

# Chapter 18

## Understanding the Formation of Costs and Environmental Impacts Using Exergy-Based Methods

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### List of Abbreviations

- b Environmental impact per unit of exergy (Points/J)
- B Environmental impact associated with an exergy stream (Points)
- c Cost per unit of exergy (€/J)
- C Cost associated with an exergy stream (€)
- e Specific exergy [J/kg]
- E Exergy (J)
- f Exergoeconomic factor (-)
- m Mass (kg)
- p Pressure (Pa)
- r Relative cost difference (%)
- T Temperature (K)
- y Exergy destruction ratio (-)
- Y Construction-of-component-related environmental impact (Points)
- Z Cost associated with investment expenditures (€)

### Greek Symbols

- $\varepsilon$  Exergetic efficiency (%)
- $\eta$  Isentropic efficiency (%)

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### Subscripts

b	Refers to environmental impact
D	Refers to exergy destruction
F	Fuel
$k$	$k$ th component
P	Product
tot	Refers to the total system
Y	Refers to construction-of-component-related environmental impact
Z	Refers to investment costs

### Superscripts

•	Time rate
AV	Avoidable
CI	Capital investment
EN	Endogenous
EX	Exogenous
UN	Unavoidable

## 18.1 Introduction

The evaluation and improvement of an energy conversion system from the perspectives of thermodynamics, economics, and environmental impact require a deep understanding of:

- the real thermodynamic inefficiencies and the processes that cause them
- the costs associated with equipment and thermodynamic inefficiencies as well as the connection between those two important factors
- the environmental impact associated with equipment and thermodynamic inefficiencies
- the interconnections among efficiency, investment cost, and component-related environmental impact associated with the selection of specific system components, and
- probable measures that would reduce the inefficiencies, the cost, and the environmental impact of the system being studied.

To reduce the thermodynamic inefficiencies, costs, and environmental impacts in a system, we must first understand their process of formation. Energy-based methods are unsuitable to help because the only thermodynamic inefficiency identified by energy-based methods is the transfer of energy to the environment. However, the inefficiencies caused by the irreversibility within the system being considered are, in general, by far the most important thermodynamic inefficiencies, and are identifiable with the aid of an exergetic analysis. Exergy-based methods reveal the location, the magnitude and the sources of inefficiencies, costs, and environmental impacts, and allow us to study the interconnections between them.

Many single analyses conducted independently, such as energetic, exergetic, and economic analyses as well as life cycle assessments (LCA), are reported in the literature (see, for example, Manish et al. 2006; Rosen 2009; Suresh et al. 2010; Ehyaei et al. 2011). The results from such analyses are useful, but by far not as useful as the results from exergoeconomic or exergoenvironmental analyses, in which an exergetic analysis is combined with an economic one, or with an LCA, respectively. These analyses calculate work and heat transfers, exergetic efficiencies and exergy destructions, investment costs, and costs of the final product, as well as emissions of pollutants. However, such analyses cannot calculate the cost or the environmental impact associated: (a) with the exergy destruction and losses in an energy conversion system; or (b) with different product streams generated simultaneously by the same system (cogenerated streams). Unfortunately, the terms *exergoeconomics* and *exergoenvironmental analyses* are employed in the literature also for cases where only separate analyses are reported, and where the principles of *exergy costing* (Tsatsaronis 1993) or *exergoenvironmental costing* (Meyer et al. 2009) are not considered.

*Exergy-based methods* applied to design improvement (optimization) represent a unique combination of: (a) *exergy analysis* and *cost analysis*, and (b) *exergy analysis* and *environmental analysis* (ecological or LCA), to provide the designer of an energy conversion system with information not available through conventional energy, exergy, cost and environmental analyses, but crucial to the design of a cost- and environmentally effective system.

*Exergy-based methods* reveal the location, the magnitude and sources of inefficiencies, costs, and environmental impact, and allow us to study the interconnections between them. These methods are based on the notion that exergy is the only rational basis for assigning monetary and environmental-impact values to the transport of energy and to thermodynamic inefficiencies within the components. Mass, energy, or entropy should not be used for assigning monetary or environmental impact values as their exclusive use always results in misleading conclusions (Bejan et al. 1996; Tsatsaronis 1999b).

Exergoeconomic analysis (term initially proposed by Tsatsaronis 1984) is an appropriate combination of an exergetic and economic analysis based on the exergy-costing principle. The exergoeconomic evaluation is based on exergoeconomic variables, and is already a powerful tool for analyzing, evaluating, and improving energy conversion systems. This analysis has been successfully applied to many energy conversion systems. The special issue of *Energy*, Tsatsaronis (1994), for example, presents different approaches of its application.

Many approaches deal with the combination of an exergetic and an ecological (environmental) analysis—cumulative exergy consumption (Szargut 1978), exer-goecological analysis (Valero 1998), extended exergy accounting (Sciubba 1999), environmental analysis (Frangopoulos and Caralis 1997), and exergoenvironmental analysis (Meyer et al. 2009). These methods have been applied to energy conversion systems, and some can be applied to a country too, i.e., cumulative exergy consumption (Szargut and Stanek 2008) and extended exergy accounting (Belli and Sciubba 2007).

In the environomic analysis (Frangopoulos and Caralis 1997), the monetary cost associated with the environmental impacts ( $\text{NO}_x$  and CO) is used, i.e., economic and environmental analyses operate with the same variables (unit of money per unit of time or per unit of exergy). A similar analysis was also applied by Lazzaretto and Toffolo (2004) and Dincer and Rosen (2011).

The most interesting results for improving energy conversion systems from the perspective of thermodynamics, economics, and environmental impact were obtained when advanced exergy-based methods were applied (Tsatsaronis and Morosuk 2008a, b, 2009; Tsatsaronis and Morosuk 2009; Morosuk and Tsatsaronis 2012). These include: (a) an advanced exergetic analysis, (b) an advanced exergoeconomic analysis that consists of an advanced exergetic analysis, an economic analysis, and an advanced exergoeconomic evaluation, and (c) an advanced exergoenvironmental analysis that consists of an advanced exergetic analysis, an LCA of the environmental impacts and an advanced exergoenvironmental evaluation. All these analyses have a similar methodological background.

