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Assessment of a Power Plant With CO_2 Capture Using an Advanced Exergoenvironmental Analysis

This paper presents an evaluation of the environmental performance of an advanced zero emission plant (AZEP) including CO_2 capture. The evaluation is conducted with the aid of an advanced exergoenvironmental analysis. The results are compared with those of a reference combined-cycle power plant without CO_2 capture. Advanced exergy-based methods are used to (a) quantify the potential for improving individual components or overall systems, and (b) reveal detailed interactions among components—two features not present in conventional analyses, but very useful, particularly when evaluating complex systems. In an advanced exergoenvironmental analysis, the environmental impacts calculated in a conventional exergoenvironmental analysis are split into avoidable/unavoidable (to evaluate the potential for component improvement) and endogenous/exogenous (to understand the interactions among components) parts. As in the reference plant, the potential for reducing the environmental impact of the AZEP has been found to be limited by the relatively low avoidable environmental impact associated with the thermodynamic inefficiencies of several of its components. However, although the environmental impacts for the majority of the components of the plant are related mainly to internal inefficiencies and component interactions are of secondary importance, there are strong interactions between the reactor and some other components.
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1 Introduction

Advanced exergy-based methods assist in quantifying detailed component interactions and the potential for improving individual plant components or overall systems [1–4]. These analyses can be used to understand the operation of a system, or to conduct comprehensive evaluations of energy conversion systems in the design phase. The final objective is to determine the operational conditions and the structure of the system that will assure the best possible thermodynamic, economic and environmental performance.

In advanced exergetic, exergoeconomic and exergoenvironmental analyses (e.g., Refs. [2–4]), the inefficiencies, costs and environmental impacts associated with each system component are split into avoidable/unavoidable parts (that reveal the potential for improvement), and into endogenous/exogenous parts (that reveal important component interactions). The splitting procedures improve the accuracy of conventional exergetic, exergoeconomic and exergoenvironmental analyses, help us better understand the formation of thermodynamic inefficiencies, costs and environmental impacts, and facilitate the improvement of a system. In conventional exergy-based methods [5–7] none of the above splitting procedures is applied.

When applying an advanced exergy-based method, one needs to define the theoretically best operational conditions of each plant component with respect to efficiency, as well as the minimum cost and environmental impact, associated with manufacturing and installation. Although some rather subjective choices might be necessary in the application of the methodology, the final conclusions from the advanced methods are robust. A drawback of advanced exergy-based methods is the fact that a large number of additional simulations and data processing are required, after the corresponding conventional analyses have been conducted. Thus, the application of the advanced methods can be very time consuming. However, despite the time required for the calculations, we obtain a much better and more in-depth understanding of the system and its potential for improvement, beyond those provided by the corresponding conventional exergy-based methods.

The ideas associated with advanced methods and some definitions are provided in Ref. [4]. The first calculations of avoidable/unavoidable exergy destructions are reported in Refs. [2,3]. The concept of endogenous/exogenous exergy destruction, costs and environmental impacts was initially presented for systems that did not include chemical reactions (e.g., refrigeration systems [1]) because in such systems it is easier to define ideal operational conditions. The first thorough application of an advanced exergoenvironmental analysis can be found in Ref. [8]. In the mentioned references, more details regarding the methodology of advanced exergy-based methods and specific applications can be found.

Reducing anthropogenic emissions for environmental reasons has been a high concern of the scientific community in recent years (e.g., Refs. [9–11]). In this paper, an oxy-fuel AZEP with CO_2 capture is evaluated using an advanced exergoenvironmental analysis to investigate the potential for reducing the environmental impact of the generated electricity. The results of the analysis are also compared to those obtained for a conventional power plant without CO_2 capture ("reference power plant") [12]. The conventional exergetic analysis of the AZEP concept [13] shows promising performance in comparison to alternatives for emission reduction. However, the AZEP concept is associated with a

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significant cost increase, while achieving only a small decrease in the environmental impact of the produced electricity [14]. To examine the potential for reducing the thermodynamic inefficiencies and the monetary costs, the plant has also been evaluated using advanced exergetic and exergoeconomic analyses in Ref. [15].

