Int.J. Applied Thermodynamics,
Vol.4, (No.3), pp.145-156, September2001

ISSN 1301-9724

A New Approach for Assigning Costs and Fuels to Cogeneration Products

Berit ERLACH•, George TSATSARONIS, Frank CZIESLA
Institute for Energy Engineering
Technical University of Berlin
Marchstr. 18, 10587 Berlin - Germany
Tel: +49-30-314-24776, -22181
Fax: +49-30-314-21683
E-mail: tsatsaronis@iet.tu-berlin.de

Abstract

Cogeneration plants generate more than one product (e.g., electricity and steam) using to some extent common fuel(s) and equipment items. Several approaches have been suggested in the past for assigning the costs associated with these common equipment items and fuels to the products of the plant. Some of these approaches use exergy-based or thermoeconomic methods. The results, however, may vary within a wide range.

This paper presents a new exergy-based approach for assigning the fuel(s) used in a cogeneration plant to the individual products of the plant. Combined with a thermoeconomic analysis, this approach provides the costs associated with the product streams. The new approach is more flexible, i.e. it allows engineers to actively participate in the fuel and cost assigning process. As expected, the results obtained with this approach differ from the results obtained from any of the previous approaches, including the exergetic cost theory and all previous thermoeconomic approaches. The application of the new approach is demonstrated using a combined heat and power plant.

1. Introduction

Thermoeconomic (exergoeconomic) methods are powerful tools for the analysis, evaluation and optimization of energy conversion systems, as they provide means to determine the internal cost flows within a plant. The cost formation process throughout a plant from the fuel to the final products is made transparent with the aid of a thermoeconomic analysis. The costs associated with the thermodynamic inefficiencies occurring in each plant component are detected.

For every plant component, an exergy balance can be formulated.

$$\sum \dot{E}_{in,k} = \sum \dot{E}_{out,k} + \dot{E}_{D,k} + \dot{E}_{L,k} \qquad (1)$$

The exergy destruction $\dot{E}_{D,k}$ and the exergy loss $\dot{E}_{L,k}$ are a measure of the inefficiencies associated with the irreversible processes taking place in the *kth* plant component. When single components of a thermal system are considered, the exergy losses are usually zero:

$$\dot{E}_{L,k} = 0 \qquad (2)$$

Several thermoeconomic approaches have been presented in the literature (Frangopoulos, 1983, Tsatsaronis and Winhold, 1985, Valero et al., 1986, von Spakovsky, 1986, Tsatsaronis and Lin, 1990, Lazzaretto et al., 1993, Penner and Tsatsaronis, 1994, Bejan et al., 1996, Valero et al., 1999). They all have in common the use of cost balances for the plant components:

$$\sum \dot{C}_{out,k} = \sum \dot{C}_{in,k} + \dot{Z}_k \qquad (3)$$

and some auxiliary equations expressed explicitly or implicitly. These auxiliary equations depend on the purpose of the component within the overall system, which is expressed by the exergetic efficiency:

• Author to whom all correspondence should be addressed.

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \tag{4}$$

The auxiliary equations have been the subject of some research aimed at the development of generally applicable rules for the formulation of the auxiliary equations (Tsatsaronis and Lin, 1990, Torres et al. 1996, Lazzaretto and Tsatsaronis, 1997 and 1999). In this paper, the rules suggested by Lazzaretto and Tsatsaronis (1999) are used.

An important characteristic of exergoeconomics is the definition of exergy related specific costs.

$$c_i = \frac{\dot{C}_i}{\dot{E}_i} \tag{5}$$

In terms of fuel and product, the cost balance for the *kth* component (Eq. 3) may be written as follows:

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \tag{6}$$

The specific costs per unit of fuel and product exergy are two important parameters for an exergoeconomic evaluation:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}}, \quad c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{7}$$

2. Problem Definition

Besides providing valuable information for the evaluation and optimization of energy conversion systems, an exergoeconomic analysis calculates the costs of each product stream from the overall system. However, the costs obtained for cogeneration processes of heat and power are not always satisfactory. In the following, the cogeneration system shown in *Figure 1* is used as an example. The thermodynamic data of the plant are given in TABLE I. The system consists of five components: air compressor (AC), air preheater (APH), combustion chamber (CC), gas turbine (GT) and heat recovery steam generator (HRSG). The cost data and exergetic efficiencies of the plant components are given in TABLE II. A conventional exergoeconomic analysis (Bejan et al., 1996) leads to a cost per unit of exergy of \$20.76/GJ for the thermal energy, while the cost of the electric power amounts to only \$14.55/GJ (see TABLE III).

The fact that the cost of thermal exergy is much higher than the cost of electric exergy contradicts our physical understanding, which suggests that electric power is more valuable than heat and should, therefore, be more expensive.

An examination of the cost formation process within the plant demonstrates how the relatively high cost of thermal exergy and the low cost of electric exergy are obtained. The exergy of the air flow is increased by the air compressor, the air preheater (cold side) and the combustion chamber. As the product exergy of the named plant components is added to the exergy of the air/exhaust gas flow, the costs of the exergetic products of the three components are added to the cost of the flow:

$$\dot{C}_4 = \dot{C}_1 + \dot{C}_{P,AC} + \dot{C}_{P,APH} + \dot{C}_{P,CC} \tag{8}$$

With

$$\dot{C}_1 = 0 \tag{9}$$

the cost per exergy unit at the inlet of the gas turbine results to

$$c_4 = \frac{c_{P,AC} \cdot \dot{E}_{P,AC} + c_{P,APH} \cdot \dot{E}_{P,APH} + c_{P,CC} \cdot \dot{E}_{P,CC}}{\dot{E}_4} \tag{10}$$

In the gas turbine, the air preheater (hot side) and the heat recovery steam generator, exergy is removed from the exhaust gas flow. The exergy removal takes place at the average specific cost at which exergy units were previously supplied to the flow by upstream components, i.e. c_4.

$$c_{F,GT} = c_{F,APH} = c_{F,HRSG} = c_4 \tag{11}$$

This model of the cost formation process implies that the exergetic fuel of the gas turbine, air preheater (cold side) and the heat recovery steam generator is composed identically from the exergetic products of the air compressor, air preheater and combustion chamber.

