# Advanced Exergoeconomic Analysis Applied to a Complex Energy Conversion System

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*Exergy-based analyses are important tools for studying and evaluating energy conversion systems. Conventional exergy-based analyses provide us with important information on the design and operation of a system. However, further insight into the improvement potential of plant components and the overall plant, as well as into component interactions, is important when optimal operation is required. This necessity led to the development of advanced exergy-based analyses, in which the exergy destruction as well as the associated costs and environmental impacts are split into avoidable/unavoidable and endogenous/exogenous parts. Based on the avoidable exergy destruction, costs and environmental impacts potential and strategies for improvement are revealed. The objective of this paper is to demonstrate the application, the advantages, and the information obtained from an advanced exergoeconomic analysis by applying it to a complex plant, i.e., to a combined cycle power plant. The largest parts of the unavoidable cost rates are calculated for the components constituting the gas turbine system and the low-pressure steam turbine. The combustion chamber has the second highest avoidable investment cost and the highest avoidable cost of exergy destruction. In general, the investment cost of most of the components is unavoidable, with the exception of some heat exchangers. Similarly, most of the cost of exergy destruction is unavoidable, with the exception of the expander of the gas turbine system and the high-pressure and intermediate-pressure steam turbines. The advanced exergoeconomic analysis reveals high endogenous values, which suggest that improvement of the total plant can be achieved by improving the design of individual components, and lower exogenous values, which means that component interactions are in general of lower significance for this plant.* [DOI: 10.1115/1.4005115]

## Introduction

Exergy-based analyses [1–11] include an exergetic analysis, an exergoeconomic analysis, and an exergoenvironmental analysis. In an exergetic analysis, the real inefficiencies of a system and their sources that are kept hidden when an energy analysis is applied are revealed and are then further related to costs in an exergoeconomic analysis. The main objective of an exergoeconomic/exergoenvironmental approach is to find appropriate trade-offs between efficiency enhancement and investment cost/environmental impact reduction at the component level that will eventually lead to the improvement of the overall system. However, *conventional* exergy-based analyses have some important limitations that motivated the development of *advanced exergy-based analyses* [12–17]: The conventional exergy-based analyses do not provide sufficient and accurate information about (1) component interactions or (2) the potential for improving a component or the overall plant [18]. These two points, however, are crucial when improving complex structures.

The advanced exergetic, exergoeconomic and exergoenvironmental analyses were developed to address these shortcomings of the respective conventional methods. Partial applications of advanced exergy-based analyses to small-scale systems [11,14,17] affirmed the usefulness and significance of the methodology. Advanced exergy-based methods provided information that could not be obtained through the respective conventional methods and indicated more accurate and non-misleading strategies for improving the overall plant, while also accounting for component interactions. A comparison of the methodology used here with other approaches is discussed in Ref. [19]. The present paper focuses on the advanced exergoeconomic analysis. Part of the costs associated with a power plant can be avoided through changes in the plant structure, reduction of the investment costs of components, or efficiency improvements in the components. Investment costs that can be avoided through technically feasible design and/or operating improvements constitute the *avoidable* part of the cost. Identification of this part plays a very significant role in determining the optimization steps of a system and in estimating its improvement potential. On the other hand, part of the overall costs is imposed by physical, technological, economic, and legal constraints and cannot be avoided (*unavoidable* cost) [13,14]. In addition, the costs of a component can also be separated depending on whether they are caused by component interactions (*exogenous*) or they are directly related to the operation of the components themselves (*endogenous*) [15–19]. The avoidable and unavoidable values are further divided into endogenous and exogenous parts. The information provided by an advanced exergoeconomic analysis is crucial for improving the cost effectiveness of a plant because this analysis identifies the most important components and processes that mainly affect the cost of the overall product and suggests strategies for reducing it. This detailed analysis has been developed as an aid to the overall optimization of energy conversion systems because it can save time and resources by revealing the real avoidable inefficiencies and costs, their sources, and the necessary steps for improving a specific process.

This paper presents the first application of a complete advanced exergoeconomic analysis to a complex power plant as a continuation of the application of conventional exergetic and exergoeconomic analyses and of the advanced exergetic analysis presented in Refs. [6,7]. The same way a conventional exergoeconomic analysis supplements a conventional exergetic analysis, the advanced exergoeconomic analysis supplements the advanced exergetic analysis. In exergetic analyses we calculate the exergy destruction within each plant component, while in

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exergoeconomic analyses we assign costs to these exergy destructions, and we reveal improvement strategies based on trades-offs between costs of exergy destruction and investment costs.

## Methodology

The complete methodology of an advanced exergoeconomic analysis is described in Ref. [17], while an application of this analysis to the power plant discussed in the present paper can be found in Ref. [6]. The methodology of the advanced exergoeconomic analysis for splitting the investment cost and the cost of exergy destruction for this plant is briefly presented below.

