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On avoidable and unavoidable exergy destructions and investment costs in thermal systems

George Tsatsaronis [a,*], Moung-Ho Park [a,b,1]

[a] Institute for Energy Engineering, Technical University of Berlin, Marchstrasse 18, 10587 Berlin, Germany
[b] Department of Energy Studies & Energy Systems Research Center, Ajou University, Suwon 442-749, South Korea

This paper is dedicated to Professor Karl-Friedrich Knoche on the occasion of his 67th birthday

Abstract

To evaluate the thermodynamic performance and cost effectiveness of thermal systems and to estimate the potential for improvements, it is always useful to know (a) the avoidable part of an exergy destruction and (b) the avoidable investment cost associated with a system component. Improvement efforts should then focus only on these avoidable parts.

Using a cogeneration system as an example, this paper discusses how to estimate the avoidable and unavoidable exergy destruction and investment costs associated with compressors, turbines, heat exchangers and combustion chambers. This general procedure, although based on many subjective decisions, facilitates and improves applications of exergoeconomics. © 2002 Published by Elsevier Science Ltd.

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1. Introduction

An appropriately defined exergetic efficiency ε is the best variable for evaluating the performance of a thermal system and its components from the thermodynamic viewpoint [1,2]:

$$\varepsilon = \frac{E_{\mathrm{P}}}{E_{\mathrm{F}}} = 1 - \frac{E_{\mathrm{D}} + E_{\mathrm{L}}}{E_{\mathrm{F}}} \tag{1}$$

* Corresponding author. Tel.: +49-30-314-24776; fax: +49-30-314-21683.
E-mail address: tsatsaronis@iet-tu-berlin.de (G. Tsatsaronis).

[1] This work was conducted during Dr. Park's tenure at the Institute for Energy Engineering at the Technical University of Berlin.

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Nomenclature

c	cost per unit of exergy ($/GJ)
$\dot{C}$	cost rate associated with exergy ($/h)
$\dot{E}$	exergy rate (MW)
T	temperature (K)
$\dot{Z}$	cost rate associated with capital investment ($/h)

Greek symbol

ε	exergetic efficiency

Subscripts

ac	air compressor
aph	air preheater
cc	combustion chamber
D	destruction
F	fuel
hrsg	heat-recovery steam generator
k	component
L	loss
P	product
0	ambient conditions

Superscripts

AV	avoidable
F	contribution of fuel cost
UN	unavoidable
Z	contribution of capital investment

Here E_P, E_F, E_D and E_L are the exergy values associated with the product, the fuel, the exergy destruction and the exergy loss of the system being considered. The sum of exergy destruction within the system and exergy loss (exergy transport to the surroundings) represents the thermodynamic inefficiencies associated with the system. The exergetic efficiency, however, cannot be used to compare the performance of dissimilar systems or components (e.g., a heat exchanger, a turbine, or a combustion chamber). In addition, in each component only a part of the thermodynamic inefficiencies can be avoided whereas the remaining part cannot. Improvement efforts should be centered on the inefficiencies that can be avoided. Thus, we need to develop approaches for estimating the avoidable part of the thermodynamic inefficiencies.

In dealing with the inefficiencies associated with a *component*, we should recognize that the exergies of all material streams exiting a component are considered either at the product side or (with a negative sign) at the fuel side [3]. Thus the only exergy loss in a component is associated with the transfer of thermal exergy to the environment (heat loss). When the boundaries for the component analysis are drawn at the ambient temperature (T_0), the exergy loss is zero and the thermodynamic inefficiencies consist exclusively of exergy destruction. Exergy losses may in this case be associated only with an *overall system* but not with any of its components. Since the following discussion refers only to components, exergy losses are not further considered in this paper.

The concepts of efficiency and costing used in the analysis of thermal systems are closely related to each other. For example, the auxiliary costing equations used in exergoeconomics must be consistent with the definition of efficiency for the respective components [3].

