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An Exergy-Based Study on the Relationship between Costs and Environmental Impacts in Power Plants

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Abstract

Exergy-based (exergetic, exergoeconomic and exergoenvironmental) analyses, are used for designing, assessing and improving energy conversion systems. In an exergoeconomic analysis, thermodynamic inefficiencies – represented by exergy destruction – are used in combination with investment costs to calculate the "cost-optimal" layout of a plant. Analogously, in an exergoenvironmental analysis, the aim is to minimize the total environmental impact of a plant. Until today exergoeconomic and exergoenvironmental analyses have been used as separate and

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distinct tools and the improvement of a plant has been considered in terms of the reduction of either costs or environmental impact. To simultaneously decrease the investment costs and the component-related (manufacturing or construction-related) environmental impacts, their relationship with exergy destruction must be studied in parallel. This paper examines the relationship between exergoeconomic and exergoenvironmental data under various plant operating conditions. A combined-cycle power plant is analyzed and options for a simultaneous improvement from the thermodynamic, economic and environmental viewpoints are discussed.

Keywords

Exergy analysis; Exergoeconomic Analysis; Exergoenvironmental Analysis.

Nomenclature

B	environmental impact associated with an exergy stream (Points)
b	environmental impact per unit of exergy (Points/J)
C	cost associated with an exergy stream (€)
c	cost per unit of exergy (€/J)
E	exergy (J)
e	specific exergy (J/kg)
j	j th stream
k	k th component
m	mass (kg)
p	pressure (bar)
T	temperature (ºC)
Y	construction-of-component-related environmental impact (Points)

Z	cost associated with investment expenditures (€)

Greek symbols

•	time rate
Δ	difference
ε	exergetic efficiency
η	isentropic efficiency
λ	stoichiometric amount of air

Subscripts

D	refers to exergy destruction
F	fuel
P	product
tot	refers to the total system

1 Introduction

In the last decades, interest in complex analytical methods that simultaneously include energy (exergy), economic, and environmental considerations has been growing. Such methods reveal:

- The thermodynamic performance of systems and the individual processes that cause the real thermodynamic inefficiencies,
- The economic expenditures linked to equipment and the real thermodynamic inefficiencies, their relations and interdependencies,
- The environmental impacts of equipment and of real thermodynamic inefficiencies, their relation and interdependencies and

- Actions that could decrease the cost(s) of the overall product(s), while, at the same time, enhancing the efficiency, and decreasing the environmental impact of the evaluated energy conversion system.

An exergoeconomic analysis has been applied to numerous energy conversion systems; different approaches for the exergoeconomic analysis have been discussed [1-3], and a review of publications related to the application of exergoeconomic analysis to cogeneration systems has been published [4].

Furthermore, different approaches that combine exergetic and environmental analyses have been developed: the cumulative exergy consumption [5, 6], the exergoecological analysis [7], the extended exergy accounting [8, 9], the environomic analysis [10] and the exergoenvironmental analysis [11]. These methods have been applied to various energy conversion systems, while the methods cumulative exergy consumption and extended exergy accounting can also be applied to countries. It should be noted that some publications use the term exergoenvironmental analysis to merely indicate the environmental impact of CO_2, NO_x and other pollutants, while at the same time ignoring the exergy destruction-related environmental impact. Sometimes, the environomic analysis is reported as an exergoenvironmental analysis. Only the use of precisely defined terms [12] eliminates this confusion.

There are publications that discuss the application of the three analyses, i.e. exergetic, economic and environmental, conducted independently. For example, in Refs. [13, 14]: (a) the exergetic analysis discusses only the value of the exergetic efficiency of the overall system, (b) the economic analysis abbreviates to the cost of the generated electricity as a function of some economic input data, and (c) the environmental analysis abbreviates to the value of emitted CO_2. Another group of publications (e.g., Refs. [15, 16]) deals with the application of an evolutionary algorithm that finds the surface of optimal solutions defined by three objective functions associated with energetic, economic and environmental aspects. Further improvements to energy conversion systems from the thermodynamic, economic, and environmental viewpoints are obtained with the aid of advanced exergy-based methods [17-19]. These include (a) an advanced exergetic analysis, (b) an advanced exergoeconomic analysis, and (c) an advanced exergoenvironmental analysis. All these analyses have a similar methodological background.

One of the first attempts to combine these two exergy-based methods is reported in Ref. [20]. In this work we investigate methods to improve an energy conversion system by simultaneously decreasing costs and environmental impacts. It should be noted that it is not our purpose to assign costs to environmental impacts (or vice versa) because this process is still arbitrary. The results from the performed environmental (Life cycle assessment, LCA) and cost analyses are obtained independent from one another.

2 Exergy-based analyses

2.1 Exergetic analysis

The exergetic balance and exergetic efficiency of a component *k*, based on its exergy rates of fuel and product ($\dot{E}_{F,k}$ and $\dot{E}_{P,k}$) [1,3,21] are $\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k}$ and $\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}$, respectively. $\dot{E}_{D,k}$ is the total exergy destruction within the component.

More variables, as well as details related to the methodology of the exergetic analysis can be found in numerous publications (e.g., Refs. 17-21).

2.2 Exergoeconomic analysis

An exergoeconomic analysis reveals the origin, magnitude and location of costs of thermodynamic inefficiencies in energy conversion systems. The analysis is realized at the component level of a system and shows the relative cost importance the components constituting the structure under examination, as well as alternative solutions for enhancing the cost effectiveness of the overall system.

The exergoeconomic methodology [3,21] includes:

(a) A cost balance for each plant component, $\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k$ or $c_{P,k}\dot{E}_{P,k} = c_{F,k}\dot{E}_{F,k} + \dot{Z}_k$. In these equations $\dot{C}_{P,k}$ and $\dot{C}_{F,k}$ are the cost rates of fuel and product, $c_{P,k}$ and $c_{F,k}$ are the associated costs per unit of exergy and $\dot{Z}_k$ represents the sum of the cost rates associated with capital investment (CI) and operating & maintenance (O&M) costs: $\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM}$.

In this work, we assume that

(a) when the plant design is varied, the contribution of $\dot{Z}_k^{OM}$ remains constant, and, thus, any changes in the $\dot{Z}_k$ are linked to changes in the capital investment cost $\dot{Z}_k^{CI}$, and (b) the auxiliary cost equations are based on the P and F rules, as explained in Ref. [3].

Exergoeconomic variables that can be used to improve the overall performance of component *k* in an iterative optimization are the cost rate associated with its exergy destruction $\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k}$ and its total cost rate, i.e., the sum ($\dot{Z}_k^{CI} + \dot{C}_{D,k}$). Other variables of the exergoeconomic analysis are given in many publications (e.g., Refs [3, 17-21]).