The exergetic product of the air compressor, being relatively expensive due to the high investment costs of this system component and the expensive mechanical power used to drive this component, is partly consumed in the heat recovery steam generator with its relatively low exergetic efficiency. With the cost of exergy destruction defined as:

$$\dot{C}_{D,K} = c_{F,k} \cdot \dot{E}_{D,k} \tag{12}$$

this results in a high cost of exergy destruction, and therefore, also in a high cost of the product exergy, the thermal energy supplied by the HRSG.

However, a careful observation of the cogeneration system reveals that the compression of the inlet air stream is only required for the subsequent expansion in the gas turbine. The steam generation in the HRSG could be realized exclusively with the thermal exergy supplied by the combustion chamber and air preheater. As the compressor serves only the gas turbine, and therefore the generation of electric power, all costs associated with it (i.e., the cost of exergy destruction and the investment cost) should be charged exclusively to the electric power.

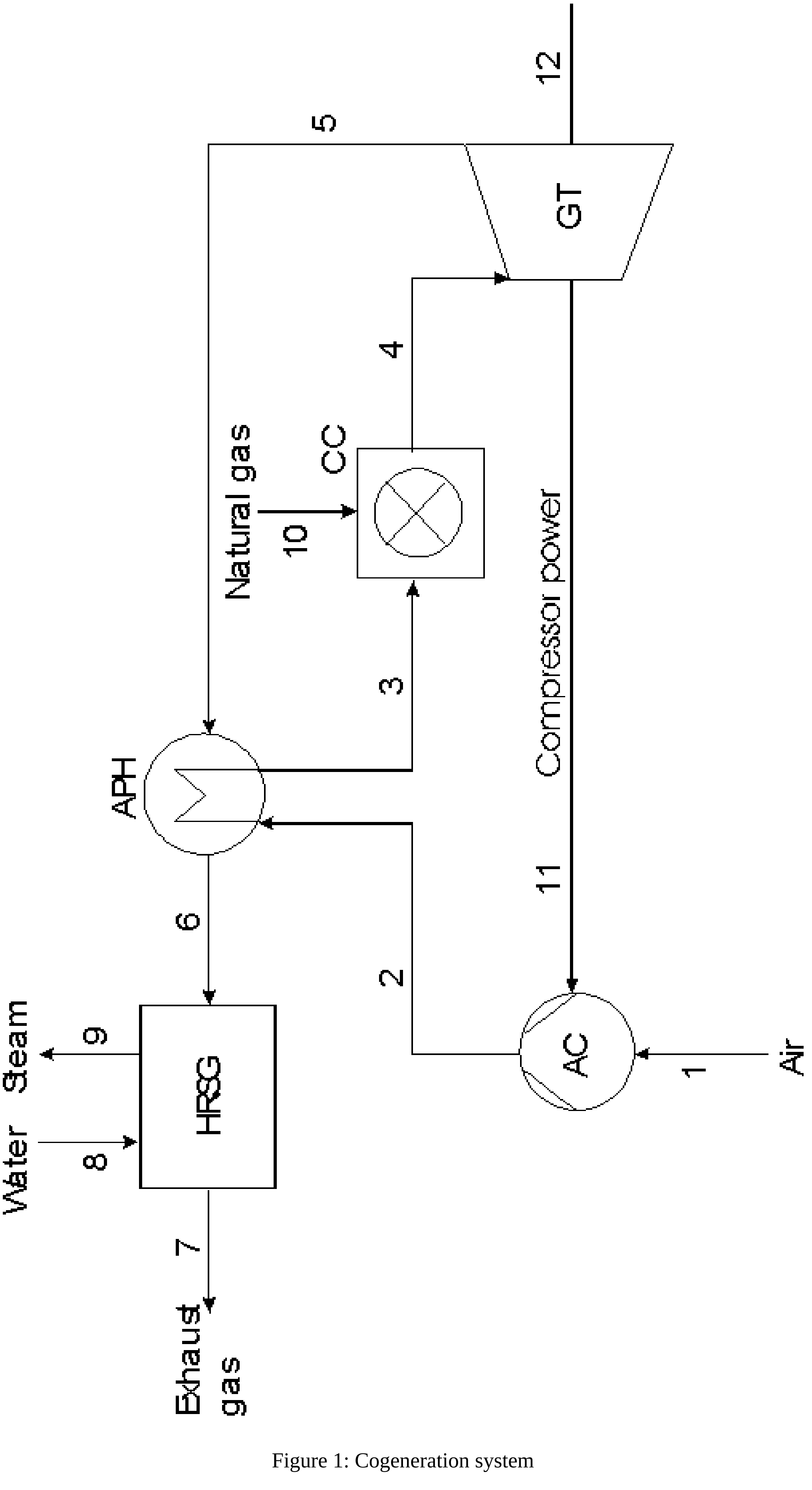

Figure 1: Cogeneration system

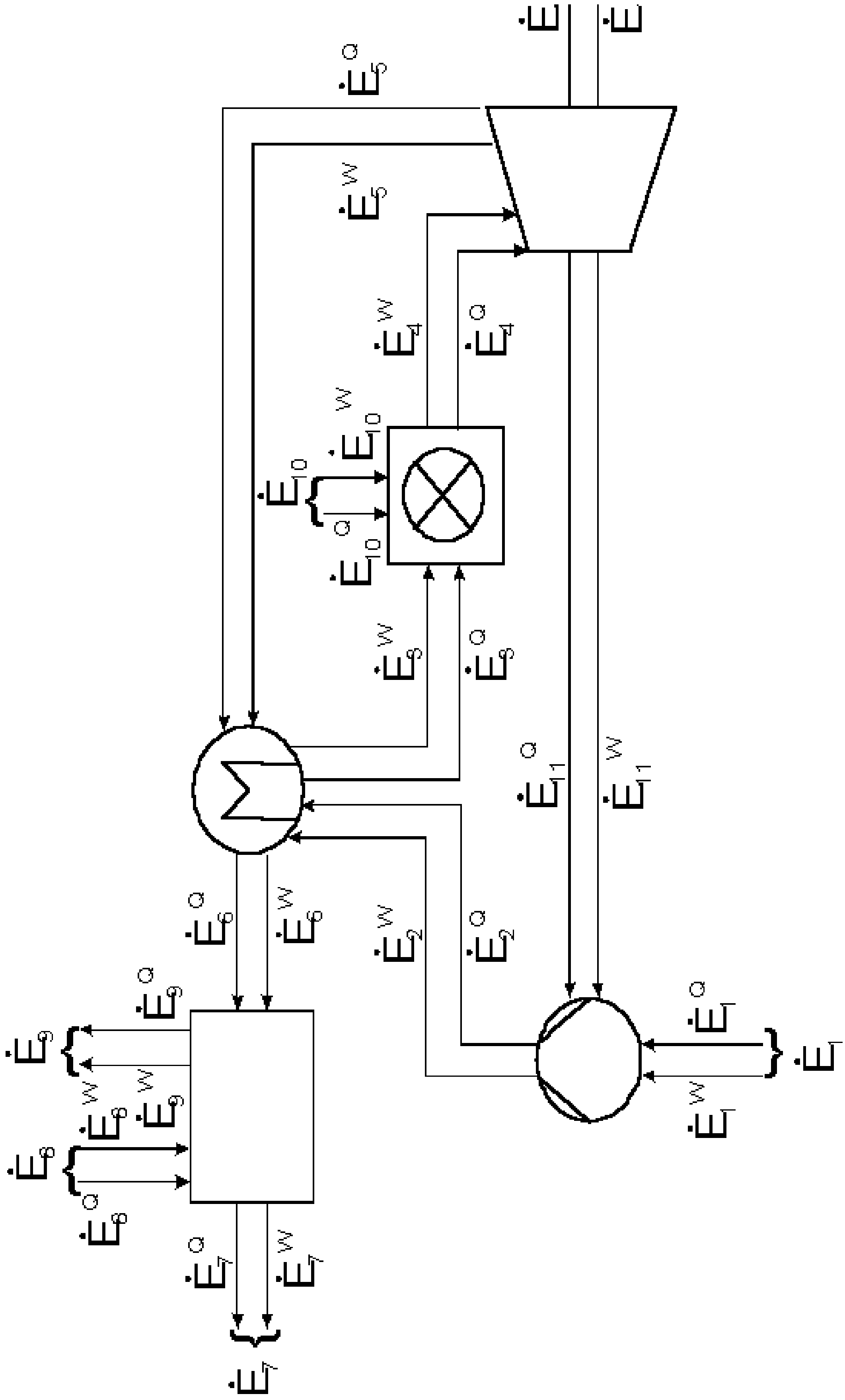

Figure 2: Cogeneration system with split exergy streams

3. A New Approach to Cost Assessment

In the following, a new approach for assessing the costs of each product stream is presented. This approach allows the costs caused by single plant components individually to be assigned to the various final products of the overall system. The new approach is based on a splitting of all exergy flows according to their purpose within the overall production process. In order to keep track of the exergy additions to and removals from the flow streams serving the generation of the individual n final products of the plant, each exergy stream $\dot{E}_i$ is divided into n components $\dot{E}_i^j$, where $\dot{E}_i^j$ is the part of $\dot{E}_i$ which serves the generation of the *jth* final product of the plant.

$$\dot{E}_i = \sum_{j=1}^{n} \dot{E}_i^j \tag{13}$$

The splitting of exergy streams can be expressed by the splitting factors y_i^j:

$$y_i^j = \frac{\dot{E}_i^j}{\dot{E}_i} \qquad \text{with} \qquad \sum_{j=1}^{n} y_i^j = 1 \tag{14}$$

Figure 2 shows the cogeneration plant of *Figure 1* with split exergy streams.