Unfortunately, some publications use the term exergoenvironmental analysis to merely indicate the environmental impact of  $\text{CO}_2$ ,  $\text{NO}_x$ , and other pollutants ignoring the exergy destruction-related environmental impact. Sometimes, also environomic analyses are reported under exergoenvironmental analysis. Only the use of precisely defined terms (Tsatsaronis 2007) eliminates confusion to the readers.

The application of a conventional and an advanced exergy-based analysis and the associated benefits are demonstrated here using the well-known CGAM problem (Valero et al. 1994) as an academic example.

## 18.2 Exergy-Based Methods

*Exergy-based methods* is a general term that includes conventional and advanced exergetic, exergoeconomic, and exergoenvironmental analyses and evaluations. The exergy concept complements and enhances the energetic analysis of a system by calculating: (a) the true thermodynamic value of the energy carriers in the system, (b) the real thermodynamic inefficiencies in the system, and (c) variables that unambiguously characterize the performance of the system (or one of its components) from the thermodynamic perspective.

### 18.2.1 Exergetic Analysis

All real processes are irreversible. The irreversibility is caused, for example, by chemical reaction, heat transfer through a finite temperature difference, mixing of matter at different compositions or states, unrestrained expansion, and friction. Exergy analysis identifies the system components with the highest contribution to the overall thermodynamic inefficiencies, and the processes that cause them. The real

thermodynamic inefficiencies in an energy conversion system are related to exergy destruction and exergy loss.

In the version of exergetic analysis we use, the exergy balance for the  $k$ th component is written using the concepts of *exergy of fuel* ( $\dot{E}_{F,k}$ ) and *exergy of product* ( $\dot{E}_{P,k}$ ) (for example, Tsatsaronis 1984; Bejan et al. 1996; Tsatsaronis 1999b; Lazaretto and Tsatsaronis 2006; Tsatsaronis 2007; Tsatsaronis 2008)

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k}. \quad (18.1)$$

The value of the total exergy destruction within the  $k$ th component ( $\dot{E}_{D,k}$ ) can be determined through an exergy balance (Eq. 18.1), or through the entropy generation within this component:

$$\dot{E}_{D,k} = \dot{m}_k \cdot T_0 \cdot s_{\text{gen},k}. \quad (18.2)$$

In thermodynamics, the exergy destruction represents a major inefficiency and a quantity to be minimized when the overall system efficiency must be maximized. In the design of a new energy conversion system, however, the exergy destruction within a component represents not only a thermodynamic inefficiency but, in general, also an opportunity to reduce the investment cost, and sometimes, also the environmental impact associated with the component being considered, and, thus, with the overall system.

The exergetic efficiency for the  $k$ th component is:

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}; \quad (18.3)$$

and the exergy destruction ratio is given by:

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,\text{tot}}}. \quad (18.4)$$

### 18.2.2 Exergoeconomic Analysis

Exergoeconomics, is based on the *exergy costing principle*, which states that exergy is the only rational basis for assigning monetary values to energy streams and to the thermodynamic inefficiencies within the system.

An exergoeconomic analysis must be conducted at the component level of a system, and identifies: (a) the importance of each component from the viewpoint of cost, and (b) options for improving the overall cost effectiveness.

According to the exergy costing principle, the cost stream ( $\dot{C}_j$ ) associated with an exergy stream ( $\dot{E}_j$ ) is given by:

$$\dot{C}_j = c_j \dot{E}_j \quad (18.5)$$

where,  $C_j$  represents the average cost per unit of exergy at which the exergy  $\dot{E}_j$  was provided to the stream under consideration. Equation 18.5 is applied to the exergy associated with streams of matter entering or exiting a system as well as to the exergy transfers associated with the transfer of work and heat. For the cost ( $\dot{C}_k$ ) associated with the exergy ( $\dot{E}_k$ ) contained within the  $k$ th component of a system, we write:

$$\dot{C}_k = c_k E_k \quad (18.6)$$

Here,  $c_k$  is the average cost per unit of stored exergy within the  $k$ th component.

The exergoeconomic model of an energy conversion system (Bejan et al. 1996; Tsatsaronis 1999a; Lazzaretto and Tsatsaronis 2006) consists of cost balances and auxiliary costing equations. The *cost balances* are written for each system component in the following form:

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \quad (18.7a)$$

or

$$c_{P,k} \dot{E}_{P,k} = c_{F,k} \dot{E}_{F,k} + \dot{Z}_k \quad (18.7b)$$

Here,  $\dot{E}_{P,k}$  and  $\dot{E}_{F,k}$  are the exergy rates associated with product and fuel, respectively,  $C_{P,k}$  and  $C_{F,k}$  are the corresponding cost rates, and  $c_{P,k}$  and  $c_{F,k}$  are the costs per unit of exergy for product and fuel. Finally,  $\dot{Z}_k$  is the sum of cost rates associated with capital investment (*CI*) and operating maintenance (*OM*) expenditures for the  $k$ th component:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM}. \quad (18.8)$$

Note that if the number of streams exiting from the  $k$ th component is higher than 1, auxiliary equations should be written based on the so-called P- and F-rules (Lazzaretto and Tsatsaronis 2006).

The cost rate associated with exergy destruction within the  $k$ th component is:

$$\dot{C}_{D,k} = c_{F,k} \cdot \dot{E}_{D,k}. \quad (18.9)$$

The cost of exergy destruction is, in general, different for each component and depends on the relative position of the component within the energy conversion system.

An exergoeconomic evaluation is based, in addition, to the exergetic variables on the variables  $c_{F,k}$ ,  $c_{P,k}$ ,  $\dot{C}_{D,k}$ ,  $\dot{Z}_k$ , the sum ( $\dot{C}_{D,k} + \dot{Z}_k$ ) as well as  $r_k$  (relative cost difference) and  $f_k$  (exergoeconomic factor), defined by

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{1 - \varepsilon_k}{\varepsilon_k} + \frac{\dot{Z}_k}{c_{F,k} \dot{E}_{P,k}}; \quad (18.10)$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}. \quad (18.11)$$

### 18.2.3 Exergoenvironmental Analysis

An exergoenvironmental analysis is also conducted at the component level of a system and identifies: (a) the relative importance of each component with respect to environmental impact, and (b) options for reducing the environmental impact associated with the overall system. In an exergoenvironmental analysis, a one-dimensional characterization indicator is obtained using LCA. This indicator is used in a similar way as the cost is used in exergoeconomics. An index (a single number) describes the overall environmental impact associated with system components and exergy carriers. The Eco-indicator 99 (Goedkoop and Spriensma 2000) is an example of such an index and is used in this chapter. It should be emphasized that the evaluation of environmental impacts will always be subjective and associated with uncertainties. However, the information extracted from the exergoenvironmental analysis is very useful. Future work should also focus on reducing the arbitrariness associated with LCA and the index used in the analysis.