The structure of the AZEP concept is shown in Fig. 1. It is a combined-cycle power plant in which 85% of the CO_2 generated is captured (this is the reason for calling the concept AZEP 85) [16,17]. In this power plant, the combustion chamber (CC) of the gas turbine (GT) system is replaced by a mixed-conducting-membrane (MCM) reactor [18–21], which consists of (a) a mixed-conducting membrane, where the oxygen of the incoming air is separated and then swept by a CO_2-rich gas, (b) a combustion chamber, in which nitrogen-free combustion takes place, and (c) two heat exchangers (HXs). In this paper, we assumed that the combustion is complete and only H_2O and CO_2 are formed. After a nitrogen-free complete combustion, the separation of the CO_2 is facilitated because the reaction products consist mainly of water vapor and CO_2. Two streams exit the MCM reactor: Stream 96, which is the oxygen-depleted air and Stream 61, which is the CO_2-rich stream generated from the oxy-fuel production. Stream 96 is led to a duct burner (DB), where part of the remaining oxygen of the air reacts with part of the incoming methane of the plant. This secondary combustion increases the inlet temperature of the main gas turbine of the plant (GT1), which would otherwise be relatively low due to material limitations of the MCM reactor. After expansion, the combustion gas stream passes through the main heat-recovery steam generator (HRSG) producing steam at three different pressure levels (124, 22, and 4.1 bars). The generated steam is then expanded in the steam turbine (ST) of the plant providing approximately 25% of the total electricity generated. On the other side of the reactor, Stream 61 (CO_2-rich stream) is used to generate steam in the secondary HRSG of the plant (HRSG II) and it is then sent to the intercooled CO_2 compression unit (compressors C2-C5 in Fig. 1), where the water vapor is extracted through condensation, allowing the separation of the CO_2.

2 Methodology

In an exergoenvironmental analysis, one needs to use a single indicator, which represents the overall environmental impact associated with streams of matter, energy streams, and plant components. The goal of an exergoenvironmental analysis of a plant is to identify options for reducing the overall environmental impact associated with the plant products. Here, the life-cycle assessment (LCA) of the AZEP concept has been performed using the life-cycle impact-assessment method Eco-indicator 99 [22]. The environmental impacts calculated using this methodology are reported with the aid of dimensionless variables or in Eco-indicator millipoints (mPts). One Pt is the equivalent of one thousandth of the yearly environmental load caused by the average European inhabitant [23].

An advanced exergoenvironmental analysis helps to determine which part of the environmental impact calculated for each plant component can be avoided, and to establish how the thermodynamic performance of an individual component affects the environmental impact associated with each one of the other important components of the plant. With these goals in mind, the environmental impact of each component, as calculated in the LCA is split into avoidable/unavoidable values that demonstrate the potential for improvement, endogenous/exogenous values that show the interactions of plant components, and the respective combined parts (e.g., avoidable exogenous and avoidable endogenous environmental impacts) [24,25].

When assessing the environmental performance of energy conversion systems, three environmental impacts are considered: the environmental impact of exergy destruction (associated with the use of the fuel within the plant), the component-related environmental impact (related to the construction and maintenance of the plant components) and the environmental impact of pollutant formation (associated only with chemical reactions that take place in the plant). Pollutant formation is calculated for reactors, where harmful chemical compounds (emissions), such as CO_2, SO_2, and NO_X are formed, and it accounts for the environmental impact that is associated with these compounds when exhausted to the environment. The unavoidable environmental impact of pollutant formation includes the CO_2 emissions, because complete combustion is assumed (thus, in Eq. 6 shown in Table 1, i: CO_2), while the avoidable pollutant formation includes the NO_X emissions, the largest part of which could eventually be avoided by modifying the operational conditions of the combustion process.

Applied conventional exergoenvironmental analyses [26] show that component-related environmental impacts are significantly

