

# CO<sub>2</sub> Capture in a Chemical Looping Combustion Power Plant Evaluated With an Advanced Exergetic Analysis

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*CO<sub>2</sub> capture and storage (CCS) is a way to minimize harmful emissions generated from the combustion of fossil fuels in power plants. Measures to increase the thermodynamic efficiency of power plants incorporating CCS can improve their economic viability, as well as reduce the environmental impact of such applications. Exergy-based analyses are tools that aid the evaluation of energy conversion systems and reveal paths to improve them. In this article, an advanced exergetic analysis is applied to a near-zero-emission power plant that incorporates chemical looping combustion. The final goal is to reveal ways toward a more efficient and less polluting operation of the power plant. The objectives of the article further include the quantification of the different parts of the exergy destruction and the demonstration of the advantages of using such an advanced method. It has been found that most of the exergy destruction of the plant is endogenous and, for the majority of the components, unavoidable. When calculating the total avoidable exergy destruction caused by each component, it is found that the most important plant component is the reactor unit, followed by the expander and the compressor of the gas turbine. Lastly, the potential for improvement is found to lie mainly with the internal operation of the components, while the interactions among the plant components are less significant.* © 2013 American Institute of Chemical Engineers Environ Prog, 33: 1017–1025, 2014

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## INTRODUCTION

Exergy (useful energy) identifies the real sources of inefficiencies in a system, which is the exergy destruction within a component (caused by irreversibility) and the exergy losses (associated with the transfer of exergy to the environment). The energy concept, on the contrary, identifies as thermodynamic inefficiencies only the transfer of energy to the environment. Therefore, an exergetic analysis can reveal pathways for improving energy conversion systems, whereas energy-based methods can mislead the improvement efforts.

Conventional exergy-based analyses provide useful information about improvements of an energy conversion system from the viewpoint of thermodynamics [1–3]. In conventional

exergoeconomic and exergoenvironmental analyses, monetary costs and environmental impacts are quantified and assigned to all exergy streams of the plants, as well as to the exergy destruction incurred within each plant component. Although this information is very useful, conventional exergy-based analyses do not identify component interdependencies in a thermal system, nor do they quantify the avoidable part of exergy destruction/cost/environmental impact [4]. These limitations of the conventional exergy-based methods are addressed by the so-called advanced exergy-based analyses.

Advanced exergy-based methods have been developed as tools to provide further insight into plant improvement and can be extremely useful when complex energy conversion systems are considered (e.g., see Refs. 5, 6). Although relatively complex in their application, these methods are very useful in revealing detailed strategies for improving complex energy conversion systems that cannot be obtained with other means. Specifically, with advanced exergy-based analyses, the improvement potential and the component interactions are revealed and quantified [7–9].

The potential for improvement is determined by separating the exergy destruction within each plant component into avoidable/unavoidable parts [7]. The avoidable part of the exergy destruction is the part that can be eliminated through design and/or operational improvements. The unavoidable part of the exergy destruction per unit of product,  $(\dot{E}_D/\dot{E}_P)_k^{UN}$ , is the part that cannot be eliminated because of physical, technological, or economic constraints. These estimations are conducted for the foreseeable future, (thus, they are not based on a specific year of operation of each component), and are somewhat chosen subjectively. The estimations assume the best possible operation of the components that leads to maximum efficiency, which is obtained when the investment cost of the component being considered becomes extremely high (Figure 1) [7].

Additionally, the exergy destruction within plant components can be separated depending on its source: If it is caused by component interactions, it is exogenous, while if it stems exclusively from the operation of the component itself, it is endogenous [8]. Exogenous and endogenous parts are also calculated for the avoidable and unavoidable parts of exergy destruction.

In this work, an advanced exergetic analysis is applied to a combined-cycle power plant incorporating oxy-fuel