The purpose of the exergy splitting is to assign the exergy destruction of the single plant components, and the cost caused by it, to the individual final products of the overall system. Therefore, in addition to the splitting factors for exergy streams, a splitting factor x_k^j is defined for the kth system component. The splitting factor x_k^j determines to what extent the component k serves the generation of the final product j of the plant. For the exergetic product of the plant component k, the following equation applies:

$$\dot{E}_{P,k}^j = x_k^j \cdot \dot{E}_{P,k} \qquad \text{with} \qquad \sum_{j=1}^{n} x_k^j = 1 \tag{15}$$

In the kth system component, the fuel exergy is transformed into product exergy with the exergetic efficiency ε_k. If a unit of product exergy of a kth component serves the generation of the final product j of the overall system, the fuel exergy consumed by the system component in order to generate this unit of product exergy must also be assigned to the generation of the final product j.

$$\dot{E}_{F,k}^j = \frac{1}{\varepsilon_k^j} \cdot \dot{E}_{P,k}^j \tag{16}$$

For a given plant component the only reasonable assumption is that each exergy unit entering the plant component is transformed into product exergy with the same exergetic efficiency ε_k.

$$\varepsilon_k^j = \varepsilon_k \tag{17}$$

Thus, the exergetic fuel of the kth component is apportioned among the final products in the same way as the product of the system component:

$$\dot{E}_{F,k}^j = x_k^j \cdot \dot{E}_{F,k} \tag{18}$$

In the same way, for the exergy destruction:

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \tag{19}$$

A part serving the generation of the final product j, can be obtained:

$$\dot{E}_{D,k}^j = \dot{E}_{F,k}^j - \dot{E}_{P,k}^j \tag{20}$$

Combination of equations (15)- (20) leads to:

$$\dot{E}_{D,k}^j = y_k^j \cdot \dot{E}_{D,k} \qquad \text{with} \qquad \sum_{j=1}^{n} x_k^j = 1 \tag{21}$$

$\dot{E}_{D,k}^j$ is the part of the exergy destruction of the plant component k which is assigned to the generation of the final product j of the overall system.

4. Application to the Cogeneration Plant

In the following, the new cost assessment approach will be illustrated by applying it to the cogeneration system shown in *Figure 1*.