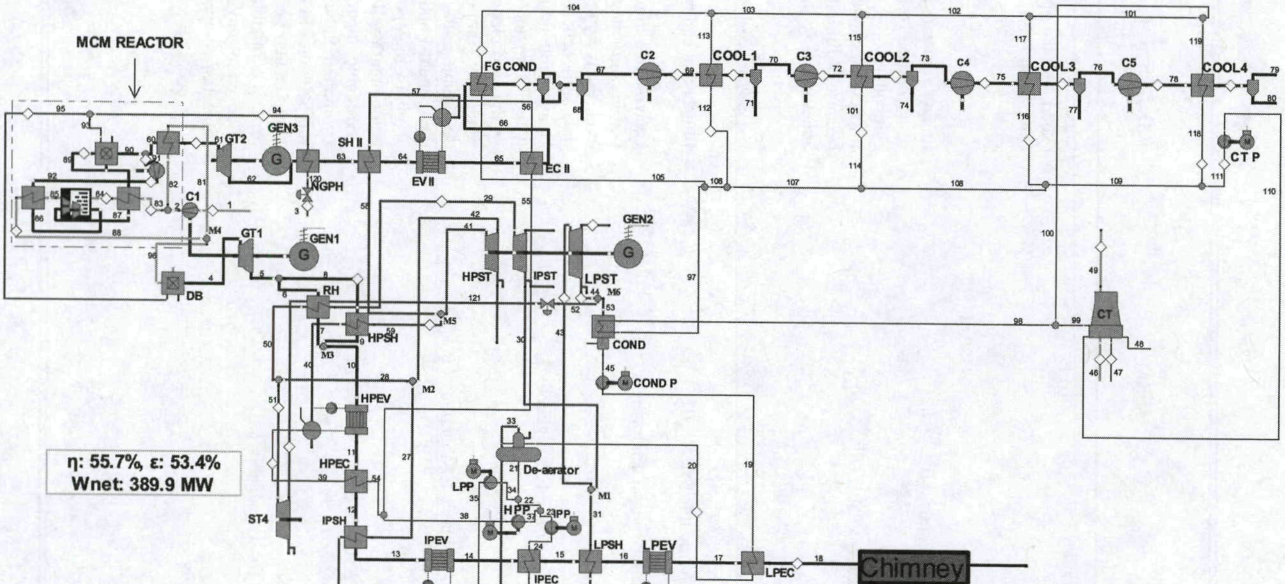

Fig. 1 Structure of the AZEP 85

Table 1 Splitting the environmental impacts

Equation Nr.	TERM	Definition of environmental impact	Environmental impact of pollutant formation, $\dot{B}_k^{PF}$ and exergy destruction, $\dot{B}_{D,k}$ *(for component k)*	Comments
(1)	Endogenous ($\dot{B}_k^{PF,EN}$,$\dot{B}_{D,k}^{EN}$)	Impact within component *k* associated with the operation of the component itself.	$\dot{B}_k^{PF,EN} = \sum_i b_i^{PF}\left(\dot{m}_{i,out} - \dot{m}_{i,in}\right)^{EN}$ $\dot{B}_{D,k}^{EN} = b_{F,k}^{real}\dot{E}_{D,k}^{EN}$	b_i^{PF}: Specific pollutant formation (varies depending on the pollutant) $\left(\dot{m}_{i,out} - \dot{m}_{i,in}\right)^{EN}$: mass flow difference of pollutant i, between outlet and inlet in the endogenous case $b_{F,k}^{real}$: Average specific environmental impact per unit of fuel exergy of component k in the real case
(2)	Exogenous ($\dot{B}_k^{PF,EX}$,$\dot{B}_{D,k}^{EX}$)	Impact associated with component *k* caused by the remaining components.	$\dot{B}_k^{PF,EX} = \dot{B}_k^{PF,real} - \dot{B}_k^{PF,EN}$ $\dot{B}_{D,k}^{EX} = \dot{B}_{D,k}^{real} - \dot{B}_{D,k}^{EN}$	
(3)	Unavoidable ($\dot{B}_k^{PF,UN}$,$\dot{B}_{D,k}^{UN}$)	Impact that cannot be avoided because of limitations in available technology and materials.	$\dot{B}_k^{PF,UN} = \sum_i b_i^{PF}\left(\dot{m}_{i,out} - \dot{m}_{i,in}\right)$ $\dot{B}_{D,k}^{UN} = b_{F,k}^{real}\dot{E}_{D,k}^{UN}$	$\dot{B}_k^{PF,UN}$: The unavoidable environmental impact of pollutant formation rate includes all emissions of CO_2 when complete combustion takes place (i: CO_2) $\dot{E}_D^{UN}$: Unavoidable part of exergy destruction rate (calculated in an advanced exergetic analysis with the most favorable operating conditions that result in the lowest possible exergy destruction).
(4)	Avoidable ($\dot{B}_k^{PF,AV}$,$\dot{B}_{D,k}^{AV}$)	Impact that can be avoided.	$\dot{B}_k^{PF,AV} = b_{NO_X}^{PF}\dot{m}_{NO_X,out}$ $\dot{B}_{D,k}^{AV} = \dot{B}_{D,k}^{real} - \dot{B}_{D,k}^{UN}$	$\dot{B}_k^{PF,AV}$: NO_X emissions that can be avoided assuming, for example, different excess air fraction (λ)
