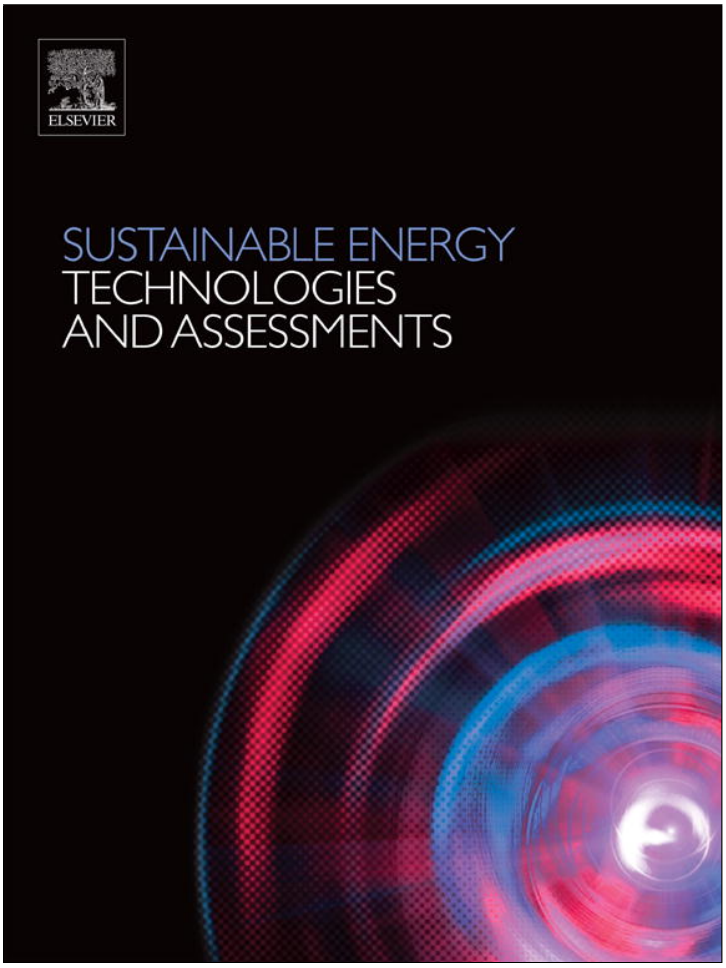
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Original Research Article

Evaluation of a power plant with chemical looping combustion using an advanced exergoeconomic analysis

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ABSTRACT

Advanced exergy-based analyses extend engineering knowledge beyond the respective conventional methods by quantifying the potential for improvement and the component interactions and facilitating the optimization of a system. In this paper, the first application of an advanced exergoeconomic analysis to a complex combined-cycle power plant with CO_2 capture is presented and the obtained results are assessed. The power plant incorporates a chemical looping combustion unit that facilitates the CO_2 capture process and has been chosen as one of the most promising oxy-combustion technologies with respect to efficiency, economic feasibility and environmental footprint. The largest avoidable costs, which represent the potential for improvement, are associated with the components constituting the main gas turbine system. The most important components based on the total avoidable cost are the reactor, expander and compressor. Furthermore, the relatively low component interactions show that most of the costs are associated with the operation of these components; i.e., no intense process interdependencies exist.

Introduction

Electric-power generation remains the single largest source of CO_2 emissions, equal to those of the rest of the industrial sectors combined [1]. While increasing greenhouse gas concentrations are correlated with temperature rise and change in climatic conditions, most of the energy demand across the globe is covered by fossil fuels that generate large amounts of pollutants such as CO_2, CH_4 and NO_X. Rising energy demand prolongs environmental aggravation, but it simultaneously acts as a strong motivator for the development of new technologies to mitigate climate change. As mentioned in the IPCC report [1], one of the measures to confine the increasing man-made CO_2 concentration in the atmosphere is carbon dioxide capture and storage (CCS).

In this paper, we examine the economics of CO_2 capture in a combined-cycle power plant using a recently developed analysis. The power plant incorporates oxy-fuel technology using a chemical looping combustion (CLC) unit for simplified CO_2 capture (Fig. 1) [2–6] and was chosen as one of the most efficient technologies among eight different methods for CO_2 capture investigated in [7]. The CLC unit of the power plant uses a metal oxide to separate oxygen from incoming air and transfer it to a reactor, where natural gas combustion takes place in the presence of almost pure oxygen. In this way, the combustion products include mainly water and CO_2 that can be easily separated after water condensation.

The initial evaluation of the CLC plant using conventional exergy-based methods, i.e., conventional exergetic, exergoeconomic and exergoenvironmental analyses, was presented in Refs. [6,8]. Conventional exergy-based methods are widely known and have been applied to a large variety of energy conversion systems (e.g., [9–15]). Although the CLC plant was shown to perform thermodynamically, economically and environmentally better than other advanced CO_2 capture alternatives, its fixed capital investment costs are by approximately 70% higher than those of a similarly-structured plant without CO_2 capture ("reference plant") and by 11% higher than those of a similarly-structured plant with *post-combustion* CO_2 capture. In this work, we seek ways to decrease the cost of the CLC plant; this could eventually improve the future implementation possibilities of CLC power plants.