The exergoenvironmental model of an energy conversion system consists of balances and auxiliary equations associated with environmental impact.

The *environmental impact balances* are written for the  $k$ th system component in the following form (Tsatsaronis 2008; Meyer et al. 2009):

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k \quad (18.12a)$$

or

$$b_{P,k} \dot{E}_{P,k} = b_{F,k} \dot{E}_{F,k} + \dot{Y}_k. \quad (18.12b)$$

Here,  $\dot{B}_{P,k}$  and  $\dot{B}_{F,k}$  are the environmental impact rates associated with product and fuel, respectively, and  $b_{P,k}$  and  $b_{F,k}$  are the corresponding environmental impacts per unit of exergy for product and fuel.

The component-related environmental impact,  $\dot{Y}_k$ , which considers the entire life cycle of the  $k$ th component, consists of the following contributions:

$$\dot{Y}_k = \dot{Y}_k^{\text{CO}} + \dot{Y}_k^{\text{OM}} + \dot{Y}_k^{\text{DI}}. \quad (18.13)$$

Here,  $\dot{Y}_k^{\text{CO}}$  is the environmental impact of construction, including manufacturing, transport and installation,  $\dot{Y}_k^{\text{OM}}$  of operation and maintenance, including production

of pollutants during operation, and  $\dot{Y}_k^{\text{DI}}$  of environmental impact associated with final disposal.

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

$$\dot{B}_{\text{D},k} = b_{\text{F},k} \cdot \dot{E}_{\text{D},k}. \quad (18.14)$$

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

An exergoenvironmental evaluation (in analogy with the exergoeconomic evaluation) is based, in addition to the exergetic variables, on the variables  $b_{\text{F},k}$ ,  $b_{\text{P},k}$ ,  $\dot{B}_{\text{D},k}$ ,  $\dot{Y}_k$  as well as on  $r_{b,k}$  (relative environmental impact difference), and  $f_{b,k}$  (exergoenvironmental factor),

$$r_{b,k} = \frac{b_{\text{P},k} - b_{\text{F},k}}{b_{\text{F},k}}; \quad (18.15)$$

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{\text{D},k}}. \quad (18.16)$$

### 18.3 Advanced Exergy-Based Methods

The benefits and shortcomings of the conventional exergetic, exergoeconomic, and exergoenvironmental analyses have been discussed elsewhere (e.g., Bejan et al. 1996; Tsatsaronis 1999a, 2008; Tsatsaronis and Morosuk 2008a, b). The significant shortcomings of these analyses are the limitations in properly evaluating: (a) the mutual interdependencies among the system components, and (b) the real potential for improving the energy conversion system. Advanced exergy-based analyses enable these evaluations.

The interactions among different components of the same system can be estimated and the quality of the conclusions obtained from an exergoeconomic and exergoenvironmental evaluation can be improved, when the

- exergy destruction in each (important) system component, investment cost associated with such component
- component-related environmental impacts associated with such component, as well as the cost of exergy destruction within each (important) system component, and
- environmental impact of exergy destruction within such component are split into endogenous/exogenous and avoidable/unavoidable (for example, Tsatsaronis 2008; Tsatsaronis and Morosuk 2008a, b; Tsatsaronis 2011).

We call the analyses based on such splitting *advanced (exergetic, exergoeconomic, or exergoenvironmental) analyses*.

*Endogenous* (exergy destruction, capital investment cost, and construction-of-component-related environmental impact) is the part of a variable within a



component obtained when all other components operate ideally and the component being considered operates with the same efficiency as in the real system. The *exogenous* part of the variable is the difference between the value of the variable within the component in the real system and the endogenous part:

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{\text{EN}} + \dot{E}_{D,k}^{\text{EX}} \quad (18.17)$$

$$\dot{Z}_k = \dot{Z}_k^{\text{EN}} + \dot{Z}_k^{\text{EX}} \quad (18.18)$$

$$\dot{Y}_k = \dot{Y}_k^{\text{EN}} + \dot{Y}_k^{\text{EX}}. \quad (18.19)$$

The *unavoidable* ( $\dot{E}_{D,k}^{\text{UN}}$ ) exergy destruction cannot be further reduced due to technological limitations such as availability and cost of materials and manufacturing methods. The difference between total and unavoidable exergy destruction for a component is the *avoidable* exergy destruction ( $\dot{E}_{D,k}^{\text{AV}}$ ) that should be considered during the improvement procedure:

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{\text{UN}} + \dot{E}_{D,k}^{\text{AV}}. \quad (18.20)$$

The unavoidable investment cost ( $\dot{Z}_{D,k}^{\text{UN}}$ ) and the construction-of-component-related environmental impact ( $\dot{Y}_{D,k}^{\text{UN}}$ ) for a component can be calculated by assessing the (minimum) values that will always be exceeded as long as such a component is used. The avoidable investment cost and avoidable construction-of-component-related environmental impact is the difference between the total value and unavoidable part of these variables, i.e.,

$$\dot{Z}_k = \dot{Z}_k^{\text{UN}} + \dot{Z}_k^{\text{AV}} \quad (18.21)$$

$$\dot{Y}_k = \dot{Y}_k^{\text{UN}} + \dot{Y}_k^{\text{AV}}. \quad (18.22)$$

Combining the two splitting approaches gives us an opportunity to calculate:

- the *avoidable endogenous* part of a variable used in an advanced exergy-based analysis ( $\dot{E}_{D,k}^{\text{AV,EN}}$ ,  $\dot{Z}_k^{\text{AV,EN}}$ , or  $\dot{Y}_k^{\text{AV,EN}}$ ), which can be reduced by improving the  $k$ th component from the exergetic, economic, and environmental points of view, respectively, and
- the *avoidable exogenous* part of the same variable ( $\dot{E}_{D,k}^{\text{AV,EX}}$ ,  $\dot{Z}_k^{\text{AV,EX}}$ , or  $\dot{Y}_k^{\text{AV,EX}}$ ) that can be reduced by a structural improvement of the overall system, or by improving the efficiency of the remaining components, and always of course by improving the efficiency in the  $k$ th component.