**Table 1.** Equations used in an advanced exergetic analysis.

	Term	Exergy destruction of component $k$	Comments
1	Exogenous exergy destruction	$\dot{E}_{D,k}^{EX} = \dot{E}_{D,k}^{real} - \dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{real}$ : Rate of product exergy of component $k$ in the real case $\dot{E}_{D,k}^{EN}$ : Rate of endogenous exergy destruction of component $k$
2	Mexogenous exergy destruction	$\dot{E}_{D,k}^{MX} = \dot{E}_{D,k}^{EX} - \sum_{\substack{r=1 \\ r \neq k}}^n \dot{E}_{D,k}^{EX,r}$	$\sum_{\substack{r=1 \\ r \neq k}}^n \dot{E}_{D,k}^{EX,r} = \sum_{\substack{r=1 \\ r \neq k}}^n (\dot{E}_{D,k}^{EN,r+k} - \dot{E}_{D,k}^{EN})$ , with $\dot{E}_{D,k}^{EN,r+k}$ the exergy destruction within component $k$ when $k$ and $r$ operate under real conditions and all remaining components theoretically
3	Unavoidable exergy destruction	$\dot{E}_{D,k}^{UN} = \dot{E}^{real} \left( \frac{\dot{E}_D^*}{\dot{E}_P} \right)_k^{UN}$	$\left( \frac{\dot{E}_D^*}{\dot{E}_P} \right)_k^{UN}$ : Unavoidable exergy destruction rate per exergy of the product of component $k$ calculated with most favorable operating conditions that result in the lowest possible exergy destruction.
4	Avoidable exergy destruction	$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k}^{real} - \dot{E}_{D,k}^{UN}$	
5	Unavoidable endogenous exergy destruction	$\dot{E}_{D,k}^{UN,EN} = \dot{E}_{D,k}^{EN} \left( \frac{\dot{E}_D^*}{\dot{E}_P} \right)_k^{UN}$	$\dot{E}_{P,k}^{EN}$ : Rate of product exergy of component $k$ when it operates under real conditions and the remaining components theoretically
6	Unavoidable exogenous exergy destruction	$\dot{E}_{D,k}^{UN,EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN,EN}$	
7	Avoidable endogenous exergy destruction	$\dot{E}_{D,k}^{AV,EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN,EN}$	
8	Avoidable exogenous exergy destruction	$\dot{E}_{D,k}^{AV,EX} = \dot{E}_{D,k}^{EX} - \dot{E}_{D,k}^{UN,EX}$	
9	Total avoidable exergy destruction	$\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r \neq k}}^n \dot{E}_{D,r}^{AV,EX,k}$ (1)	$\dot{E}_{D,r}^{AV,EX,k} = \dot{E}_{D,r}^{EX,k} - \dot{E}_{D,r}^{UN,EX,k}$
9a	Avoidable exogenous exergy destruction within component $r$ due to component $k$	(1) $\dot{E}_{D,r}^{AV,EX,k} = \dot{E}_{D,r}^{EX,k} - \dot{E}_{D,r}^{UN,EX,k}$ (2)	$\dot{E}_{D,r}^{UN,EX,k} = \dot{E}_{D,r}^{UN,EN,r+k} - \dot{E}_{D,r}^{UN,EN}$
9b	Unavoidable exogenous exergy destruction within component $r$ due to component $k$	(2) $\dot{E}_{D,r}^{UN,EX,k} = \dot{E}_{D,r}^{UN,EN,r+k} - \dot{E}_{D,r}^{UN,EN}$	$\dot{E}_{D,r}^{UN,EN,r+k} = \dot{E}_{P,r}^{EN,r+k} \left( \frac{\dot{E}_D^*}{\dot{E}_P} \right)_r^{UN}$ , with $\dot{E}_{P,k}^{EN,r+k}$ : Rate of product exergy of component $r$ when components $k$ and $r$ operate under real conditions and the remaining components operate theoretically and $\dot{E}_{D,r}^{UN,EN}$ : Unavoidable endogenous part of exergy destruction rate (calculated in an advanced exergetic analysis)

without pressure losses, the pressure losses of any components operating in parallel are also considered to be zero, even if the parallel components are assumed to operate under real conditions. Moreover, changes in the minimum temperature differences of some components might affect the operation of parallel components by increasing or decreasing their exergy destruction. When chemical reactions take place, the theoretical conditions cannot be easily defined. To overcome this problem, different methods have been proposed [13]. The exergy balance method is more appropriate for complex systems and it has been applied here. In this method, theoretical reactors are defined assuming zero exergy destruction, while the mass and energy balances for these components are not maintained [13,14]. To realize this, the evaluated overall system must be split into different subsystems.

The incorporated CLC reactor unit (Figure 2) in the considered plant makes the splitting in this concept different from that in the conventional combined-cycle power plant presented in Ref. 6. The main difference is that in the CLC

plant two subsystems follow the reactor. The first subsystem starts with the main gas turbine (GT1) followed by the primary heat recovery steam generator (HRSG), whereas the second subsystem starts with the secondary GT (GT2), used for the expansion of the CO<sub>2</sub> stream exiting the CLC reactor and followed by the secondary HRSG of the plant. In order to control the exergy balance of the reactors, both exiting streams must be split into two parts as shown in Figure 3. These two streams are the CO<sub>2</sub> stream (Stream 8, led to GT2) and the oxygen-depleted air (Stream 4, led to GT1).