The cogeneration plant has two final products: electric and thermal energy; therefore each exergy flow has to be divided into two parts:

$$\dot{E}_i = \dot{E}_i^W + \dot{E}_i^Q \tag{22}$$

$$\dot{E}_i = x_i^W \cdot \dot{E}_i + x_i^Q \cdot \dot{E}_i \quad \text{with} \quad x_i^W + x_i^Q = 1 \tag{23}$$

Here y_k^W and y_k^Q are the splitting factors for the ith exergy stream. In the first step, the splitting factors x_k^W and x_k^Q for the k^{th} system component are defined according to the purpose of the component.

The air compressor and gas turbine serve exclusively the generation of the electric power. Therefore:

$$x_{AC}^W = 1 \qquad x_{AC}^Q = 0 \tag{24}$$

$$x_{GT}^W = 1 \qquad x_{GT}^Q = 0 \tag{25}$$

The heat recovery steam generator serves the generation of thermal energy only:

$$x_{HRSG}^W = 0 \qquad x_{HRSG}^Q = 1 \tag{26}$$

The combustion chamber and air preheater are involved in the production process of both heat and power. It is assumed that the air preheater contributes to the generation of each product with the same percentage as the combustion chamber.

$$x^W_{APH} = x^W_{CC} \qquad x^Q_{APH} = x^Q_{CC} \tag{27}$$

In the second step, the splitting factors of the exergy flows leaving the overall system are defined.

The exergy of the final product *j* of the system is, per definition, exclusively assigned to the final product *j*.

We obtain for the electric power:

$$x^W_{12} = 1 \qquad x^Q_{12} = 0 \tag{28}$$

resulting in

$$\dot{E}^W_{12} = \dot{E}_{12} \qquad \dot{E}^Q_{12} = 0 \tag{29}$$

and for the thermal power:

$$x^W_9 = 0 \qquad x^Q_9 = 1 \tag{30}$$

resulting in

$$\dot{E}^W_9 = 0 \qquad \dot{E}^Q_9 = \dot{E}_9 \tag{31}$$

For each stream that leaves the system and does not represent a final product (e.g., exhaust gas or cooling water), the splitting factors must also be determined. In the case of the cogeneration plant, this concerns the exhaust gas leaving the heat recovery steam generator. We assume that the exergy of streams is divided between the final products according to the power/heat ratio of the overall system:

$$x^W_7 = \frac{\dot{E}_{12}}{\dot{E}_{12} + (\dot{E}_9 - \dot{E}_8)} \tag{32}$$

$$x^Q_7 = \frac{\dot{E}_9 - \dot{E}_8}{\dot{E}_{12} + (\dot{E}_9 - \dot{E}_8)} \tag{33}$$

The exergy shares of the exhaust gas stream are:

$$\dot{E}^W_7 = x^W_7 \cdot \dot{E}_7 \tag{34}$$

$$\dot{E}^Q_7 = x^Q_7 \cdot \dot{E}_7 \tag{35}$$

This is equivalent to the assumption required for the distribution of the costs of the exhaust gas stream between the electric and thermal power made in the exergoeconomic analysis without division of the exergy flows.

Once the exergy splitting factors for all streams leaving the system have been defined, the parts of the exergy streams added to and removed from the material streams by each plant component have to be determined. With the aid of the splitting factors of the system components, the fuel and product of each component is divided into two parts $\dot{E}^W_{F,k}$ and $\dot{E}^Q_{F,k}$, as well as $\dot{E}^W_{P,k}$ and $\dot{E}^Q_{P,k}$. Based on the splitting of the fuel and product of the *kth* system component, one equation can be formulated for each stream $\dot{E}^j_i$ entering the plant component, assuming that the exiting streams are known either from downstream plant components or because they are leaving the overall system. This way, all the exergy streams $\dot{E}^j_i$ within the system can be determined.

In the following, the exergy streams $\dot{E}^W_i$ and $\dot{E}^Q_i$ of the cogeneration plant are calculated. At first, the idea on which the new approach is based will be illustrated with the help of the air compressor. From its exergetic efficiency:

$$\varepsilon_{AC} = \frac{\dot{E}_{P,AC}}{\dot{E}_{F,AC}} = \frac{\dot{E}_2 - \dot{E}_1}{\dot{E}_{11}} \tag{36}$$

and equations (15)-(18), we obtain:

$$\dot{E}^W_{F,AC} = \dot{E}^W_{11} = x^W_{AC} \cdot \dot{E}_{11} = \dot{E}_{11} \tag{37}$$

$$\dot{E}^W_{P,AC} = \dot{E}^W_2 - \dot{E}^W_1 = x^W_{AC} \cdot (\dot{E}_2 - \dot{E}_1) = \dot{E}_2 - \dot{E}_1 \tag{38}$$

$$\dot{E}^Q_{F,AC} = \dot{E}^Q_{11} = x^Q_{AC} \cdot \dot{E}_{11} = 0 \tag{39}$$

$$\dot{E}^Q_{P,AC} = \dot{E}^Q_2 - \dot{E}^Q_1 = x^Q_{AC} \cdot (\dot{E}_2 - \dot{E}_1) = 0 \tag{40}$$

The product of the air compressor consists in the increase of the exergy of the air stream passing through the compressor. Thus:

$$\dot{E}_2 = \dot{E}_1 + \dot{E}_{P,AC} \tag{41}$$

This equation applied separately to the exergy parts $\dot{E}^W_2$ and $\dot{E}^Q_2$ leads to:

$$\dot{E}^W_2 = \dot{E}^W_1 + \dot{E}^W_{P,AC} = \dot{E}^W_1 + x^W_{AC} \cdot (\dot{E}_2 - \dot{E}_1) \tag{42}$$

$$\dot{E}^Q_2 = \dot{E}^Q_1 + \dot{E}^Q_{P,AC} = \dot{E}^Q_1 + x^Q_{AC} \cdot (\dot{E}_2 - \dot{E}_1) \tag{43}$$

Applying Equations (42) and (43) in combination with Equation (24), the example of the air compressor illustrates an important aspect of the new approach: If a plant component serves exclusively the production of one final product of the system (e.g., electric work), the exergy parts associated with the other final products (e.g., heat) pass through the component unchanged. Thus, in the production process of the final product *j*, only those components participate that contribute to the generation of the final product *j*. Each system component that contributes to more than one product stream has the same thermodynamic behavior (i.e. the same exergetic efficiency) for each contribution. In *Figure 3* the flow sheets for generating electric and thermal energy are illustrated separately.