The following variables should be used in an advanced evaluation:

- Avoidable endogenous ( $\dot{E}_{D,k}^{AV,EN}$ ) and avoidable exogenous ( $\dot{E}_{D,k}^{AV,EX}$ ) exergy destruction,
- Cost and environmental impact of the avoidable endogenous exergy destruction

$$C_{D,k}^{AV,EN} = c_{F,k} \cdot \dot{E}_{D,k}^{AV,EN}; \tag{18.23}$$

and

$$\dot{B}_{D,k}^{AV,EN} = b_{F,k} \cdot \dot{E}_{D,k}^{AV,EN}. \tag{18.24}$$

- Avoidable endogenous ( $\dot{Z}_k^{AV,EN}$ ) investment cost, and
- Avoidable endogenous ( $\dot{Y}_k^{AV,EN}$ ) construction-of-component-related environmental impact.

Finally, the role of a component from the perspective of cost and environmental impact is given by the variables ( $\dot{C}_{D,k}^{AV,EN} + \dot{Z}_k^{AV,EN}$ ) and ( $\dot{B}_{D,k}^{AV,EN} + \dot{Y}_k^{AV,EN}$ ). With the aid of these variables, we can also establish priorities for improving the components.

### 18.4 Application: CGAM Problem

The approaches discussed above are applied to a gas-turbine-based cogeneration system, the so-called CGAM problem (Fig. 18.1), which was used as an academic example (Valero et al. 1994; Bejan et al. 1996; Tsatsaronis 1999b; Tsatsaronis and

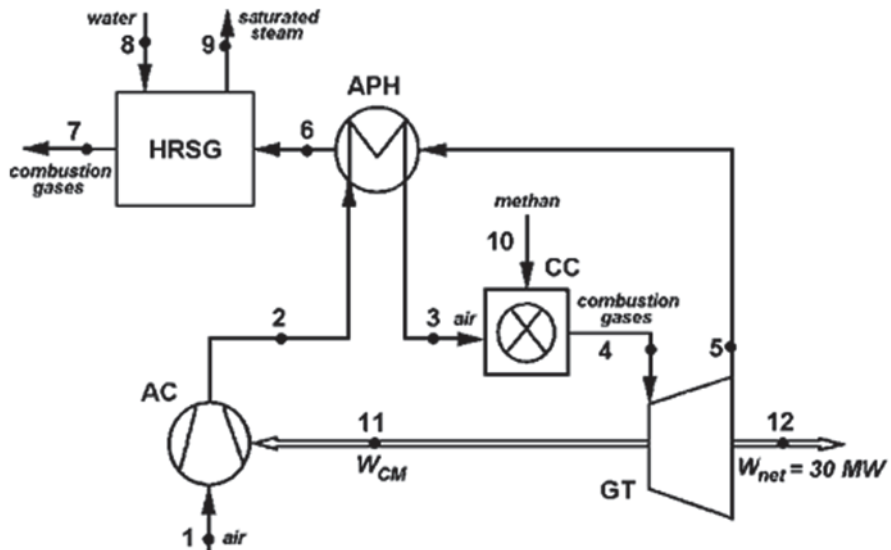


Fig. 18.1 A gas-turbine-based cogeneration system

Morosuk 2008a, b). All results reported here were obtained using the same assumptions for the exergetic, economic, and conventional exergoeconomic analyses as in Bejan et al. (1996).

In this chapter, the capital investment costs of the components are recalculated for the year 2011 (using cost indices), and the cost of the natural gas is assumed to be \$ 8/GJ of exergy of the fuel. This results in a leveled value of fuel of \$ 9.44/GJ of fuel exergy.

The gas turbine-based cogeneration system (Fig. 18.1) consists of an air compressor (AC), an air preheater (APH), a combustion chamber (CC), a gas turbine (GT), and an HRSG (heat-recovery steam generator). There are two products of the overall system: mechanical power (net power output  $\dot{W}_{\text{net}} = 30\text{MW}$ ) and 14 kg/s of saturated water vapor produced at  $p=20$  bar.

Table 18.1 shows the material, mass flow rate, temperature, pressure, and specific exergy of all streams of matter shown in Fig. 18.1.

The exergy destruction within each component of the cogeneration system is calculated from  $\dot{E}_{D,AC} = \dot{W}_{AC} - (\dot{E}_2 - \dot{E}_1)$ ,  $\dot{E}_{D,APH} = (\dot{E}_5 - \dot{E}_6) - (\dot{E}_3 - \dot{E}_2)$ ,  $\dot{E}_{D,CC} = \dot{E}_{10} - (\dot{E}_4 - \dot{E}_3)$ ,  $\dot{E}_{D,GT} = (\dot{E}_4 - \dot{E}_5) - \dot{W}_{GT}$ , and  $\dot{E}_{D,HRSG} = (\dot{E}_6 - \dot{E}_7) - (\dot{E}_9 - \dot{E}_8)$ .

Table 18.2 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 and for the overall cogeneration system.

The exergoeconomic model for the cogeneration system is discussed in detail by Valero et al. (1994) and Bejan et al. (1996); here, only the cost balances and the auxiliary equations are given

- Air compressor:

$$c_w \dot{W}_{AC} + \dot{Z}_{AC} = c_2 \dot{E}_2 - c_1 \dot{E}_1. \quad (18.25)$$

$$c_1 = 0$$

- Air preheater:

$$(c_5 \dot{E}_5 - c_6 \dot{E}_6) + \dot{Z}_{APH} = c_3 \dot{E}_3 - c_2 \dot{E}_2. \quad (18.26)$$

$$c_5 = c_6 \text{ (F rule)}$$

- Combustion chamber:

$$c_{10} \dot{E}_{10} + \dot{Z}_{CC} = c_4 \dot{E}_4 - c_3 \dot{E}_3. \quad (18.27)$$

$$c_{10} = 9.44\$/GJ$$

**Table 18.1** Thermodynamic, economic, and environmental data for the streams of the cogeneration system (shown in Fig. 18.1)