Analogous to the reference combined-cycle power plant presented in Ref. 6, the  $\dot{W}_{net}$  of the overall plant and the excess air fraction, controlled here through the air-fuel mass flow ratio, are kept constant. When the reactor operates as in the real case, its exergetic efficiency is equal to that of the real case ( $\dot{E}_2 + \epsilon_{reactors} \dot{E}_6 = \dot{E}_4 + \dot{E}_8$  with  $\epsilon_{reactors} = \epsilon_{reactors}^{real}$ ). On the other hand, when the CLC unit is assumed to operate theoretically, its exergy destruction is set to zero ( $\dot{E}_{D,reactors} = 0 \Rightarrow \epsilon_{reactors} = 1 \Rightarrow \dot{E}_2 + \dot{E}_6 = \dot{E}_4 + \dot{E}_8$ ). To define all unknowns of the considered system, an auxiliary assumption

**Table 2.** Assumptions related to the conditions for the theoretical and unavoidable operation of the components.

Component <i>k</i>	$E_{D,k}^{real}$	Theoretical operation	$E_{D,k}^{UN}$	Component <i>k</i>	$E_{D,k}^{real}$	Theoretical operation	$E_{D,k}^{UN}$
GT1	$\eta_{is} = 92-94\%$ $\eta_{mech} = 99\%$	$\eta_{is} = 100\%$ $\eta_{mech} = 100\%$	$\eta_{is} = 96\%$ $\eta_{mech} = 100\%$	C2-C5	$\eta_{is} = 75-79\%$ $\eta_{mech} = 99\%$	$\eta_{is} = 100\%$ $\eta_{mech} = 100\%$	$\eta_{is} = 94\%$ $\eta_{mech} = 100\%$
GT2	$\eta_{is} = 90-94\%$ $\eta_{mech} = 99\%$	$\eta_{is} = 100\%$ $\eta_{mech} = 100\%$	$\eta_{is} = 96\%$ $\eta_{mech} = 100\%$	G6	$\eta_{is} = 96.8\%$ $\eta_{mech} = 85-88\%$	$\eta_{is} = 100\%$ $\eta_{mech} = 100\%$	$\eta_{is} = 94\%$ $\eta_{mech} = 100\%$
C1	$\eta_{is} = 91-94\%$ $\eta_{mech} = 99\%$ $Q_{loss} = 0.01$	$\eta_{is} = 100\%$ $\eta_{mech} = 100\%$ $Q_{loss} = 0$	$\eta_{is} = 94\%$ $\eta_{mech} = 100\%$ $Q_{loss} = 0$	SH/RH	$\Delta T_{min} = 20^\circ C$ $\Delta p_{HS}^*$	$\Delta T_{min} = 0$ $\Delta p = 0$	$\Delta T_{min} = 4$ $\Delta p = 0$
CC	$\Delta p = 3\%^{**}$ $\lambda = 2.05$	$\Delta p = 0$ $\lambda = 2.05$	$\Delta p = 0$ $\lambda = 1$	EV	Pinch point = 10°C Appr. $T = 6^\circ C$	$\Delta T_{min} = 0$ Appr. $T = 0$	$\Delta T_{min} = 1$ Appr. $T = 0$
STs	$\eta = 86-94\%$ $\eta_{mech} = 99\%$	$\eta_{is} = 100\%$ $\eta_{mech} = 100\%$	$\eta_{is} = 95\%$ HP, IP 92% LP $\eta_{mech} = 100\%$		$\Delta p_{HS}^*$ $\Delta p_{CS} = 5\%^{**\dagger}$	$\Delta p = 0$	$\Delta p = 0$
CLC reactors	$Q_{loss} = 0$ $\Delta p = 3\%^{\dagger\dagger}$ $\lambda = 1.05$	$Q_{loss} = 0$ $\Delta p = 0$ $\lambda = 1.05$	$Q_{loss} = 0$ $\Delta p = 0$ $\lambda = 1$	EC	$\Delta T_{min} = \text{dependant}^{\dagger\dagger}$ $\Delta p_{HS}^*$ $\Delta p_{CS} = 3\%/100^\circ C$	$\Delta T_{min} = 0$ $\Delta p = 0$	$\Delta T_{min} = 1$ $\Delta p = 0$
COOL Pumps	$\Delta T_{min} = 20^\circ C$ (10°C in FG COND) $\Delta p_{HS}^*$ $\Delta p_{CS} = 3\%/100^\circ C$	$\Delta T_{min} = 0$ $\Delta p = 0$	$\Delta T_{min} = 1$ $\Delta p = 0$	NGPH	$\Delta T_{min} = 400^\#$ $\Delta p_{HP} = 0.65\% \text{ bar}/100^\circ C$ $\Delta p_{LP} = 0.60\% \text{ bar}/100^\circ C$	$\Delta T_{min} = \text{dependant}^{\dagger\dagger}$ $\Delta p = 0$	$\Delta T_{min} = 20$ $\Delta p = 0$
Motors	$\eta_{is} = 67-90\%$ $\eta_{mech} = 98\%$	$\eta_{is} = 100\%$ $\eta_{mech} = 100\%$	$\eta_{is} = 95\%$ $\eta_{mech} = 100\%$	Air HX	$\Delta T_{min} = 700^{\#\#}$ $\Delta p_{HP} = 0.65\% \text{ bar}/100^\circ C$	$\Delta T_{min} = \text{dependant}^{\dagger\dagger}$ $\Delta p = 0$	$\Delta T_{min} = 20$ $\Delta p = 0$
Generators	$\eta_{el} = 80-95\%$ $\eta_{el} = 98.5\%$	$\eta_{el} = 100\%$ $\eta_{el} = 100\%$	$\eta_{el} = 98\%$ $\eta_{el} = 99.5\%$				