2.3 Exergoenvironmental analysis

Analogous to the exergoeconomic analysis, an exergoenvironmental analysis reveals the origin and magnitude of environmental impacts of thermodynamic inefficiencies in energy conversion systems [11]. The exergoenvironmental analysis is also realized at the component level of a system and shows the relative importance of the components with respect to their environmental impact, as well as alternative solutions for reducing the environmental impact of the overall system.

An exergoenvironmental analysis combines a Life Cycle Assessment (LCA) with an exergetic analysis. For the purpose of the work presented here, the LCA is realized using the life cycle impact assessment method Eco-indicator 99 [22], as this is the method employed in the reference case [24]. With this method, a one-dimensional characterization indicator is obtained and used in a similar manner as the specific monetary cost in exergoeconomics. This indicator (a single number measured in mPts) describes the overall environmental impact associated with system components and exergy carriers. Although the calculation of environmental impacts, in this way, is subjective and associated with uncertainties, the information extracted from the analysis is very useful when used in conjunction with exergy-based methods.

The exergoenvironmental methodology involves:

(a) The definition of environmental impact balances for each system component as $\dot{B}_{P,k} = \dot{B}_{F,k} + \left(\dot{Y}_k + \dot{B}_k^{PF}\right)$, or $b_{P,k}\dot{E}_{P,k} = b_{F,k}\dot{E}_{F,k} + \left(\dot{Y}_k + \dot{B}_k^{PF}\right)$. In these equations $\dot{Y}_k$ represents the component-related environmental impact, i.e., the impact associated with manufacturing, operation and retirement [11]; $\dot{B}_{P,k}$ and $\dot{B}_{F,k}$ are the environmental impacts that belong to product and fuel, respectively, and $b_{P,k}$ and $b_{F,k}$ are the corresponding product and fuel environmental impacts per unit of exergy. $\dot{B}_k^{PF}$ represents the pollutant formation (PF) within component *k* [23]. $\dot{B}_k^{PF}$ equal to zero means that no pollutants are formed from the operation of the component, i.e., no chemical reactions take place (compression, expansion, heat transfer, etc.). If, on the other hand, $\dot{B}_k^{PF}$ is higher than zero, pollutants are formed during the operation of the component due to chemical reactions (e.g., combustion). The procedure of how to calculate the pollutant formation variable is described in Ref. [23].

(b) The definition of auxiliary environmental impact equations based on the P- and F-rules, also used in exergoeconomics [3,21].

An exergoenvironmental variable that can be used as an indicator of how to reduce the environmental impact of component *k* is the environmental impact rate connected with the exergy destruction, $\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k}$. More variables of the exergoenvironmental analysis are presented in various publications, e.g., Refs. [11, 17-19].

2.4 3D Analysis

Fig. 1 shows the expected relationships among exergy destruction ($\dot{E}_{D,k}$), capital investment cost, ($\dot{Z}_k^{CI}$), and component-related environmental impact, ($\dot{Y}_k^{CO}$) [17, 18]. The effect of the size of the components is also accounted for by linking the exergy destruction, the capital investment cost and the component-related environmental impact to the product exergy rate of the same component at given operation conditions ($\dot{E}_{P,k}$). The following three axes are used: “exergy destruction per unit of product exergy”, “cost per unit of product exergy”, and “component-related environmental impact per unit of product exergy”. For simplicity, Fig.1 depicts only single lines. In reality each line represents a rather wide area, illustrating the fact that for each value of the relative exergy destruction ($\dot{E}_{D,k} / \dot{E}_{P,k}$), both the $\dot{Z}_k^{CI} / \dot{E}_{P,k}$, and the $\dot{Y}_k^{CO} / \dot{E}_{P,k}$ values can vary within a significant range.

In general, there are two possibilities for quarters I and II:

- The values of $\dot{E}_{D,k} / \dot{E}_{P,k}$ decrease with increasing values of $\dot{Z}_k^{CI} / \dot{E}_{P,k}$ (line 1), or with decreasing values of $\dot{Y}_k^{CO} / \dot{E}_{P,k}$ (line 3), or
- The values of $\dot{E}_{D,k} / \dot{E}_{P,k}$ increase with increasing values of $\dot{Z}_k^{CI} / \dot{E}_{P,k}$ (line 2), or with decreasing values of $\dot{Y}_k^{CO} / \dot{E}_{P,k}$ (line 4).

As a result, we have two possibilities for quarter III:

- The lower the $\dot{Z}_k^{CI} / \dot{E}_{P,k}$ value, the lower the $\dot{Y}_k^{CO} / \dot{E}_{P,k}$ value (Lines 1-3 and 2-4), or
- The lower the $\dot{Z}_k^{CI} / \dot{E}_{P,k}$ value, the higher the $\dot{Y}_k^{CO} / \dot{E}_{P,k}$ value (Lines 1-4 and 2-3).

The question is: How to use this information for an optimization (improvement) based on exergoeconomic (quarter I), exergoenvironmental (quarter II) or 3D (quarter III) analyses?

In the case "the lower … the lower…", the analyses give the same recommendation for improving the *k*th component. A compromise for the *k*th component is required only if we have the case "the lower … the higher".

In the following we study the relationship among the three variables: $\dot{E}_{D,k} / \dot{E}_{P,k}$, $\dot{Z}_k^{CI} / \dot{E}_{P,k}$, and $\dot{Y}_k^{CO} / \dot{E}_{P,k}$ using a case study, the example of a combined-cycle power plant.

3 Case study

The energy conversion system used as an example in this work is a combined-cycle power plant. The plant incorporates a three-pressure-level Rankine cycle with one reheat stage. The plant operates with natural gas (in the simulations assumed to be pure methane) and generates electricity. The flow diagram of the plant is presented in Fig. 2. The values of the thermodynamic variables for selected streams of the system can be found in Table 1. The total exergy, $\dot{E}_j$, of a material stream *j* includes both its chemical and physical exergy.

628 kg/s of flue gas exits the gas turbine (GT), enters the heat recovery steam generator (HRSG) of the plant at 1.058 bar and 580°C and it is exhausted to the atmosphere at 1.013 bar and 95°C. In the HRSG, the thermal energy of the flue gas is used to generate steam at the pressure levels of 124, 22 and 4.1 bar. High-pressure steam at 560°C is expanded to 23 bar in the high-pressure steam turbine (HPST) and reenters the HRSG to be reheated to 560°C. The reheated steam passes through the intermediate-pressure steam turbine (IPST) and is expanded to 4.1 bar. The exiting stream is mixed with low-pressure superheated steam and it is then directed to the low-pressure steam turbine (LPST). The steam exits the steam turbine at 0.05 bar, it is condensed in the condenser, preheated in the preheaters and conveyed to the feedwater pumps to continue the cycle.