To achieve this we analyze the power plant using an *advanced exergoeconomic method*. Advanced exergy-based methods use the results of the corresponding conventional analyses, but advance the examination process by introducing new calculation steps to reveal component interactions and potential for improvement [16–18]. Until very recently, advanced exergy-based methods were applied only to relatively simple processes [19–21]. The first applications of advanced exergetic, exergoeconomic and exergoenvironmental analyses to a more complex plant were on a conventional

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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 symbol

ε	exergetic efficiency (%)

Abbreviations

C1–C6	compressor
CCS	carbon dioxide capture and storage
CLC	chemical looping combustion
COND	condenser
COOL	cooler
CT	cooling tower
EV	evaporator
EC	economizer
GEN	generator
GT	gas turbine
HP	high pressure
HRSG	heat recovery steam generator
HX	heat exchanger
IP	intermediate pressure
LP	low pressure
MX	mexogenous
NG	natural gas
PEC	purchased equipment cost
PH	preheater
RH	reheater
SH	superheater

combined cycle power plant, the previously-mentioned "reference plant" and were presented in Refs. [22–24]. The CLC plant was the first complex power plant with CO_2 capture that was analyzed using advanced exergy-based methods [25]. The work reported here represents the first attempt to evaluate the economics associated with a CLC power plant in such detail. The results can be used as a tool to decrease the cost of the product of the overall plant and to increase its operating efficiency.

Methodology and application

The application of advanced exergy-based methods requires carefully defined steps that use as input results from conventional exergy-based analyses. This means that to perform an advanced analysis, the corresponding conventional analysis has to be conducted first. The role of advanced exergy-based analyses is (a) to reveal avoidable thermodynamic inefficiencies, costs, and environmental impacts that show the potential for improvement of a component/process, and (b) to calculate the magnitude of internal or external thermodynamic inefficiencies, costs and environmental impacts that show how strongly the components of a process influence one another. The final goal when using such methods is to improve ("optimize") a process through the implementation of changes pinpointed by the results of the advanced analyses.

In this paper we focus on the presentation of the application and the results of an advanced exergoeconomic analysis. Such an analysis is used to separate the component-related costs (investment, operating, and maintenance costs, $\dot{Z}$)[1] and the costs associated with exergy destruction, $\dot{C}_D$, into avoidable/unavoidable (AV/UN), endogenous/exogenous (EN/EX) and their combined parts (e.g., avoidable endogenous, AV EN). The equations used to perform the analysis can be found in Table 1 [23].

For the calculation of endogenous/exogenous costs, the investment costs and the costs of exergy destruction of each component are split into costs associated with the operation of the component itself (endogenous) and the part of the cost originating from the thermodynamic inefficiencies of other components in the plant (exogenous). The total exogenous cost of each component is further split to its individual sources, in order to pinpoint the components with the largest influence on the component being considered. This splitting requires additional simulations performed during the application of the advanced exergetic analysis [7]. In each of these simulations we consider a pair of components operating under real conditions, while all the remaining components operate theoretically. In this way, we isolate and quantify the influence the two chosen components have on one another.

Avoidable investment costs are costs that could eventually be avoided, in most cases by using less efficient components. As seen in Table 1, the calculation of the unavoidable exergy destruction cost combines results from the conventional exergoeconomic and advanced exergetic analyses. To calculate the avoidable investment costs, however, we must perform additional simulations to calculate the costs when the components operate in isolation and with very high thermodynamic inefficiencies. For example, to estimate the unavoidable investment cost of a heat exchanger (HX), the component operates in isolation with a high minimum temperature difference and pressure drops. Since we need to optimize only components for which the thermodynamic inefficiencies are inversely proportional to costs, maximum thermodynamic inefficiencies will result in the lowest possible construction and operating costs, i.e., the costs of the component that cannot be avoided (unavoidable investment costs). When subtracting the unavoidable costs from the total costs, we calculate the avoidable costs. To perform the simulations required to calculate the avoidable/unavoidable investment costs, the operating conditions shown in Table 2 have been assumed. These assumptions depend on the decision maker and are arbitrary to some extent. For example, most of the costs of the GT system, the steam turbines (STs) and the pumps were assumed to be unavoidable, due to limited modification possibilities in their design. More details on the calculation procedure can be found in Refs. [7,23].

Due to the complexity of the advanced exergoeconomic method, the present form of the analysis does not offer solutions that

[1] The total cost (excluding fuel cost) associated with a plant consists of investment costs and operating and maintenance expenses. These costs are calculated in a conventional exergoeconomic analysis. However, because investment costs largely dominate the total (excluding fuel) costs, we will refer here to these costs for brevity as "investment costs".