**Splitting the Costs.** The total cost, on which the performance of component $k$ is initially evaluated, is the sum of its cost of exergy destruction, $\dot{C}_{D,k}$, and its investment cost, $\dot{Z}_k$, i.e., $\dot{C}_{D,k} + \dot{Z}_k$. These costs are split into endogenous/exogenous parts $\left(\dot{C}^{EN}_{D,k}/\dot{C}^{EX}_{D,k} \text{ and } \dot{Z}^{EN}_{D,k}/\dot{Z}^{EX}_{D,k}\right)$ and avoidable/unavoidable parts $\left(\dot{C}^{AV}_{D,k}/\dot{C}^{UN}_{D,k} \text{ and } \dot{Z}^{AV}_k/\dot{Z}^{UN}_k\right)$, which are then further separated into their respective endogenous and exogenous parts $\left(\dot{C}^{UN,EN}_{D,k}/\dot{C}^{UN,EX}_{D,k}, \dot{C}^{AV,EN}_{D,k}/\dot{C}^{AV,EX}_{D,k}, \dot{Z}^{UN,EN}_k/\dot{Z}^{UN,EX}_k, \text{ and } \dot{Z}^{AV,EN}_k/\dot{Z}^{AV,EX}_k\right)$ in analogy to the theory applied in splitting the exergy destruction.

With the exception of the unavoidable investment cost, no new simulations are required for further cost estimates, since the required data can be derived either from a simulation of the real case of the plant (assumed or given reference operating conditions of the plant) or from the advanced exergetic analysis [6].

**Splitting the Cost of Exergy Destruction, $\dot{C}_{D,k}$.** Depending on whether the cost of exergy destruction within component $k$, $\dot{C}_{D,k}$, can be avoided or not, and on whether it is caused by internal operating conditions of the component $k$ itself or by component interactions, this cost is split into avoidable/unavoidable and endogenous/exogenous parts, respectively, as:

$$\left\{\begin{array}{l} \dot{C}^{UN}_{D,k} = c^{real}_{F,k}\dot{E}^{UN}_{D,k} \\ \dot{C}^{AV}_{D,k} = \dot{C}^{real}_{D,k} - \dot{C}^{UN}_{D,k} \end{array}\right\} \text{ and } \left\{\begin{array}{l} \dot{C}^{EN}_{D,k} = c^{real}_{F,k}\dot{E}^{EN}_{D,k} \\ \dot{C}^{EX}_{D,k} = \dot{C}^{real}_{D,k} - \dot{C}^{EN}_{D,k} \end{array}\right\} \tag{1}$$

Here, $c^{real}_{F,k}$ is the average cost per unit of exergy of the fuel provided to component $k$ in the base case, and $\dot{E}^{UN}_{D,k}$ is the unavoidable part of the exergy destruction already calculated in the advanced exergetic analysis [6]. The calculations of the unavoidable exergy destruction assume the most favorable operating conditions for the components, resulting in the lowest possible exergy destruction that cannot be further reduced.

The avoidable/unavoidable parts of $\dot{C}_{D,k}$ are further divided into their endogenous/exogenous parts:

$$\left\{\begin{array}{ll} \dot{C}^{UN,EN}_{D,k} & = c^{real}_{f,k}\dot{E}^{UN,EN}_{D,k} \\ \dot{C}^{UN,EX}_{D,k} & = \dot{C}^{UN}_{D,k} - \dot{C}^{UN,EN}_{D,k} \end{array}\right\} \text{ and } \left\{\begin{array}{ll} \dot{C}^{AV,EN}_{D,k} & = \dot{C}^{EN}_{D,k} - \dot{C}^{UN,EN}_{D,k} \\ \dot{C}^{AV,EX}_{D,k} & = \dot{C}^{AV}_{D,k} - \dot{C}^{AV,EN}_{D,k} \end{array}\right\} \tag{2}$$

The unavoidable endogenous exergy destruction, $\dot{E}^{UN,EN}_{D,k}$, is the part of the unavoidable exergy destruction caused by the operation of component $k$ itself (endogenous). For its calculation, see Ref. [6].

**Splitting the Investment Costs, $\dot{Z}_k$.** The endogenous and exogenous parts of the investment cost are related to internal operating conditions and to mutual interactions of the plant components, respectively. These parts are calculated using the group of equations in Eq. (3).

$$\dot{Z}^{EN}_k = \dot{E}^{EN}_{P,k}\left(\frac{\dot{Z}_k}{\dot{E}_{P,k}}\right)^{real} \text{ and } \dot{Z}^{EX}_k = \dot{Z}^{real}_k - \dot{Z}^{EN}_k \tag{3}$$

Here, $\dot{E}^{EN}_{P,k}$ is the exergy rate of the product of component $k$ when all other components operate theoretically (without any internal irreversibility). For calculating the unavoidable investment cost of heat exchangers, a new simulation for each component is required. The least favorable operating conditions are assumed with low effectiveness and high irreversibilities. The assumptions for simulating unavoidable conditions depend on the decision maker and are somewhat arbitrary. The unavoidable cost of other components, such as steam turbines, etc., is predefined, due to limited possible design changes for these components. The specific assumptions made for all of the components are shown in Table 1.