Here, HS: hot side and CS: cold side

\*The  $\Delta p_{HS}$  of a HX is calculated based on the pressure drop within the overall HRSG and the temperature variation within the HX

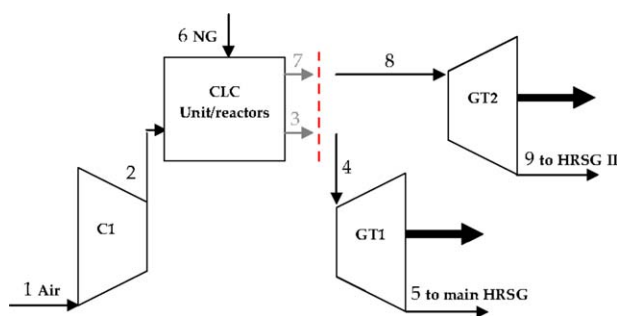
\*\*Percentage decrease based on the pressure of the incoming stream.

†Covered by an integrated pump.

††Depends on the operation of other components.

‡Result of temperature limitation at the exit of the component.

##Due to design requirements.



**Figure 3.** The CLC unit as part of the GT system of the CLC plant. [Color figure can be viewed in the online issue, which is available at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).]

is required for one of the two streams exiting the CLC unit. Due to material limitations, the temperatures of the streams exiting the CLC unit should not exceed 1200°C. Therefore, the temperature of Stream 4 has been kept constant at 1200°C and the temperature of Stream 8 has been varied depending on simulation requirements. The exergy of Stream 2 that has to be predefined in the exergy balance of the component depends on the thermodynamic states of C1 and the CLC unit. Thus, there are four possible component-operating combinations (2<sup>2</sup>) that result in different values of exergy for Stream 2.

The exogenous exergy destruction is calculated by subtracting the endogenous exergy destruction from the exergy destruction calculated in the real case. The exogenous exergy destruction is the exergy destruction imposed on component *k* through the operation of the remaining *n* - 1 components that constitute the overall plant. To split the exogenous exergy destruction of component *k* ( $\dot{E}_{D,k}^{EX}$ ) further and trace it to the specific components that cause it, additional simulations must be performed. In each simulation, two components that are chosen for evaluation operate under real conditions, while all remaining components operate theoretically. These assumptions lead to a total of  $(n^2+n)/2$  simulations, with *n* being the number of the components in the plant. In each simulation, we calculate the effect one component has on the other by subtracting the endogenous exergy destruction of the component of interest from the exergy destruction found here. After realization of the required simulations, the sum of the individual exogenous exergy destruction terms is not equal to the exogenous exergy destruction for each component calculated previously (using Eq. (1) of Table 1). The difference between the two values is the mixed-exogenous (mexogenous) exergy destruction (MX,  $\dot{E}_{D,k}^{MX}$ ), which is calculated using Eq. (2) of Table 1 and represents the simultaneous interactions of the remaining plant components [3].