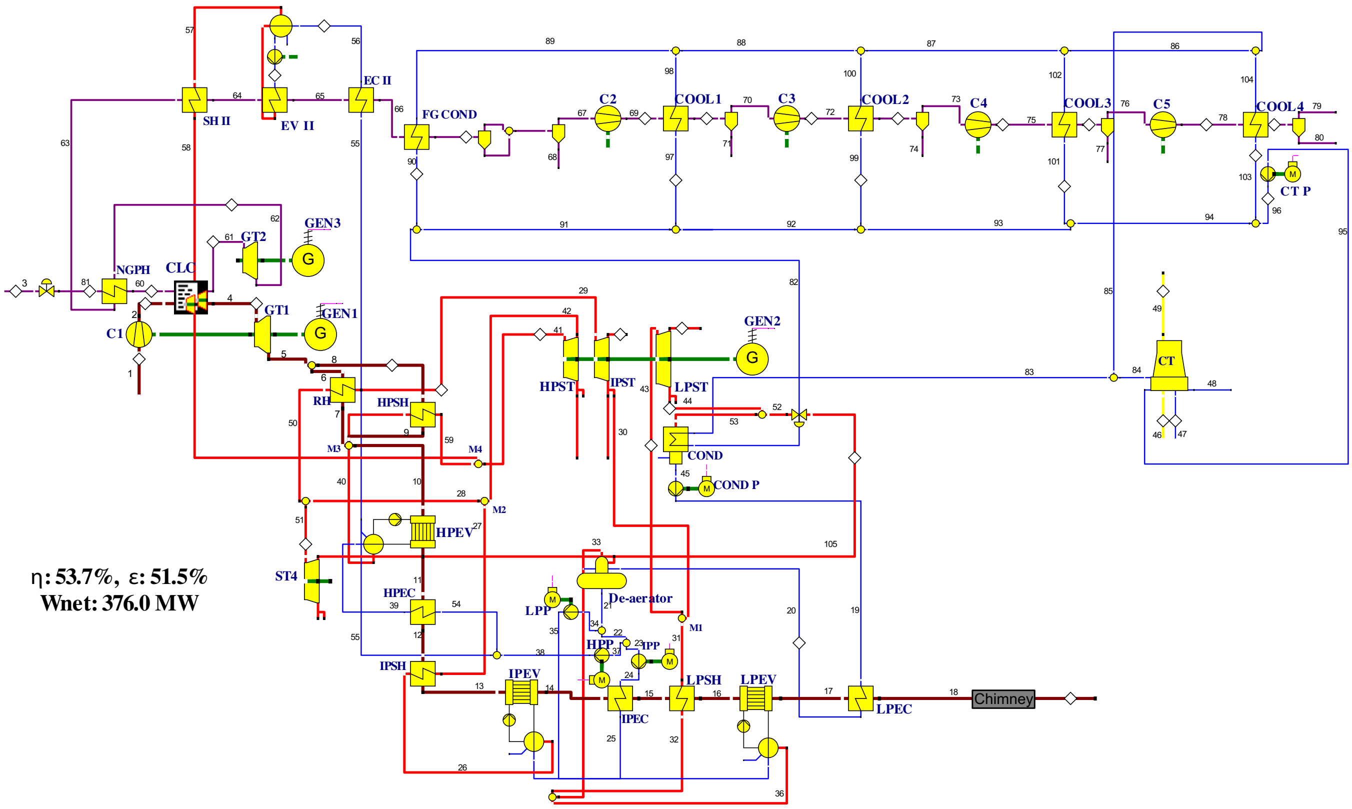

Fig. 1. Structure of the considered plant with chemical looping combustion.

can be followed without further filtering, but its results require engineering knowledge and judgment (incl. appropriate interpretation of the results) to reach correct conclusions. Thus, although the results provide a very detailed overview on the performance of the process, the user needs to understand and correctly interpret them. The primary focus when interpreting the results of an advanced exergoeconomic analysis is the avoidable costs (both avoidable endogenous and avoidable exogenous) that show the potential for improvement of individual components, as well as the plant as a whole. Better-guided improvement strategies and more accurate evaluations of individual components are realized when using the *total avoidable cost*. This variable is calculated at the end of the analysis by adding the avoidable endogenous costs of a component and the avoidable costs the component being considered causes to the remaining components of the plant ("cost" in this sentence includes both investment cost and cost of exergy destruction):

$$\dot{C}_{D,k}^{AV,\Sigma} + \dot{Z}_{k}^{AV,\Sigma} = \left(\dot{C}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{C}_{D,r}^{AV,EX,k} \right) + \left(\dot{Z}_{k}^{AV,EN} + \sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{Z}_{r}^{AV,EX,k} \right).$$

$\sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{C}_{D,r}^{AV,EX,k}$ and $\sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{Z}_{r}^{AV,EX,k}$ are the total avoidable cost rates caused by component k on component r and associated with the exogenous exergy destruction and the investment cost of component r, respectively [23].