The purchased equipment cost (PEC) is recalculated for the unavoidable conditions ($PEC^{UN}_k$), and it is then used to calculate the cost rate $\dot{Z}^{UN}_k$ using Eq. (4). Then, the avoidable cost is estimated with Eq. (5).

$$\dot{Z}^{UN}_k = \left(\frac{PEC^{UN}_k}{PEC^{real}_k}\right) \times \dot{Z}^{real}_k \tag{4}$$

$$\dot{Z}^{AV}_k = \dot{Z}^{real}_k - \dot{Z}^{UN}_k \tag{5}$$

The avoidable/unavoidable parts of the investment cost are further divided into endogenous/exogenous parts as:

$$\left\{\begin{array}{l} \dot{Z}^{UN,EN}_k = \dot{E}^{EN}_{P,k}\left(\frac{\dot{Z}_k}{\dot{E}^{real}_{P,k}}\right)^{UN} \\ \dot{Z}^{UN,EX}_k = \dot{Z}^{UN}_k - \dot{Z}^{UN,EN}_k \end{array}\right\} \text{ and } \left\{\begin{array}{ll} \dot{Z}^{AV,EN}_k & = \dot{Z}^{EN}_k - \dot{Z}^{UN,EN}_k \\ \dot{Z}^{AV,EX}_k & = \dot{Z}^{AV}_k - \dot{Z}^{AV,EN}_k \end{array}\right\} \tag{6}$$

**Total Avoidable Costs, $\sum_{\substack{r=1\\ r\neq k}}^{n}\dot{C}^{AV,k}_{D,r}$ and $\sum_{\substack{r=1\\ r\neq k}}^{n}\dot{Z}^{AV,k}_{r}$.** To identify the real importance and the real potential for improving the $k^{\text{th}}$ plant component, both the sum of the avoidable costs associated with exergy destruction and the sum of the avoidable investment costs of the component are calculated [20].

$$\dot{C}^{AV,\sum}_{D,k} = \dot{C}^{AV,EN}_{D,k} + \sum_{\substack{r=1\\ r\neq k}}^{n}\dot{C}^{AV,EX,k}_{D,r} \tag{7}$$

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

$\sum_{\substack{r=1\\ r\neq k}}^{n}\dot{C}^{AV,EX,k}_{D,r}$ and $\sum_{\substack{r=1\\ r\neq k}}^{n}\dot{Z}^{AV,EX,k}_{r}$ are caused by component $k$ and represent the sums of avoidable costs associated with the exogenous exergy destruction within component $r$ and of exogenous investment cost associated with component $r$, respectively.

The term related to the avoidable exogenous investment cost is calculated for each component $r$ separately via the unavoidable exogenous investment cost caused by component $k$, $\dot{Z}^{UN,EX,k}_r$:

$$\dot{Z}^{AV,EX,k}_r = \dot{Z}^{EX}_r - \dot{Z}^{UN,EX,k}_r \tag{9}$$

**Table 1 Assumptions for calculating the unavoidable investment cost of the plant components**

| *Heat exchangers* | ΔT = 75–100°C |
|---|---|
| *Pumps* | 85% of $\dot{Z}^{real}_k$ |
| *CC* | 80% of $\dot{Z}^{real}_k$ |
| *Compressor* | 85% of $\dot{Z}^{real}_k$ |
| *GT1* | 90% of $\dot{Z}^{real}_k$ |
| *STs* | 90% of $\dot{Z}^{real}_k$ |

The unavoidable exogenous part of the investment cost is calculated through the unavoidable endogenous cost, $\dot{Z}_r^{UN,EN}$:

$$\dot{Z}_r^{UN,EX,k} = \dot{Z}_r^{UN,EN,r+k} - \dot{Z}_r^{UN,EN} \tag{10}$$

where,

$$\dot{Z}_{D,r}^{UN,EN,r+k} = \dot{E}_{P,r}^{UN,EN,r+k}\left(\frac{\dot{Z}}{\dot{E}_p}\right)_r^{UN} \tag{11}$$

$\dot{E}_{P,r}^{UN,EN,r+k}$ is the exergy rate of the product of component $r$, when components $r$ and $k$ operate under real conditions and all remaining components operate theoretically, i.e., without internal irreversibilities.

The unavoidable endogenous cost of exergy destruction is calculated with Eq. (12).

$$\dot{C}_{D,r}^{AV,EX,r+k} = c_{F,r}^{real}\dot{E}_{D,r}^{AV,EX} \tag{12}$$

Here the $\dot{E}_{D,r}^{AV,EX}$ is calculated in an advanced exergetic analysis [6,17], similarly to the investment cost described above.

The total avoidable costs associated with exergy destruction and investment expenditures reveal the most influential components and pinpoint the necessary actions to improve the overall system.

## The Combined Cycle Power Plant

**Process Description.** The power plant examined in this paper is a three-pressure-level combined cycle plant. It has only one product – electricity – and works with natural gas that, for simplicity reasons, was assumed to be pure methane. This plant has been used in Ref. [21] as a reference for the comparison and simulation of several power plants with $CO_2$ capture. The plant analyses using advanced exergy-based methods are an important step in the application of these newly developed methods to complex plants. In future work, the results obtained from this application will be compared to those obtained by plants with $CO_2$ capture.