While endogenous and exogenous exergy destruction reveal component interactions, avoidable and unavoidable exergy destruction reveal potential for improvement. The unavoidable part of exergy destruction,  $\dot{E}_{D,k}^{UN}$ , is associated with technological and economic design limitations that determine a subjective minimum value of exergy destruction. For the calculation of the unavoidable exergy destruction, the best possible operational conditions are considered (e.g., very low temperature differences and pressure drops and very high efficiencies). For calculating the unavoidable parts, simultaneous component interactions are not a concern and each component is considered in isolation. The assumptions made for unavoidable operation of the most important components are shown in Table 2. The ratio of exergy destruction per unit of product exergy ( $\dot{E}_{D,k}^*/\dot{E}_P$ )<sub>k</sub><sup>UN</sup>, that is a

necessary part for performing these calculations, is estimated by assuming operation with very high efficiency. The avoidable part of exergy destruction, on which improvement strategies are based, is then calculated by subtracting the unavoidable part from the initially calculated exergy destruction in the real case. It should be mentioned here that for dissipative components no exergy of product can be defined and, thus, no distinction between avoidable and unavoidable exergy destruction has been realized here.

Lastly, the avoidable and unavoidable exergy destructions are further split into endogenous and exogenous parts offering deeper insight into the operation of the plant. The avoidable endogenous and the avoidable exogenous exergy destructions ( $\dot{E}_{D,k}^{AV,EN}$  and  $\dot{E}_{D,k}^{AV,EX}$ ) are calculated by subtracting the corresponding unavoidable parts from the total endogenous and total exogenous exergy destruction, as also shown in Table 1.

### Calculating the Total Avoidable Exergy Destruction Associated with a Component

In general, high avoidable exergy destruction indicates high potential for improvement. However, it is possible that a component has relatively low avoidable endogenous exergy destruction, but relatively high total avoidable exogenous exergy destruction (exergy destruction caused by both the component itself and the other components of the system). In this case, the potential for improvement is associated not so much with the component being considered but with the remaining components of the plant. For this reason, an evaluation should account for all available data and the conclusions of each step of the analysis should be adjusted accordingly. The total avoidable exergy destruction caused by component *k* that facilitates the identification of the real potential for improvement of plant components is calculated

as shown in Table 1. The term  $\sum_{\substack{r=1 \\ r \neq k}}^n \dot{E}_{D,r}^{AV,EX,k}$  represents the sum

of the avoidable exergy destruction caused by component *k* within the remaining *n* - 1 components (see Eq. 9a in Table 1). Each part of this sum is calculated for each component *r* separately, via the unavoidable exogenous exergy destruction. The unavoidable exogenous exergy destruction in component *r* due to component *k*,  $\dot{E}_{D,r}^{UN,EX,k}$ , is calculated by subtracting the unavoidable endogenous exergy destruction from the unavoidable endogenous exergy destruction calculated in the simulation where components *r* and *k* operate under real conditions and the remaining components operate theoretically (see Eq. 9b in Table 1). Finally, the avoidable exogenous exergy destruction of component *r* caused by component *k* is found by subtracting the unavoidable exogenous exergy destruction from the total exogenous exergy destruction, caused by component *k* (see comments of Eq. 9 in Table 1).

## RESULTS AND DISCUSSION

### Splitting the Exergy Destruction

In a conventional exergetic analysis, the improvement priority of a component depends on its exergy destruction. In an advanced exergetic analysis, the main variable used to evaluate the potential for improvement of a component and a plant is the avoidable part of the exergy destruction,  $E_D^{AV}$ . High values of avoidable exergy destruction indicate significant improvement potential and vice versa. The second quantity for consideration is the endogenous part of the exergy destruction,  $E_D^{EN}$ . Endogenous exergy destructions are usually easier to influence than exogenous ones ( $E_D^{EX}$ ), because the former depend only on the operation of the component itself and not on component interactions.