Stream	Material of stream	Thermodynamic analysis			
		$\dot{m}$	$T$	$p$	$e$
		kg/s	K	bar	MJ/kg
1	Air	91.28	298.1	1.01	0
2	Air	91.28	603.7	10.13	0.302
3	Air	91.28	850.0	9.62	0.459
4	CG	92.92	1520.0	9.14	1.092
5	CG	92.92	1006.2	1.10	0.417
6	CG	92.92	779.8	1.07	0.234
7	CG	92.92	426.9	1.01	0.030
8	Water	14.00	298.1	20.00	0.040
9	Water	14.00	485.6	20.00	0.915
10	CH <sub>4</sub>	1.64	298.1	12.00	51.825
11	Power to AC <sup>a</sup>	–	–	–	
12	Net power <sup>b</sup>	–	–	–	
Exergoeconomic analysis			Exergoenvironmental analysis		
$\dot{C}$	$c$		$\dot{B}$		$b$
\$/h	\$/GJ		mPts/h		mPts/GJ
1	Air	0	0	0	0
2	Air	4666	47.06	0.944E+06	9523
3	Air	6561	43.46	1.462E+06	9682
4	CG	9554	26.16	3.083E+06	8442
5	CG	3652	26.16	1.179E+06	8442
6	CG	2048	26.16	0.661E+06	8442
7	CG	261	26.16	0.084E+06	8442
8	Water	0	0	0	0
9	Water	2195	47.60	0.577E+06	12510
10	CH <sub>4</sub>	2887	9.44	1.622E+06	5300
11	Power to AC <sup>a</sup>	–	31.90	–	8600
12	Net power <sup>b</sup>	–	31.90	–	8600

<sup>a</sup>  $\dot{W}_{AC} = 29.66$  MW, <sup>b</sup>  $\dot{W}_{net} = 30$  MW

- Gas turbine:

$$(c_4 \dot{E}_4 - c_5 \dot{E}_5) + \dot{Z}_{GT} = c_w \dot{W}_{GT}. \tag{18.28}$$

$c_4 = c_5$  (F rule)

- Heat-recovery steam generator:

$$(c_6 \dot{E}_6 - c_7 \dot{E}_7) + \dot{Z}_{HRSG} = c_9 \dot{E}_9 - c_8 \dot{E}_8. \tag{18.29}$$

**Table 18.2** Exergetic analysis of the cogeneration system shown in Fig. 18.1

Component	$\dot{E}_{F,k}^{real}$	$\dot{E}_{P,k}^{real}$	$\dot{E}_{D,k}^{real}$	$\epsilon_k$	$y_k$
	MW	MW	MW	%	%
AC	29.66	27.54	2.12	92.84	2.50
APH	16.93	14.40	2.53	84.55	3.09
CC	85.00	59.52	25.48	80.37	29.98
GT	62.67	59.66	3.01	95.20	3.54
HRSG	18.98	12.75	6.23	67.17	7.33
<i>Overall system</i>	<i>85.00</i>	<i>42.75</i>	<i>39.37</i>	<i>50.30</i>	<i>46.30</i>

**Table 18.3** Exergoeconomic analysis of the cogeneration system shown in Fig. 18.1

Component	$\dot{Z}_k$	$\dot{C}_{D,k}$	$\dot{Z}_k + \dot{C}_{D,k}$	$c_{F,k}$	$c_{P,k}$	$r_k$	$f_k$
	\$/h	\$/h	\$/h	\$/GJ	\$/GJ	–	–
AC	1164	243	1407	31.90	47.06	0.47	83
APH	292	248	540	26.16	36.57	0.40	54
CC	105	865	970	9.44	13.97	0.48	11
GT	1164	283	1447	26.16	31.90	0.22	80
HRSG	408	587	995	26.16	47.83	0.83	41
<i>Overall system</i>	<i>3133</i>	<i>372</i>	<i>3505</i>	<i>9.44</i>	<i>38.35</i>	<i>3.06</i>	<i>11</i>

$c_6 = c_7$  (F rule) and  $c_8 = 0$  (arbitrary assumption)

Tables 18.1 and 18.3 summarize the results of the exergoeconomic analysis. In Table 18.3, the value of  $c_{P,tot}$  is calculated as the average cost of both products (electricity and steam) after the cost of the losses ( $\dot{C}_7$ ) is charged to the cost of the products:

$$c_{P,tot} = \frac{c_w \dot{W}_{net} + (\dot{C}_9 - \dot{C}_8) + \dot{C}_7}{\dot{W}_{net} + (\dot{E}_9 - \dot{E}_8)} \tag{18.30}$$

The exergoenvironmental model for the cogeneration system is similar to the exergoeconomic model:

- Air compressor:

$$b_w \dot{W}_{AC} + \dot{Y}_{AC} = b_2 \dot{E}_2 - b_1 \dot{E}_1 \tag{18.31}$$

$$b_1 = 0,$$

- Air preheater:

$$(b_5 \dot{E}_5 - b_6 \dot{E}_6) + \dot{Y}_{\text{APH}} = b_3 \dot{E}_3 - b_2 \dot{E}_2. \quad (18.32)$$

$$b_5 = b_6 \text{ (F rule)}$$

- Combustion chamber:

$$b_{10} \dot{E}_{10} + \dot{Y}_{\text{CC}} = b_4 \dot{E}_4 - b_3 \dot{E}_3. \quad (18.33)$$

$$b_{10} = 5.3 \text{ pts} / \text{MJ} \text{ (Goedkoop and Spriensma 2000)}$$

- Gas turbine:

$$(b_4 \dot{E}_4 - b_5 \dot{E}_5) + \dot{Y}_{\text{GT}} = b_w \dot{W}_{\text{GT}}. \quad (18.34)$$

$$b_4 = b_5 \text{ (F rule)}$$

- Heat-recovery steam generator:

$$(b_6 \dot{E}_6 - b_7 \dot{E}_7) + \dot{Y}_{\text{HRSG}} = b_9 \dot{E}_9 - b_8 \dot{E}_8. \quad (18.35)$$

$$b_6 = b_7 \text{ (F rule) and } b_8 = 0 \text{ (arbitrary assumption).}$$

Using LCA, the values of the construction-of-component-related environmental impacts were calculated. Here, the Eco-indicator 99 (Goedkoop and Spriensma 2000) is used. Tables 18.1 and 18.4 summarize the results obtained from the conventional exergoenvironmental analysis. In Table 18.4, in analogy with the exergoeconomic analysis, the value of  $b_{\text{p,tot}}$  is calculated as the average environmental impact of both products (electricity and steam) after the environmental impact of the losses ( $\dot{B}_7$ ) has been charged to the environmental impact of the products

$$b_{\text{p,tot}} = \frac{b_w \dot{W}_{\text{net}} + (\dot{B}_9 - \dot{B}_8) + \dot{B}_7}{\dot{W}_{\text{net}} + (\dot{E}_9 - \dot{E}_8)}. \quad (18.36)$$