The configuration of the power plant is shown in Fig. 1. High-temperature flue gas (628 kg/s) exits the gas turbine (GT) of the plant and is led into the heat-recovery steam generator (HRSG), where it provides thermal energy to produce steam at three different pressure levels, 124/22/4.1 bars. The combustion products enter the HRSG with a pressure of 1.058 bars at 580 °C and are rejected to the atmosphere at 1.013 bars and 95 °C. Selected thermodynamic variables from the simulation of the plant and a more detailed description of the process can be found in Refs. [4,5] where the results from conventional exergy-based analyses are also presented. Improved design alternatives of the considered plant, as indicated by the current exergy-based analyses, will be investigated in the future.

## Results and Discussion

**Avoidable/Unavoidable Cost of Exergy Destruction, $\dot{C}_{D,k}^{AV}/\dot{C}_{D,k}^{UN}$.** The calculations used for splitting the cost of exergy destruction, $\dot{C}_{D,k}$, are based on the group of Eqs. (1) and (2). The results are shown in Table 2. Aside from those of the expander of the GT system and the high-pressure steam turbines (HPST) and intermediate-pressure steam turbines (IPST), the larger part of the $\dot{C}_{D,k}$ is unavoidable for the individual components of the plant. In the combustion chamber (CC), the unavoidable cost of exergy destruction is more than double the avoidable part. Furthermore, almost 61% of the unavoidable cost is endogenous. For the CC, although the avoidable part of the $\dot{C}_{D,CC}$ is much lower than the unavoidable part, its absolute value is significantly larger than that of the remaining plant components.

The effect of components on the overall system is expressed by the range of their absolute values of costs. The main part of the avoidable cost of exergy destruction for the most influential components (the components of the GT system and the LPST that have the highest absolute values) is endogenous, i.e., it stems from the operation of the components themselves.

Evaluating the sources of the cost of exergy destruction, the overall plant can potentially be improved through improvement of the CC, the expander, the LPST, and the compressor. A mean value of 30% of the cost of exergy destruction caused by the GT system and 25% of that caused by the LPST can be avoided through changes in the operating conditions of the respective components.

The signs of the values presented in Table 2 and the following Tables represent positive or negative component interactions, i.e.,