One of the most interesting features of exergoeconomics is that the exergy destruction cost associated with a component is calculated and compared with the investment cost of the same component, to decide about the design changes that might improve its cost effectiveness. When dealing with avoidable exergy destruction and the associated cost, it is appropriate to compare the latter with the *avoidable* investment cost. The definitions of the avoidable costs associated with exergy destruction and investment are discussed next. For simplicity, only steady-state processes are considered in the following discussion.

2. General definition of avoidable exergy destruction and avoidable cost

The exergy destruction rate $\dot{E}_{\mathrm{D}}$ associated with the kth component of a thermal system consists of one avoidable (superscript AV) and another unavoidable (superscript UN) part

$$\dot{E}_{\mathrm{D},k} = \dot{E}^{\mathrm{AV}}_{\mathrm{D},k} + \dot{E}^{\mathrm{UN}}_{\mathrm{D},k} \tag{2}$$

A modified exergetic efficiency ε^*_k that focuses on avoidable exergy destruction within the kth component may be defined as

$$\varepsilon^*_k = \frac{\dot{E}_{\mathrm{P},k}}{\dot{E}_{\mathrm{F},k} - \dot{E}^{\mathrm{UN}}_{\mathrm{D},k}} = 1 - \frac{\dot{E}^{\mathrm{AV}}_{\mathrm{D},k}}{\dot{E}_{\mathrm{F},k} - \dot{E}^{\mathrm{UN}}_{\mathrm{D},k}} \tag{3}$$

The first question that arises is how to define the unavoidable part of the exergy destruction. To answer this question we must consider the relation between investment cost and exergy destruction (or efficiency) shown in Fig. 1. This figure presents the relation between investment cost per unit of product exergy $(\dot{Z}_k/\dot{E}_{\mathrm{P},k})$ and exergy destruction per unit of product exergy $(\dot{E}_{\mathrm{D},k}/\dot{E}_{\mathrm{P},k})$. The last ratio is equal to $(1-\varepsilon_k)/\varepsilon_k$ with the efficiency defined as

$$\varepsilon_k = \frac{\dot{E}_{\mathrm{P},k}}{\dot{E}_{\mathrm{F},k}} = 1 - \frac{\dot{E}_{\mathrm{D},k}}{\dot{E}_{\mathrm{F},k}} \tag{4}$$

From the cost balance formulated for the kth component we obtain for the cost per unit of product exergy

$$c_{\mathrm{P},k} = \frac{c_{\mathrm{F},k}\dot{E}_{\mathrm{F},k} + \dot{Z}_k}{\dot{E}_{\mathrm{P},k}} = c^{\mathrm{F}}_{\mathrm{P},k} + c^{\mathrm{Z}}_{\mathrm{P},k} \tag{5}$$

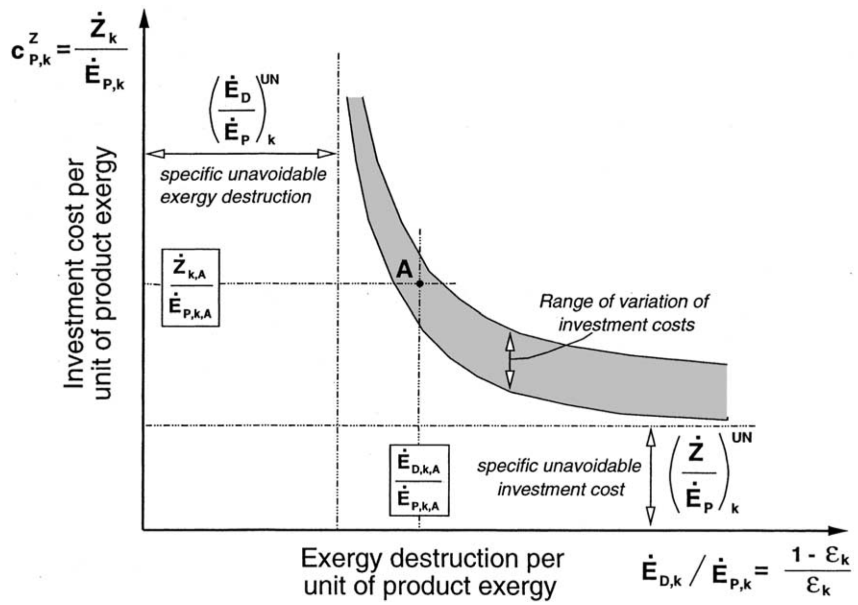

Fig. 1. Expected relationship between investment cost and exergy destruction (or exergetic efficiency) for the kth component of a thermal system. The figure shows the definition of specific unavoidable exergy destruction $(\dot{E}_D/\dot{E}_P)_k^{UN}$ and specific unavoidable investment cost $(\dot{Z}/\dot{E}_P)_k^{UN}$. The term *specific* means here *per unit of product exergy*.