**Table 18.4** Exergoenvironmental analysis of the cogeneration system shown in Fig. 18.1

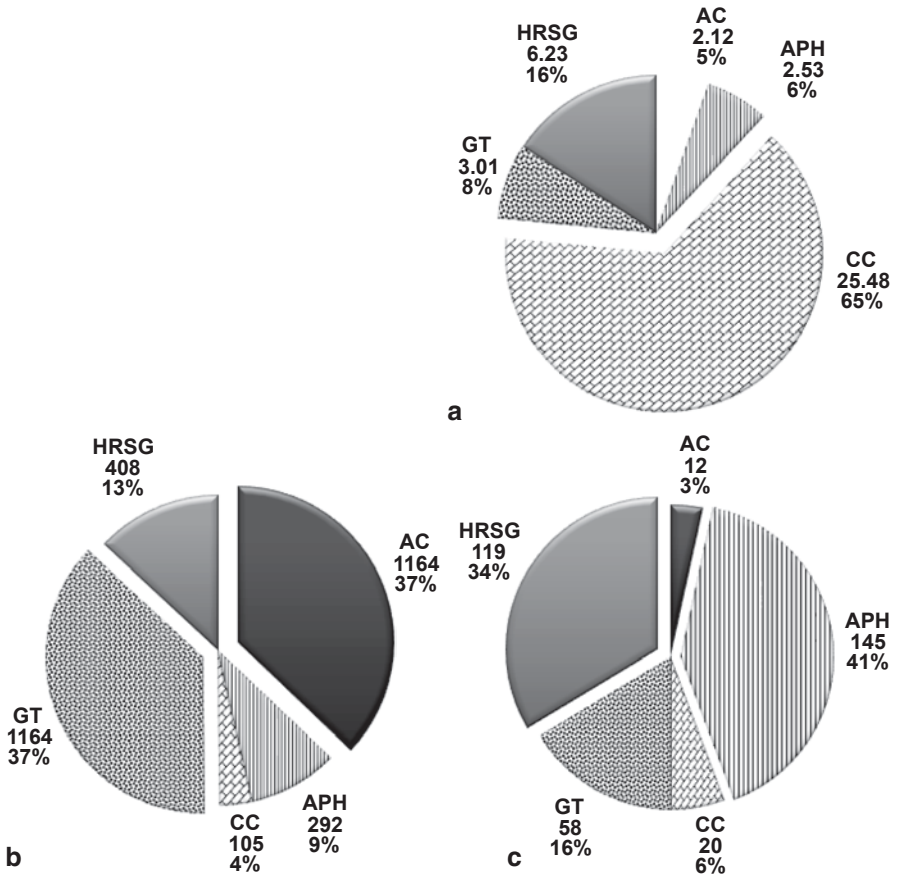
Component	$\dot{Y}_k$	$\dot{B}_{\text{D},k}$	$\dot{Y}_k + \dot{B}_{\text{D},k}$	$b_{\text{F},k}$	$b_{\text{P},k}$	$r_{b,k}$
	mPts/h	mPts/h	mPts/h	mPts/GJ	mPts/GJ	–
AC	12	65635	65647	8600	9523	0.11
APH	145	79934	80079	8442	9987	0.18
CC	20	486158	486178	5300	7569	0.43
GT	58	91483	91541	8442	8600	0.02
HRSG	119	189348	189468	8442	12570	0.49
<i>Overall system</i>	<i>354</i>	<i>751180</i>	<i>751534</i>	<i>5300</i>	<i>10330</i>	<i>0.95</i>

Note that for all components, the value of  $f_{b,k} < 1\%$  (Eq. 18.16).

### 18.5 Results and Discussions

Based on the values of  $\dot{E}_{D,k}^{real}$ ,  $\varepsilon_k^{real}$ , and  $y_k^{real}$  (Table 18.2 and Fig. 18.2a), we can conclude that the efforts to improve the efficiency of the overall system should focus on the combustion chamber and HRSG.

From the economic perspective (Fig. 18.2b), the most important components are the gas turbine and the air compressor. The results obtained from the exergoeconomic analysis (Table 18.3, sum of  $\dot{Z}_k$  and  $\dot{C}_{D,k}$ ) show again that the gas turbine



**Fig.18.2** Distribution of **a** exergy destruction (values in MW), **b** capital investment cost (values in \$/h), and **c** component-related environmental impact (values in mPts/h) among the components of the cogeneration system

**Table 18.5** Splitting the exergy destruction within the components of the cogeneration system

Component	$\dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{EX}$	$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	Splitting $\dot{E}_{D,k}^{real}$			
					$\dot{E}_{D,k}^{UN}$		$\dot{E}_{D,k}^{AV}$	
					$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{UN,EX}$	$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,EX}$
	MW	MW	MW	MW	MW	MW	MW	MW
AC	0.88	1.24	1.49	0.63	0.61	0.88	0.27	0.36
AHP	1.59	1.04	0.24	2.39	0.07	0.17	1.52	0.87
CC	16.09	9.39	15.89	9.59	8.97	6.92	7.12	2.47
GT	2.09	0.92	1.61	1.40	1.11	0.50	0.98	0.42
HRSG	3.78	2.45	4.40	1.83	2.57	1.83	1.21	0.62

and the air compressor are the most expensive components followed by HRSG and CC.