(5)	Unavoidable Endogenous $\left(\dot{B}_k^{PF,UN,EN},\dot{B}_{D,k}^{UN,EN}\right)$	Unavoidable impact created within component *k* and caused exclusively by the operation of the component itself.	$\dot{B}_k^{PF,UN,EN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{B}_k^{PF*}}{\dot{E}_{P,k}}\right)^{UN}$ $\dot{B}_{D,k}^{UN,EN} = b_{F,k}^{real}\dot{E}_{D,k}^{UN,EN}$	$\left(\frac{\dot{B}^{PF*}}{\dot{E}_P}\right)_k^{UN} = \left(\frac{\dot{B}^{PF,UN}}{E_P^{real}}\right)_k$
(6)	Unavoidable Exogenous $\left(\dot{B}_k^{PF,UN,EX},\dot{B}_{D,k}^{UN,EX}\right)$	Unavoidable impact created within component *k*, but caused by the inefficiencies in the remaining components.	$\dot{B}_k^{PF,UN,EX} = \dot{B}_k^{PF,UN} - \dot{B}_k^{PF,UN,EN}$ $\dot{B}_{D,k}^{UN,EX} = \dot{B}_{D,k}^{UN} - \dot{B}_{D,k}^{UN,EN}$	
(7)	Avoidable Endogenous $\left(\dot{B}_k^{PF,AV,EN},\dot{B}_{D,k}^{AV,EN}\right)$	Avoidable impact created within component *k* and caused exclusively by the operation of the component itself.	$\dot{B}_k^{PF,AV,EN} = \dot{B}_k^{PF,EN} - \dot{B}_k^{PF,UN,EN}$ $\dot{B}_{D,k}^{AV,EN} = \dot{B}_{D,k}^{EN} - \dot{B}_{D,k}^{UN,EN}$	
(8)	Avoidable Exogenous $\left(\dot{B}_k^{PF,AV,EX},\dot{B}_{D,k}^{AV,EX}\right)$	Avoidable impact created within component k, but caused by the inefficiencies in the remaining components.	$\dot{B}_k^{PF,AV,EX} = \dot{B}_k^{PF,AV} - \dot{B}_k^{PF,AV,EN}$ $\dot{B}_{D,k}^{AV,EX} = \dot{B}_{D,k}^{EX} - \dot{B}_{D,k}^{UN,EX}$	
(9)	Total avoidable $\left(\dot{B}_k^{PF,AV,\sum}, \dot{B}_{D,k}^{AV,\sum}\right)$	Sum of avoidable exogenous and endogenous environmental impact of component k.	$\dot{B}_k^{PF,AV,\sum} = \dot{B}_k^{PF,AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n} \dot{B}_r^{PF,AV,EX,k}$ $\dot{B}_{D,k}^{AV,\sum} = \dot{B}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n} \dot{B}_{D,r}^{AV,EX,k}$	$\dot{B}_r^{PF,AV,EX,k} = \dot{B}_r^{PF,EX,k} - \dot{B}_r^{PF,UN,EX,k}$ with $\dot{B}_r^{PF,UN,EX,k} = \dot{B}_r^{PF,UN,EN,r+k} - \dot{B}_r^{PF,UN,EX,k}$ and , $\dot{B}_r^{PF,UN,EN,r+k} = \dot{E}_{P,r}^{EN,r+k}\left(\frac{\dot{B}^{PF}}{\dot{E}_P}\right)_r^{UN}$ $\dot{B}_{D,r}^{AV,EX,k} = b_{F,k}^{real}\dot{E}_{D,r}^{AV,EX,k}$

Table 2 Selected results from splitting the environmental impact of exergy destruction (mPts/s)