Results and discussion

As presented in Refs. [6,8], the investigated CLC plant has an efficiency of 51.3%. The highest exergy destruction occurs in the gas turbine (GT) system due to the chemical reactions taking place there. The components that follow in magnitude of thermodynamic inefficiencies are the heat-recovery steam generator (HRSG) and the low-pressure steam turbine (LPST). Although among all plant components, the combustion process considered here is associated with the highest thermodynamic inefficiency, it is more efficient than the conventional combustion process in the reference combined-cycle power plant [8].

Selected results of the advanced exergoeconomic analysis are presented in Tables 3–5. Table 3 presents the results from splitting the investment costs of selected plant components. The endogenous investment cost rate, $\dot{Z}_{k}^{EN}$, is higher than the exogenous rate, $\dot{Z}_{k}^{EX}$, for all plant components. This shows, in general, that the interactions among components do not affect significantly the investment costs. In particular, 85% and 76% of the investment cost of the CLC reactors and GT1, respectively, is endogenous, i.e., it is affected only by the internal operating conditions of the components. For some components, the difference between the absolute values of the endogenous and exogenous investment cost rates is essential. This indicates that the investment cost of the considered component is mainly affected by internal thermodynamic inefficiencies and much less by the structure of the plant and the operation of the remaining components. For example, the CLC reactors and GT1 have endogenous investment costs five and three times higher than the corresponding exogenous values. On the other hand, the difference between the endogenous and exogenous costs of the compressor is rather small. Both the absolute values and the differences between the endogenous and exogenous investment costs decrease significantly when we consider the avoidable parts of the endogenous/exogenous costs. Here the importance of the components of the gas-turbine system decreases significantly, but this system remains the most important one within the overall plant. The most interesting results are found for GT1, the avoidable endogenous cost of which decreases to approximately that of C1, while its avoidable exogenous cost is surpassed by that of other plant components.

Table 1
Splitting the costs.