Results from the exergetic, exergoeconomic and exergoenvironmental analyses of this combined-cycle power plant have been reported in other publications (e.g., [24]), where the performance of the plant including different systems for CO_2 capture was discussed. Reference data have been obtained from Ref. [24] and the calculations were based on this base case. Some data obtained from the exergetic, exergoeconomic and exergoenvironmental analyses for selected components of the power plant (Figure 2) are presented in Table 2. For the base case, the cost of electricity is equal to 7.19 €/kWh, whereas the environmental impact associated with electricity production is equal to 14.69 mPts/kWh.

For each important component, we need to find a way to reduce the total cost associated with the component, i.e., the sum $(\dot{Z}_k + \dot{C}_{D,k})$ from the economic point of view, whereas from the environmental viewpoint we want to reduce the total environmental impact associated with the component, i.e., the sum ($\dot{Y}_k + \dot{B}_{D,k}$). The final goal for the improvements is to decrease the cost of the final product, electricity. Afterwards, the effect of the economics-based modifications on the environmental impact of the final product is investigated. Taking into account these modifications, an exergoenvironmental analysis is carried out to obtain the total environmental impact of the produced electricity.

4 Sensitivity Analysis

The improvement suggestions can be divided into two groups:

- Design changes that lead to an increase in the exergetic efficiency of the components (a decrease in the exergy destruction), i.e., a decrease in the values of $\dot{C}_{D,k}$ and $\dot{B}_{D,k}$, or
- Design changes that lead to a decrease in the values of $\dot{Z}_k$ and $\dot{Y}_k$ by decreasing the exergetic efficiency and increasing the exergy destruction.

The assumptions made for the sensitivity analysis are given in the subsequent sections.

4.1 Combustion Chamber

From the viewpoint of the 3D analysis, the combustion chamber can be improved by increasing its exergetic efficiency. In order to achieve this goal, we studied the effects of:

A) The excess air (Fig. 3a): For the sensitivity analysis, λ was set to 2.1, 2.05 (Base Case), 1.95, and 1.9, and

B) The fuel inlet temperature (T_4, Fig. 3b): For the sensitivity analysis, T_4 was set to 15ºC (Base Case), 50ºC, 100ºC and 150ºC.

4.2 Gas Turbine

For the sensitivity analysis, we assumed that the isentropic efficiency of the gas turbine remains constant and it can only be improved through modification of its operational conditions, for example, through a change in the temperature of the combustion gases entering the gas turbine. For the sensitivity analysis (Fig. 4), T_5 was set to 1264ºC (Base Case), 1300ºC, 1324 ºC and 1350ºC.

4.3 Compressor

Two effects were considered for the improvement of the compressor:

- The effect of the isentropic efficiency (Fig. 5a): For the sensitivity analysis, η_{CM} was set to 0.91, 0.915 (Base Case), 0.92, and 0.925.
- The effect of the pressure ratio (Fig. 5b): For the sensitivity analysis p_2/p_1 was set to 16/1.013, 17/1.013 (Base Case), 18/1.013 and 19/1.013.

4.4 High-pressure superheater

The modifications included:

- changes of the temperature difference between hot inlet and cold outlet streams (Fig. 6a). For the sensitivity analysis $T_9 - T_{43}$ was set to 15K, 20K (Base Case), 25K and 30K.
- changes of the inlet pressure (Fig. 6b). For the sensitivity analysis P_{42} was set to 125 bar, 130.5 bar (Base Case), 135 bar and 140 bar.

4.5 High-pressure evaporator

The modifications involved changes of the pinch temperature: For the sensitivity analysis (Figure 7), ΔT_{pinch} was set to 9K, 10K (Base Case), 15K and 20K.

4.6 Low-pressure steam turbine

The effect of the isentropic efficiency was considered for the low-pressure steam turbine (Fig. 9): For the sensitivity analysis, η_{CM} was set to 0.85, 0.88 (Base Case), 0.90, 0.91, and 0.915.

4.7 Overall system

The effects of the improvement of the selected components to the overall cost and the environmental impact of the electricity are shown in Figures 9 and 10. For this analysis we selected only variables that have a positive effect on the reduction of the cost and the environmental impact of electricity.

5 Results and Discussion

The results of the sensitivity analysis (Figs 3 through 8) for the selected components of the analyzed combined-cycle power plant show, that for the assumptions made, the results obtained from the exergoeconomic and the exergoenvironmental analyses are qualitatively the same. We find two types of curves:

- The case "the lower … the lower" − for the combustion chamber (Figs 3a and 3b), compressor (Fig. 5b) and low-pressure steam turbine (Fig. 8), and
- The case "the lower … the higher" – for the gas turbine (Fig. 4), compressor (Fig. 5a), high-pressure superheater (Fig. 6a and 6b), and high-pressure evaporator (Fig. 7).

As already mentioned, if during the variation of a given process variable we obtain the case "the lower … the lower" (lines 1, 3 and 1-3 in Fig. 1), then no variation is required, because the lower the value of $\dot{E}_{D,k} / \dot{E}_{P,k}$ (i.e., of the thermodynamic inefficiencies), the lower the values of

$\dot{Z}_k^{CI} / \dot{E}_{P,k}$ and/or $\dot{Y}_k^{CO} / \dot{E}_{P,k}$ (i.e., of the investment costs and/or of the component-related environmental impact). It is apparent that in this case we would select the most efficient option that also happens to exhibit the lowest investment cost and/or the lowest environmental impact. Thus, for example, for the combustion chamber, and according to the model and the assumptions used in this paper (e.g., NO_x formation and material cooling were not considered), we would select the lowest possible amount of excess air and the highest possible preheating temperature of the fuel (see Figs 3a and 3b). Along the same line, for the compressor we would select the highest possible pressure ratio and for the low-pressure steam turbine we would select the highest possible isentropic efficiency.

If during the variation of a given process variable we obtain the case "the lower … the higher", then optimization is necessary, because the higher the value of $\dot{E}_{D,k} / \dot{E}_{P,k}$, the lower the values of $\dot{Z}_k^{CI} / \dot{E}_{P,k}$ and/or $\dot{Y}_k^{CO} / \dot{E}_{P,k}$. Thus, an optimal value needs to be determined. This happens, for example, with the temperature of the combustion gases at the inlet of the gas turbine, the isentropic efficiency of the compressor, the minimum temperature difference between hot inlet and cold outlet streams in the high-pressure superheater, as well as with the inlet pressure of this equipment and the pinch temperature difference of the high-pressure evaporator.