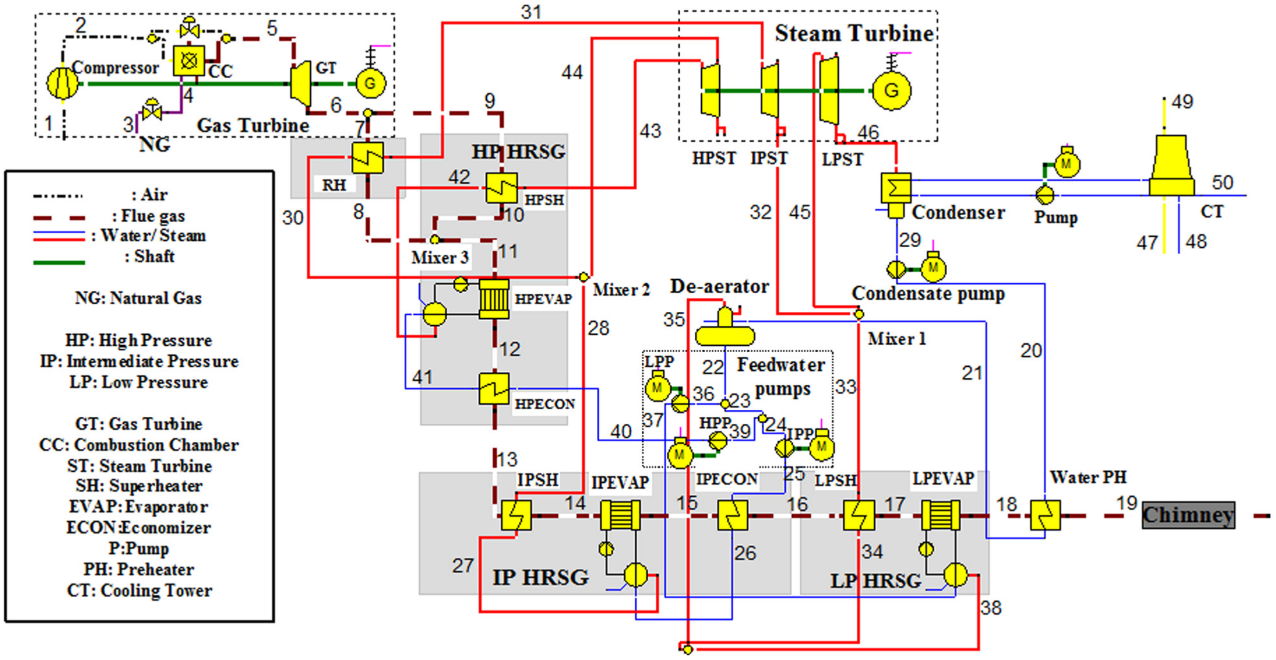

**Fig. 1 Structure of the plant**

Table 2 Splitting the cost of exergy destruction, $\dot{C}_{D,k}$

| | | | | | | $\dot{C}_{D,k}^{AV}$ | | $\dot{C}_{D,k}^{UN}$ | |
|---|---|---|---|---|---|---|---|---|---|
| | $\dot{C}_{D,k}^{real}$ [€/h] | $\dot{C}_{D,k}^{UN}$ [€/h] | $\dot{C}_{D,k}^{AV}$ [€/h] | $\dot{C}_{D,k}^{EN}$ [€/h] | $\dot{C}_{D,k}^{EX}$ [€/h] | $\dot{C}_{D,k}^{AV,EN}$ [€/h] | $\dot{C}_{D,k}^{AV,EX}$ [€/h] | $\dot{C}_{D,k}^{UV,EN}$ [€/h] | $\dot{C}_{D,k}^{UN,EX}$ [€/h] |
| *Compressor* | 682.8 | 375.9 | 306.9 | 417.0 | 265.8 | 188.9 | 118.1 | 228.2 | 147.7 |
| *CC* | 7,276.3 | 4,936.4 | 2,339.9 | 6,372.2 | 904.1 | 2,055.0 | 284.9 | 4,317.2 | 619.2 |
| *GT expander* | 1,127.9 | 427.8 | 700.0 | 746.2 | 381.6 | 402.5 | 297.5 | 343.7 | 84.1 |
| *HP ST* | 152.9 | 56.6 | 96.2 | 80.2 | 72.7 | 44.2 | 52.0 | 36.0 | 20.7 |
| *IP ST* | 157.4 | 67.5 | 89.9 | 85.9 | 71.4 | 38.6 | 51.3 | 47.3 | 20.2 |
| *LP ST* | 734.3 | 388.4 | 345.9 | 458.5 | 275.8 | 189.9 | 156.0 | 268.6 | 119.8 |
| *Cond. Pump* | 0.7 | 0.1 | 0.6 | 0.2 | 0.5 | 0.1 | 0.4 | 0.1 | 0.0 |
| *HP Pump* | 11.7 | 3.7 | 8.0 | 4.4 | 7.3 | 2.2 | 5.8 | 2.2 | 1.5 |
| *IP Pump* | 0.7 | 0.3 | 0.4 | 0.5 | 0.2 | 0.2 | 0.3 | 0.4 | **−0.1** |
| *LP Pump* | 0.1 | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 |
| *Reheater* | 141.9 | 92.7 | 49.2 | 109.5 | 32.4 | 48.1 | 1.1 | 61.4 | 31.3 |
| *HPSH* | 184.5 | 136.8 | 47.7 | 98.4 | 86.1 | 26.7 | 21.0 | 71.7 | 65.1 |
| *HP Evap* | 205.3 | 168.4 | 36.9 | 110.6 | 94.7 | 8.8 | 28.1 | 101.8 | 66.6 |
| *HP Econ* | 220.5 | 149.8 | 70.7 | 123.7 | 96.8 | 27.2 | 43.4 | 96.4 | 53.4 |
| *IPSH* | 3.1 | 0.3 | 2.7 | 4.7 | **−1.7** | 4.1 | **−1.4** | 0.6 | **−0.3** |
| *IP Evap* | 23.8 | 15.3 | 8.5 | 22.6 | 1.2 | 9.0 | **−0.5** | 13.6 | 1.7 |
| *IP Econ* | 10.2 | 6.6 | 3.6 | 8.9 | 1.4 | **−0.8** | 4.4 | 9.7 | **−3.1** |
| *LPSH* | 21.0 | 8.8 | 12.2 | 9.9 | 11.1 | 6.6 | 5.5 | 3.2 | 5.6 |
| *LP Evap* | 195.4 | 164.2 | 31.2 | 93.1 | 102.3 | 1.6 | 29.6 | 91.5 | 72.7 |
| *LP Econ* | 208.5 | 107.7 | 100.8 | 121.1 | 87.4 | 45.0 | 55.9 | 76.1 | 31.6 |

they show whether improving the remaining components would result in an improvement or a deterioration of the efficiency of the component being considered. For example, a deterioration of the efficiency of some components in the plant could lead to an improvement of the IPSH (negative exogenous cost of exergy destruction of the IPSH). This, however, does not mean that we would need to decrease the efficiency of all remaining components of the plant but only decrease the efficiency of the components that influence the IPSH negatively (as this is partly shown in Table 4). However, since the IPSH is not a significant component of the plant, such an action should not be considered.

**Avoidable/Unavoidable Investment Cost, $\dot{Z}_k^{AV}/\dot{Z}_k^{UN}$.** The calculation of the unavoidable investment cost, $\dot{Z}_k^{UN}$, of heat exchangers involves additional simulations with new operating conditions. The assumptions made to calculate this cost are shown in Table 1. High temperature differences and pressure drops, as well as low efficiencies, are used to estimate the lowest possible investment cost. The design of steam turbines, pumps, and gas turbine systems cannot be changed drastically; thus, most of their investment cost is predetermined as unavoidable.