with

$$c_{P,k}^{F} = c_{F,k}\frac{\dot{E}_{F,k}}{\dot{E}_{P,k}} = \frac{c_{F,k}}{\varepsilon_k} \tag{6}$$

and

$$c_{P,k}^{Z} = \frac{\dot{Z}_k}{\dot{E}_{P,k}} \tag{7}$$

Here $c_{F,k}$ is the cost per exergy unit associated with the fuel of the kth component. Eq. (5) reveals the real cost sources associated with the kth component, that is the fuel cost $(c_{F,k}^{F})$ and the investment cost $(c_{P,k}^{Z})$. The operating and maintenance costs are assumed to be constant and independent of the selection of the design point for the component being considered.

The shaded area in Fig. 1 illustrates the range of variation of the investment cost due to uncertainty and to multiple technical design solutions that might be available. As this figure shows, the investment cost per unit of product exergy $(c_{P,k}^{Z})$ increases with decreasing exergy destruction per unit of product exergy or with increasing efficiency. This is the normal cost behavior exhibited by most components. The components that exhibit a decrease of $(c_{P,k}^{Z})$ with increasing efficiency (see for example, the recent developments in the gas turbine systems) do not need to be considered in an exergoeconomic evaluation since for these components no optimization dilemma exists: Among all available solutions we should use the most efficient component that has both the lowest specific fuel expenses $c^{F}_{P,k}$ *and* the lowest specific investment cost $c^{Z}_{P,k}$ and, thus, the minimum $c_{P,k}$ value.

Due to technological limitations imposed, for example, by the availability and/or costs of materials and manufacturing methods, a maximum value of the exergetic efficiency of the kth component cannot be exceeded regardless of the amount of investment. This efficiency is obtained at the point where the investment cost becomes extremely large, mathematically speaking infinite. This point determines the unavoidable exergy destruction per unit of product exergy $(\dot{E}_D/\dot{E}_P)^{UN}_k$ as shown in Fig. 1. In practical applications this term is determined by appropriately selecting the most important thermodynamic parameters of the kth component to obtain its maximum achievable efficiency. It is apparent that this procedure is associated with more or less arbitrary decisions.

Similarly, the unavoidable investment costs per unit of product exergy $(\dot{Z}/\dot{E}_P)^{UN}_k$ are obtained by considering an extremely inefficient version of the kth component, that is a version that would never be realized in practice because of the very high fuel costs ($c^{F}_{P,k}$) associated with it. In practical applications the term $(\dot{Z}/\dot{E}_P)^{UN}_k$ is determined by arbitrarily selecting a set of thermodynamic parameters for this component that lead to a very inefficient solution and by estimating the investment costs for this solution. From the above discussion it is apparent that we do not need to know the curve shown in Fig. 1 in order to estimate the terms $(\dot{E}_D/\dot{E}_P)^{UN}_k$ and $(\dot{Z}/\dot{E}_P)^{UN}_k$. For this purpose it is sufficient to know the values of the thermodynamic parameters and investment costs for the two extreme design solutions.