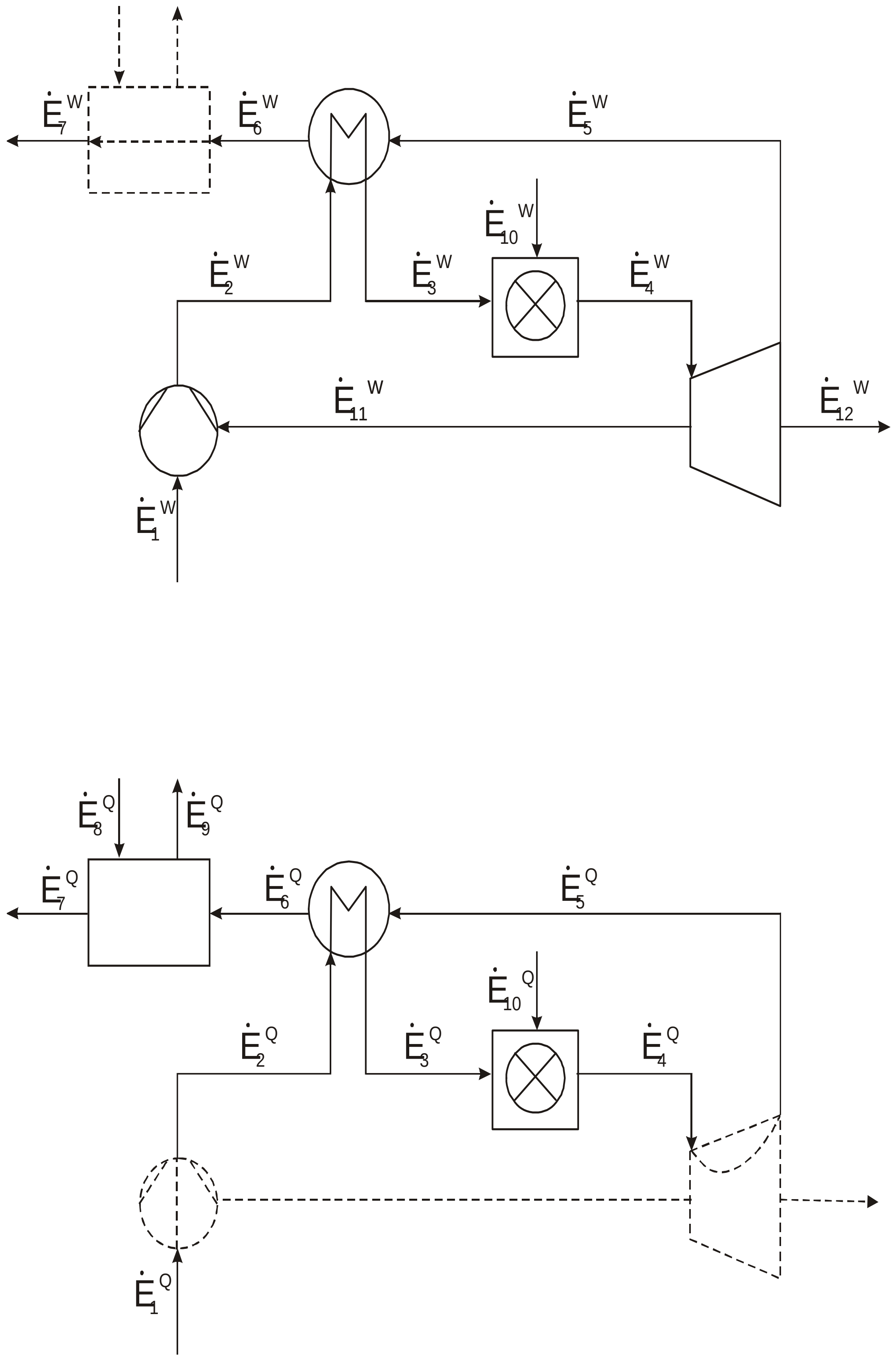

Figure 3: Flow sheets showing the separate generation of electric and thermal energy

The air compressor has four entering flows (exergy parts $\dot{E}^W$ and $\dot{E}^Q$ of the inlet air and the mechanical work), therefore four equations are needed. The exergy part $\dot{E}^W$ of the inlet air flow is calculated with Equation (42).

For the exergy part $\dot{E}^W$ of the mechanical power, we obtain from Equation (37)

$$\dot{E}_{11}^W = x_{AC}^W \cdot \dot{E}_{11} \tag{44}$$

The exergy part $\dot{E}_{11}^Q$ can be determined with Equation (22). In the following, only the equations for the exergy part serving the generation of the electric energy are given.

The next plant component to be considered is the air preheater with the exergetic efficiency:

$$\varepsilon_{APH} = \frac{\dot{E}_3 - \dot{E}_2}{\dot{E}_5 - \dot{E}_6} \tag{45}$$

Its product is added to the air flow.

$$\dot{E}_3^W = \dot{E}_2^W + x_{APH}^W \cdot \dot{E}_{P,APH} \tag{46}$$

The fuel of the air preheater is subtracted from the hot gas stream.