TERM	Definition of cost rate	Cost rate of investment, $\dot{Z}_k$, and exergy destruction, $\dot{C}_{D,k}$, *(of component k)*	Comments
Endogenous ($\dot{Z}^{EN}$, $\dot{C}_D^{EN}$)	Cost rate within component *k* associated with the operation of the component itself	$\dot{Z}_k^{EN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{real}$ $\dot{C}_{D,k}^{EN} = c_{F,k}^{real}\dot{E}_{D,k}^{EN}$	$\dot{E}_{P,k}^{EN}$: Rate of product exergy of component k when the remaining components operate theoretically $\dot{E}_P^{real}$ and $\dot{Z}^{real}$: Rate of product exergy and investment cost in the real case $c_{F,k}^{real}$: Average cost per unit of fuel exergy provided to component k in the real case
Exogenous ($\dot{Z}^{EX}$, $\dot{C}_D^{EX}$)	Cost rate within component *k* caused by the remaining components	$\dot{Z}_k^{EX} = \dot{Z}_k^{real} - \dot{Z}_k^{EN}$ $\dot{C}_{D,k}^{EX} = \dot{C}_{D,k}^{real} - \dot{C}_{D,k}^{EN}$	
Mexogenous ($\dot{Z}^{MX}$, $\dot{C}_D^{MX}$)	Difference between exogenous and sum of split exogenous cost rates for component *k*, caused by simultaneous interactions between the component and the remaining components of the plant	$\dot{Z}_k^{MX} = \dot{Z}_k^{EX} - \sum_{r=1, r\neq k}^{n} \dot{Z}_k^{EX,r}$ $\dot{C}_{D,k}^{MX} = \dot{C}_{D,k}^{EX} - \sum_{r=1, r\neq k}^{n} \dot{C}_{D,k}^{EX,r}$	$\sum_{r=1, r\neq k}^{n} \dot{Z}_k^{EX,r} = \sum_{r=1, r\neq k}^{n}\left(\dot{Z}_k^{EN,r+k} - \dot{Z}_k^{EN}\right)$, with $\dot{Z}_k^{EN,r+k} = E_P^{EN,r+k}\left(\frac{\dot{Z}_k}{\dot{E}_{P,k}}\right)^{real}$ $\sum_{r=1, r\neq k}^{n} \dot{C}_{D,k}^{EX,r} = \sum_{r=1, r\neq k}^{n}\left(\dot{C}_{D,k}^{EN,r+k} - \dot{C}_{D,k}^{EN}\right)$, with $\dot{C}_{D,k}^{EN,r+k} = c_{F,k}^{real}\dot{E}_{D,k}^{EN,r+k}$
Unavoidable ($\dot{Z}^{UN}$, $\dot{C}_D^{UN}$)	Cost rate that cannot be avoided	$\dot{Z}_k^{UN} = \left(\frac{PEC^{UN}}{PEC^{real}}\right)_k \times \dot{Z}_k^{real}$ for HXs % of $\dot{Z}_k^{real}$ for other components $\dot{C}_{D,k}^{UN} = c_{F,k}^{real}\dot{E}_{D,k}^{UN}$	$\dot{Z}_k^{UN}$: Unavoidable investment cost rate, i.e., minimum cost associated with component k. For each heat exchanger a new simulation of the component in isolation, operating with low effectiveness and high irreversibility, is required. For other components, part of their $\dot{Z}^{real}$ is chosen as unavoidable PEC_k^{UN}: Purchased equipment cost of component k, calculated at the unavoidable conditions $\dot{E}_D^{UN}$: Unavoidable part of exergy destruction rate (calculated in an advanced exergetic analysis with most favorable operating conditions that result in the lowest possible exergy destruction)
Avoidable ($\dot{Z}^{AV}$, $\dot{C}_D^{AV}$)	Cost rate that can be avoided	$\dot{Z}_k^{AV} = \dot{Z}_k^{real} - \dot{Z}_k^{UN}$ $\dot{C}_{D,k}^{AV} = \dot{C}_{D,k}^{real} - \dot{C}_{D,k}^{UN}$	
Unavoidable endogenous ($\dot{Z}^{UN,EN}$, $\dot{C}_D^{UN,EN}$)	Unavoidable cost rate within component *k* associated with the operation of the component itself	$\dot{Z}_k^{UN,EN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{Z}^*}{\dot{E}_P}\right)_k^{UN}$ $\dot{C}_{D,k}^{UN,EN} = c_{F,k}^{real}\dot{E}_{D,k}^{UN,EN}$	$\left(\frac{\dot{Z}^*}{\dot{E}_P}\right)_k^{UN} = \left(\frac{\dot{Z}^{UN}}{\dot{E}_P^{real}}\right)_k$ $\dot{E}_D^{UN,EN}$: Unavoidable endogenous part of exergy destruction rate (calculated in an advanced exergetic analysis)
Unavoidable exogenous ($\dot{Z}^{UN,EX}$, $\dot{C}_D^{UN,EX}$)	Unavoidable cost rate within component *k* caused by the remaining components	$\dot{Z}_k^{UN,EX} = \dot{Z}_k^{UN} - \dot{Z}_k^{UN,EN}$ $\dot{C}_{D,k}^{UN,EX} = \dot{C}_{D,k}^{UN} - \dot{C}_{D,k}^{UN,EN}$	
Avoidable endogenous ($\dot{Z}^{AV,EN}$, $\dot{C}_D^{AV,EN}$)	Avoidable cost rate within component *k* associated with the operation of the component itself	$\dot{Z}_k^{AV,EN} = \dot{Z}_k^{EN} - \dot{Z}_k^{UN,EN}$ $\dot{C}_{D,k}^{AV,EN} = \dot{C}_{D,k}^{EN} - \dot{C}_{D,k}^{UN,EN}$	
Avoidable Exogenous ($\dot{Z}^{AV,EX}$, $\dot{C}_D^{AV,EX}$)	Avoidable cost rate within component *k* caused by the remaining components	$\dot{Z}_k^{AV,EX} = \dot{Z}_k^{EX} - \dot{Z}_k^{UN,EX}$ $\dot{C}_{D,k}^{AV,EX} = \dot{C}_{D,k}^{EX} - \dot{C}_{D,k}^{UN,EX}$	

Table 2
Assumptions for the calculation of the unavoidable investment cost rates.

Components[a]	$\dot{Z}_k^{UN}$ (operating conditions or % of $\dot{Z}_k^{real}$)	Components	$\dot{Z}_k^{UN}$ (operating conditions or % of $\dot{Z}_k^{real}$)
GT1	90%	SH/RH	ΔT_{min} = 100 °C
GT2	90%		$\Delta P_{UN} = \Delta P_{real}$
C1	85%	EV	ΔT_{min} = 50 °C
C2–C5	90%		$\Delta P_{UN} = \Delta P_{real}$
C6	85%	EC	ΔT_{min} = 75 °C
STs	90%		$\Delta P_{UN} = \Delta P_{real}$
CLC reactors	80%	NGPH	ΔT_{min} = 600 °C
Pumps (P)	60%		$\Delta P_{UN} = \Delta P_{real}$
Motors	Incl. with pumps	COOL	ΔT_{min} = 75 °C
GEN	Incl. with turbines		$\Delta P_{UN} = \Delta P_{real}$

[a] No distinction between avoidable and unavoidable investment cost rates has been made for mixers, de-aerators, or dissipative components.

The total avoidable investment costs indicate that priority for improvement should be given to the GT system, with the reactors first, C1 second and GT1 third. The components that follow, priority-wise, are the heat exchangers (HXs) of the high- and low-pressure (HP and LP) HRSG. The high avoidable endogenous investment costs of the components of the GT system show that if we wanted to decrease this cost for a component (remember that the final objective of optimization is to decrease the product cost for the overall system, and not the investment costs of specific components), changes should relate to the component itself. This could be, for example, by replacing the construction materials or the manufacturing techniques with less expensive ones, when the operating conditions allow it. When the total cost associated with a component should be reduced, a more cost effective operation might be obtained by using the most efficient available component (e.g., for conventional gas turbine systems).