From LCA, we conclude (Fig. 18.2c) that both heat exchangers (APH and HRSG) have the highest component-related environmental impact. The exergoenvironmental analysis (Table 18.4) shows that the total environmental impact associated with the combustion chamber is the highest among all components (because of the environmental impact associated with the exergy destruction). More interesting conclusions are obtained from the advanced exergy-based analyses reported in the following.

The advanced exergetic analysis (Table 18.5) shows that the combustion chamber has the highest potential for improvement (the avoidable endogenous exergy destruction is  $\dot{E}_{D,CC}^{AV,EN} = 7.12\text{MW}$ ) or through the improvement of other components (avoidable exogenous exergy destruction is  $\dot{E}_{D,CC}^{AV,EX} = 2.47\text{MW}$ ). From the engineering perspective, it is much easier to improve the heat exchangers; therefore, to improve the overall system, the designer should focus on the APH ( $\dot{E}_{D,APH}^{AV,EN} = 1.52\text{MW}$ ) and the HRSG ( $\dot{E}_{D,HRSG}^{AV,EN} = 1.21\text{MW}$ ).

From the exergoeconomic perspective, the highest potential for reducing the total cost associated with the components is within the turbomachinery (AC and GT) because of the total cost associated with these components (sum of  $\dot{Z}_k$  and  $\dot{C}_{D,k}$ , Table 18.3). The advanced exergoeconomic analysis (Tables 18.6 and 18.7, Fig. 18.3a) confirms this conclusion (the values of  $\dot{Z}_k^{AV,EN}$  for the AC and GT are high) with the additional information, that the avoidable endogenous cost of the exergy destruction within the combustion chamber is also high. Therefore, the thermodynamic improvement of the CC is meaningful from the exergoeconomic point of view also.

The exergoenvironmental analysis (Table 18.4) shows that the values of the component-related environmental impacts are negligible compared to those of the environmental impact of exergy destruction. Therefore, the conclusions for improving the components from the exergoenvironmental and the exergetic analysis points of view are the same.



**Table 18.6** Splitting the capital investment cost within the components of the cogeneration system

Component	$\dot{Z}_k^{\text{EN}}$	$\dot{Z}_k^{\text{EX}}$	$\dot{Z}_k^{\text{UN}}$	$\dot{Z}_k^{\text{AV}}$	Splitting $\dot{Z}_k^{\text{real}}$			
					$\dot{Z}_k^{\text{UN}}$		$\dot{Z}_k^{\text{AV}}$	
	\$/h	\$/h	\$/h	\$/h	$\dot{Z}_k^{\text{UN,EN}}$	$\dot{Z}_k^{\text{UN,EX}}$	$\dot{Z}_k^{\text{AV,EN}}$	$\dot{Z}_k^{\text{AV,EX}}$
AC	474	690	155	1009	63	92	411	598
AHP	93	199	122	170	39	83	54	116
CC	59	46	11	94	6	5	53	41
GT	805	359	178	986	122	56	683	303
HRSG	238	170	108	300	63	45	175	125

**Table 18.7** Data obtained from the advanced exergoeconomic analysis for the components of the cogeneration system

Component	$\varepsilon_k^{\text{AV,EN}}$	$\dot{Z}_k^{\text{AV,EN}}$	$\dot{C}_{D,k}^{\text{AV,EN}}$	$\dot{Z}_k^{\text{AV,EN}} + \dot{C}_{D,k}^{\text{AV,EN}}$	$f_k^{\text{AV,EN}}$
	%	\$/h	\$/h	\$/h	%
AC	96.0	411	9	420	98
AHP	90.1	54	52	106	51
CC	80.9	53	242	295	18
GT	97.6	683	33	716	95
HRSG	80.7	175	41	216	81

The advanced exergoenvironmental analysis (Table 18.8, Fig. 18.3b) shows that the value of the component-related environmental impact can be decreased through selecting more environment-friendly materials for the HRSG. The combustion chamber has the highest potential for reducing the total environmental impact associated with the components.

The validity of the suggestions obtained by exergy-based methods can be confirmed by using sensitivity analyses, conducting an iterative improvement, using a mathematical method for optimization of the overall system, or doing experimental research with variation of important operation parameters. Table 18.9 briefly reports some results of a component-by-component sensitivity analysis based on exergy analysis (Azzarelli 2009). For the sensitivity analysis, every time only one design parameter was changed in each component. Note that the symbol “-” means a decrease in the value of the exergy destruction, i.e., a thermodynamic improvement of the component being considered, whereas “+” means an increase in the value of the corresponding exergy destruction. We compare these data with the results of the advanced exergetic analysis (Table 18.9).

A thermodynamic improvement of the  $k$ th component leads to a decrease in the value of the exergy destruction within this component (Table 18.9). An improvement of the  $k$ th component affects (not always positively) the exergy destruction