						$\dot{B}_{\mathrm{D,k}}^{\mathrm{AV}}$		$\dot{B}_{\mathrm{D,k}}^{\mathrm{UN}}$	
AZEP 85	$\dot{B}_{\mathrm{D,k}}^{\mathrm{real}}$	$\dot{B}_{\mathrm{D,k}}^{\mathrm{UN}}$	$\dot{B}_{\mathrm{D,k}}^{\mathrm{AV}}$	$\dot{B}_{\mathrm{D,k}}^{\mathrm{EN}}$	$\dot{B}_{\mathrm{D,k}}^{\mathrm{EX}}$	$\dot{B}_{\mathrm{D,k}}^{\mathrm{AV,EN}}$	$\dot{B}_{\mathrm{D,k}}^{\mathrm{AV,EX}}$	$\dot{B}_{\mathrm{D,k}}^{\mathrm{UN,EN}}$	$\dot{B}_{\mathrm{D,k}}^{\mathrm{UN,EX}}$
C1	69.66	38.35	31.31	46.08	23.58	20.77	10.54	25.31	13.04
MCM	28.66	21.53	7.13	17.38	11.28	10.01	−2.88	7.37	14.17
GT1	107.05	42.41	64.64	63.93	43.12	33.15	31.49	30.78	11.63
CC	536.81	489.44	47.36	421.22	115.59	37.59	9.78	383.63	105.81
DB	109.20	50.72	58.48	70.43	38.77	37.47	21.01	32.96	17.76
MCM LTHX	48.89	23.79	25.09	23.47	25.42	5.36	19.73	18.11	5.68
MCM HTHX	6.33	4.29	2.04	3.93	2.40	1.26	0.78	2.68	1.61
HPST	16.06	5.95	10.11	8.89	7.17	4.83	5.28	4.05	1.89
HPSH	18.01	12.97	5.04	6.10	11.92	0.62	4.42	5.48	7.50
HPEC	21.15	14.91	6.24	10.36	10.79	2.34	3.90	8.02	6.89
LPEV	16.55	13.85	2.70	7.77	8.78	0.42	2.28	7.35	6.50
LPEC	20.25	5.80	14.44	12.39	7.86	9.05	5.40	3.34	2.46
ST4	47.40	7.02	40.38	31.65	15.75	27.00	13.37	4.65	2.37
GT2	14.16	3.36	10.80	13.82	0.34	9.18	1.62	4.64	−1.28
C2	5.67	1.30	4.37	7.50	−1.83	5.83	−1.46	1.67	−0.38
C3	5.98	1.28	4.70	8.16	−2.17	6.44	−1.74	1.72	−0.44
C4	6.20	1.27	4.92	8.48	−2.29	6.77	−1.85	1.71	−0.44
C5	6.64	1.28	5.36	9.10	−2.47	7.38	−2.02	1.72	−0.44
NG PH	28.88	0.23	28.65	18.84	10.04	18.79	9.85	0.05	0.18
Air HX	8.91	1.71	7.20	11.19	−2.27	8.78	−1.57	2.41	−0.70

lower than those associated with exergy destruction or pollutant formation. Thus, here, the environmental impacts associated with exergy destruction and pollutant formation are analyzed in detail, while the component-related environmental impact is neglected. The equations used to perform the analysis are shown in Table 1 [8]. It is apparent that the advanced exergoenvironmental analysis also uses results obtained from the advanced exergetic analysis of the plant [22].

For a component of interest, the endogenous environmental impact is associated exclusively with its internal operating conditions (Eq. (1) in Table 1), and it is calculated by assuming that all remaining components operate under ideal conditions (reversibly). The exogenous environmental impact associated with a plant component is the impact imposed on the component by the exergy destruction within the remaining plant components. The exogenous impact is used to quantify component interactions and to reveal the real importance of each component in the overall structure. For a given component, its exogenous environmental impact is first found by subtracting its endogenous impact from the impact calculated in the conventional analysis for the real case (starting simulation, Eq. (2) in Table 1). The exogenous impact can also be traced to the specific environmental impacts caused by each one of the other plant components. The calculation of these individual impacts requires a large number of simulations, in each one of which we assume that only two components operate under real conditions, whereas all remaining components operate without thermodynamic inefficiencies (reversibly).

The calculation of the unavoidable environmental impact of a component is based on its unavoidable exergy destruction, $\dot{E}_{\mathrm{D,k}}^{\mathrm{UN}}$, and its specific environmental impact of fuel, $b_{\mathrm{F,k}}^{\mathrm{real}}$ (Eq. (3)) [15]. The avoidable and unavoidable environmental impacts of a component can also be split into endogenous and exogenous parts using Eqs. (5)–(8) of Table 1.

To identify the components with the largest influence on the plant, we estimate their total environmental impact using Eq. (9) of Table 1. This is calculated by adding the avoidable endogenous environmental impact of a component to the sum of the avoidable exogenous environmental impacts caused by this component to the remaining components of the plant.

The effect one component can have on another plant component can be either concurrent or opposing. Concurrent effects are represented by positive exogenous values and show that a decrease in the environmental impact of one component would lead to a decrease in the environmental impact of another component. Negative exogenous values show opposing effects among plant components. These opposing effects show that improving the operation of one plant component (reducing its exergy destruction) would increase the environmental impact of another component. Modifications to the operating conditions of individual plant components, while simultaneously accounting for component interactions, are expected to lead to a faster and higher reduction of the overall environmental impact of the plant.

