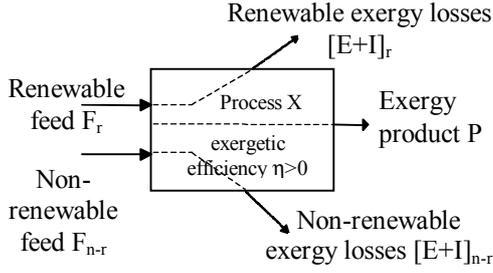
Basically it can be said that the use of fossil sources is no more than a decrease in the potential power of the earth. However it has been discovered by the evaluation of some LC-analyses that the loss of non-renewable exergy is a good indicator of the environmental impact of a process. The use of renewable sources lessens, or even 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 the 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 paragraph a new exergetic based process indicator will be introduced: *the eco-efficiency*<sup>1</sup> ( $\eta_{eco}$ ). This value represents the endeavor of the process to achieve complete thermodynamic sustainability, so this number has a range of 0 to 100%.

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<sup>1</sup> Eco-efficiency in connection to this concept has been introduced by Cornelissen (1995)

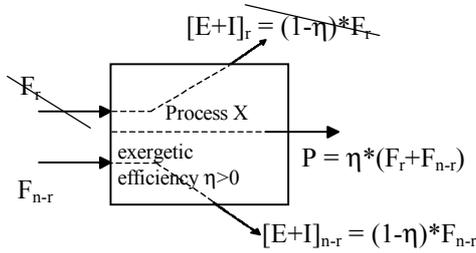
### 3.1. Calculation of the eco-efficiency

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. According to the definition 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.

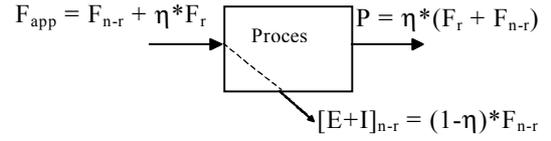


**Figure 2. The impact related presentation of an energy process**

The process, as shown in figure 2 does not satisfy the 1<sup>st</sup> 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

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

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 1<sup>st</sup> law of thermodynamics. The efficiency of the process, as presented in figure 3, is the so-called eco-



**Figure 3. The rebalanced presentation of an energy process**

efficiency. This efficiency is a recalculation of the original efficiency, as presented in Figure 1 and can be defined by:

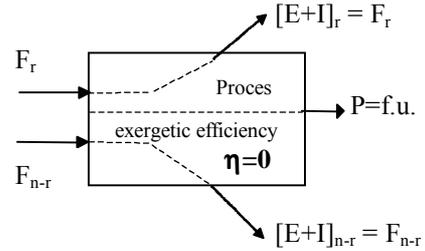
$$\eta_{eco} = \frac{P}{F_{app}} = \frac{\eta \cdot (F_{n-r} + F_r)}{F_{n-r} + \eta \cdot F_r} \quad \text{and}$$

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

Looking forward to Valero the eco-efficiency also often appears in its reciprocal form.

### 3.2. The sustainability concept and service processes

The concept of the new indicator can also be given for service processes and is basically consistent with the calculations in the former paragraph. However, according to the definition of a service process the new indicator cannot be an efficiency, but the indicator 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 (f.u)<sup>2</sup>. If proposition 2

<sup>2</sup> According to CML (1995) a functional unit is the basis for comparison between two or more processes. It defines the function of the process and an useful calculation unit.

and the calculations in the former paragraph are taken into account then the results of  $C_{fos}$  can be presented as:

$$C_{fos} = \frac{F_{n-r}}{P} = \frac{F_{n-r}}{f.u.} \quad \text{and} \quad (3)$$

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

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)

An 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 CML (1995). This kind of study can often be executed with life cycle oriented software. One commonly used program is *Simapro* by Pre (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 exergetic cost method (1986). The importance of this method is that it is a procedure to analyse 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 concept 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:

$F_{n-r}$  : the non-renewable exergy feed

$F_r$  : the renewable exergy feed

$B_{n-r}^*$  : The non-renewable exergetic cost

$B_r^*$  : The renewable exergetic cost

$\kappa_{n-r}$  : The non-renewable exergetic unit cost of a flow ( $\kappa_{n-r}^* = B_{n-r}^*/B^*$ )

$\kappa_r$  : The renewable exergetic unit cost of a flow ( $\kappa_r^* = B_r^*/B^*$ )

$\kappa_{n-r}$  : The non-renewable exergetic unit consumption of a (sub)system ( $\kappa_{n-r} = F_{n-r}/P$ )

$\kappa_r$  : The renewable exergetic unit consumption of a (sub)system ( $\kappa_r = F_r/P$ )

These definitions yield the following equations,

$$F = F_{n-r} + F_r \quad (4)$$

$$B^* = B_{n-r}^* + B_r^* \quad (5)$$

$$\kappa^* = \kappa_{n-r}^* + \kappa_r^* \quad (6)$$

$$\kappa = \kappa_{n-r} + \kappa_r \quad (7)$$

It must be noted that either  $\kappa_{n-r}^*$  or  $\kappa_r^*$  or  $\kappa_{n-r}$  or  $\kappa_r$  can be smaller than one, however  $\kappa^*$  and  $\kappa$  are always greater than or equal to one.