**Table 3.** Selected results at the component level of the advanced exergetic analysis (MW).

Component <i>k</i>	$E_{D,k}^{real}$	$E_{D,k}^{EN}$	$E_{D,k}^{EX}$	$E_{D,k}^{AV}$	$E_{D,k}^{UN}$	$E_{D,k}^{UN,EN}$	$E_{D,k}^{UN,EX}$	$E_{D,k}^{AV,EN}$	$E_{D,k}^{AV,EX}$
<i>C1</i>	13.21	7.79	5.42	5.94	7.27	4.26	3.01	3.53	2.41
<i>CLC</i>	194.06	166.54	27.52	64.72	129.34	109.49	19.85	57.05	7.67
<i>GT1</i>	16.01	13.00	3.01	7.69	8.31	6.33	1.98	6.67	1.03
<i>GT2</i>	2.02	1.49	0.54	1.21	0.81	0.60	0.22	0.89	0.32
<i>NGPH</i>	5.20	2.98	2.22	0.04	5.17	2.84	2.33	0.14	-0.10
<i>HPSH</i>	1.99	0.66	1.33	0.68	1.31	0.57	0.74	0.09	0.59
<i>HPEV</i>	2.77	1.26	1.51	0.79	1.98	1.03	0.95	0.23	0.56
<i>HPEC</i>	3.67	1.86	1.80	0.94	2.72	1.55	1.17	0.31	0.63
<i>RH</i>	2.24	1.35	0.89	0.69	1.55	1.00	0.55	0.34	0.34
<i>IPSH</i>	0.14	0.15	-0.01	0.11	0.03	0.03	0.00	0.11	0.00
<i>IPEV</i>	0.97	0.85	0.12	0.40	0.57	0.46	0.11	0.39	0.01
<i>IPEC</i>	0.33	0.21	0.12	0.10	0.23	0.23	0.01	-0.02	0.12
<i>LPSH</i>	0.32	0.17	0.14	0.21	0.11	0.05	0.06	0.13	0.08
<i>LPEV</i>	3.03	1.52	1.52	0.83	2.20	1.24	0.97	0.28	0.55
<i>LPEC</i>	3.76	2.26	1.50	1.65	2.11	1.13	0.98	1.14	0.52
<i>SH II</i>	0.05	0.02	0.03	0.04	0.02	0.01	0.01	0.01	0.02
<i>EV II</i>	0.10	0.04	0.05	0.05	0.05	0.03	0.02	0.02	0.03
<i>EC II</i>	0.27	0.16	0.11	0.13	0.14	0.10	0.04	0.06	0.07
<i>HPST</i>	1.39	0.81	0.57	0.73	0.66	0.37	0.29	0.44	0.28
<i>IPST</i>	1.08	0.81	0.27	0.45	0.62	0.45	0.17	0.36	0.10
<i>LPST</i>	5.99	4.33	1.66	2.48	3.51	2.53	0.97	1.79	0.69
<i>ST4</i>	5.06	2.82	2.25	4.32	0.74	0.41	0.33	2.40	1.92
<i>HPP</i>	0.09	0.05	0.04	0.06	0.03	0.02	0.01	0.03	0.03
<i>C1</i>	0.61	0.43	0.18	0.46	0.15	0.10	0.05	0.33	0.13
<i>C2</i>	0.64	0.47	0.18	0.50	0.15	0.11	0.04	0.36	0.13
<i>C3</i>	0.64	0.47	0.17	0.50	0.15	0.10	0.04	0.37	0.13
<i>C4</i>	0.67	0.49	0.18	0.52	0.15	0.10	0.04	0.38	0.14
<i>FG COND</i>	20.31	14.84	5.47	-	-	-	-	-	-
<i>COOL1</i>	0.69	0.31	0.38	-	-	-	-	-	-
<i>COOL2</i>	0.82	0.40	0.42	-	-	-	-	-	-
<i>COOL3</i>	0.77	0.37	0.39	-	-	-	-	-	-
<i>COOL4</i>	0.78	0.36	0.41	-	-	-	-	-	-
<i>COND</i>	8.57	5.62	2.95	-	-	-	-	-	-
<i>CT</i>	3.06	2.23	0.83	-	-	-	-	-	-
<i>MOT3</i>	0.05	0.02	0.03	0.03	0.02	0.01	0.01	0.02	0.02
<i>GEN1</i>	1.31	0.99	0.32	0.88	0.43	0.33	0.10	0.67	0.21
<i>GEN2</i>	3.65	3.99	-0.34	2.44	1.20	1.32	-0.11	2.67	-0.23
<i>GEN3</i>	0.78	0.62	0.16	0.52	0.26	0.21	0.05	0.42	0.11
<b>Total</b>	<b>307.13</b>	<b>242.77</b>	<b>64.36</b>						
<i>Total (%)</i>		79.04	20.96						

Nonetheless, a change in the endogenous exergy destruction can alter component interactions as well. Thus, these two parts of exergy destruction should be examined in parallel.

Results for selected components from the advanced exergetic analysis for the considered plant are shown in Table 3. When compared to the other plant components, the CLC reactor presents the highest absolute value of exergy destruction. Although the largest part of this exergy destruction is calculated to be unavoidable, the reactor is found to have the highest avoidable exergy destruction when compared to the remaining components of the plant. In the examined plant, the CLC reactor has similar values to those of the combustion chamber (CC) of the reference plant presented in Ref. 6. The components that follow the reactor in absolute values of avoidable exergy destruction are GT1, C1, ST4, and the LPST.