3 Results

3.1 Splitting the Environmental Impact of Exergy Destruction. The results for selected components of the AZEP concept are presented in Table 2. It can be seen that the environmental impact of the components with the largest environmental impact is mostly unavoidable, with notable exceptions being the expander of the main gas turbine system, i.e., GT1, and the DB, where more than half of the impacts associated with exergy destruction are avoidable. In the reference plant, the majority of the environmental impacts associated with the most important components were found to be unavoidable with the exceptions of the main expander and the high- and intermediate-pressure steam turbines of the plant [27]. Most of the environmental impact in the AZEP is avoidable for the CO_2 compressors, the steam turbine used to drive the CO_2 compressors (ST4), and the expander of the secondary GT system (GT2). Based on the avoidable environmental impact of exergy destruction, the AZEP can potentially be improved by enhancing the operation of GT1, followed by the DB, the CC and ST4 (see Table 2).

Moreover, in both the AZEP and the reference plant, most of the impact $\dot{B}_{\mathrm{D,k}}$ is endogenous, showing that component interactions are relatively low. For example, in the AZEP, the endogenous impacts of the CC and the DB are approximately four and two times higher than the exogenous impacts, respectively. In the reference plant, the endogenous environmental impact of the CC is six times higher than its exogenous impact. Similar results are obtained for the endogenous parts of the avoidable and unavoidable environmental impacts of the plants. However, as will be shown in Sec. 3.3, the exogenous values reported in Table 2 represent impacts caused by all of the remaining plant components simultaneously and may mask concurrent and opposing effects among the different components. To unmask and analyze these values and to calculate the effect of individual components, the exogenous environmental impacts must be split into the specific contributions of each other component to the component being considered.

3.2 Splitting the Environmental Impact of Pollutant Formation. The results from splitting the environmental impact of pollutant formation within the reactors of the AZEP concept and the reference plant are shown in Table 3. As already mentioned, all CO_2 emissions are considered to be unavoidable, while avoidable emissions include the remaining emissions (e.g., NO_X emissions). The endogenous environmental impact has been calculated using data derived from the simulations performed to estimate the endogenous exergy destruction [15].

As shown in Table 3, most of the environmental impacts of pollutant formation are endogenous and unavoidable (with the exception of the DB). Moreover, the avoidable impact of pollutant formation is endogenous and can, therefore, be decreased through changes in the design and operational parameters of the respective reactors.

3.3 Splitting the Exogenous Environmental Impact of Exergy Destruction. Results from splitting the exogenous environmental impacts of selected components of the AZEP are shown in Table 4. The column labeled "SUM" shows the total environmental impact of exergy destruction caused to component k by

Table 3 Splitting the environmental impact of pollutant formation for the reference plant and the AZEP concept (mPts/s)

	CO_2		NO_X							$\dot{B}_k^{PF,AV}$		$\dot{B}_k^{PF,UN}$	
	(kg/s)	(Pts/t)	(kg/s)	(Pts/t)	$\dot{B}_k^{PF}$	$\dot{B}_k^{PF,AV}$	$\dot{B}_k^{PF,UN}$	$\dot{B}_k^{PF,EN}$	$\dot{B}_k^{PF,EX}$	$\dot{B}_k^{PF,AV,EN}$	$\dot{B}_k^{PF,AV,EX}$	$\dot{B}_k^{PF,UN,EN}$	$\dot{B}_k^{PF,UN,EX}$
Ref. Plant	38.41	5.4	0.05	2749.4	349.69	140.19	209.5	332.56	17.12	149.67	−9.48	182.89	26.61
AZEP 85 DB	5.76		0.03		178.11	0.00	178.11	125.93	52.18	0.00	0.00	139.60	38.51
CC	32.65				127.51	96.08	31.43	118.69	8.82	98.26	−2.18	20.42	11.01

the operation of the surrounding plant components, while the values in the parentheses show the effect of component k on the other components (obtained by summing the individual impacts the component causes to each one of the other components). The operation of the CC has an opposing effect on some components, which means that when improving the environmental operation of the CC, the operation of these components becomes worse. Because the components that experience an opposing effect from the CC have relatively low environmental impacts, they are not shown in Table 4, but can be found in detailed tables in Ref. [15].

