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Conventional and advanced exergetic analyses applied to a combined cycle power plant☆

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ABSTRACT

Conventional exergy-based methods pinpoint components and processes with high irreversibilities. However, they lack certain insight. For a given advanced technological state, there is a minimum level of exergy destruction related to technological and/or economic constraints that is *unavoidable*. Furthermore, in any thermodynamic system, exergy destruction stems from both component interactions (*exogenous*) and component inefficiencies (*endogenous*). To overcome the limitations of the conventional analyses and to increase our knowledge about a plant, advanced exergy-based analyses have been developed.

In this paper, a combined cycle power plant is analyzed using both conventional and advanced exergetic analyses. Except for the expander of the gas turbine system and the high-pressure steam turbine, most of the exergy destruction in the plant components is unavoidable. This unavoidable part is constrained by internal technological limitations, i.e. each component's endogenous exergy destruction. High levels of endogenous exergy destruction show that component interactions do not contribute significantly to the thermodynamic inefficiencies. In addition, these inefficiencies are unavoidable to a large extent. With the advanced analysis, new improvement strategies are revealed that could not otherwise be found.

1. Introduction

Conventional exergetic, economic and exergoeconomic analyses constitute a rigorous evaluation of energy conversion systems. A conventional exergetic analysis reveals irreversibilities within each component of a plant. The costs related to the irreversibilities are then estimated in an exergoeconomic analysis [1–5]. Advanced exergetic and exergoeconomic analyses are needed in order to determine which part of the inefficiencies and the related costs is caused by component interactions (i.e. the structure of the plant), and which part can be avoided through technological improvements of a plant. These analyses explicitly identify the exergy destruction and costs and separate them into two main groups: (1) *avoidable-unavoidable exergy destruction/cost* and (2) *endogenous-exogenous exergy destruction/cost*. A similar strategy is possible for environmental impacts in an advanced exergoenvironmental analysis. Component interactions determine the *exogenous exergy destruction* and operating inefficiencies within the component determine the *endogenous exergy destruction*. Moreover, part of the overall irreversibilities exists due to physical, technological and economic constraints and cannot be avoided (*unavoidable exergy destruction*). Irreversibilities that can be prevented through design improvements constitute the *avoidable exergy destruction*. The exogenous and endogenous parts can be further split into avoidable and unavoidable parts facilitating the understanding of component interconnections and the estimation of the potential for improvement. In a similar way, the imposed costs and environmental impacts can be separated in the advanced exergoeconomic and exergoenvironmental analyses, respectively. Work in this field has been conducted in recent years at the Technical University of Berlin [6–13]. Through the classifications developed in these analyses, the components that influence the performance of the overall process are identified, and the focus lies on the avoidable part of the endogenous and exogenous exergy destruction.

The present paper focuses on the application of the advanced exergetic analysis, while the advanced exergoeconomic and exergoenvironmental analyses will be presented in subsequent publications. The analysis is applied to a complex energy conversion system: a three-pressure-level combined cycle power plant. The

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Table 1
Assumptions made for calculating the theoretical processes and the unavoidable exergy destructions.

Component	Theoretical conditions	Unavoidable conditions
Compressor	$\eta_{is} = 100\%$	$\eta_{is} = 98\%$
	$\eta_{mech} = 100\%$	$\eta_{mech} = 100\%$
Combustion Chamber (CC)	$Q_{loss} = 0$	$Q_{loss} = 0$
	$\Delta p = 0$	$\Delta p = 0$
	$\lambda = 2.05$	$\lambda = 1$
	$\epsilon = 100\%$	
Expander	$\eta_{is} = 100\%$	$\eta_{is} = 99\%$
	$\eta_{mech} = 100\%$	$\eta_{mech} = 100\%$
Generators	$\eta_{electr} = 100\%$	$\eta_{electr} = 99.5\%$
Superheaters	$\Delta T_{min} = 0$	$\Delta T_{min} = 4$
Reheater	$\Delta p = 0$	$\Delta p = 0$
	$\Delta T_{min} = 0$	$\Delta T_{min} = 1$
Evaporators	Approach Temp. = 0	Approach Temp. = 0
	$\Delta p = 0$	$\Delta p = 0$
Economizers	$\Delta T_{min} = 0$	$\Delta T_{min} = 1$
	$\Delta p = 0$	$\Delta p = 0$
Steam	$\eta_{is} = 100\%$	$\eta_{is} = 97\%$
Turbines	$\eta_{mech} = 100\%$	$\eta_{mech} = 100\%$
Pumps	$\eta_{is} = 100\%$	$\eta_{is} = 95\%$
	$\eta_{mech} = 100\%$	$\eta_{mech} = 100\%$
Motors	$\eta_{electr} = 100\%$	$\eta_{electr} = 98\%$

main objective is to identify the most influential components, in order to indicate changes related to (1) the structure and (2) the operation of the plant components that will result in a more efficient performance of the overall plant.

2. Methodology

2.1. Conventional exergetic analysis

Through an exergetic analysis, the components with high irreversibilities in a system are identified. Attributes and advantages of the exergetic analysis are well established [14].