$$\dot{E}_6^W = \dot{E}_5^W - x_{APH}^W \cdot \dot{E}_{F,APH} \tag{47}$$

Equations (46) and (47) provide the means for calculating the exergy parts $\dot{E}^W$ for the two streams entering the air preheater:

$$\dot{E}_2^W = \dot{E}_3^W + x_{APH}^W \cdot (\dot{E}_2 - \dot{E}_3) \tag{48}$$

$$\dot{E}_5^W = \dot{E}_6^W + x_{APH}^W \cdot (\dot{E}_5 - \dot{E}_6) \tag{49}$$

For the combustion chamber with the exergetic efficiency:

$$\varepsilon_{CC} = \frac{\dot{E}_4 - \dot{E}_3}{\dot{E}_{10}} \tag{50}$$

We obtain the following equation related to the inlet air stream:

$$\dot{E}_3^W = \dot{E}_4^W + x_{CC}^W \cdot (\dot{E}_3 - \dot{E}_4) \tag{51}$$

For the fuel, i.e. the natural gas flow we get:

$$\dot{E}_{10}^W = x_{CC}^W \cdot \dot{E}_{10} \tag{52}$$

The exergetic efficiency of the gas turbine:

$$\varepsilon_{GT} = \frac{\dot{E}_{11} + \dot{E}_{12}}{\dot{E}_4 - \dot{E}_5} \tag{53}$$

leads to the equation:

$$\dot{E}_4^W = \dot{E}_5^W + x_{GT}^W \cdot (\dot{E}_4 - \dot{E}_5) \tag{54}$$

The last plant component is the heat recovery steam generator with the exergetic efficiency:

$$\varepsilon_{HRSG} = \frac{\dot{E}_9 - \dot{E}_8}{\dot{E}_6 - \dot{E}_7} \tag{55}$$

and the following relations for the exergy parts serving the generation of the electric energy:

$$\dot{E}_8^W = \dot{E}_9^W + x_{HRSG}^W \cdot (\dot{E}_8 - \dot{E}_9) \tag{56}$$

$$\dot{E}_6^W = \dot{E}_7^W + x_{HRSG}^W \cdot (\dot{E}_6 - \dot{E}_7) \tag{57}$$

with Equation (26) we obtain:

$$\dot{E}_8^W = \dot{E}_9^W \tag{58}$$

$$\dot{E}_6^W = \dot{E}_7^W \tag{59}$$

The system of equations to be solved consists of (a) the definitions of the splitting factors of the plant components (Equations (24) to (27)), (b) the splitting factors of the streams leaving the overall plant (Equations (28), (30), (32)), (c) the equations for the calculation of the exergy parts associated with the production of the electric energy (Equations (29), (31), (34), (42), (44), (48), (49), (51), (52), (54), (56), (57)), and (d) Equation (22) applied to each stream. Note that only four equations are formulated for the splitting factors of the five components. One degree of freedom is needed to ensure that the overall exergy balance of the plant is fulfilled. The exergy streams entering the overall system are calculated based on the splitting factors of the components and the streams leaving the plant. As the exergy of the air stream entering the compressor is zero, the exergy parts $\dot{E}_1^W$ and $\dot{E}_1^Q$ of this stream are also zero:

$$\dot{E}_1^W = 0 \tag{60}$$

$$\dot{E}_1^Q = 0 \tag{61}$$

When Equation (60) is also considered in the equation system, the exergy parts serving the generation of the electric and thermal energy can be calculated. The exergy parts of the flow streams of the cogeneration plant are given in TABLE I.

The equations formulated for the inlet streams of a component can be generalized as follows:

If the exergy stream being considered is "continuous", i.e. it appears in the definition of the exergetic efficiency as an exergy difference $\dot{E}_{in} - \dot{E}_{out}$ (Lazzaretto and Tsatsaronis, 1999), we obtain:

$$\dot{E}_{in}^j = \dot{E}_{out}^j + x_k^j \cdot (\dot{E}_{in} - \dot{E}_{out}) \tag{62}$$

This equation can be applied regardless of whether the exergy stream in consideration belongs to the fuel or product of the component.

If the entering exergy stream is an "interrupted" one, we obtain:

$$\dot{E}_{in}^{j} = x_k^j \cdot \dot{E}_{in} \tag{63}$$

Once the exergy parts are determined, the exergoeconomic cost balances and auxiliary equations presented in previous exergoeconomic approaches (e.g. Bejan et al. 1996, Lazzaretto and Tsatsaronis 1999) can be applied separately for each final product of the system. For this purpose, the non-exergy related costs (i.e. investment, operation and maintenance costs) of the *k*th *system* component are apportioned among the final products of the system using the applicable splitting factors for this component:

$$\dot{Z}_k^j = \sum_{j=1}^{n} x_k^j \cdot \dot{Z}_k \tag{64}$$

or, formulated for the cogeneration plant:

$$\dot{Z}_k^W = x_k^W \cdot \dot{Z}_k \tag{65}$$

and:

$$\dot{Z}_k^Q = x_k^Q \cdot \dot{Z}_k \tag{66}$$

The cost balance of the *k*th component related to the generation of the final product *j* reads:

$$\sum \dot{C}_{k,out}^{j} = \sum \dot{C}_{k,in}^{j} + \dot{Z}_k^j \tag{67}$$

The required auxiliary equations are formulated according to the *f-rule* and *p-rule* *(*Lazzaretto and Tsatsaronis 1999*)*, based on specific costs per unit of exergy related to the individual final products of the plant:

$$c_i^j = \frac{\dot{C}_i^j}{\dot{E}_i^j} \tag{68}$$

As an example, the costing equations obtained for the air preheater are given. For the production of electric energy, the following equations are obtained:

$$\dot{C}_3^W + \dot{C}_6^W = \dot{C}_2^W + \dot{C}_5^W + \dot{Z}_{APH}^W \tag{69}$$

$$c_6^W = c_5^W \tag{70}$$

The costing equations related to the production of thermal energy are identical, with the superscript *W* being replaced by *Q*.

The costs of the exergy flows obtained with the new approach are given in TABLE I, the investment costs and costs of exergy destruction of the components related to the generation of thermal and electric energy are listed in TABLE II. The costs of the final products of the system are shown in TABLE III. The specific costs per unit of exergy calculated with the new approach amount to $17.05/GJ for the electric energy and $14.89/GJ for the thermal energy. These results obtained with the new approach agree with the expected production costs.