The results of splitting the investment costs, $\dot{Z}_k$, are presented in Table 3. As already mentioned, for the components constituting the GT system, the largest part of the investment cost is unavoidable $\left(\dot{Z}_k^{UN}\right)$. Moreover, for all components, with the exception of the low-pressure superheater (LPSH) and the low-pressure pump, the larger part of the investment cost is endogenous $\left(\dot{Z}_k^{EN}\right)$. In addition, the differences between the endogenous and exogenous parts of investment cost are very significant in some cases. For example,

Table 3 Splitting the investment cost

| | | | | | | $\dot{Z}_k^{AV}$ | | $\dot{Z}_k^{UN}$ | |
|---|---|---|---|---|---|---|---|---|---|
| | $\dot{Z}_k^{real}$ [€/h] | $\dot{Z}_k^{UN}$ [€/h] | $\dot{Z}_k^{AV}$ [€/h] | $\dot{Z}_k^{EN}$ [€/h] | $\dot{Z}_k^{EX}$ [€/h] | $\dot{Z}_k^{AV,EN}$ [€/h] | $\dot{Z}_k^{AV,EX}$ [€/h] | $\dot{Z}_k^{UN,EN}$ [€/h] | $\dot{Z}_k^{UN,EX}$ [€/h] |
| *Compressor* | 1,297.0 | 1,102.5 | 194.6 | 786.7 | 510.3 | 118.0 | 76.6 | 668.7 | 433.8 |
| *CC* | 926.5 | 741.2 | 185.3 | 810.3 | 116.1 | 162.1 | 23.2 | 648.3 | 92.9 |
| *GT expander* | 1,482.3 | 1,334.1 | 148.2 | 1,192.1 | 290.2 | 119.2 | 29.0 | 1,072.9 | 261.2 |
| *HP ST* | 165.6 | 149.0 | 16.6 | 105.3 | 60.3 | 10.5 | 6.0 | 94.7 | 54.3 |
| *IP ST* | 299.7 | 269.8 | 30.0 | 210.0 | 89.7 | 21.0 | 9.0 | 189.0 | 80.7 |
| *LP ST* | 696.3 | 626.7 | 69.6 | 481.4 | 214.9 | 48.1 | 21.5 | 433.3 | 193.4 |
| *Cond. Pump* | 6.7 | 5.7 | 1.0 | 5.2 | 1.5 | 0.8 | 0.2 | 4.5 | 1.3 |
| *HP Pump* | 38.2 | 32.4 | 5.7 | 22.5 | 15.6 | 3.4 | 2.3 | 19.2 | 13.3 |
| *IP Pump* | 7.3 | 6.2 | 1.1 | 9.3 | **−2.0** | 1.4 | **−0.3** | 7.9 | **−1.7** |
| *LP Pump* | 2.4 | 2.0 | 0.4 | 0.0 | 2.4 | 0.0 | 0.4 | 0.0 | 2.0 |
| *Reheater* | 105.4 | 49.9 | 55.5 | 69.8 | 35.6 | 36.7 | 18.7 | 33.1 | 16.9 |
| *HPSH* | 149.5 | 69.3 | 80.2 | 78.3 | 71.2 | 42.0 | 38.2 | 36.3 | 33.0 |
| *HP Evap* | 183.6 | 119.8 | 63.8 | 111.0 | 72.6 | 38.5 | 25.2 | 72.4 | 47.4 |
| *HP Econ* | 88.6 | 52.7 | 35.9 | 57.0 | 31.6 | 23.1 | 12.7 | 33.8 | 18.9 |
| *IPSH* | 3.8 | 1.3 | 2.5 | 6.8 | **−3.0** | 4.5 | **−2.0** | 2.3 | **−1.0** |
| *IP Evap* | 65.0 | 36.9 | 28.1 | 57.9 | 7.1 | 25.1 | 3.1 | 32.8 | 4.0 |
| *IP Econ* | 5.2 | 3.2 | 1.9 | 7.5 | **−2.4** | 2.8 | **−0.9** | 4.7 | **−1.5** |
| *LPSH* | 18.3 | 8.9 | 9.4 | 6.7 | 11.6 | 3.5 | 6.0 | 3.3 | 5.6 |
| *LP Evap* | 172.8 | 104.2 | 68.7 | 96.3 | 76.5 | 38.3 | 30.4 | 58.0 | 46.1 |
| *LP Econ* | 92.7 | 52.5 | 40.3 | 65.5 | 27.2 | 28.5 | 11.8 | 37.1 | 15.4 |

Table 4 Source of the exogenous costs for selected components

| In | By: | *Compressor* | *GT expander* | *LPST* | *GT generator* | **MEXO** |
|---|---|---|---|---|---|---|
| ***CC*** | $\dot{C}_{D,k}$[€/h] | 172.6 | 293.4 | 110.5 | 71.6 | 105.4 |
| | $\dot{Z}_k$ [€/h] | 21.6 | 37.3 | 14.1 | 9.1 | −1.6 |
| In | By: | ***CC*** | *Compressor* | *LPST* | *GT generator* | |
| *GT expander* | $\dot{C}_{D,k}$ [€/h] | 61.8 | 16.3 | 13.6 | 8.1 | 263.4 |
| | $\dot{Z}_k$ [€/h] | 142.9 | 37.7 | 21.8 | 12.9 | 45.6 |
| In | By: | ***CC*** | *GT expander* | *LPST* | *GT generator* | |
| *Compressor* | $\dot{C}_{D,k}$ [€/h] | 196.3 | 17.7 | 6.7 | 4.8 | 31.2 |
| | $\dot{Z}_k$ [€/h] | 378.5 | 33.4 | 12.6 | 9.1 | 58.3 |
| In | By: | *GT expander* | ***CC*** | *Compressor* | *IPST* | |
| *LPST* | $\dot{C}_{D,k}$ [€/h] | 80.7 | 53.0 | 14.0 | 9.0 | 110.1 |
| | $\dot{Z}_k$ [€/h] | 84.7 | 55.6 | 14.7 | 9.5 | 40.8 |