By defining the exergy of the product, $\dot{E}_{P,k}$, and the exergy of the fuel, $\dot{E}_{P,k}$, for component k, we can determine its exergetic efficiency: $\epsilon_k = \dot{E}_{P,k}/\dot{E}_{F,k}$. A useful variable for comparison of dissimilar components is the exergy destruction ratio defined as: $y_{D,k} = \dot{E}_{D,k}/\dot{E}_{F,\mathrm{tot}}$, with $\dot{E}_{D,k}$ being the exergy destruction within component k and $\dot{E}_{F,\mathrm{tot}}$ the exergy of the fuel provided to the overall plant (subscript tot). The ratio $y_{D,K}$ is a measure of the contribution of the exergy destruction within component k to the reduction of the exergetic efficiency of the overall plant.

2.2. Advanced exergetic analysis

Through an advanced exergetic analysis, the exergy destruction is split into avoidable, $\dot{E}_D^{AV}$, and unavoidable, $\dot{E}_D^{UN}$, parts as well as into endogenous, $\dot{E}_D^{EN}$, and exogenous, $\dot{E}_D^{EX}$, parts. With this analysis, the effects of component interactions and technological limitations on the efficiency of a system are estimated. A detailed description of the methodology is provided in Refs. [8,11,15], but its main principles are presented below.

2.2.1. Endogenous – exogenous exergy destruction

In a system with n components, the endogenous exergy destruction, $\dot{E}_{D,k}^{EN}$, is the exergy destruction related to the operation of component k itself. It is obtained when the considered component operates under real conditions and all other components of the process operate without irreversibilities (theoretically). The power output of the overall plant is kept constant in all estimations. The theoretical conditions for the most important components are shown in Table 1. For the combustion chamber no theoretical conditions can be defined, due to the chemical reactions taking place there. Different methods have been proposed to overcome this problem [9]. One approach, proposed in Ref. [11], is valid for more complex systems and has been applied here.

In the case of the plant considered here, when either the combustion chamber or the neighboring components operate theoretically, streams 3 and 4 in Fig. 1 will change to maintain the predefined (either real- or theoretical-related) exergy balance for the reactor. When theoretical operation is assumed for a component or a group of components, the mass flows of the required air

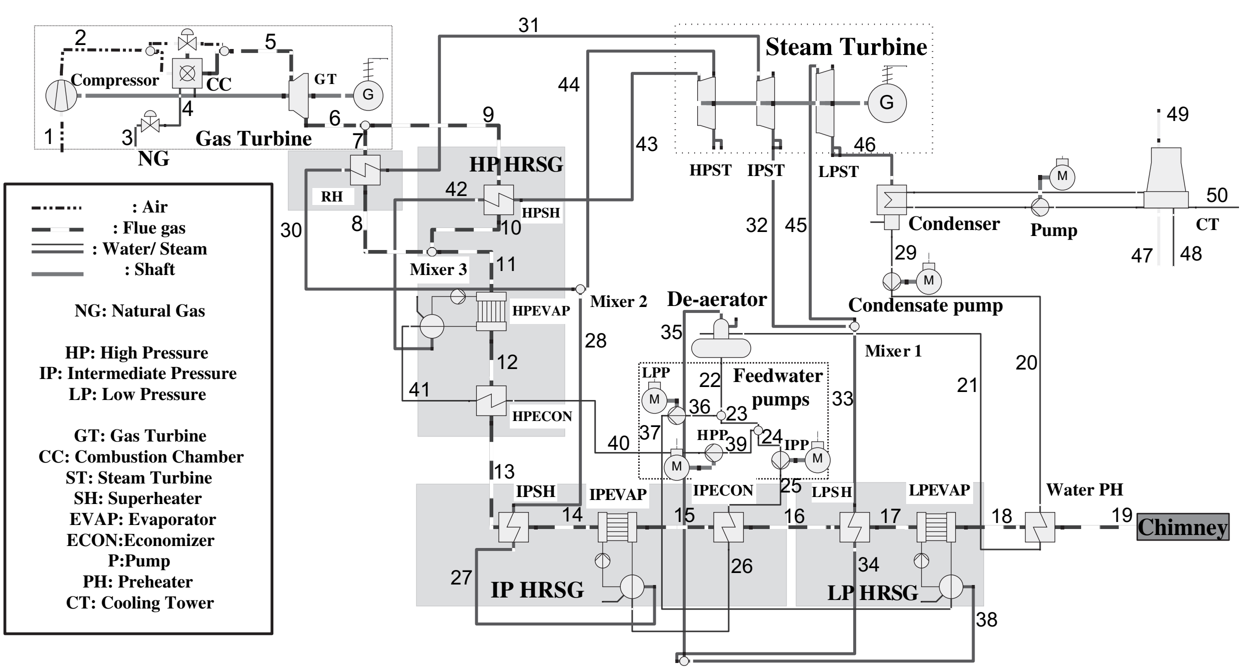

Fig. 1. Structure of the combined cycle power plant.

and fuel are calculated through the net power output of the plant, $\dot{W}_{net}$, and the excess air fraction (λ) for the combustion chamber, which have the same values as in the real case.