The results from splitting the cost of exergy destruction are given in Table 4. As seen in this table, it is possible to obtain negative values of split costs (for example for the NGPH). Such results show opposite effects and are related with increased mass flow rates in the simulations used to calculate the endogenous values, when compared to those of the initial process. Higher mass flow rates result in higher exergy of the product that is correlated with higher costs. The interpretation of these results is that the thermodynamic inefficiency associated with a component with negative exogenous cost of exergy destruction increases when other components operate under theoretical conditions. Thus, to decrease its thermodynamic inefficiencies, inefficiencies of some other components must increase. Nevertheless this negative value represents the total effect of all plant components to the component of interest. To find out which pairs of components have such an opposing effect, and to improve the decision-making process, the exogenous costs are split into their individual parts.

Based on the avoidable cost of exergy destruction, the plant can potentially be improved through improvements of the CLC, GT1, C1, and ST that drives the CO_2 compressors (ST4). This ranking differs from that of the investment costs and highlights the stronger influence of the thermodynamic inefficiencies of GT1 when compared with C1. Additionally, the LPST and ST4 exhibit significant costs of exergy destruction that ensure their ranking priority over HXs. In contrast to the investment costs, the avoidable endogenous and exogenous costs of exergy destruction clearly give priority for improvement to the three components of the GT system. Nevertheless, it should be noted that the avoidable exogenous cost of ST4 is calculated to be quite similar to that of C1, an observation that increases the significance of ST4 within the overall structure.

Similar to the investment cost, the cost of exergy destruction is mostly endogenous for the majority of the components. Thus, here once again, most of the costs stem from the internal operation of the components and component interactions are of lower importance. Measures that could be taken to decrease the cost of exergy destruction may include the increase of the operating temperature of the reaction and/or the inlet of the expander or, as in the previous case, the replacement of existing components with others of newer and more efficient technology. Nevertheless, although the exogenous costs are of relatively low significance when compared to the endogenous costs, their sources reveal additional improvement potential for the overall plant.

The splitting of the exogenous cost rates for the components with the highest investment and exergy destruction costs is shown in Tables 5 and 6, respectively. The values under "SUM" show the total exogenous costs of component *k* originating from the remaining plant components, while the values in parentheses show the cost influence of component *k* on the remaining (*r*) components. The components highly influenced by the operation of others are the CLC reactors, C1, and GT1. However, the most important components from the cost viewpoint, in general, are in descending order of importance the CLC reactors, GT1 and C1.

The sum of the individual exogenous values of a component originating from other plant components differs from the total exogenous cost of the component. The difference between the two numbers is called "mexogenous cost" (MX, mixed exogenous), is shown in Tables 5 and 6, and represents further component interactions (simultaneous interactions among the component being considered and at least two other components) during the splitting of the costs. The mexogenous investment cost is relatively

Table 3
Splitting the investment cost rates (€/h).

	$\dot{Z}_k^{real}$	$\dot{Z}_k^{UN}$	$\dot{Z}_k^{AV}$	$\dot{Z}_k^{EN}$	$\dot{Z}_k^{EX}$	$\dot{Z}_k^{AV}$		$\dot{Z}_k^{UN}$	
						$\dot{Z}_k^{AV,EN}$	$\dot{Z}_k^{AV,EX}$	$\dot{Z}_k^{UN,EN}$	$\dot{Z}_k^{UN,EX}$
C1	964.4	819.7	144.7	564.7	399.7	84.7	59.9	480.0	339.7
CLC	4974.5	3979.6	994.9	4211.1	763.3	842.2	152.7	3368.9	610.7
GT1	1102.2	992.0	110.2	839.6	262.6	84.0	26.3	755.6	236.4
HPSH	105.2	40.6	64.6	46.0	59.2	28.2	36.4	17.8	22.9
HPEV	139.7	71.4	68.3	72.7	67.0	35.5	32.7	37.2	34.3
HPST	102.8	92.5	10.3	57.8	45.0	5.8	4.5	52.0	40.5
IPST	148.5	133.6	14.8	107.5	40.9	10.8	4.1	96.8	36.8
LPST	386.9	348.2	38.7	279.8	107.1	28.0	10.7	251.8	96.4
ST4	156.5	140.9	15.7	86.5	70.1	8.6	7.0	77.8	63.1
GT2	215.8	194.2	21.6	158.5	57.3	15.8	5.7	142.6	51.6
C2	313.8	266.7	47.1	216.8	97.0	32.5	14.6	184.3	82.5
C3	322.8	274.3	48.4	230.7	92.0	34.6	13.8	196.1	78.2
C4	318.4	270.7	47.8	228.8	89.6	34.3	13.4	194.5	76.2
C5	320.0	272.0	48.0	230.3	89.7	34.5	13.5	195.7	76.3

Table 4
Selected results from splitting the exergy destruction cost rates (€/h).