For some of the studied elements, the variation of different parameters follow the same trend, as in the case of the combustion chamber, in which variation of excess air and preheating temperature leads to lower…lower case. Nevertheless, in other pieces of equipment, such as the compressor, the effect of modifying the pressure ratio is a lower…lower case, while the effect of the isentropic efficiency is a lower…higher one. It is also worth mentioning that one variable can present different trends depending on the equipment, as it happens with the isentropic efficiency. Both the low-pressure steam turbine and the compressor have been improved through modifications of their isentropic efficiency. While for the steam turbine increasing isentropic efficiency is a lower…lower case, for the compressor increasing isentropic efficiency is a lower…higher one.

Figs 9 and 10 show how the considered options for improving the components of the combined-cycle power plant affect the cost and the environmental impact of the generated electricity. For the cases identified as lower…lower, the straight-through modifications lead to lower specific costs and specific environmental impact (significant improvements are achieved when improving the performance of the combustion chamber and the turbomachinery). For the cases identified as lower…higher, the effect of these components on the overall specific cost and environmental impact present the opposite trend than the individual one. Decreasing the isentropic efficiency of the compressor leads to lower $\dot{Z}_k^{CI} / \dot{E}_{P,k}$ and $\dot{Y}_k^{CO} / \dot{E}_{P,k}$, but higher specific costs and environmental impact, thus emphasizing the need to find an optimal value.

6 Conclusions

In this paper, a three-pressure-level combined cycle power plant was used to study interdependencies among costs, environmental impacts and thermodynamic inefficiencies. Data obtained from applying exergoeconomic and exergoenvironmental analyses under various plant operating conditions have been considered simultaneously.

The results demonstrate that improvements in efficiency in the three-pressure-level combined-cycle power plant result, in most cases, in decreases in both costs and environmental impacts. However, the trends of the functions $\dot{Z}_k / \dot{E}_{P,k}$ and $\dot{B}_{D,k} / \dot{E}_{P,k}$ are not always similar. The analysis presented here suggests ways for improving a three-pressure-level combined-cycle power plant from the thermodynamic, economic, and ecological viewpoints, simultaneously.

Future work should focus on more detailed analyses, such as the examination of the relationship between the three functions: $\dot{E}_{D,k}/\dot{E}_{P,k}$, $\left(\dot{Z}_k+\dot{C}_{D,k}\right)/\dot{E}_{P,k}$ (consideration of the total cost associated with the component) and $\left(\dot{Y}_k+\dot{B}_{D,k}\right)/\dot{E}_{P,k}$ (consideration of the total environmental impact associated with the component).

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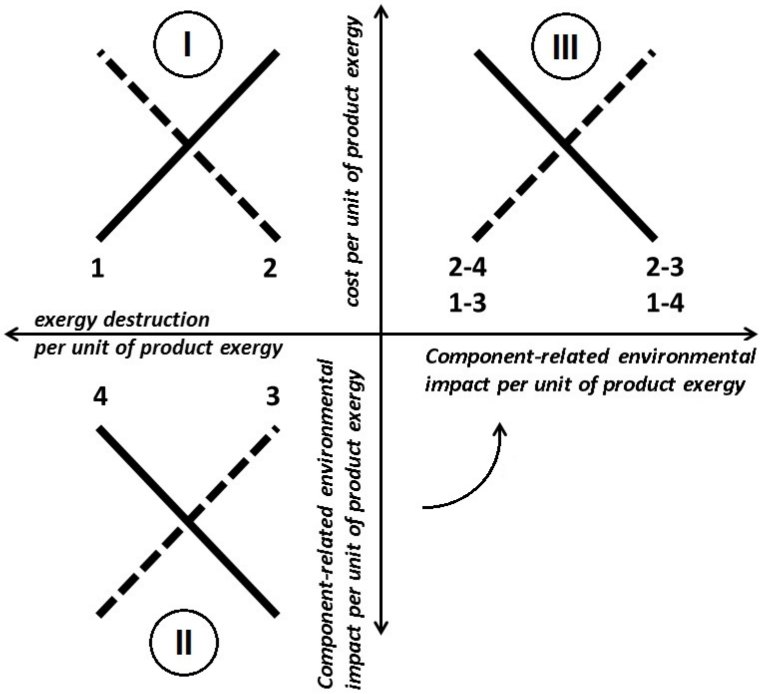

Fig. 1. Expected relationships among capital investment, construction-of-component-related environmental impact and exergy destruction for the *k*th component of an energy conversion system