in the CC, the endogenous investment cost, $\dot{Z}_{D,k}^{EN}$, is almost seven times higher than the exogenous part, $\dot{Z}_{D,k}^{EX}$, while in the expander, $\dot{Z}_{D,k}^{EN}$ is almost four times higher than $\dot{Z}_{D,k}^{EX}$. For the compressor, this difference is found to be much smaller, while its high $\dot{Z}_{D,k}^{EX}$ shows that it is greatly influenced by the remaining components of the plant.

For all components, with the exception of the LPSH, most of the $\dot{Z}_k^{AV}$ is endogenous. For the compressor, the CC, and the expander, the difference between the endogenous and exogenous parts is relatively large. Additionally, the larger part of the $\dot{Z}_k^{UN}$ of the components is also endogenous.

In summary, for the majority of the components the larger part of investment cost is unavoidable, with the exception of some heat exchangers. Additionally, most of the exogenous values are relatively low, when compared to the endogenous values, showing that component interactions are not as important as the internal operation of the components. Specifically, 61%, 87%, and 80% of the investment cost of the compressor, the CC, and the expander of the GT system (the components with the highest investment cost rates) can be avoided through operating changes in the components themselves.

**Splitting the Exogenous Costs, $\dot{C}_{D,k}^{EX}$ and $\dot{Z}_k^{EX}$.** Although the exogenous costs are of relatively low significance when compared to the endogenous costs, their specific sources can reveal additional improvement potential for the overall plant. The components with the highest costs, both investment-related and exergy destruction-related, are the components of the GT system and the LPST. The splitting of the exogenous costs for these four components into their most important sources is shown in Table 4.

The main source of the exogenous costs for the compressor and the expander is the CC, while for both the LPST and the CC, the main contributor is the expander. The mexogenous (MEXO) cost is the cost difference between the exogenous cost (shown in Tables 2 and 3) and the sum of the split parts caused to each of the remaining components (partly shown in Table 4) [15,17]. The mexogenous values are associated with the interactions of the component being considered simultaneously with more than one of the remaining plant components. Thus, the mexogenous values of exergy destruction and cost could be further split (calculated in more detail) only through significant additional work, which is not deemed to be of value here.

**Total Avoidable Costs, $\sum_{\substack{r=1\\ r\neq k}}^{n}\dot{C}_{D,r}^{AV,k}$ and $\sum_{\substack{r=1\\ r\neq k}}^{n}\dot{Z}_r^{AV,k}$.** The total avoidable cost associated with component $k$ is calculated as the sum of its endogenous cost of exergy destruction or its investment cost and the total cost of exergy destruction or investment cost caused by this component to the remaining components (part of the exogenous cost of exergy destruction or exogenous investment cost of the other components). The results for the most influential components of the plant are shown in Table 5. The avoidable exogenous costs of component $k$ are calculated using Eqs. (9) and (12).

The effect of the CC on the remaining components is critical because large values of the investment cost rate of the other components stem from its operation. Although the avoidable endogenous cost of the expander and the compressor are similar, the avoidable exogenous cost of the expander is almost seven times higher due to the high total exogenous cost caused by it to the remaining components of the plant. For the compressor, the LPST, and the expander 17–20% of their exogenous cost is avoidable, while almost 84% of the exogenous investment cost rate of the CC is unavoidable. Nonetheless, the CC has both the highest absolute avoidable endogenous and exogenous investment cost; thus, it is shown to be the most important component. The LPST has the lowest avoidable exogenous and endogenous investment cost rates, resulting in an approximately three times lower total exogenous investment cost rate when compared to the compressor.

While the differences in the investment cost rates are kept at relatively low levels, the differences in the exergy destruction-related costs show large spreads among the different components. The avoidable exogenous cost of exergy destruction of the expander and the CC are at similarly high levels. However, the significantly larger endogenous avoidable cost of exergy destruction for the CC results in a fourfold higher overall cost of exergy destruction. The compressor follows the expander with approximately half of the overall cost. Comparing the compressor with the LPST, both components have almost the same avoidable endogenous cost of exergy destruction, but because the latter has a lower avoidable influence on the remaining components, it results in an approximately 8% lower overall avoidable cost.