Overall, most of the exergy destructions within the plant components are found to be unavoidable. Moreover, most of the total exergy destruction of the plant is endogenous (79%). This shows that component interactions, represented by the exogenous exergy destruction, do not play a very significant role. The same conclusion had been extracted from the advanced exergetic analysis of the reference power plant

[6]. Therefore, focus should be placed more on the reduction of internal component inefficiencies. Examples of measures to reduce the internal inefficiencies of a heat exchanger would be to decrease the minimum temperature difference between the material streams and/or the pressure drop associated with each stream. The efficiency of a compressor can be enhanced by decreasing the inlet temperature of the entering stream, while the opposite should be done in the case of an expander. Nevertheless, such changes are not considered here, because they may require the utilization of different manufacturing materials, which may affect the associated investment costs of the power plant. For the reactors, C1, the IPST, the LPST, and the majority of the HXs most of the endogenous exergy destruction is unavoidable. On the other hand, in GT1, the HPST, and the CO<sub>2</sub> compressors the avoidable endogenous exergy destruction is larger than the unavoidable. Similarly, the exogenous exergy destruction is found to be mostly unavoidable for the majority of the components.

Negative exogenous exergy destruction (Table 3) is calculated when there are mass flow changes between the initial (real) and the endogenous cases. As already mentioned, for the calculation of each component's endogenous exergy

**Table 4.** Splitting the exogenous rate of exergy destruction (MW).\*

Component <i>k</i>	$E_{D,k}^{EX}$	Component <i>r</i>	$E_{D,k}^{EX,r}$	Component <i>k</i>	$E_{D,k}^{EX}$	Component <i>r</i>	$E_{D,k}^{EX,r}$
CLC	27.52	C1	3.13	ST4	2.25	C1	0.10
		GT1	8.27			CLC	0.39
		ST4	1.10			GT1	0.12
		SUM	23.46 (12.81)			SUM	1.63 (1.41)
		MX	4.06			MX	0.62
C1	5.42	CLC	3.77	GT1	3.01	C1	0.34
		GT1	0.35			CLC	1.36
		ST4	0.05			ST4	0.08
		SUM	4.65 (5.17)			SUM	2.65 (14.23)
		MX	0.78			MX	0.36

\*The sum of exergy destruction caused by component *k* to the remaining components *r* is shown in parentheses

destruction, the examined component operates under real conditions, while all other components operate theoretically. When the theoretically-operating component causes an increase in the mass flow, its exergy destruction is higher than in the real case,  $E_D^{real}$ , leading to a negative  $E_D^{EX}$  value. Such a case is the generator of the GT system (GEN1) in the plant. The power output of the steam cycle is decreased, due to the lower temperature of the combustion products entering the HRSG. With this lower temperature, the power generated by the steam turbines is reduced. To keep the overall power output of the process constant, the power output of the GT must increase. Since the inlet temperature of the expander remains constant, the power output is controlled only by the mass flow rate. When the mass flow rate increases, the  $E_D^{EN}$  of the generator gets higher than its  $E_D^{real}$  value, resulting in a negative  $E_D^{EX}$  value. Similar explanations can be given for the negative values of the  $E_D^{UN,EX}$ , since their calculation depends on the calculation of the  $E_D^{UN,EN}$ , which is a function of the  $E_p^{EN}$  (see Table 1). Generally, with the exception of the generators and motors that are influenced only by the components to which they are directly connected, the components with negative exergy destruction values (e.g., some HXs of the IPHRSG, SH II and EV II) do not need to operate at maximum efficiency, in order for the overall system to be improved.

**Splitting the Exogenous Exergy Destruction**

Although only a relatively small amount of the exergy destruction in the CLC plant is exogenous, the detection of its specific sources can shed light onto improvement options. The results for the components with the highest exogenous exergy destruction of the plant and their exogenous values are shown in Table 4. Four components have been selected to be discussed here, while the complete results can be found in Ref. 3. As shown in Table 4, approximately 49% of the exogenous exergy destruction in the CLC reactors stem from GT1 and C1, a small part of which is avoidable. Similarly, in GT1 and C1, the exogenous exergy destruction is mainly imposed by the reactors. Nonetheless, a large part of the exogenous exergy destruction stemming from the reactors is avoidable (32% for GT1 and approximately 44% for C1). It should be noted that the exogenous exergy destruction caused by GT1 is higher than that caused by the CLC reactors by 11% (SUM, the value in parentheses in Table 4), showing a higher influence of GT1 on the overall process. The highest difference between the starting results of the exogenous exergy destruction and the amount calculated by splitting is found for the CLC reactors, while for the remaining components, the exogenous values are relatively small.