For calculating the endogenous exergy destruction, the CC (combustion chamber) must operate with its real exergetic efficiency ($\dot{E}_2 + \epsilon_{cc}\dot{E}_6 = \dot{E}_4$, with $\epsilon_{cc} = \epsilon_{CC}^{real}$), while in the theoretical case its exergy destruction must be set to zero ($\dot{E}_{D,CC} = 0 \Rightarrow \epsilon_{CC} = 1 \Rightarrow \dot{E}_2 + \dot{E}_6 = \dot{E}_4$). The thermodynamic variables of stream 4 agree with those of the real case throughout the analysis, while those of stream 2 vary depending on different combinations of the operating states of the compressor (C1) and the CC. For example, when both components operate theoretically, no pressure losses are incurred within the CC. With lower pressure losses present, stream 1 must be compressed to a lower pressure, since the inlet pressure of the expander (GT) is kept constant, resulting in lower temperatures for streams 2 and 3. Moreover, the temperatures of streams 2 and 3 are also decreased by the high isentropic efficiency of the theoretical compressor. In total, there are two possible thermodynamic states (real and theoretical) and two considered components (the CC and the compressor), thus $2^2 = 4$ possible combinations to take into account when defining the exergy balance of the CC. The temperature and pressure of stream 2 is calculated for all 4 combinations and its exergy is provided as input to the respective simulations.

After estimating the endogenous exergy destruction of component k, its exogenous exergy destruction is calculated by subtracting its endogenous exergy destruction from its real exergy destruction, $\dot{E}_{D,k}^{real}$:

$$\dot{E}_{D,k}^{EX} = \dot{E}_{D,k}^{real} - \dot{E}_{D,k}^{EN} \tag{1}$$

The exogenous exergy destruction, $\dot{E}_{D,k}^{EX}$, is, therefore, the exergy destruction imposed on component k through the operation of the remaining *n-1* components that constitute the overall system. The $\dot{E}_{D,k}^{EX}$ of component k can also be further split, revealing the specific components that cause it. The sum of the exogenous exergy destruction terms is different from the exogenous exergy destruction of the kth component. This difference, the *mexogenous exergy destruction* $\dot{E}_{D,k}^{MX}$, is caused by the simultaneous interconnections of all (n) components and it is calculated as in Ref. [11]:

$$\dot{E}_{D,k}^{MX} = \dot{E}_{D,k}^{EX} - \sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{E}_{D,k}^{EX,r} \tag{2}$$

2.2.2. Avoidable – unavoidable exergy destruction

Technological and economic design limitations determine a minimum value of the exergy destruction. The part of the exergy destruction that cannot be avoided with technologically feasible design modifications is the unavoidable exergy destruction, $\dot{E}_{D,k}^{UN}$. The unavoidable exergy destruction is calculated by considering each component in isolation, separated from the system, assuming the most favorable operating conditions. These conditions refer to minimum exergy destruction and are associated with very low temperature differences and thermal/pressure losses within the components. The assumptions for simulating unavoidable conditions depend on the decision maker and are arbitrary to some extent. In this paper these assumptions have been selected based on the authors' knowledge and experience on plant operation and by considering the maximum improvement potential that could be achieved for each plant component in the foreseeable future.

The assumptions taken into consideration for calculating the unavoidable exergy destruction are shown in Table 1. The ratio of exergy destruction per unit of product exergy $(\dot{E}_D^*/\dot{E}_P)_k^{UN}$ is then calculated. For component k with exergy of the product in the real process $\dot{E}_{P,k}^{real}$, the unavoidable exergy destruction $\dot{E}_{D,k}^{UN}$ is calculated from

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}^{real} \times \left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN} \tag{3}$$

When the unavoidable exergy destruction of component k is known, its avoidable exergy destruction is obtained with Eq. (4):

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k}^{real} - \dot{E}_{D,k}^{UN} \tag{4}$$

For the mixers, the deaerator and the condenser, no distinction between avoidable and unavoidable exergy destruction has been made here. The mixers and the deaerator depend mainly on the operation of the neighboring components they also present very small values of exergy destruction. The condenser is a dissipative component and cannot be analyzed with the equations presented here. Thus, the evaluation must be expanded to include dissipative components in the future.

2.2.3. Splitting avoidable and unavoidable exergy destruction into endogenous and exogenous parts

The unavoidable endogenous exergy destruction, $\dot{E}_{D,k}^{UN,EN}$, within component k is calculated from

$$\dot{E}_{D,k}^{UN,EN} = \dot{E}_{P,k}^{EN} \times \left(\frac{\dot{E}_D^*}{\dot{E}_P}\right)_k^{UN} \tag{5}$$

The unavoidable exogenous exergy destruction is calculated with Eq. (6).

$$\dot{E}_{D,k}^{UN,EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN,EN} \tag{6}$$

The avoidable endogenous and the avoidable exogenous exergy destructions are then calculated by subtracting the unavoidable endogenous and unavoidable exogenous from the total endogenous and exogenous exergy destructions, respectively:

$$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN} \tag{7a}$$

and

$$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{EX} - \dot{E}_{D,k}^{UN,EX} \tag{7b}$$

To identify the effect of each plant component on the overall plant performance, the sum of the avoidable exergy destructions caused by the component being considered is calculated by

$$\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{E}_{D,r}^{AV,EX,k} \tag{8}$$

$\sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{E}_{D,r}^{AV,EX,k}$ is the sum of the avoidable exogenous exergy destruction caused by component k within the remaining components. Each part of this sum is calculated for each component r ($n \neq k$) separately, via the unavoidable exogenous exergy destruction, as in Ref. [11]:

$$\dot{E}_{D,r}^{UN,EN,r+k} = \dot{E}_{P,r}^{EN,r+k}\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_r^{*\,UN} \tag{9}$$

$\dot{E}_{P,r}^{EN,r+k}$ is the $\dot{E}_P$ of component r, when components r and k operate under real conditions and all remaining components operate under theoretical conditions.