If we set the non-exergy-related costs of all system components to zero:

$$\dot{Z}_k = 0 \tag{71}$$

and divide all cost values by the cost per exergy unit for the fuel of the overall system:

$$c_{F,tot} = c_{10} \tag{72}$$

We calculate the exergetic costs (Lozano and Valero, 1993), i.e. the exergy units of fuel required to generate a unit of exergy in the system. The exergetic costs of the flow streams and the exergetic costs per unit of fuel and product exergy for the components of the cogeneration plant obtained with the new approach and without splitting of the exergy flows are shown in TABLES I and IV. The exergetic costs are denoted with the superscript 0. The exergetic costs of the final products are given in TABLE III

TABLE III. COSTS OF THE FINAL PRODUCTS WITHOUT EXERGY SPLITTING AND WITH THE NEW APPROACH

	Without exergy splitting	New Approach
c_{el}	$14.55 /GJ	$17.05 /GJ
c_{th}	$20.76/GJ	$14.89 /GJ
$\dot{C}_{el}$	$1572 /h	$1841 /h
$\dot{C}_{th}$	$950 /h	$683 /h
c_{el}^0	1.780 GJ/GJ	1.847 GJ/GJ
c_{th}^0	2.479 GJ/GJ	2.321 GJ/GJ

5. Conclusions

The systematic application of the new approach may be summarized as follows:

1) The final products of the plant are identified.

2) The splitting factors of the system components are defined depending on the purpose of each component.

3) The splitting factors for the exergy streams leaving the overall system are determined.

4) For each component *k* with *m* entering exergy streams, *m* equations of the form of Equation (62) or Equation (63) are formulated

TABLE I. THERMODYNAMIC AND COST DATA OF THE FLOW STREAMS WITHIN THE COGENERATION PLANT

flow	***Thermodynamic data***				***Costs without exergy splitting***			***New approach: exergy shares and costs***							
	m	T	p	E	C	c	c^0	E^W	$\mathbf{E^Q}$	C^W	$\mathbf{C^Q}$	c^W	c^Q	$c^{0,W}$	$\mathbf{c^{0,Q}}$
No.	*[kg/s]*	*[°C]*	*[bar]*	*[MW]*	*[$/h]*	*[$/GJ]*	*[GJ/GJ]*	*[MW]*	*[MW]*	*[$/h]*	*[$/h]*	*[$/GJ]*	*[$/GJ]*	*[GJ/GJ]*	*[GJ/GJ]*
1	91.276	25.0	1.013	0.000	0.0	0.000	0.000	0.000	0.000	0.0	0.0	0.000	0.000	0.000	0.000
2	91.276	330.6	10.130	27.538	1894.2	19.107	1.805	27.538	0.000	2145.0	0.0	21.637	0.000	1.873	0.000
3	91.276	576.9	9.623	41.938	2692.1	17.831	1.833	36.924	5.014	2754.5	197.2	20.722	10.925	1.895	1.767
4	92.918	1246.9	9.142	101.454	4128.2	11.303	1.596	75.719	25.735	3690.6	697.2	13.539	7.525	1.656	1.494
5	92.918	733.0	1.099	38.782	1578.1	11.303	1.596	13.047	25.735	635.9	697.2	13.539	7.525	1.656	1.494
6	92.918	506.6	1.066	21.752	885.1	11.303	1.596	1.946	19.806	94.9	536.6	13.539	7.525	1.656	1.494
7	92.918	153.8	1.013	2.773	112.8	11.303	1.596	1.946	0.827	94.9	22.4	13.539	7.525	1.656	1.494
8	14.000	25.0	20.000	0.062	0.0	0.000	0.000	0.000	0.062	0.0	0.0	0.000	0.000	0.000	0.000
9	14.000	212.4	20.000	12.810	918.9	19.927	2.364	0.000	12.810	0.0	660.8	0.000	14.330	0.000	2.214
10	1.642	25.0	12.000	84.994	1398.3	4.570	1.000	55.402	29.592	911.5	486.9	4.570	4.570	1.000	1.000
11	-	-	-	29.662	1475.8	13.821	1.676	29.662	0.000	1726.7	0.0	16.170	0.000	1.739	0.000
12	-	-	-	30.000	1492.7	13.821	1.676	30.000	0.000	1746.4	0.0	16.170	0.000	1.739	0.000

TABLE II. EXERGETIC EFFICIENCY AND COST DATA FOR THE COMPONENTS OF THE COGENERATION PLANT

Comp.		***Costs without exergy splitting***				***New approach: splitting factors and costs***								
	ϵ	**Z**	C_D	c_f	c_p	x^W	Z^W	Z^Q	$C_D{}^W$	$C_D{}^Q$	$c_f{}^W$	$c_f{}^Q$	$c_p{}^W$	$c_p{}^Q$
	%	*[$/GJ]*	*[$/GJ]*	*[$/GJ]*	*[$/GJ]*	*[-]*	*[$/h]*	*[$/h]*	*[$/h]*	*[$/h]*	*[$/GJ]*	*[$/GJ]*	*[$/GJ]*	*[$/GJ]*
AC	92.8	418.3	105.7	13.821	19.107	1.000	418.3	0.0	123.6	0.0	16.170	0.000	21.637	0.000
CC	70.0	37.8	419.2	4.570	6.703	0.652	24.6	13.2	273.2	145.9	4.570	4.570	6.703	6.703
APH	84.6	105.0	107.0	11.303	15.393	0.652	68.4	36.6	83.6	24.8	13.539	7.525	18.037	10.925
GT	95.2	418.3	122.5	11.303	13.821	1.000	418.3	0.0	146.7	0.0	13.539	0.000	16.170	0.000
HRSG	67.2	146.7	253.5	11.303	20.024	0.000	0.0	146.7	0.0	168.8	0.000	7.525	0.000	14.399

TABLE IV. EXERGETIC COSTS OF FUELS AND PRODUCTS OF THE COMPONENTS OF THE COGENERATION PLANT

	without e. splitting		***New approach***			
Comp.	$c_F{}^0$	$c_P{}^0$	$c_F{}^{0,W}$	$c_F{}^{0,Q}$	$c_P{}^{0,W}$	$c_P{}^{0,Q}$
	[GJ/GJ]	*[GJ/GJ]*	*[GJ/GJ]*	*[GJ/GJ]*	*[GJ/GJ]*	*[GJ/GJ]*
AC	1.676	1.805	1.739	0.000	1.873	0.000
CC	1.000	1.428	1.000	1.000	1.428	1.428
APH	1.596	1.887	1.656	1.494	1.958	1.767
GT	1.596	1.676	1.656	0.000	1.739	0.000
HRSG	1.596	2.376	0.000	1.494	0.000	2.224

depending on whether the exergy stream being considered is a continuous or an interrupted one.