**Calculating the Total Avoidable Rate of Exergy Destruction**

To better understand the improvement potential of the components, the variable  $\dot{E}_{D,k}^{AV,\Sigma}$ , as defined using Eq. 9 of Table 1, has been calculated and shown in Table 5. The total avoidable exergy destruction associated with component *k*, consists of both the avoidable endogenous exergy destruction within the component and the avoidable exogenous exergy destruction caused by it to the remaining components of the plant [15]. The higher this value for a given component is, the larger the effect this component has on the overall system.

As seen in Table 5, the avoidable exogenous exergy destruction of GT1 and the CLC reactor are similar (with the exergy destruction of GT1 14% lower than that of the reactor). However, due to the significantly larger endogenous exergy destruction of the reactor, its total avoidable exergy destruction ( $\dot{E}_{D,k}^{AV,\Sigma}$ ) results in a value approximately five times higher, when compared to that of GT1. Comparing GT1 with C1, GT1 is found to cause higher avoidable exogenous exergy destruction. Additionally, due to the much higher avoidable endogenous exergy destruction of GT1, its total avoidable exergy destruction is found to be approximately three times higher than that of C1.

**CONCLUSIONS**

An advanced exergetic analysis has been applied to an oxy-fuel combined cycle power plant incorporating CLC and CO<sub>2</sub> capture. The main sources of thermodynamic inefficiencies of the complex structure have been revealed and quantified, and the relative significance of the individual plant components has been estimated using the total avoidable exergy destruction caused by each component. The most important components in the operation of the power plant are the reactor unit, the expander, and the compressor of the

**Table 5.** Splitting the rate of exergy destruction caused by each component (MW).

CLC plant	$\sum_{r \neq k}^n \dot{E}_{D,r}$	$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,\Sigma}$
Component <i>k</i>			
CLC	6.71 (11%)	57.05 (89%)	63.76
GT1	5.75 (46%)	6.67 (54%)	12.42
C1	0.74 (17%)	3.53 (83%)	4.28
ST4	0.66 (63%)	0.39 (37%)	1.05

main gas turbine system. Each one of these components is also responsible for a large part of exergy destruction caused within the other two (exergy destruction due to component interactions). The expander and the reactor unit are found to have similar total avoidable exogenous exergy destruction, i.e., they influence the remaining plant components in a similar way. Nevertheless, the component with the highest total avoidable exergy destruction is found to be the reactor, and for this reason, it is the component with the highest priority for improvement.

For the overall plant, most of the exergy destruction was found to be endogenous and, for the majority of the plant components, unavoidable. Thus, the improvement potential lies with the internal operational conditions of the components, while component interactions are less significant. Overall, there is a relatively restricted window of improvement potential because avoidable quantities are found to be generally low. Nevertheless, using the advanced exergetic analysis allowed us to evaluate the complex plant and to pinpoint components that should be improved and measures with which the thermodynamic efficiency of the overall plant can be increased.

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#### NOMENCLATURE

$c$	Cost per unit of exergy (€/GJ)
$\dot{E}$	Exergy rate (MW)
$\dot{m}$	Mass flow (kg/s)
$n$	Number of components
$p$	Pressure (bar)
$T$	Temperature (°C)
$\dot{Z}$	Cost rate associated with capital investment (€/h)

#### SUPER-/SUBSCRIPTS

AV	Avoidable
CS	Cold side
D	Exergy destruction
el	electric
EN	Endogenous
EX	Exogenous
F	Fuel (exergy)
HS	Hot side
P	Product (exergy)
$i, j$	Stream
is	Isentropic
$k, r$	Component
mech	Mechanical
min	Minimum
real	Calculated when components operate under real conditions
UN	Unavoidable
$\sum$	Sum

#### ABBREVIATIONS

C	Compressor
CC	Combustion chamber
CCS	Carbon capture and storage
CLC	Chemical looping combustion
COND	Condenser
COOL	Cooler
CT	Cooling tower
EC	Economizer
EV	Evaporator
GT	Gas turbine

HP, IP, LP	High pressure, intermediate pressure, low pressure
HRSG	Heat recovery steam generator
HX	Heat exchanger
NG	Natural gas
PH	Preheater
RH	Reheater
SH	Superheater
ST	Steam turbine

#### GREEK LETTERS

$\varepsilon$	Exergetic efficiency
$\eta$	Energetic efficiency
$\lambda$	Excess air ratio

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