Table 5 Total avoidable cost of exergy destruction and investment cost caused by component *k* (Eqs. (7)–(8))

| *Component, k* | $\sum_{\substack{r=1\\ r\neq' k}}^{n}\dot{C}_{D,r}^{EX,k}$ [€/h] | $\sum_{\substack{r=1\\ r\neq' k}}^{n}\dot{C}_{D,r}^{AV,EX,k}$ [€/h] | $\dot{C}_{D,k}^{AV,EN}$ [€/h] | $\dot{C}_{D,k}^{AV,\Sigma}$ [€/h] | $\sum_{\substack{r=1\\ r\neq' k}}^{n}\dot{Z}_{r}^{EX,k}$ [€/h] | $\sum_{\substack{r=1\\ r\neq' k}}^{n}\dot{Z}_{r}^{AV,EX,k}$ [€/h] | $\dot{Z}_{k}^{AV,EN}$ [€/h] | $\dot{Z}_{k}^{AV,\Sigma}$ [€/h] |
|---|---|---|---|---|---|---|---|---|
| *CC* | 526.8 | 160.6 (7%) | 2055.0 (93%) | 2215.6 | 680.5 | 108.5 (40%) | 162.1 (60%) | 270.5 |
| *GT expander* | 542.5 | 150.4 (27%) | 402.5 (73%) | 552.9 | 327.3 | 67.1 (36%) | 119.2 (64%) | 186.3 |
| *Compressor* | 224.9 | 76.9 (29%) | 188.9 (71%) | 265.8 | 100.5 | 17.8 (13%) | 118.0 (87%) | 135.6 |
| *LPST* | 140.2 | 54.4 (22%) | 189.9 (78%) | 244.3 | 59.0 | 10.0 (17%) | 48.1 (83%) | 58.1 |

## Conclusions

An advanced exergoeconomic analysis of a combined cycle power plant has been presented in this paper. This analysis is conducted using assumptions made by the analyst. Although the specific values obtained depend on these assumptions, the conclusions extracted from the results are usually independent of them. With the assumptions made here, the power plant shows some improvement potential related to the avoidable investment cost and the avoidable cost of exergy destruction. The most important components with respect to the avoidable investment cost are the compressor, the expander, and the combustion chamber. This ranking order changes when the avoidable cost of exergy destruction is considered. In this case, the combustion chamber comes first, the expander second, the low-pressure steam turbine third, and the compressor fourth. This priority change is due to the relatively large exergy destruction within the combustion chamber compared to the remaining components of the GT system and to the higher cost of exergy destruction for the steam turbine compared to the compressor.

For the three most influential components of the plant, the largest part of their investment cost rates is unavoidable. For the cost of exergy destruction, the results are similar, since the largest parts of the cost of exergy destruction of the combustion chamber and the compressor are unavoidable. On the other hand, most of the exergy destruction costs are avoidable for the expander. For both the investment cost and the cost of exergy destruction, the interactions of the components, represented by the exogenous part of the costs, are of lower importance, since for the majority of the components, the endogenous part of the costs is significantly larger.

To examine the overall significance of the different plant components, the total avoidable cost of exergy destruction and investment cost have been calculated at the component level. The improvement priority of the components based on both the cost of exergy destruction and the investment cost is: (1) the combustion chamber, (2) the expander, (3) the compressor, and (4) the low-pressure steam turbine. For all four components, the main source of the avoidable costs is the internal operating conditions of the components themselves (endogenous). Nonetheless, for the combustion chamber and the expander, the difference between the endogenous and exogenous parts is relatively low. In the case of the cost of exergy destruction, the avoidable endogenous values of the considered components are always higher than their avoidable exogenous values.

Summarizing the recommendations for improvement, efforts should focus on internal improvements for the most important components identified above. Changes in the endogenous values will most probably affect the overall efficiency and costs positively, through the component interactions (shown through the exogenous parts). Thus, improvements at the component level will lead to an enhanced improvement of the overall plant.

The application of a novel advanced exergoeconomic analysis to a combined cycle power plant presented is one of the first complete applications of this analysis to a complex power plant. The purpose of this application is to validate the methodology and to demonstrate its advantages (the additional information that is obtained) that usually justify the additional work necessary for applying this novel approach. Most of the results obtained by advanced exergy-based analyses cannot be obtained by any other approaches. Conventional and advanced methods might coincide in assigning the priority improvement of some components, but in advanced methods, (1) the effects of component interactions are revealed, and (2) while the improvement priority of conventional methods is based on the total amount of exergy destruction/cost/environmental impact, here it is based strictly on the avoidable part of these values. The magnitude of the two (total and avoidable values) can differ significantly in some cases. Additionally, it should be emphasized that to improve a system successfully, its component interactions must be considered together with their avoidable exergy destruction, cost, or environmental impact.

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## Nomenclature

$c$ = cost per unit of exergy (€/GJ)
$\dot{C}$ = cost rate associated with an exergy stream, (€/h)
$\dot{E}$ = exergy rate (MW)
$\dot{Z}$ = cost rate associated with capital investment (€/h)

## Subscripts

$D$ = exergy destruction
$F$ = fuel (exergy)
$P$ = product (exergy)
$k$ = component
$L$ = loss

## Superscripts

$AV$ = avoidable
$AV,EN$ = avoidable endogenous
$AV,EX$ = avoidable exogenous
$UN$ = unavoidable
$UN,EN$ = unavoidable endogenous
$UN,EX$ = unavoidable exogenous

## Greek Symbols

$\varepsilon$ = exergetic efficiency (%)

## Abbreviations

EVAP = evaporator
ECON = economizer
GT = gas turbine
HP = high pressure
HRSG = heat recovery steam generator
IP = intermediate pressure
LP = low pressure
SH = superheater
ST = steam turbine

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