The unavoidable exogenous exergy destruction, $\dot{E}_{D,r}^{UN,EX,k}$, in component r due to component k is calculated from

$$\dot{E}_{D,r}^{UN,EX,k} = \dot{E}_{D,r}^{UN,EN,r+k} - \dot{E}_{D,r}^{UN,EN} \tag{10}$$

Finally, the avoidable exogenous exergy destruction of component r caused by component k, is found by subtracting its unavoidable exogenous exergy destruction from its total exogenous exergy destruction:

$$\dot{E}_{D,r}^{AV,EX,k} = \dot{E}_{D,r}^{EX} - \dot{E}_{D,r}^{UN,EX,k} \tag{11}$$

The calculation of avoidable and unavoidable values is subjective and is conducted in a rather simple way. Yet the information obtained by this approach is very valuable because it provides us with an approximate number that shows the avoidable inefficiencies, on which we need to focus.

3. The combined cycle power plant

3.1. Process description

The power plant studied in this paper is a three-pressure-level combined cycle with one reheat stage. The plant has one product – electricity – and works with natural gas that was assumed here to be pure methane. The configuration of the process is shown in Fig. 1. The thermodynamic variables for selected streams of the plant are shown in Table 2. The total exergy, $\dot{E}_{tot,j}$, includes both the chemical and physical exergy of each material stream j.

High-temperature flue gas with a mass flow rate of 628 kg/s exits the plant's GT (*gas turbine*) and is led to the HRSG (*heat recovery steam generator*), where it provides thermal energy to produce steam at three different pressure levels, 124, 22, and 4.1 bar. The combustion products enter the HRSG with a pressure of 1.058 bar at 580 °C and are exhausted to the atmosphere at 95 °C. The high-pressure steam at 560 °C is expanded to 23 bar in the HPST (*high-pressure steam turbine*) and returns to the HRSG, where it is reheated to 560 °C. The reheated steam is sent to the IPST (*intermediate-pressure steam turbine*), where it is expanded to 4.1 bar. This low-pressure steam is mixed with low-pressure superheated steam and it is then led to the LPST (*low-pressure steam turbine*), where it is expanded to 0.05 bar. The steam is condensed in the condenser, preheated, led to the deaerator of the plant and further conveyed to the feedwater pumps to continue the cycle.

Table 2
Calculated thermodynamic variables for selected material streams.

Stream, j	$\dot{m}_j$ [kg/s]	T_j [°C]	p_j [bar]	$\dot{E}_{tot,j}$ [MW]
1	614.50	15.0	1.01	0.96
2	614.50	392.9	17.00	232.25
3	14.00	15.0	50.00	729.62
4	14.00	15.0	17.00	727.37
5	628.50	1264.0	16.49	741.01
6	628.50	580.6	1.06	189.87
7	268.50	580.6	1.06	81.11
8	268.50	447.6	1.05	54.64
9	360.00	580.6	1.06	108.75
10	360.00	449.3	1.05	73.68
11	628.50	448.6	1.05	128.33
12	628.50	341.2	1.04	84.69
13	628.50	257.9	1.04	55.77
14	628.50	257.3	1.04	55.59
15	628.50	237.6	1.04	49.49
16	628.50	234.1	1.04	48.43
17	628.50	229.3	1.04	47.01
18	628.50	156.4	1.03	27.98
19	628.50	95.3	1.03	16.49
20	94.58	32.9	3.73	0.47
21	94.58	135.6	3.62	8.18
22	95.41	140.0	3.62	8.79
23	72.43	140.0	3.62	6.67
24	7.22	140.0	3.62	0.67
25	7.22	140.5	25.13	0.68
26	7.22	216.6	24.38	1.56
27	7.22	222.6	24.38	7.23
28	7.22	237.9	23.16	7.35
29	94.58	32.9	0.05	0.44
30	72.43	305.1	23.16	79.53
31	72.43	560.6	22.00	103.42
32	72.43	317.2	4.10	66.03
33	22.15	214.1	4.10	18.01
34	22.15	146.4	4.32	16.96
35	0.83	146.4	4.32	0.63
36	22.97	140.0	3.62	2.12
37	22.97	140.0	4.32	2.12
38	22.97	146.4	4.32	17.60
39	65.21	140.0	3.62	6.01
40	65.21	141.8	134.56	6.96
41	65.21	325.2	130.53	31.88
42	65.21	331.2	130.53	71.79
43	65.21	560.6	124.00	103.51
44	65.21	313.2	23.16	72.22
45	94.58	293.0	4.10	83.86
46	94.58	32.9	0.05	12.87