After the terms $(\dot{E}_D/\dot{E}_P)^{UN}_k$ and $(\dot{Z}/\dot{E}_P)^{UN}_k$ have been estimated, the unavoidable exergy destruction rate ($\dot{E}^{UN}_{D,k,A}$) and the cost rates associated with the unavoidable exergy destruction ($\dot{C}^{UN}_{D,k,A}$) and the unavoidable investment cost ($\dot{Z}^{UN}_{k,A}$) at a given design point A (Fig. 1) are obtained from the following equations:

$$\dot{E}^{UN}_{D,k,A} = \dot{E}_{P,k,A}\left(\frac{\dot{E}_D}{\dot{E}_P}\right)^{UN}_k \tag{8}$$

$$\dot{C}^{UN}_{D,k,A} = c_{F,k}\dot{E}^{UN}_{D,k,A} \tag{9}$$

$$\dot{Z}^{UN}_{k,A} = \dot{E}_{P,k,A}\left(\frac{\dot{Z}}{\dot{E}_P}\right)^{UN}_k \tag{10}$$

Then the avoidable costs are calculated by subtracting the unavoidable cost rates from the respective total cost rates:

$$\dot{C}^{AV}_{D,k,A} = \dot{C}_{D,k,A} - \dot{C}^{UN}_{D,k,A} \tag{11a}$$

or

$$\dot{C}^{AV}_{D,k,A} = c_{F,k}\dot{E}^{AV}_{D,k,A} \tag{11b}$$

and

$$\dot{Z}^{AV}_{k,A} = \dot{Z}_{k,A} - \dot{Z}^{UN}_{k,A} \tag{12}$$

The advantages of dealing with avoidable exergy destruction and avoidable costs are many: the sum of *avoidable* cost rates $(\dot{C}^{AV}_{D,k,A} + \dot{Z}^{AV}_{k,A})$ characterizes much better the potential for reducing the costs associated with the kth component in the design point A than the sum $(\dot{C}_{D,k,A} + \dot{Z}_{k,A})$ of the *total* cost rates used until now (see, for example, [4,5]). Similarly the modified exergetic efficiency ε^*_k (Eq. (3)) based on avoidable exergy destruction characterizes the potential for exergy savings associated with the kth component better than the efficiency ε_k (Eq. (4)). In addition, the performance of dissimilar components may be compared using the modified exergetic efficiency ε^*_k.

3. Application to a cogeneration system

The concept of avoidable exergy destruction and avoidable costs was applied to the cogeneration system used by many researchers in the past (for example, [4–6]). This system is shown in Fig. 2. All results reported here were obtained using the same input data for the base-case design and the same assumptions for its exergetic, economic and exergoeconomic analysis as in [4]. The reader should consider that not all data assumed for this system are realistic. The investment costs have been artificially increased in this reference to demonstrate the application of the exergoeconomic methodology to a variety of components. In addition, the optimization of an actual cogeneration system would be significantly easier than the presentation in Ref. [4] because the components of a gas turbine system would not be optimized individually, as done here. The additional assumptions made here to calculate the unavoidable costs are discussed next for each component.

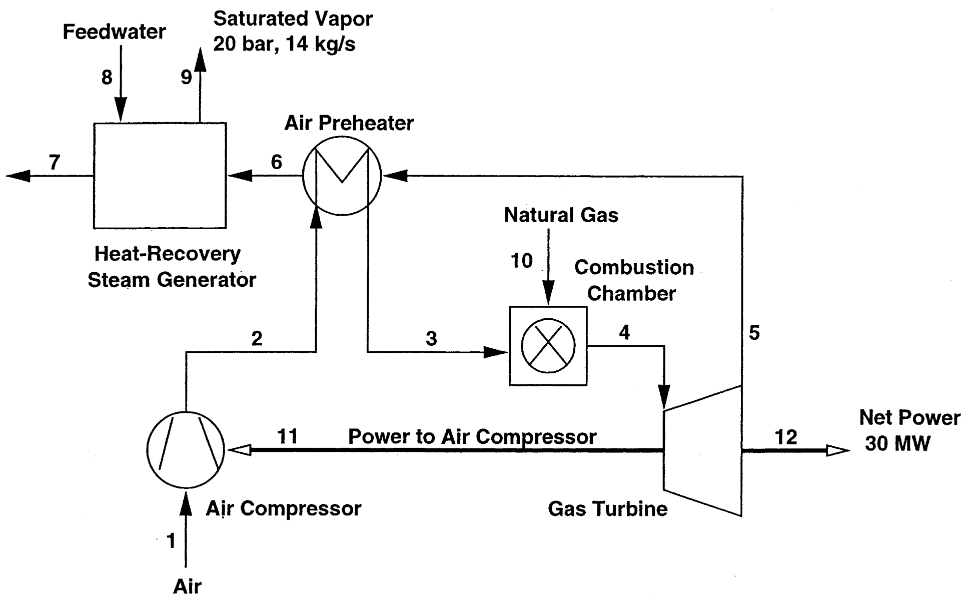

Fig. 2. Cogeneration system.