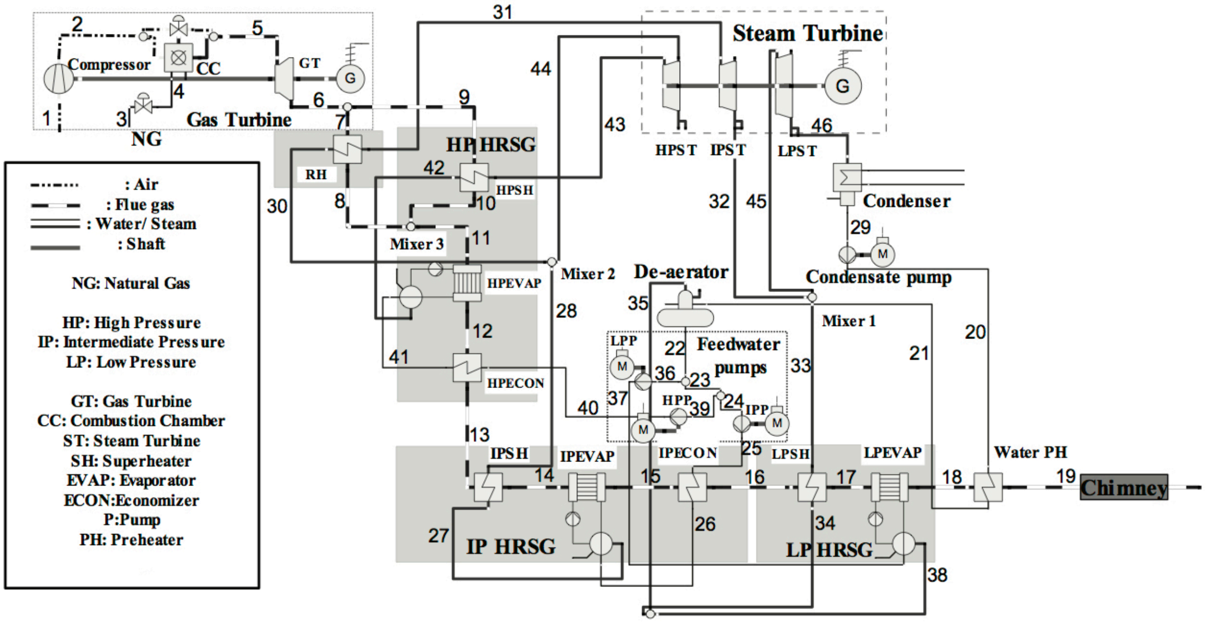

Fig. 2. Schematic of a three-pressure-level combined cycle power plant

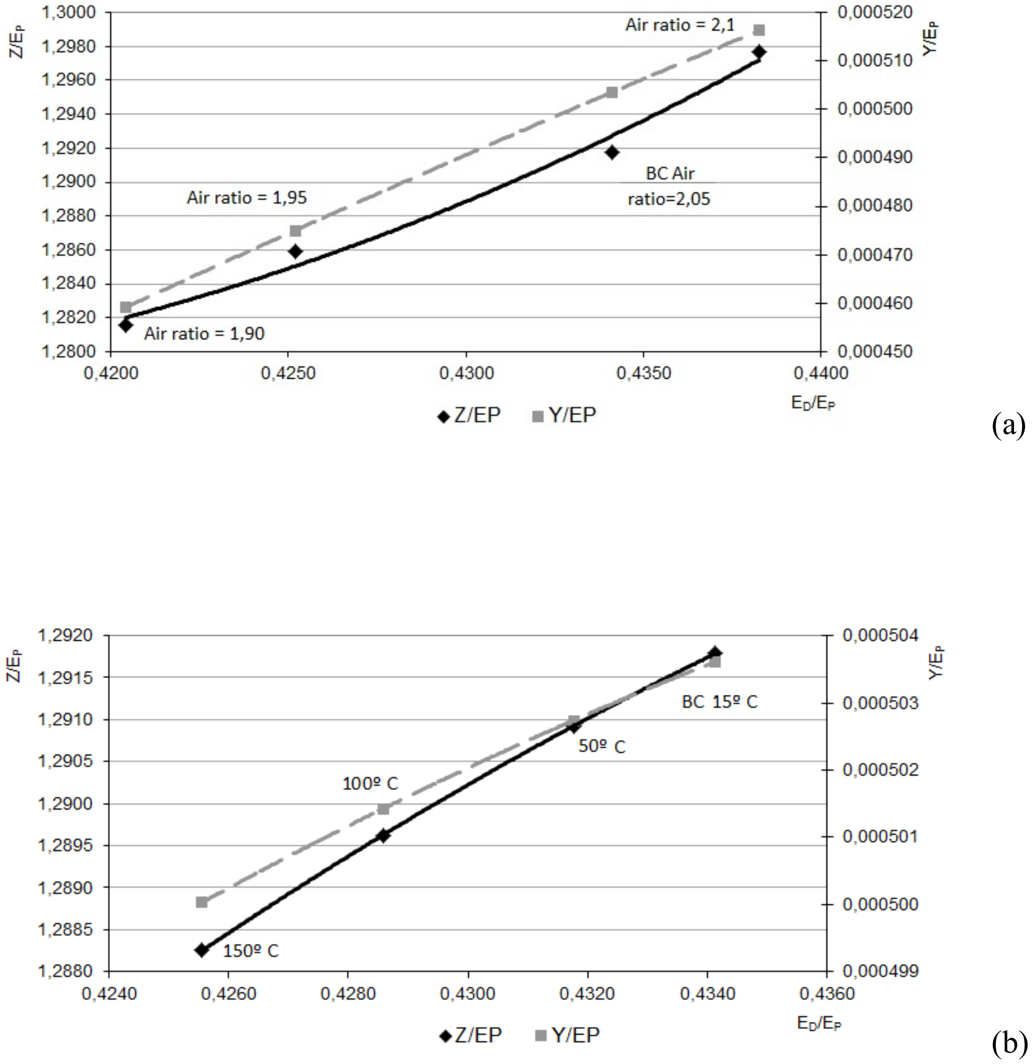

Fig. 3. Combustion Chamber:

(a) Effect of the excess air and (b) effect of the inlet temperature of the fuel

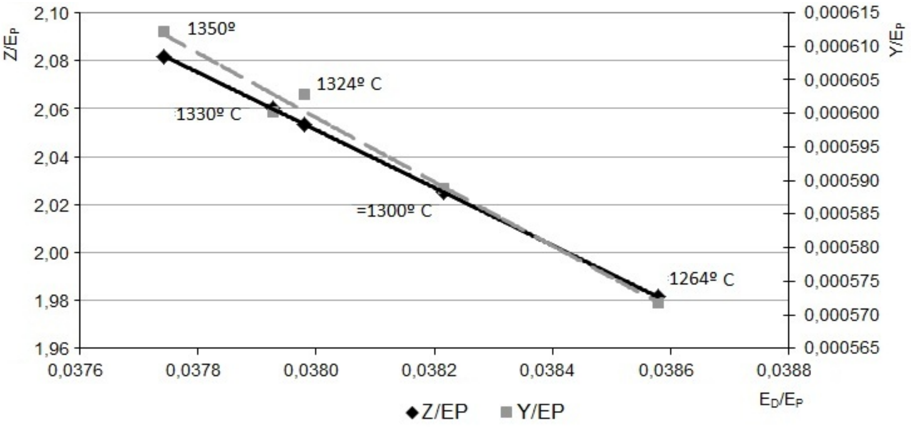

Fig. 4. Gas turbine: Effect of the temperature at the inlet.