4. Results and discussion

4.1. Exergetic analysis

Table 3 shows the main results obtained by the conventional exergetic analysis of the plant under consideration. The results of this analysis have been partly presented in previous publications [16,17]. However, here, the motors and generators used for pumps and turbines, respectively, are examined separately. Thus, the values presented here may differ from those in the references. The exergy destruction ratio, $y_{D,K}$, provides information about the performance of each component and enables the comparison of dissimilar components. As shown in Table 3, the highest exergy destruction ratio is found for the components that constitute the GT system, with the CC (*combustion chamber*) having the highest value, followed by the HPHRSG, consisting of the HPSH (*high-pressure superheater*), the HPEVAP (*high-pressure evaporator*) and the HPECON (*high-pressure economizer*).

4.2. Advanced exergetic analysis

The results of the advanced exergetic analysis are shown in Tables 4–6 and are obtained using Eqs. (1) and (3)–(11). When evaluating a plant, we mainly focus on its avoidable exergy destruction, because it represents the potential for improvement. With the main exceptions being the expander of the GT system and the HPST, the unavoidable exergy destruction within the components of the plant is larger than the avoidable one. In the CC approximately 68% of the exergy destruction is unavoidable. Moreover, most of the overall exergy destruction of the plant is endogenous (approximately 83%). This means that component interactions, represented by the exogenous exergy destruction, do not play a very important role. Therefore, the focus should be on reducing the internal inefficiencies of the components. Additionally, for the CC, the compressor, the IPST and LPST and the

Table 3
Calculated exergetic variables for selected components.

Component, k	$\dot{E}_{F,k}$ [MW]	$\dot{E}_{P,k}$ [MW]	$\dot{E}_{D,k}$ [MW]	ϵ_k [%]	$y_{D,K}$ [%]
Compressor	242.675	231.298	11.378	95.31	1.56
CC	729.624	508.758	220.866	69.73	30.23
Expander	551.146	535.059	16.087	97.08	2.20
Reheater	26.468	23.893	2.575	90.27	0.35
HPSH	35.072	31.724	3.348	90.45	0.46
HPEVAP	43.638	39.910	3.727	91.46	0.51
HPECON	28.916	24.914	4.002	86.16	0.55
IPSH	0.179	0.123	0.055	69.01	0.01
IPEVAP	6.100	5.668	0.432	92.92	0.06
IPECON	1.061	0.875	0.186	82.47	0.03
LPSH	1.425	1.044	0.381	73.27	0.05
LPEVAP	19.026	15.479	3.547	81.36	0.49
LPECON	11.494	7.709	3.785	67.07	0.52
HPST	31.289	29.620	1.668	94.67	0.23
IPST	37.394	35.748	1.646	95.60	0.23
LPST	70.992	62.285	8.707	87.73	1.19
Condensate Pump	0.039	0.035	0.004	90.34	0.00
HP Pump	1.063	0.957	0.107	89.96	0.01
IP Pump	0.025	0.019	0.006	75.81	0.00
LP Pump	0.002	0.002	0.000	83.22	0.00
GT generator	292.384	287.998	4.386	98.50	0.60
ST generator	127.654	125.739	1.915	98.50	0.26
Condensate Pump Motor	0.045	0.039	0.006	87.20	0.00
HP Pump Motor	1.122	1.063	0.058	94.80	0.01
IP Pump Motor	0.029	0.025	0.004	86.20	0.00
LP Pump Motor	0.003	0.002	0.001	80.70	0.00
Condenser	12.428	–	9.240	–	1.26
Total	730.580	412.538	300.408	56.47	41. 12

majority of the heat exchangers, most of the endogenous exergy destruction is unavoidable. In contrast, in the expander, the HPST and the generator, the avoidable part of the endogenous exergy destruction is larger than the unavoidable part. However, when the exogenous exergy destruction is split into avoidable and unavoidable parts, for most components (including expander and LPST), the unavoidable part is found to be larger. To determine the real relative importance of the components, we further split the exogenous exergy destruction within each component into the parts caused by the remaining components. This separation results in a number of simulations totaling $n^2 + n/2$, with n being the number of the plant components. The results for the components with the highest exogenous exergy destruction are shown in Table 5. The mexogenous exergy destruction is associated with the simultaneous interactions of more than one component with the component being considered, and is calculated using Eq. (2).