	$\dot{C}^{real}_{D,k}$	$\dot{C}^{UN}_{D,k}$	$\dot{C}^{AV}_{D,k}$	$\dot{C}^{EN}_{D,k}$	$\dot{C}^{EX}_{D,k}$	$\dot{C}^{AV}_{D,k}$		$\dot{C}^{UN}_{D,k}$	
						$\dot{C}^{AV,EN}_{D,k}$	$\dot{C}^{AV,EX}_{D,k}$	$\dot{C}^{UN,EN}_{D,k}$	$\dot{C}^{UN,EX}_{D,k}$
C1	919.2	506.0	413.2	542.0	377.2	245.7	167.5	296.3	209.7
CLC	6390.8	4259.4	2131.4	5484.5	906.3	1878.7	252.7	3605.8	653.6
GT1	1277.8	540.4	737.4	845.2	432.6	433.5	303.9	411.7	128.8
HPEC	238.5	177.0	61.4	121.2	117.2	20.3	41.1	101.0	76.1
LPEV	197.3	143.3	54.0	98.7	98.6	18.3	35.7	80.4	62.9
LPEC	244.7	137.2	107.5	147.3	97.4	74.0	33.6	73.3	63.9
LPST	587.3	310.7	276.7	383.6	203.8	158.9	117.8	224.6	86.0
ST4	423.8	62.3	361.5	235.6	188.2	201.2	160.3	34.4	27.9
GT2	118.9	34.5	84.4	63.0	55.9	37.6	46.8	25.3	9.2
C4	84.6	19.2	65.4	61.8	22.8	48.0	17.4	13.8	5.4
C5	87.8	19.2	68.7	64.3	23.6	50.5	18.2	13.8	5.4
NGPH	220.5	5.7	214.8	126.3	94.2	5.9	208.9	120.4	-114.7

Table 5
Selected results from splitting the exogenous investment cost rates (€/h).[a]

Component, *k*	$\dot{Z}^{EX}_k$	Component, *r*	$\dot{Z}^{EX,r}_k$	Component, *k*	$\dot{Z}^{EX}_k$	Component, *r*	$\dot{Z}^{EX,r}_k$
CLC	763.33	C1	141.71	ST4	70.06	C1	3.09
		GT1	209.03			CLC	12.02
		ST4	27.77			GT1	3.78
		SUM	655.70 (667.11)			SUM	50.53 (30.94)
		MX	107.64			MX	19.52
C1	399.66	CLC	278.97	*GT1*	262.62	C1	31.50
		GT1	25.40			CLC	122.79
		ST4	3.39			ST4	5.11
		SUM	342.58 (246.67)			SUM	215.32 (478.35)
		MX	57.09			MX	47.30

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

Table 6
Selected results from splitting the exogenous cost rates of exergy destruction (€/h).[a].

Component, *k*	$\dot{C}^{EX}_{D,k}$	Component, *r*	$\dot{C}^{EX,r}_{D,k}$	Component, *k*	$\dot{C}^{EX}_{D,k}$	Component, *r*	$\dot{C}^{EX,r}_{D,k}$
CLC	906.30	C1	103.23	ST4	188.20	C1	8.43
		GT1	272.24			CLC	32.72
		ST4	36.17			GT1	9.75
		SUM	772.62 (813.84)			SUM	136.13 (52.23)
		MX	133.68			MX	52.07
C1	377.20	CLC	262.15	GT1	432.64	C1	22.37
		GT1	24.38			CLC	88.40
		ST4	3.25			ST4	5.14
		SUM	323.20 (236.06)			SUM	172.20 (689.31)
		MX	54.00			MX	260.44

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

high for the CLC unit, whereas the mexogenous cost of exergy destruction is high for GT1. Complete tables presenting the results for all plant components can be found in [7].

Although the cost rates of investment and exergy destruction are split separately, the performance of a component is finally evaluated based on the total avoidable cost, which includes both the component's avoidable costs associated with exergy destruction and investment. This sum is used to assess the components by showing their overall significance in the process and is the basis of the final evaluation. The calculations of the total avoidable investment cost and cost of exergy destruction for the most influential components of the plant are shown in Tables 7 and 8.

Among GT1, C1 and the CLC reactor of the plant, the lowest avoidable exogenous investment cost is calculated for C1. Because of this, C1 results in a lower total cost, although its avoidable endogenous cost is similar to that of GT1. Also, while GT1 has a similar avoidable exogenous investment cost to that of the CLC reactors, the reactors have a much higher total cost due to their significantly higher endogenous value. Similar results are found when the costs of exergy destruction are examined (Table 8). However, while the differences in the investment costs are kept at relatively low levels, the differences in the exergy destruction-related costs show large spreads among the different components. Comparing the individual components, the reactors result in a 35% higher avoidable exogenous cost of exergy destruction when compared to GT1, and since the difference between the endogenous values of the components is much larger, the total cost rate of the reactors is approximately three times higher than that of GT1. As shown in Table 9, the cost of exergy destruction is the main parameter of the overall cost in the plant. To calculate the variable of total avoidable costs, we add the total avoidable investment cost with the total avoidable cost of exergy destruction of Tables 7 and

Table 7
Avoidable investment cost rates (€/h).