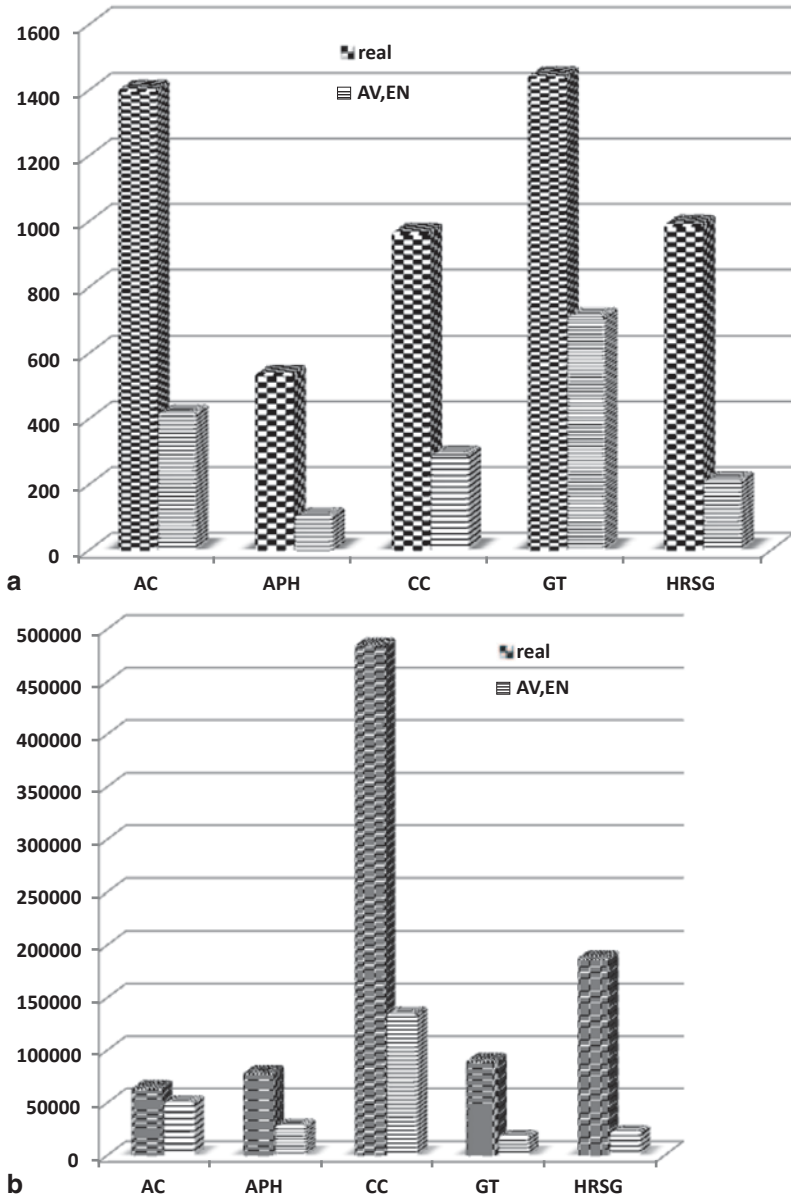


Fig. 18.3 Real and avoidable endogenous **a** total costs (in \$/h), and **b** environmental impacts (in mPts/h) associated with the components of the cogeneration system

within the remaining components, i.e., each component is responsible for some exogenous exergy destruction. In the following, we discuss three components: combustion chamber (CC), gas turbine (GT) and HRSG. The thermodynamic improvement of the combustion chamber can be significant only if the process within the combustion chamber itself is improved (for example, if the temperature,  $T_4$ , is

**Table 18.8** Splitting the construction-of-component-related environmental impact within each component of the cogeneration system

Component	$\dot{Y}_k^{EN}$	$\dot{Y}_k^{EX}$	$\dot{Y}_k^{UN}$	$\dot{Y}_k^{AV}$	Splitting $\dot{Y}_k^{real}$				
					$\dot{Y}_k^{UN}$		$\dot{Y}_k^{AV}$		
	$\dot{Y}_k^{UN,EN}$	$\dot{Y}_k^{UN,EX}$	$\dot{Y}_k^{AV,EN}$	$\dot{Y}_k^{AV,EX}$					
	mpts/h	mpts/h	mpts/h	mpts/h	mpts/h	mpts/h	mpts/h	mpts/h	mpts/h
AC	5	7	11	1	5	6	0	1	
AHP	46	99	116	29	37	79	9	20	
CC	11	9	17	3	10	7	1	2	
GT	40	18	43	15	30	13	10	5	
HRSG	70	49	27	92	16	11	54	38	

**Table 18.9** The difference between the values of the exergy destruction within the  $k$ th component in the original design and the value after changing the design parameter (MW)

Component	Design parameter	AC	AHP	CC	GT	HRSG
AC	$\eta_{AC}$ : 86% $\rightarrow$ 88%	-0.340	+0.083	$\approx 0$	$\approx 0$	-0.215
APH	$\Delta T_{APH, pinch}$ : 161 K $\rightarrow$ 141 K	$\approx 0$	-0.059	+1.384	$\approx 0$	-0.672
CC	$T_4$ : 1247 °C $\rightarrow$ 1297 °C	$\approx 0$	+0.267	-2.571	-0.002	-0.102
GT	$\eta_{GT}$ : 86% $\rightarrow$ 88%	$\approx 0$	-0.090	-0.886	-0.424	-0.034
HRSG	$\Delta T_{HRSG, pinch}$ : 50 K $\rightarrow$ 30 K	$\approx 0$	$\approx 0$	$\approx 0$	$\approx 0$	-0.276

raised from 1247 to 1297 °C), whereas the improvement of the remaining components is smaller. Similar issues apply to GT also. For these two components, we have  $\dot{E}_{D,k}^{EN} > \dot{E}_{D,k}^{EX}$ . For the HRSG, on the contrary, an improvement in any of the components of the overall system leads to a decrease in the value of the exergy destruction within HRSG.

The results obtained from the advanced exergoeconomic analysis are confirmed by the first publications, where the CGAM problem was defined and the first optimization results were presented (Valero et al. 1994), and by some subsequent publications (Tsatsaronis 1999a; Lazzaretto and Toffolo 2004). The difference between the values of the exergy destruction within the  $k$ th component (Table 18.2) in the original design and the value after the design parameter has been changed resulting in a thermodynamic improvement (Table 18.9)

## 18.6 Conclusions

Cost improvement of energy conversion systems requires, among others, appropriate tradeoffs between costs of thermodynamic inefficiencies and investment costs. These tradeoffs can be identified with the aid of exergy-based methods, which calculate the costs (and environmental impacts) of thermodynamic inefficiencies and compare them with the corresponding investment costs (and component-related environmental impact) at the system component level. Thus, exergy-based methods identify and properly evaluate the real sources of inefficiencies, costs, and environmental impacts.

From the thermodynamic perspective, the value of each unit of exergy destruction is the same. Exergoeconomics demonstrates that the average cost per unit of exergy destruction is different for each component and depends on the relative position of the component within the system: Components closer to the supply of exergy to the overall system have, in general, a lower cost per unit of exergy destruction than those closer to the point of supply of the product streams from the overall system. Similar conclusions apply to the environmental impact associated with exergy destruction.

The approaches reported here allow an integrated, consistent, and detailed evaluation of an energy conversion system from the perspectives of thermodynamics, economics, and environmental protection.

Advanced exergetic, exergoeconomic, and exergoenvironmental analyses are based on splitting the exergy destruction, cost, and environmental impact into avoidable endogenous, avoidable exogenous (with a further splitting to include the effects of the remaining components), unavoidable endogenous, and unavoidable exogenous values. Through these techniques, we improve our understanding of energy conversion processes, of the interactions among system components, and of the interactions among thermodynamics, economics, and environmental impact.

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