The negative values calculated for the exogenous exergy destruction within some components (see Table 4) are the result of mass flow differences between the endogenous and the real operating conditions. For example, for calculating the endogenous exergy destruction of the IPSH, all other components operate under theoretical conditions, while the IP superheater operates under real conditions. Due to the elimination of any pressure drops within the theoretical components, the operating pressure of the heat exchanger during the calculation of the $\dot{E}_D^{EN}$ is lower. These conditions result in an increased mass of steam flowing through the heat exchanger. Thus, the endogenous exergy destruction is found to be higher than the $\dot{E}_D^{real}$ and the $\dot{E}_D^{EX}$ negative. The negative $\dot{E}_D^{EX}$ of the GT generator can be justified similarly. For the calculation of the $\dot{E}_D^{EN}$, the power output of the steam cycle is decreased, due to the lower temperature of the combustion products entering the HRSG – a result of the high isentropic efficiency of the expander. With this lower temperature, the total power produced by the steam turbines is reduced. However, to keep the overall power output of the process constant, the power output from the expander must increase. This is achieved by increasing the mass flow rate through the expander, since the inlet temperature of the expander remains constant. With increased mass flow, the $\dot{E}_D^{EN}$ of the GT generator becomes higher than the $\dot{E}_D^{real}$, thus resulting in a negative value of $\dot{E}_D^{real}$. Similar explanations can be given for the negative values of

Table 4
Selected results from the advanced exergetic analysis at the component level (negative values shown in bold).

Component, k	$\dot{E}_{D,k}^{EN}$ [MW]	$\dot{E}_{D,k}^{EX}$ [MW]	$\dot{E}_{D,k}^{AV}$ [MW]	$\dot{E}_{D,k}^{UN}$ [MW]	$\dot{E}_{D,k}^{UN}$		$\dot{E}_{D,k}^{AV}$	
					$\dot{E}_{D,k}^{UN,EN}$ [MW]	$\dot{E}_{D,k}^{UN,EX}$ [MW]	$\dot{E}_{D,k}^{AV,EN}$ [MW]	$\dot{E}_{D,k}^{AV,EX}$ [MW]
Compressor	6.94	4.44	5.11	6.26	3.79	2.47	3.14	1.97
CC	193.06	27.80	71.03	149.84	130.81	19.03	62.25	8.77
Expander	13.52	2.57	8.32	7.77	6.23	1.53	7.29	1.03
Reheater	1.98	0.59	0.89	1.68	1.11	0.57	0.87	0.02
HPSH	1.78	1.57	0.87	2.48	1.30	1.18	0.48	0.38
HPEVAP	2.00	1.72	0.67	3.06	1.84	1.21	0.16	0.51
HPECON	2.24	1.76	1.28	2.72	1.75	0.97	0.49	0.79
IPSH	0.09	**−0.03**	0.05	0.01	0.01	**−0.01**	0.07	**−0.03**
IPEVAP	0.41	0.02	0.15	0.28	0.25	0.03	0.16	**−0.01**
IPECON	0.16	0.03	0.07	0.12	0.18	**−0.06**	**−0.01**	0.08
LPSH	0.19	0.19	0.22	0.16	0.06	0.10	0.13	0.09
LPEVAP	1.68	2.06	0.76	2.98	1.65	1.33	0.03	0.73
LPECON	2.42	1.37	1.83	1.95	1.13	0.82	1.28	0.55
HPST	1.11	0.56	0.89	0.78	0.50	0.29	0.61	0.28
IPST	1.19	0.46	0.71	0.94	0.65	0.28	0.54	0.17
LPST	6.10	2.61	3.61	5.10	3.57	1.53	2.53	1.08
Condensate Pump	0.00	0.44	0.45	0.00	0.00	0.00	0.00	0.44
HP Pump	0.00	0.11	0.11	0.00	0.00	0.00	0.00	0.11
IP Pump	0.06	**−0.06**	**−0.03**	0.03	0.02	0.01	0.04	**−0.07**
LP Pump	0.01	0.02	0.02	0.00	0.00	0.00	0.01	0.02
GT generator	4.76	**−0.38**	2.94	1.45	1.57	**−0.12**	3.19	**−0.25**
ST generator	1.44	0.48	1.28	0.63	0.47	0.16	0.96	0.32
Condensate Pump Motor	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
HP Pump Motor	0.00	0.15	0.15	0.00	0.00	0.00	0.00	0.15
IP Pump Motor	0.00	0.06	0.04	0.02	0.01	0.01	**−0.01**	0.05
LP Pump Motor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SUM	**248.94**	**52.03**						
SUM (%)	**82.71**	**17.29**						

Table 5
Splitting of the exogenous exergy destruction.

Component, k	$\dot{E}_{D,k}^{EX}$ [MW]	Component, r	$\dot{E}_{D,k}^{EX,r}$ * [MW]	Component, k	$\dot{E}_{D,k}^{EX}$ [MW]	Component, r	$\dot{E}_{D,k}^{EX,r}$ [MW]
CC	27.44	Expander	8.84	LPECON	1.59	LPEVAP	0.31
		Compressor	5.59			CC	0.28
		LPST	3.39			Expander	0.18
		GT generator	2.16			Compressor	0.07
		LP EVAP	0.86			LPST	0.04
		mexo	**2.14**			**mexo**	**0.32**
Compressor	4.43	CC	3.51	HPSH	1.56	Expander	0.92
		Expander	0.29			CC	0.20
		LPST	0.11			Compressor	0.05
		GT generator	0.08			Reheater	0.03
		LP EVAP	0.03			LPST	0.03
		mexo	**0.26**			**mexo**	**0.32**
LPST	2.69	Expander	1.07	Reheater	0.59	CC	0.23
		CC	0.70			HPSH	0.18
		Compressor	0.19			Expander	0.15
		IPST	0.12			Compressor	0.06
		GT generator	0.07			IPSH	0.05
		mexo	**0.65**			**mexo**	**0.12**
Expander	2.54	CC	1.12	LPSH	0.20	IP Evaporator	0.11
		Compressor	0.30			CC	0.02
		LPST	0.25			Reheater	0.02
		Generator GT	0.15			Expander	0.02
		Generator STs	0.06				
		mexo	**0.35**			**mexo**	**0.07**
HPECON	1.76	HPEVAP	0.28	LPEVAP	2.05	IPEVAP	0.83
		CC	0.25			CC	0.19
		Expander	0.22			Expander	0.17
		Deaerator	0.19			Reheater	0.14
		Compressor	0.07			IPSH	0.11
		mexo	**0.58**			**mexo**	**0.54**
HPEVAP	1.72	Expander	0.85				
		CC	0.23				
		Reheater	0.11				
		IPEVAP	0.08				
		Compressor	0.06				
		mexo	**0.40**				