3.1. Air compressor (ac)

The equations given in Appendix B of Ref. [4] show that the purchased-equipment cost of the compressor becomes infinite when its isentropic efficiency is 90%. Using this value of the isentropic efficiency we calculate

$$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_{ac}^{UN} = 0.054$$

In the base-case design of the air compressor it is $\dot{E}_{P,ac} = 27.54$ MW, $\dot{E}_{D,ac} = 2.12$ MW, $\dot{Z}_{ac} = \$753/\text{h}$, and $c_{F,ac} = \$18.76/\text{GJ}$ [4]. Thus, we calculate using Eqs. (2),(8),(9) and (11b):

$$\dot{E}_{D,ac}^{UN} = \dot{E}_{P,ac}\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_{ac}^{UN} = 27.54 \times 0.054 = 1.49 \text{ MW}$$

$$\dot{C}_{D,ac}^{UN} = c_{F,ac}\dot{E}_{D,ac}^{UN} = 18.76 \times 1.49 \times 3.6 = \$100/\text{h}$$

$$\dot{E}_{D,ac}^{AV} = \dot{E}_{D,ac} - \dot{E}_{D,ac}^{UN} = 2.12 - 1.49 = 0.63 \text{ MW}$$

$$\dot{C}_{D,ac}^{AV} = c_{F,ac}\dot{E}_{D,ac}^{AV} = 18.76 \times 0.63 \times 3.6 = \$43/\text{h}$$

The term $\left(\dot{Z}/\dot{E}_P\right)_{ac}^{UN}$ is calculated from the cost functions of Appendix B in [4] using an isentropic efficiency of 70% for the air compressor: \$3.62/MWh. Then for the base-case design of the air compressor we obtain using Eqs. (10) and (12):

$$\dot{Z}_{ac}^{UN} = \dot{E}_{P,ac}\left(\frac{\dot{Z}}{\dot{E}_P}\right)_{ac}^{UN} = 27.54 \times 3.62 = \$100/\text{h}$$

$$\dot{Z}_{ac}^{AV} = \dot{Z}_{ac} - \dot{Z}_{ac}^{UN} = 753 - 100 = \$653/\text{h}$$

$$\dot{Z}_{ac}^{AV} + \dot{C}_{D,ac}^{AV} = 653 + 43 = \$696/\text{h}$$

3.2. Air preheater (aph)

In the base-case design of the air preheater we have $\dot{E}_{P,aph} = 14.40$ MW, $\dot{E}_{D,aph} = 2.63$ MW, $\dot{Z}_{aph} = \$189/\text{h}$, and $c_{F,aph} = \$14.51/\text{GJ}$ [4]. To calculate the unavoidable exergy destruction for this gas–air heat exchanger we assume a minimum temperature difference of 10 K. Then we obtain

$$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_{aph}^{UN} = 0.0164$$

$$\dot{E}_{D,aph}^{UN} = \dot{E}_{P,aph}\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_{aph}^{UN} = 14.51 \times 0.0164 = 0.24 \text{ MW}$$

$$\dot{E}_{D,aph}^{AV} = \dot{E}_{D,aph} - \dot{E}_{D,aph}^{UN} = 2.63 - 0.24 = 2.39 \text{ MW}$$