Component, k	$\sum_{r=1, r\neq k}^{n} \dot{Z}_r^{AV,EX,k}$	$\dot{Z}_k^{AV,EN}$	$\dot{Z}_k^{AV,\Sigma}$
CLC	109.79 (11.5%)	842.23 (88.5%)	952.02
GT1	102.51 (55.0%)	83.96 (45.0%)	186.47
C1	47.07 (35.7%)	84.71 (64.3%)	131.78
ST4	7.00 (44.7%)	8.65 (55.3%)	15.65

Table 8
Avoidable exergy destruction cost rates (€/h).

Component, k	$\sum_{r=1, r\neq k}^{n} \dot{C}_{D,r}^{AV,EX,k}$	$\dot{C}_{D,k}^{AV,EN}$	$\dot{C}_{D,k}^{AV,\Sigma}$
CLC	241.83 (11.4%)	1,878.68 (88.6%)	2,120.51
GT1	179.12 (29.2%)	433.52 (70.8%)	612.64
C1	19.99 (7.5%)	245.71 (92.5%)	265.70
ST4	12.52 (5.9%)	201.17 (94.1%)	213.69

Table 9
Ranking of the components with the highest total avoidable cost rate, $\dot{C}_{D,k}^{AV,\Sigma} + \dot{Z}_k^{AV,\Sigma}$ (€/h).

Component, k	
CLC	3072.5
GT1	799.1
C1	397.5
ST4	229.3

8. The results are shown in Table 9. Overall, the CLC reactors are ranked first, GT1 second and C1 third.

Advanced exergy-based methods are recently-developed analyses that still require some improvement. Putting aside the time-consuming and relatively complex application of the methods, their conclusions are very valuable and their operation is seen to be consistent. Comparing this paper with Ref. [8], we see that the splitting of the investment costs of the reference and the CLC plant results in, overall, similar conclusions. The components with the highest avoidable costs for both combined-cycle power plants are those of the GT systems. Additionally, in both cases, the avoidable endogenous costs of the compressor and the expander are very similar. In the CLC plant, the component ranked first, when the avoidable endogenous investment cost is considered, is the reactor, due to its high initial cost necessary to implement this technology. In the reference plant, on the other hand, the reactor of the reference plant is ranked third after the expander and the compressor.

In contrast to the reference power plant, the avoidable costs of exergy destruction of the CLC plant clearly give improvement priority to the GT system, with first the CLC reactor. In the reference plant, the improvement strategies can vary based on the values considered. For example, the ranking of the components changes significantly when the avoidable part of the cost of exergy destruction or the avoidable investment cost is considered. The more consistent results of the CLC plant are based on the larger difference between the initially calculated costs of exergy destruction of the GT system and the remaining components of the plant. Since the low-pressure steam turbine of the reference plant has a higher cost rate of exergy destruction than the compressor, the ranking of the components changes easily depending on the assumptions made for the calculations.

Besides the above-mentioned "intermediate" similarities and differences, the results of the two applications could be better compared using the variable of total avoidable cost. When comparing the results of the CLC plant with those of the reference combined-cycle power plant without CO_2 capture, we see that the overall ranking of the components based on this variable is the same. Although the reactor of the reference plant is significantly less expensive than the CLC reactors, it has the highest total avoidable cost. Additionally, the absolute cost rates of the total avoidable investment and exergy destruction of GT1 and C1 are very similar. This is also true for similar components in the two plants. The difference between the total costs of the reactors of the two plants is justified by the much higher investment cost rate of the CLC unit.

Conclusions

In this paper, the first application of an advanced exergoeconomic analysis on a plant with CO_2 capture was presented. In this analysis, the investment costs and the costs of exergy destruction of each plant component are split into avoidable/unavoidable and endogenous/exogenous parts. The avoidable parts of the investment cost and cost of exergy destruction indicate the potential for improvement of components, while the endogenous/exogenous values quantify the component interactions and reveal strategies for improving the overall plant structure based on interdependencies of individual components.

The plant analyzed here is a chemical looping combustion plant with CO_2 capture. The most important components of the power plant, in terms of the absolute values of its total avoidable costs, are the reactor, the expander and the compressor of the main gas turbine system. Although the percentages of the avoidable investment cost of these components are relatively low, their absolute values largely surpass those of other plant components. Additionally, higher percentages and relative absolute values were calculated for the avoidable cost of exergy destruction of these components. For both the investment cost and the cost of exergy destruction, the interactions among 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. Lastly, in contrast to the results obtained for a conventional power plant without CO_2 capture, the analysis of the chemical looping combustion plant clearly indicates the components to which improvement priority should be given at all steps.

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