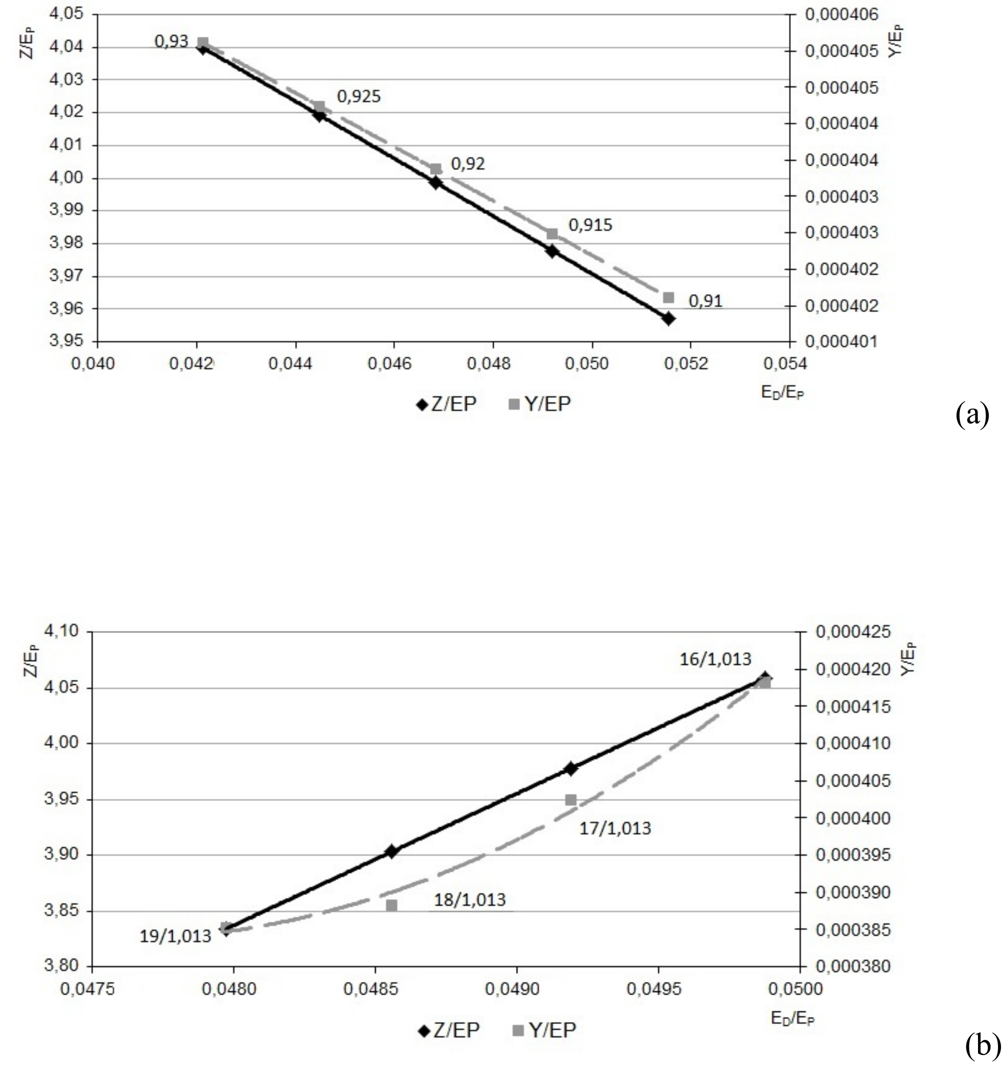

Fig. 5. Compressor: Effects of (a) the isentropic efficiency and (b) the pressure ratio.

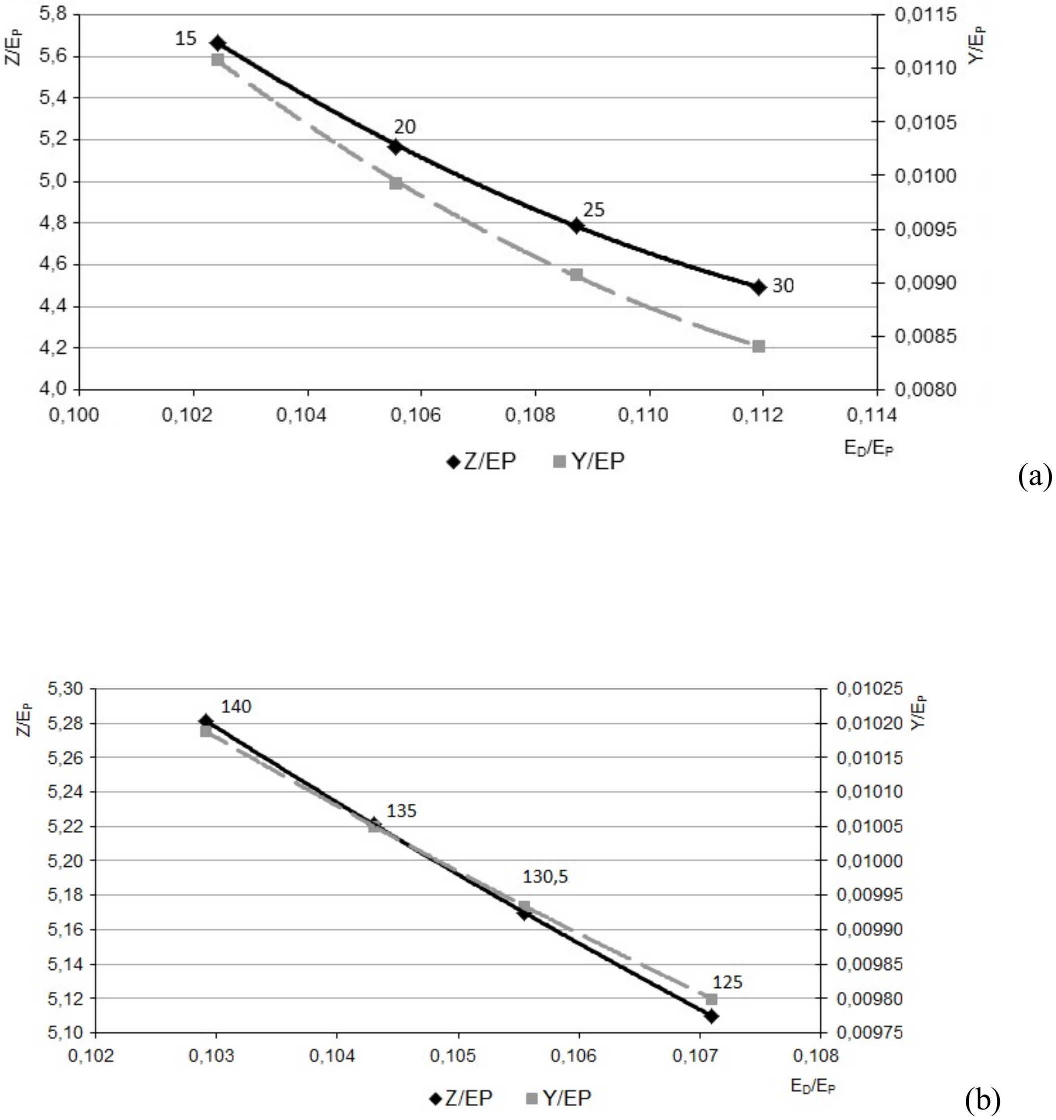

Fig. 6. High-pressure superheater: Effect of (a) the minimum temperature difference between hot stream inlet and cold stream outlet and (b) the inlet pressure.