Table 1
Calculation of avoidable cost rates for the cogeneration system

Component (k)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	$c_{F,k}$ ($/GJ)	$\dot{Z}_k$ ($/h)	$(\dot{E}_D/\dot{E}_P)_k^{UN}$ ($/MW)	$\dot{E}_{D,k}^{UN}$ (MW)	$\dot{E}_{D,k}^{AV}$ (MW)	$\dot{C}_{D,k}^{AV}$ ($/h)	$(\dot{Z}/\dot{E}_P)_k^{UN}$ ($/MW)	$\dot{Z}_k^{UN}$ ($/h)	$\dot{Z}_k^{AV}$ ($/h)	$\dot{Z}_k^{AV} + \dot{C}_k^{AV}$ ($/h)
Air compressor	27.54	2.12	18.76	753	0.054	1.49	0.63	43	3.62	100	652	696
Air preheater	14.40	2.63	14.51	189	0.0164	0.24	2.39	125	5.50	79	110	235
Combustion chamber	59.52	25.84	4.57[a]	68	0.267	15.89	9.95	164	0.126	7	61	225
Gas turbine	59.66	3.01	14.51	753	0.027	1.61	1.40	73	1.92	115	638	711
Heat-recovery steam generator	12.75	6.23	14.51	264	0.345	4.40	1.83	96	5.46	70	194	290

The data in the first four columns were taken from the base-case design of the cogeneration system discussed by Bejan et al. [4].
[a] The value $c_{F,cc} = \$4.57/\mathrm{GJ}$ is obtained when the exergetic efficiency of the combustion chamber is defined as $\varepsilon = (\dot{E}_4 - \dot{E}_3)/\dot{E}_{10}$.

$$\dot{C}^{AV}_{D,aph} = c_{F,aph}\dot{E}^{AV}_{D,aph} = 14.51 \times 2.39 \times 3.6 = \$125/\text{h}$$

The unavoidable investment costs are calculated by assuming a low value for T_2 (achieved through an air-compressor isentropic efficiency of 90% and a pressure ratio of 10), a low value for T_3 (700 K)), and a high value for T_5 (achieved through a high value of the gas-turbine inlet temperature (1773 K) and an isentropic efficiency of 70% for the gas turbine:

$$\left(\frac{\dot{Z}}{\dot{E}_P}\right)^{UN}_{aph} = \$5.50/\text{MWh}$$

Thus,

$$\dot{Z}^{UN}_{aph} = \dot{E}_{P,aph}\left(\frac{\dot{Z}}{\dot{E}_P}\right)^{UN}_{aph} = 14.40 \times 5.50 = \$79/\text{h}$$

$$\dot{Z}^{AV}_{aph} = \dot{Z}_{aph} - \dot{Z}^{UN}_{aph} = 189 - 79 = \$110/\text{h}$$

$$\dot{Z}^{AV}_{aph} + \dot{C}^{AV}_{D,aph} = \$235/\text{h}$$

The results are summarized in Table 1.

3.3. Combustion chamber (cc)

The ratio $\left(\dot{E}_D/\dot{E}_P\right)^{UN}_{cc}$ is estimated for this component by assuming high temperatures of the reactants (811 K for fuel and 1000 K for air), a high outlet temperature (1773 K), and adiabatic combustion. With the aid of the cost function given in [4] we calculate

$$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)^{UN}_{cc} = 0.267$$

To estimate the ratio $\left(\dot{Z}/\dot{E}_P\right)^{UN}_{cc}$ we assume ambient temperatures at the inlet, ambient pressure in the combustion chamber and a low temperature at the outlet (1273 K), then we calculate with the aid of the cost function

$$\left(\frac{\dot{Z}}{\dot{E}_P}\right)^{UN}_{cc} = 0.126$$

The remaining variables calculated as in the previous two components are presented in Table 1.

3.4. Gas turbine (gt)

The unavoidable exergy destruction is estimated assuming an isentropic efficiency of 92% for the gas turbine since at this value the purchased-equipment cost of the turbine according to the costing-equations model considered in [4] becomes infinite

$$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_{gt}^{UN} = 0.027$$

The unavoidable investment costs for the gas turbine are obtained by assuming an isentropic efficiency of 70%, a pressure ratio of 10, and a low inlet temperature of 1273 K

$$\left(\frac{\dot{Z}}{\dot{E}_P}\right)_{gt}^{UN} = 1.92$$

The remaining variables are shown in Table 1.