5) The exergy parts serving the generation of each final product are calculated.

6) The investment costs of the plant components are apportioned among the final products of the system with the aid of the splitting factors of the plant components.

7) The cost balances and auxiliary equations of the components are formulated separately for each exergy form $\dot{E}^j$ and the costs of the exergy flows and the final products of the plant are calculated.

The new exergoeconomic approach leads to results that differ significantly from the results obtained with conventional thermoeconomic or other approaches. Applied to a cogeneration plant, the new approach provides among these approaches the best cost estimates for the costs of the final products generated in the same system. One specific characteristic of the new approach lies in the freedom left to the engineer to define the purpose of each system component through the splitting factors to be used for this component. As the equations for the calculation of the exergy streams follow a fixed scheme and the same cost balances and auxiliary equations are applied as in previous exergoeconomic approaches, the main additional task is the definition of the splitting factors of the plant components. These splitting factors depend on the judgment of the engineer, and are therefore to some extent arbitrary. The influence of the assumed splitting factors on the costs of the final products of the cogeneration plant used as an example was investigated by Erlach (2000). While in a simple energy conversion system like the cogeneration plant considered in this article a physically reasonable and well thought-out definition of the splitting factors is feasible, it might get very complicated in a more complex plant. The practicability of the method, therefore, depends on the complexity of the analyzed system. Further research and applications of the presented approach, particularly applications to more complex systems, are required.

Nomenclature

Symbols

c	cost per unit of exergy [$/GJ]
$\dot{C}$	cost rate [$/h]
$\dot{E}$	exergy rate [MW]
$\dot{m}$	mass flow rate [kg/s]
n	number of product streams for the overall system[-]
p	pressure [bar]
T	temperature [°C]
x	splitting factor for equipment[-]
y	splitting factor for exergy streams [-]
$\dot{Z}$	non-exergy-related cost rate [$/h]

Greek Symbols

ε	exergic efficiency [-]

Subscripts

D	exergy destruction
F	exergy of fuel
i	stream
k	plant component
L	exergy loss
P	exergy of product

Superscripts

j	serving the generation of the *jth* product stream of the plant
W	serving the generation of electric energy
Q	serving the generation of thermal energy
0	only fuel costs are considered

References

Bejan, A., Tsatsaronis, G., Moran, M. 1996, *Thermal Design and Optimization*, J. Wiley, New York.

Erlach, B., 2000, *Zuweisung zu den Kosten energieintensiver Prozesse*, Diploma Thesis, Technical University of Berlin, Institute for Energy Engineering.

Frangopoulos, C., 1983, "Thermoeconomic Functional Analysis: A Method for the Optimal Design or Improvement of Complex Thermal Systems", PhD Thesis, Georgia Institute of Technology.

Lazzaretto, A., Macor, A., Reini, M., 1993, "EXSO: Exergoeconomic Symbolic Optimization for Energy Systems", Part I and II, *Proceedings of Energy Systems and Ecology*, pp. 323-337, Krakow.

Lazzaretto, A., Tsatsaronis, G., 1997, "On the Quest for Objective Equations in Exergy Costing", *Proceedings of the ASME Advanced Energy Systems Division*, AES-Vol. 37, pp. 413-428.

Lazzaretto, A., Tsatsaronis, G., 1999, "On the Calculation of Efficiencies and Costs in Thermal Systems", *Proceedings of the ASME Advanced Energy Systems Division*, AES-Vol. 39, S. 421-430, (ed.: Aceves, S. M., Garimella, S., Peterson, R.).

Lozano, M. A., Valero, A., 1993, "Theory of the Exergetic Cost", *Energy – The International Journal*, Vol. 18, No. 3, pp. 939-960.

Penner, S. S., Tsatsaronis, G. (eds.), 1994, "Invited Papers on Exergoeconomics", *Energy –*

The International Journal, Vol. 19, No. 3, pp. 279-381.

Torres, C., Valero, A., Serra, L., Lozano, M. A., 1996, “The Productive Structure and Thermoeconomic Theories of System Optimization”, AES-Vol. 36, *Proceedings of the ASME Advanced Energy Systems Division*.

Tsatsaronis, G., Lin, L., 1990, *On Exergy Costing in Exergoeconomics,* Computer-Aided Energy Systems Analysis, American Society of Mechanical Engineers, AES-Vol. 21, pp. 1-11, (ed.: Tsatsaronis, G., Bajura, R.A., Kenney, W.F., Reistad, G.M.), New York.

Tsatsaronis, G., Winhold, M., 1985, “Exergoeconomic Analysis and Evaluation of Energy-Conversion Plants – Part I and II”, *Energy – The International Journal*, Vol. 10, No. 1, pp. 69-80.

Valero, A., Lozano, M. A., Munoz, M., 1986, “A General Theory of Exergy Saving – Part I and II”, *Computer-Aided Engineering of Energy Systems*, AES-Vol. 2-3, pp. 1-21.

Valero, A., Correas, L., Serra, L., 1999, “On-line Thermoeconomic Diagnosis of Thermal Power Plants, Thermodynamic Optimization of Complex Energy Systems”, (ed.: Mamut, E., Bejan, A.), “*NATO Science Series 3, High Technology*”, Vol. 69, Kluwer Academic Publishers, Dordrecht, Netherlands.

Von Spakovsky, M. R., 1986, “A Practical Generalized Analysis Approach to the Optimal Thermoeconomic Design and Improvement of Real-World Thermal Systems”, PhD Thesis, Georgia Institute of Technology