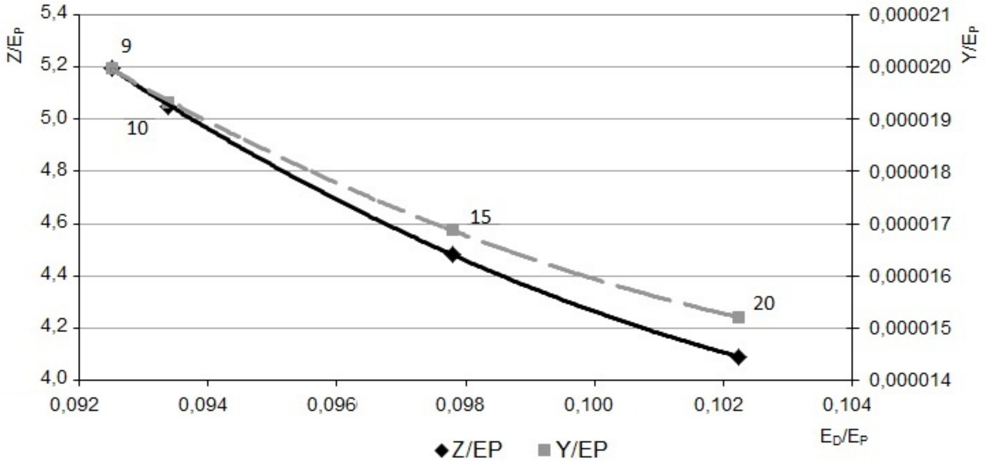

Fig. 7. High-pressure evaporator: Effect of the pinch temperature difference.

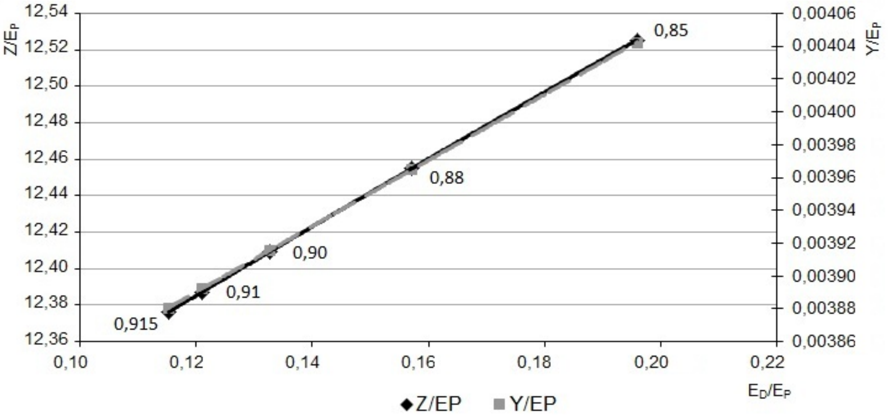

Fig. 8. Low-pressure steam turbine: Effect of the isentropic efficiency.

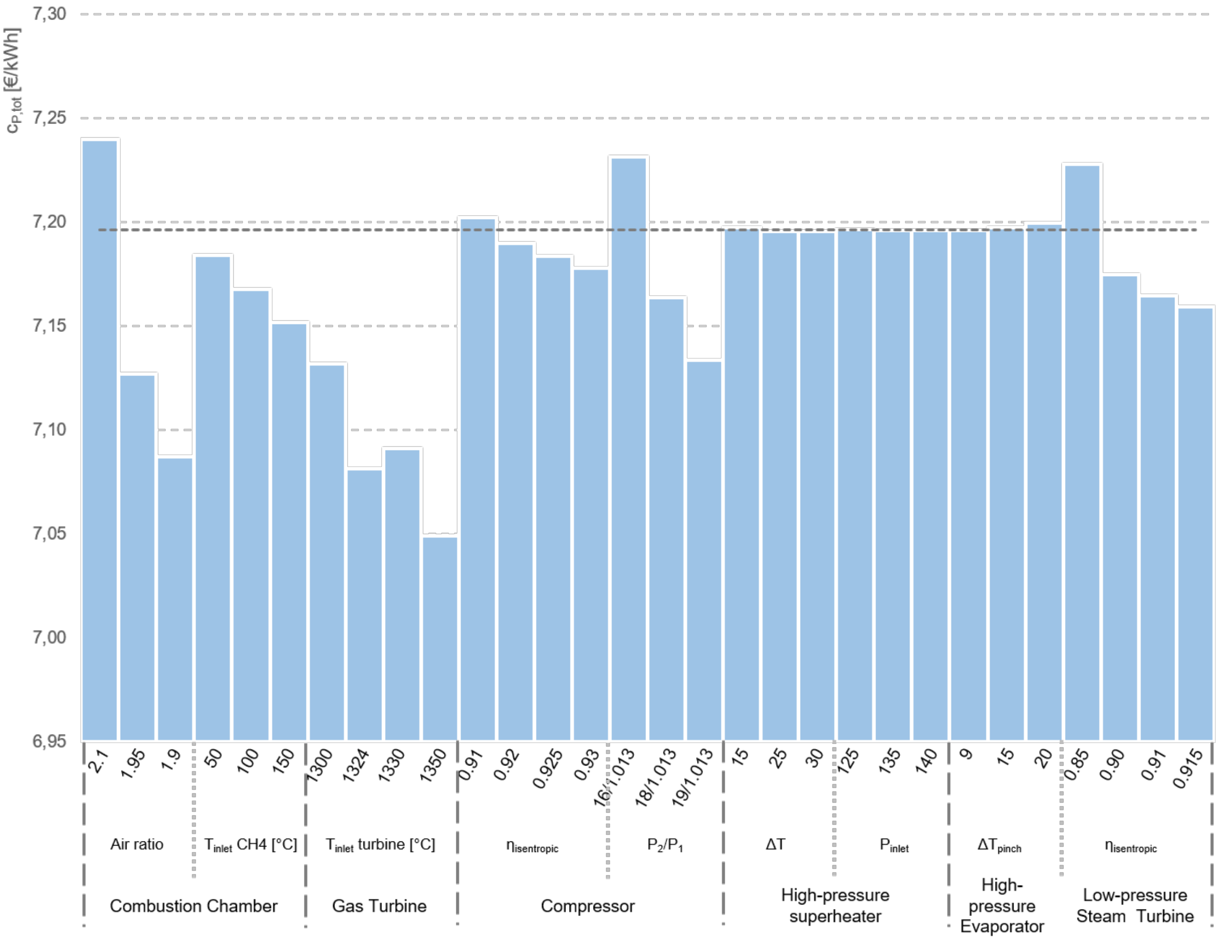

Fig. 9. Specific cost of generated electricity, $c_{P,tot}$ (€/kWh).

Effects of improving selected components on the overall cost (Base case: dashed line 7.19 €/kWh).