3.5. Heat-recovery steam generator (hrsg)

Assuming a minimum temperature difference of 10 K for this component we calculate

$$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_{hrsg}^{UN} = 0.345$$

The unavoidable investment costs are estimated by assuming a very high temperature (1270 K) of the combustion gas into this component

$$\left(\frac{\dot{Z}}{\dot{E}_P}\right)_{hrsg}^{UN} = 5.46$$

The remaining variables for the heat-recovery steam generator are presented in Table 1.

4. Discussion and closure

Table 2 compares the sum $\left(\dot{Z}_k + \dot{C}_{D,k}\right)$ with the sum $(\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV})$ for each component of the cogeneration system. The latter gives a more realistic picture of the potential to achieve cost savings in the kth component and of the components that need to be improved first. Based on the assumptions made here, the percentage of total costs that could theoretically be avoided in today's technological and economic environment for each component of the cogeneration system is between 45% and 79%. Consideration of the avoidable costs emphasizes the need to improve the cost effectiveness of the gas turbine and the air compressor and, compared with the case where total costs are considered, reduces the economic importance of the heat-recovery steam generator and the combustion chamber.

In addition to the exergoeconomic factor f_k defined by

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{13}$$

Table 2
Comparison of total and avoidable cost rates and of the respective exergoeconomic factors f_k and f_k^* associated with the components of the cogeneration system

Component (k)	$\dot{Z}_k + \dot{C}_{D,k}$ (\$/h)	$\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}$ (\$/h)	$(\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV})/(\dot{Z}_k + \dot{C}_{D,k})$ (%)	f_k (%)	f_k^* (%)
Air compressor	896	696	77.7	84	94
Air preheater	326	235	72.1	58	47
Combustion chamber	493	225	45.6	14	27
Gas turbine	910	711	78.1	83	90
Heat-recovery steam generator	590	290	49.1	45	67

a modified exergoeconomic factor f_k^* based on avoidable costs can be defined through

$$f_k^* = \frac{\dot{Z}_k^{AV}}{\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}} \tag{14}$$

The factor f_k indicates the contribution of investment cost on the total cost $(\dot{Z}_k + \dot{C}_{D,k})$ associated with the kth component. The factor f_k^* shows the contribution of the avoidable investment cost on the total avoidable cost $(\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV})$ associated with the kth component. A comparison of the factors f_k and f_k^* in Table 2 shows that the factor f_k^* emphasizes the need to reduce the investment costs associated with the air compressor, gas turbine, and heat-recovery steam generator. For the air compressor, for example the f factor shows that 84% of the total costs associated with this component are due to investment cost. The f^* factor demonstrates that 94% of the total avoidable costs associated with the air compressor are investment costs. Thus, an improvement of the cost effectiveness of the air compressor can be achieved by reducing the investment cost for this component. The use of f^* instead of f increases the certainty with which this conclusion is obtained. All these indications are reasonable and assist the designer in the iterative cost minimization process better than the indications obtained by f_k.

In the exergetic analysis, the avoidable exergy destruction gives a realistic picture of the potential for improving the thermodynamic effectiveness of each component. The additional advantage is that the modified exergetic efficiency ε^* calculated for dissimilar components may be used not only to evaluate each component separately, but also to compare the thermodynamic performance of dissimilar components assuming a "correct" assessment of $\dot{E}_D^{UN}$ for each component involved in the comparison.

The calculation of avoidable exergy destruction and avoidable investment costs is associated with arbitrary decisions that reflect the maximal and minimal efficiency that can be achieved for the component being considered in today's technological and economic environment. In the authors' opinion, this arbitrariness must be accepted, in order for engineers to improve their understanding of the potential for improvements. The decisions required to calculate the unavoidable exergy destruction and costs, if made prudently, should not significantly affect the conclusions to be drawn from this analysis. However, additional studies involving more complex systems are needed to confirm this claim. Current work at the Institute for Energy Engineering in Berlin focusses on the thermodynamic parameters that should be used to calculate the avoidable costs for each type of system component.

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