*$\dot{E}_{D,k}^{EX,r}$: Exogenous exergy destruction within component k caused by component r.

the unavoidable $\dot{E}_{D}^{EX}$, since their calculation is dependent on the calculation of $\dot{E}_{D}^{UN,EX}$. When in the simulation used for the calculation of the $\dot{E}_{D}^{EN}$, the exergy of the product, $\dot{E}_{P}^{EN}$, increases in comparison to the real case, the value of $\dot{E}_{D}^{UN,EX}$ becomes negative.

The CC has the highest absolute value of exergy destruction, 68% of which cannot be avoided and only approximately 12% of its avoidable exergy destruction is exogenous. Thus, the remaining 88% of the avoidable exergy destruction is due to the component itself. Additionally, 53% of the exogenous exergy destruction in the CC stems from the expander and the compressor (Table 5), almost 33% (4.8 MW) of which is avoidable. In the expander and the compressor, the main part of the exergy destruction is also endogenous, i.e., caused internally by the operation of the components themselves, while the exogenous part is mainly due to the CC. However, a large part of the exogenous exergy destruction stemming from the CC is avoidable (44% in the compressor and 33% in the GT). As mentioned, in every simulation performed to calculate the endogenous exergy destruction of components, the overall, net power output (W_{net}) of the plant was kept constant and equal to the net power output of the real case. When something was varied, all components were affected as well. For example, when the generator operates under theoretical conditions with 100% electrical efficiency, it reduces the overall thermodynamic inefficiencies of the plant and the same amount of net product can be generated with less fuel. Thus, because the GT system must generate less power, the mass flow rates of the involved streams must be reduced analogously.

The larger the effect of a component on the overall performance, the higher its improvement priority must be, if the improvement of the overall plant is considered. The CC is the component with the highest absolute value of exergy destruction, and the highest avoidable exergy destruction. The expander and the compressor follow in absolute values of avoidable exergy destruction.

To better understand the improvement potential of the components, we also calculated the variable $\dot{E}_{D,k}^{AV,\Sigma}$, as stated in Eq. (8) (Table 6). The total avoidable exergy destruction associated with component k, consists of both the avoidable endogenous exergy destruction and the avoidable exogenous exergy destruction this component causes to the remaining components of the plant. The higher this value is, the higher the influence of the considered component on the overall system.

In the first column of Table 6 the total exogenous exergy destruction caused by each component is presented. As shown, the exogenous exergy destruction caused by the expander is almost double that caused by the CC. However, the avoidable parts

Table 6
Total avoidable exergy destruction caused by component k (Eq. (8)).

Component, k	$\sum_{r=1, r\neq k}^{n} \dot{E}_{D,r}^{EX,k}$ [MW]	$\sum_{r=1, r\neq k}^{n} \dot{E}_{D,r}^{EX,AV,k}$ [MW]	$\dot{E}_{D,r}^{EN,AV}$ [MW]	$\dot{E}_{D,r}^{AV,\Sigma}$ [MW]
CC	8.0	3.65 (6%)	62.25 (94%)	65.90
Expander	14.1	4.89 (40%)	7.29 (60%)	12.18
Compressor	6.8	2.53 (45%)	3.14 (55%)	5.67
LPST	4.5	1.81 (42%)	2.53 (58%)	4.34
LPEVAP	0.9	0.13 (81%)	0.03 (9%)	0.16
HPECON	0.0	0.01 (2%)	0.49 (98%)	0.51
HPSH	0.5	0.24 (33%)	0.48 (67%)	0.72

of the two components are similar. Additionally, the endogenous exergy destruction of the CC is significantly larger, resulting in a total avoidable exergy destruction approximately five times higher than that of the expander. When comparing the expander with the compressor, the former causes double the exergy destruction in the plant, resulting in a higher absolute value of avoidable exogenous exergy destruction. Moreover, due to the doubled endogenous avoidable exergy destruction of the expander, its total avoidable exergy destruction is also almost double that of the compressor.

The results of the conventional exergetic analysis are strongly supplemented by the advanced exergetic analysis. Irreversibilities identified in the conventional exergetic analysis have been split, according to their origins, in the advanced exergetic analysis. Only the part of the irreversibilities that can be avoided should be considered for the improvement of a plant with interacting processes.