In summary, the highest impact in the AZEP is caused by GT1, CC (opposing effect), MCM HTHX (35.2 mPts/s) and C1. On the other hand, as shown by the "SUM" column in Table 4, the environmental performance of the CC is significantly influenced by the other components, while the DB, GT1, and C1 are influenced relatively less. In the reference plant, the highest exogenous environmental impact is caused by GT1 and it is of similar magnitude as that calculated in the AZEP. The component with the second highest exogenous impact in the reference plant is the CC with the difference that, in this case, the overall effect of the component is concurrent (i.e., positive). Finally, in the reference case, in contrast to the AZEP concept, C1 is found to be more dependent on other components than GT1.

High values of the exogenous environmental impact in the AZEP and reference plant are found for the reactors and the components of the GT system. A large part of the impact of the CC is caused by C1 and GT1. Specifically, in the AZEP and the reference plant, 35% and 52% of the impact imposed to the CC stems from GT1 and C1, respectively [27]. This percentage decreases to 11% for the DB of the AZEP. Analogously, large amounts of the impact imposed on C1 and GT1 stem from the CC.

3.4 Calculating the total avoidable environmental impact of exergy destruction. The total avoidable environmental impact, calculated using Eq. (9) of Table 1, is a variable used to evaluate the overall significance of plant components [15]. The results of the most influential components of the plants are shown in Table 5. In contrast to the reference plant, where the CC is the most important component, in the AZEP, the CC has a lower total impact than GT1. This is a result of the rather small avoidable exogenous environmental impact of the CC, which mainly stems from the opposing influence on the components of the CO_2 compression unit. The DB has a negative avoidable exogenous environmental impact (opposing effect), which mainly stems from its opposing influence on the MCM LTHX of the plant. Due to the complex structure of the AZEP that includes two reactors, opposing effects

Table 4 Selected results from splitting the exogenous environmental impact of exergy destruction (mPts/s)[a]

AZEP 85	Component, k	$\dot{B}_{D,k}^{EX}$	Component, r	$\dot{B}_{D,k}^{EX,r}$	$\dot{E}_{D,k}^{EX,r}$ Component, k	$\dot{B}_{D,k}^{EX}$	Component, r	$\dot{B}_{D,k}^{EX,r}$
	CC	115.59	DB	0.16	GT1	43.12	CC	13.26
			MCM LTHX	0.20			DB	0.04
			C1	12.01			MCM LTHX	0.05
			GT1	17.92			C1	0.88
			MCM	0.22			MCM	0.09
			ST4	2.84			ST4	0.61
			LPST	5.80			LPST	0.96
			SUM	86.21 (−47.92)			SUM	20.07 (56.03)
	DB	38.77	CC	14.90	MCM	11.28	CC	3.35
			MCM LTHX	0.02			DB	0.17
			C1	1.62			MCM LTHX	−0.11
			GT1	2.48			C1	0.35
			MCM	0.04			GT1	0.95
			ST4	0.65			ST4	0.16
			LPST	1.23			LPST	0.35
			SUM	28.56 (1.50)			SUM	8.42 (3.13)
	MCM LTHX	25.42	CC	3.89	ST4	15.75	CC	−8.14
			DB	0.21			DB	0.09
			C1	−1.36			MCM LTHX	0.51
			GT1	1.18			C1	2.19
			MCM	−1.04			GT1	1.01
			ST4	0.56			MCM	1.09
			LPST	−0.50			LPST	0.38
			SUM	14.51 (1.07)			SUM	12.92 (7.31)
	C1	23.58	CC	9.92	LPST	14.95	CC	2.83
			DB	0.16			DB	0.27
			MCM LTHX	0.05			MCM LTHX	−0.70
			GT1	1.66			C1	1.00
			MCM	0.07			GT1	6.00
			ST4	0.45			MCM	0.00
			LPST	0.60			ST4	−0.25
			SUM	17.93 (32.80)			SUM	6.80 (10.39)

[a] In parentheses, the sum of exergy destruction caused by component k to the remaining components is shown.