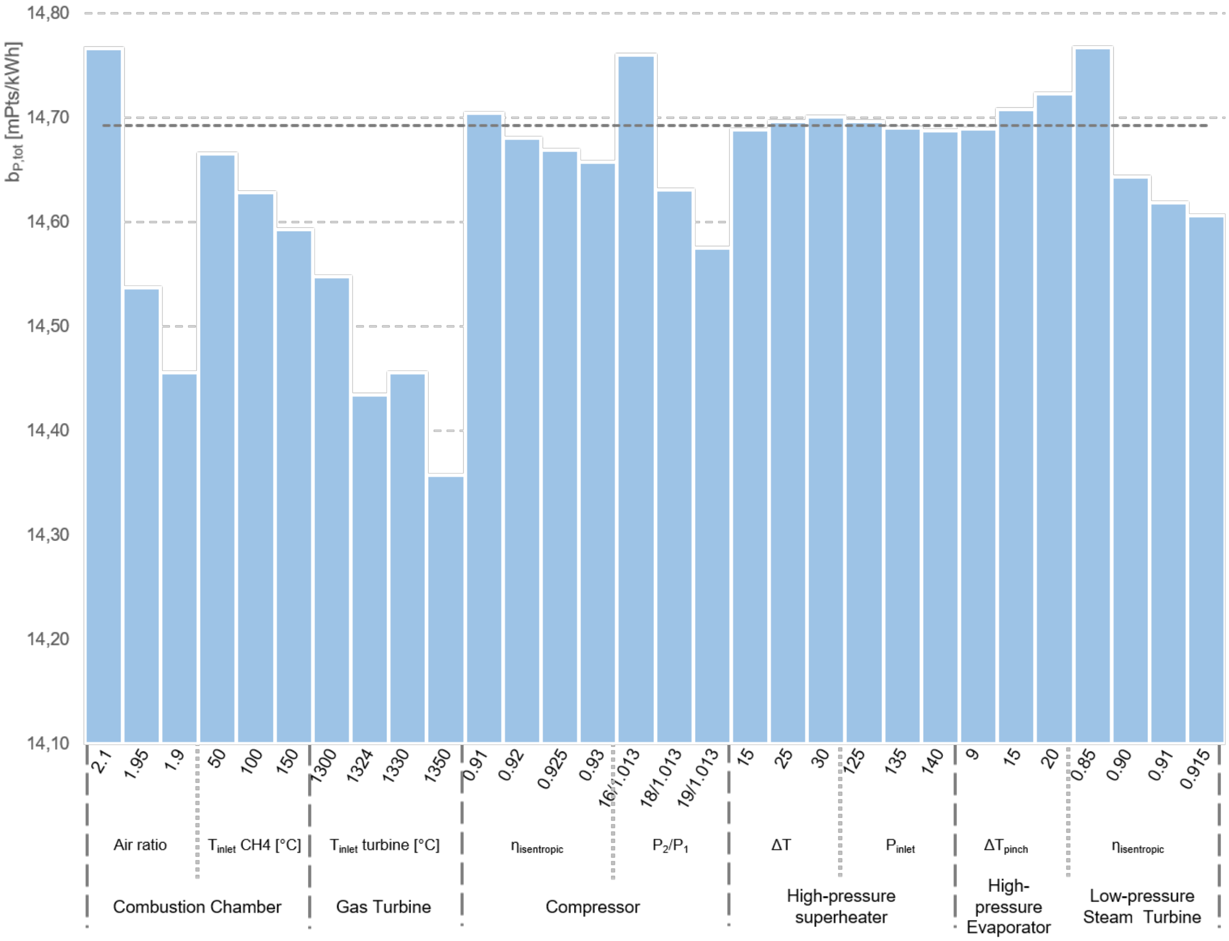

Fig. 10. Specific environmental impact of the generated electricity, $b_{P,tot}$ (mPts/kWh). Effects of improving selected components on the overall environmental impact (Base case: dashed line 14.69 mPts/kWh).

Table 1. Calculated thermodynamic variables for selected material streams [9].

Stream, j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_j$ (MW)	Stream, j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_j$ (MW)
1	614.50	15.0	1.01	0.96	**24**	7.22	140	3.62	0.67
2	614.50	393	17.00	232.25	**25**	7.22	140	25.13	0.68
3	14.00	15.0	50.00	729.62	**26**	7.22	217	24.38	1.56
4	14.00	15.0	17.00	727.37	**27**	7.22	223	24.38	7.23
5	628.50	1264	16.49	741.01	**28**	7.22	238	23.16	7.35
6	628.50	581	1.06	189.87	**29**	94.58	33	0.05	0.44
7	268.50	581	1.06	81.11	**30**	72.43	305	23.16	79.53
8	268.50	448	1.05	54.64	**31**	72.43	561	22.00	103.42
9	360.00	581	1.06	108.75	**32**	72.43	317	4.10	66.03
10	360.00	449	1.05	73.68	**33**	22.15	214	4.10	18.01
11	628.50	449	1.05	128.33	**34**	22.15	146	4.32	16.96
12	628.50	341	1.04	84.69	**35**	0.83	146	4.32	0.63
13	628.50	258	1.04	55.77	**36**	22.97	140	3.62	2.12
14	628.50	257	1.04	55.59	**37**	22.97	140	4.32	2.12
15	628.50	238	1.04	49.49	**38**	22.97	146	4.32	17.60
16	628.50	234	1.04	48.43	**39**	65.21	140	3.62	6.01
17	628.50	229	1.04	47.01	**40**	65.21	142	134.56	6.96
18	628.50	156	1.03	27.98	**41**	65.21	325	130.53	31.88
19	628.50	95	1.03	16.49	**42**	65.21	331	130.53	71.79
20	94.58	33	3.73	0.47	**43**	65.21	561	124.00	103.51
21	94.58	136	3.62	8.18	**44**	65.21	313	23.16	72.22
22	95.41	140	3.62	8.79	**45**	94.58	293	4.10	83.86
23	72.43	140	3.62	6.67	**46**	94.58	33	0.05	12.87

Table 2. Data obtained from the exergetic, exergoeconomic and exergoenvironmental analyses for selected components of the power plant shown in Figure 2.

Component	Exergetic analysis	Exergoeconomic analysis			Exergoenvironmental analysis		
	$\dot{E}_{D,k}$ (MW)	$\dot{Z}_k$ (€/h)	$\dot{C}_{D,k}$ (€/h)	$\dot{Z}_k + \dot{C}_{D,k}$ (€/h)	$\dot{Y}_k$ (Pts/h)	$\dot{B}_{D,k}$ (Pts/h)	$\dot{Y}_k + \dot{B}_{D,k}$ (Pts/h)
CC	220.87	926.46	202.12	8202.79	0.381	2862	2862
GT	20.47	1482.34	31.33	2610.20	1.126	396	397
Compressor	11.38	1297.05	18.97	1979.83	0.236	228	228
PHSH	3.35	149.46	5.12	333.92	1.237	65	66
HPEVAP	3.73	183.60	5.70	388.93	0.139	72	72
LPST	9.64	696.33	20.40	1430.61	0.493	232	232