5. Conclusions

In this paper, a combined cycle power plant, has been analyzed using both conventional and advanced exergetic analyses. The exergetic analysis uses variables that reveal the components with the highest thermodynamic inefficiencies (exergy destruction). Specific insight, however, about the interactions among components and the improvement potential of the plant is revealed by an advanced exergetic analysis.

The highest exergy destruction is caused by the CC. Almost 87% of the total exergy destruction within this component results from the operation of the component itself (*endogenous exergy destruction*) and 68% of the total exergy destruction cannot be avoided (*unavoidable exergy destruction*). In total, there is some improvement potential for the overall plant, most of which is related to the internal operating conditions of the components (*endogenous exergy destruction*), while component interactions (*exogenous exergy destruction*) are less significant. Considering the avoidable exergy destruction caused by each component both to itself and the remaining components of the plant, the results are well justified. Similar to the results of the conventional analysis, the advanced analysis ranks the improvement priority of the combustion chamber first, followed by the expander and the compressor. When considering the total avoidable exergy destruction of each component, the expander and the compressor increase in importance moving closer to the combustion chamber, because of their relatively high percentage of avoidable exergy destruction.

An advanced exergetic analysis is a valuable supplement to a conventional exergetic analysis. The application of the advanced exergoeconomic and exergoenvironmental analyses is the next step of this study and will be presented in the future.

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References

[1] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. USA: John Wiley.; 1996.
[2] Tsatsaronis G. Design optimization using exergoeconomics in thermodynamic optimization of complex energy systems. In: Bejan A, Mamut E, editors. Dordrecht, Boston, London: Kluwer Academic Publishers; 1999. p. 101–15.
[3] Tsatsaronis G, Cziesla F. Thermoeconomics in encyclopedia of physical science and technology. 3rd ed., vol. 16. Academic Press; 2002. 659–680.
[4] Lazzaretto A, Tsatsaronis G. SPECO: a systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy 2006;31:1257–89.
[5] Tsatsaronis G, Cziesla F. Six articles published in exergy, energy systems analysis and optimization as part of the Encyclopedia of Life Support Systems (EOLSS), developed under the auspices of UNESCO, vol. 1. Oxford, UK: Eolss Publishers; 2009. 34–146.
[6] Tsatsaronis G, Park MH. On avoidable and unavoidable exergy destructions and investment costs in thermal systems. Energy Conversion and Management 2002;43:1259–70.
[7] Cziesla F, Tsatsaronis G, Gao Z. Avoidable thermodynamic inefficiencies and costs in an externally fired combined cycle power plant. Energy – The International Journal 2006;31(10–11):1472–89.
[8] Tsatsaronis G, Kelly S, Morosuk T. Endogenous and exogenous exergy destruction in thermal systems. In: Proceedings of the ASME IMECE, [CD-ROM], 2006–13675 Chicago, USA; 2006.
[9] Kelly S. Energy systems improvement based on endogenous and exogenous exergy destruction, Ph.D. Thesis, Technische Universität Berlin, Germany; 2008.
[10] Tsatsaronis G, Morosuk T. Advanced exergoeconomic evaluation and its application to compression refrigeration machines. In: Proceedings of the ASME IMECE; 2007. File IMECE2007-41202, Seattle, USA.
[11] Morosuk T, Tsatsaronis G. How to calculate the parts of exergy destruction in an advanced exergetic analysis. In: Ziebik A, Kolenda Z, Stanek W, editors. Proceedings ECOS 2008, Cracow-Gliwice, Poland; 2008. p. 185–94.
[12] Tsatsaronis G, Morosuk T. A general exergy-based method for combining a cost analysis with an environmental impact analysis. Part I – theoretical development. In: Proceedings of the ASME IMECE, File IMECE2008-67218, Boston, USA; 2008.
[13] Tsatsaronis G, Morosuk T. A general exergy-based method for combining a cost analysis with an environmental impact analysis. Part II – application to a cogeneration system. In: Proceedings of the ASME IMECE, file IMECE2008–67219, Boston, USA; 2008.
[14] Tsatsaronis G. Strengths and limitations of exergy analysis, thermodynamic optimization of complex energy systems. In: Bejan A, Mamut E, editors. Dordrecht: Kluwer Academic Publishers; 1999. p. 93–100.
[15] Petrakopoulou F. Comparative evaluation of power plants with CO_2 capture: thermodynamic, economic and environmental performance, Ph.D. dissertation, Technische Universität Berlin; 2011.
[16] Petrakopoulou F, Boyano A, Cabrera M, Tsatsaronis G. Exergoeconomic and exergoenvironmental analyses of the AZEP concept, a combined cycle power plant with CO_2 capture. International Journal of Low-Carbon Technologies; 2010. doi:10.1093/ijlct/ctq028.
[17] Petrakopoulou F, Boyano A, Cabrera M, Tsatsaronis G. Exergoeconomic and exergoenvironmental analyses of a combined cycle power plant with chemical looping technology. International Journal of Greenhouse Gas Control; 2010. doi:10.1016/j.ijggc.2010.06.008.