Table 5 Total avoidable environmental impact of exergy destruction as defined with Eq. (9) (mPts/s)[a]

AZEP 85 Component, k	$\sum_{r=1, r\neq k}^{n} \dot{B}_{D,r}^{AV,EX,k}$	$\dot{B}_{D,k}^{AV,EN}$	$\dot{B}_{D,k}^{AV,\Sigma}$
GT1	10.91 (24.8%)	33.15 (75.2%)	44.06
CC	1.24 (3.2%)	37.59 (96.8%)	38.83
DB	−0.71	37.47	36.76
C1	5.73 (21.6%)	20.77 (78.4%)	26.50
LPST	4.53 (24.4%)	14.06 (75.6%)	18.59
MCM	3.33 (25.0%)	10.01 (75.0%)	13.34
MCM LTHX	0.39 (6.8%)	5.36 (93.2%)	5.75

[a] Values in parentheses show the relative contribution of avoidable exogenous and endogenous environmental impacts.

among plant components are more common than in other examined cases [15]. The complexity of the plant is expected to make its improvement more challenging than that of other systems. Thus, all information that can be obtained using advanced exergy-based analyses is of great value.

Overall, although the avoidable endogenous values of the CC and DB are similar in the AZEP, the CC has a higher total avoidable impact ($\dot{B}_{D,k}^{AV,\Sigma}$) due to its slightly higher avoidable exogenous value. Meanwhile, although the MCM HTHX was found to have a higher influence on the remaining plant components, it is greatly surpassed by GT1 in total impact, due to the relatively high avoidable endogenous part of the latter (Table 5). In this way, GT1 is ranked first, followed by the CC and the DB. These results differ from those obtained for the reference plant, in which, for example, GT1 causes an avoidable exogenous environmental impact similar to that caused by the CC [27].

4 Conclusions

In this study, the environmental impact of an oxy-fuel advanced zero emission plant involving CO_2 capture was evaluated and compared with a conventional plant without CO_2 capture (reference plant). The reason for choosing an oxy-fuel technology is that it represents a relatively promising alternative for CO_2 capture that keeps the energy penalty at relatively low levels. Although relatively efficient, the AZEP is still associated with an efficiency penalty when compared to the reference plant. The goal of this paper is to extract new useful information that cannot be obtained by conventional exergy-based approaches (i.e., potential of improvement of individual components and the overall plant; interactions among interrelated plant components), in order to suggest measures to improve the plant operation.

Overall, we found that a significant part of the environmental impact of exergy destruction of plant components is unavoidable and endogenous. This means that although the environmental impact of the plant can be decreased, a significant part of it cannot be avoided using structural or operational changes. Additionally, the largest values of endogenous environmental impacts suggest that the improvement measures should initially involve modifications in the internal operation of the plant components and subsequently account for component interactions. In contrast to the reference plant, in the AZEP we found strong component interactions, some of which show opposing effects. The most important components in the AZEP and, thus, the components on which improvement efforts should focus, are the gas turbine system, the duct burner, the low-pressure steam turbine and the components of the mixed-conducting membrane reactor. For the supplementary firing and the mixed-conducting membrane reactor an opposing effect is calculated. Due to the opposing effects of the reactors, the expander of the AZEP concept results in a higher total avoidable environmental impact than the combustion chamber.

Summarizing our general findings about the advanced exergy-based methods, we conclude the following:

1. A detailed advanced exergy-based method establishes the true relative importance of each plant component and allows engineers to set objective priorities with respect to the improvement of components.
2. Knowledge about the intensity of component interactions in a system can assist engineers in making improvements through modifications of the structure of a plant when the interactions are strong, or by improving individual components when the interactions are weak.
3. The iterative improvement process is significantly facilitated when the *avoidable* exergy destruction, costs, and environmental impacts are used.
4. Conclusions obtained for one plant (reference plant) cannot be assumed to also apply to a modified plant (AZEP), in which one component (combustion chamber) is replaced by another (mixed-conducting membrane reactor).
5. The method used here is complex and its application is time consuming. Future efforts should focus on finding ways to reduce the complexity and time of application without a significant effect on the accuracy of the results.

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Nomenclature

b = specific environmental impact per unit of exergy (mPts/MJ) or per unit of mass (mPts/kg)
$\dot{B}, \dot{Y}$ = environmental impact rate (mPts/s)
$\dot{E}$ = exergy rate (W)

Subscripts

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

Superscripts

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

Abbreviations

AZEP = advanced zero emission plant
C1–C6 = compressors
CC = combustion chamber
CCS = CO_2 capture and storage
COND = condenser
DB = duct burner
EC = economizer
EV = evaporator
FG = flue gas
GT = gas turbine
HP = high pressure
HRSG = heat-recovery steam generator
HT = high temperature
HX = heat exchanger
IP = intermediate pressure
LCA = life-cycle assessment
LP = low pressure
LT = low temperature
MCM = mixed-conducting membrane
NG = natural gas

PF = pollutant formation
SH = superheater
ST = steam turbine

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