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<sup>3</sup> exergetic unit consumption. Two types of apparent exergetic unit consumption can be distinguished:

$\kappa_{app}^*$  : The apparent exergetic unit cost of a flow

$\kappa_{app}$  : The apparent exergetic unit consumption of a (sub)system

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

$$\eta_{eco}^* = 1/\kappa_{app}^* : \text{The eco-efficiency of an exergy flow} \quad (8)$$

$$\eta_{eco} = 1/\kappa_{app} : \text{The eco-efficiency of a (sub)-system} \quad (9)$$

It can be proven that:

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

$$\kappa_{app} = 1 + \kappa_{n-r} - \frac{\kappa_{n-r}}{\kappa} \quad (10)$$

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

#### Additional propositions to Valero's method:

The renewable and non-renewable part of the exergy product of a subsystem can be calculated by:

<sup>3</sup> The fact that this exergetic unit consumption is called *apparent* is consistent with the definition of an apparent exergy feed.

$$P_{n-r} = \frac{F_{n-r}}{\kappa} \quad \text{and} \quad P_r = \frac{F_r}{\kappa} \quad (11)$$

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

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

$$\text{moreover} \quad \frac{B_i^*}{B_j^*} = \frac{B_{n-r,i}^*}{B_{n-r,j}^*} \quad (12)$$

In conformity with proposition 2F 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  $f_j$ :

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

$$\frac{P_{n-r,i}}{P_{n-r,j}} = \frac{P_i}{P_j} \quad (13)$$

## 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 paragraphs 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 paragraph 5.3 a comparison is made with the production of electricity by 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 1 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 2. These values are necessary to calculate the complete system.

The important results of the exergy product, referred as flow 38 and 39, are given in Table 3. 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:

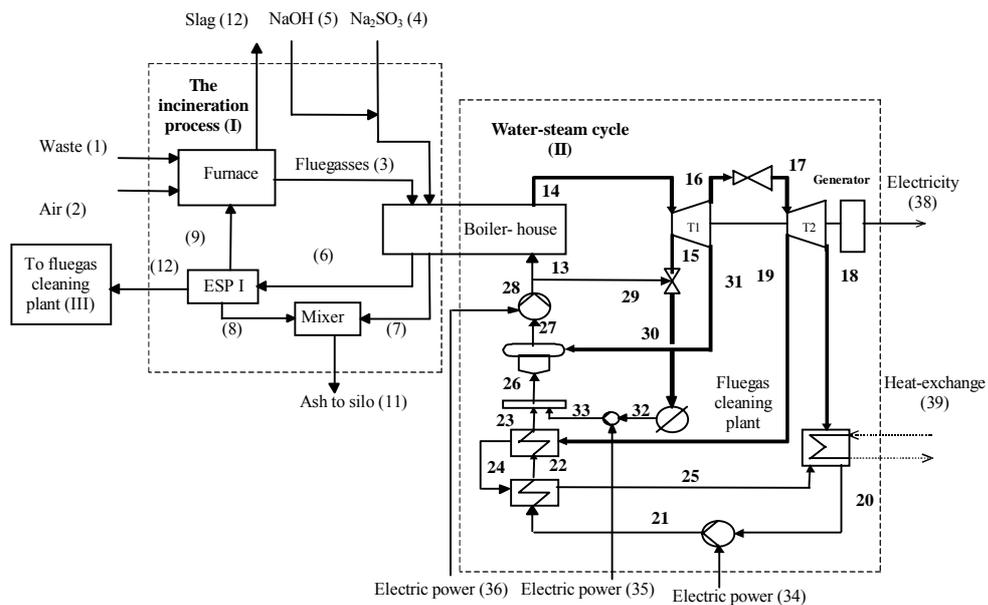


Figure 5. View of a waste incinerating system

- 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<sup>4</sup>.
- 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 1. The results of system I**

Flow # <sup>a</sup>	B (kW) <sup>b</sup>	B* (kW)	B <sub>n-r</sub> * (kW)	B <sub>r</sub> * (kW)	$\kappa^*$	$\kappa_{app}^*$
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

<sup>a</sup>. The flows 2, 4, 5, 7, 8, 11 and 12 are not found, since their exergy flows equal zero.

## 5.2. A Natural Gas fired power Plant

One of the conventional electricity production methods is a Natural Gas fired power Plant (NGP). Without any detailed calculations it is stated that the overall exergetic efficiency of a general NGP power plant is around 50% and thus the exergetic unit cost of the electricity production is,  $\kappa^* = 2.00$ . Since natural gas is a fossil fuel it can be assumed that the exergy feed of the power plant is non-renewable. Hence the apparent exergetic unit cost of a NGP remains,  $\kappa_{app}^* = 2.00$ .

<sup>b</sup>. Data has been taken from Fichtner (1994) and Stavenga (1994).

**Table 2: The exergy of the flows in system II**

Flow # <sup>a</sup>	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

<sup>a</sup>. Flow 35 is not found, since its exergy flow equals zero.

**Table 3. The major results of system II**

Flow #	B* (kW)	B <sub>n-r</sub> * (kW)	B <sub>r</sub> * (kW)	$\kappa^*$	$\kappa_{app}^*$	Comment
38	71911	36039	35872	3.19	2.10	Electricity
39	15305	7670	7635	2.94	1.97	Condenser heat

Table 3 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 analysed.

<sup>4</sup> 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.

## 5.3. 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:

$$\text{WIP: } \eta = 1/\kappa^* = 1/3.19 = 0.313 = 31.3\%$$

$$\text{NGP: } \eta = 1/\kappa^* = 1/2.00 = 0.500 = 50.0\%$$

According to the results in paragraph 5.1 and paragraph 5.2 the eco-efficiency of the

production of electricity of both systems can be determined by Eq. 8.

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

$$\text{NGP: } \eta_{\text{eco}} = 1/\kappa_{\text{app}}^* = 1/2.00 = 0.50 = 50\%$$

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%<sup>5</sup> of renewable exergy feed from biomass. 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 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 thermodynamical sustainability.

## 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 method that can be produced over 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 paragraph 5.3 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 and 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 a more complex energetic system.

## 7. Acknowledgements

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<sup>5</sup> 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%.