energy&fuels Article
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Evaluating the Potential for Improvement of an Oxy-Fuel Power Plant with CO_2 Capture Using an Advanced Exergetic Analysis

Fontina Petrakopoulou,[†,‡,*] George Tsatsaronis,[†] and Tatiana Morosuk[†]

[†]Technische Universität Berlin, Marchstr. 18, 10587 Berlin, Germany
[‡]National Technical University of Athens, Iroon Polytechneiou 9, 157 73 Athens, Greece

ABSTRACT: Conventional exergy-based analyses provide useful information that can be used to improve the thermodynamic, economic, and environmental performance of energy conversion systems. However, when the complexity of a system is high, component interactions increase, and improvement strategies become more difficult to detect. Advanced exergy-based analyses have been developed to address such issues, to aid further assessment and to reveal options for improving the overall thermodynamic, economic, and environmental-impact-related effectiveness of energy conversion systems. Specifically, with an advanced exergetic analysis, exergy destruction is separated into (a) avoidable/unavoidable parts that deal with the potential for improving a component and/or a system and (b) endogenous/exogenous parts that show the way and magnitude of component interactions. The purpose of this paper is two-fold: first, to demonstrate the applicability of the method to a complex system by applying it to a new power plant concept and, second, to evaluate the design and operation of the plant and the improvement potential of the implemented CO_2 capture technology. The results from this analysis can be used in improving the design of the power plant. The considered power plant is an advanced zero-emission plant that incorporates oxy-fuel technology and has been selected because of its relatively high efficiency in comparison with other alternatives. Overall, the improvement potential of the plant is rather limited due to the relatively low values of the avoidable exergy destruction. Additionally, the analysis shows that component interactions are of relatively low importance because of low exogenous values. However, when the exogenous exergy destructions within the components are further split, additional improvement possibilities are revealed.

1. INTRODUCTION

Carbon capture and storage (CCS) from power plants started attracting scientific attention a little more than three decades ago, as a powerful tool for limiting the impact of fossil fuel use on the climate.[1] When evaluating options for CO_2 capture from power stations, engineers are faced with a large variety of alternatives. However, although several alternative approaches for capturing CO_2 have been proposed in a short period of time, few appear promising with respect to efficiency and cost. Any emission reduction (up to practically 100%) could be achieved with a sufficiently high level of expenditure.[2,3] The question, however, is whether a CO_2 capture technology is a reasonable measure when balancing the benefit to the environment against a greatly increased cost (associated with new facilities to perform the CO_2 capture) and risk (mainly associated with the long-term storage of captured CO_2).[3]

In this paper, a plant with CO_2 capture incorporating oxy-fuel combustion is evaluated using an advanced exergetic analysis (Figure 1). The plant is an advanced zero emission plant with 85% CO_2 capture (AZEP 85) and involves a mixed conducting membrane (MCM) reactor that separates the oxygen of the provided air for the needs of the oxy-fuel process.[4] This plant has been found to be one of the most promising plants among eight different concepts evaluated with conventional exergetic analysis.[5,6]

An exergetic analysis permits the identification of the quality of energy carriers and pinpoints thermodynamic inefficiencies that a conventional energy analysis cannot detect.[7] The results of exergy-based methods can be used in iterative improvement steps that can eventually lead to an optimization of a system from the thermodynamic viewpoint. Although conventional exergy-based analyses[8−12] already reveal information about improvement possibilities of energy conversion systems, they suffer from some limitations, which are addressed by advanced exergy-based analyses.[13,14] Advanced methods identify interdependencies among plant components and quantify the real improvement potential both at the component and plant level.[15,16] Information obtained from advanced exergy-based methods cannot be obtained by any other known optimization technique. This information is crucial for identifying strengths and weaknesses of complex plants with a large number of interrelated components. Nevertheless, the current application procedure of the advanced methods is still relatively complex and time-consuming. Thus, actions for their further development and simplification can facilitate their application and are of great engineering value.

Until recently, advanced exergetic analysis had been applied to relatively simple energy conversion systems, while advanced exergoeconomic and exergoenvironmental analyses had only been partially applied.[17−19] This paper presents one of the first applications of an advanced exergetic analysis to a complex power plant with CO_2 capture.

2. POWER PLANT

The power plant evaluated here is the AZEP 85%.[4,20−22] In this plant, the conventional combustion chamber (CC) of the gas

Received: March 24, 2013
Revised: July 9, 2013
Published: July 9, 2013

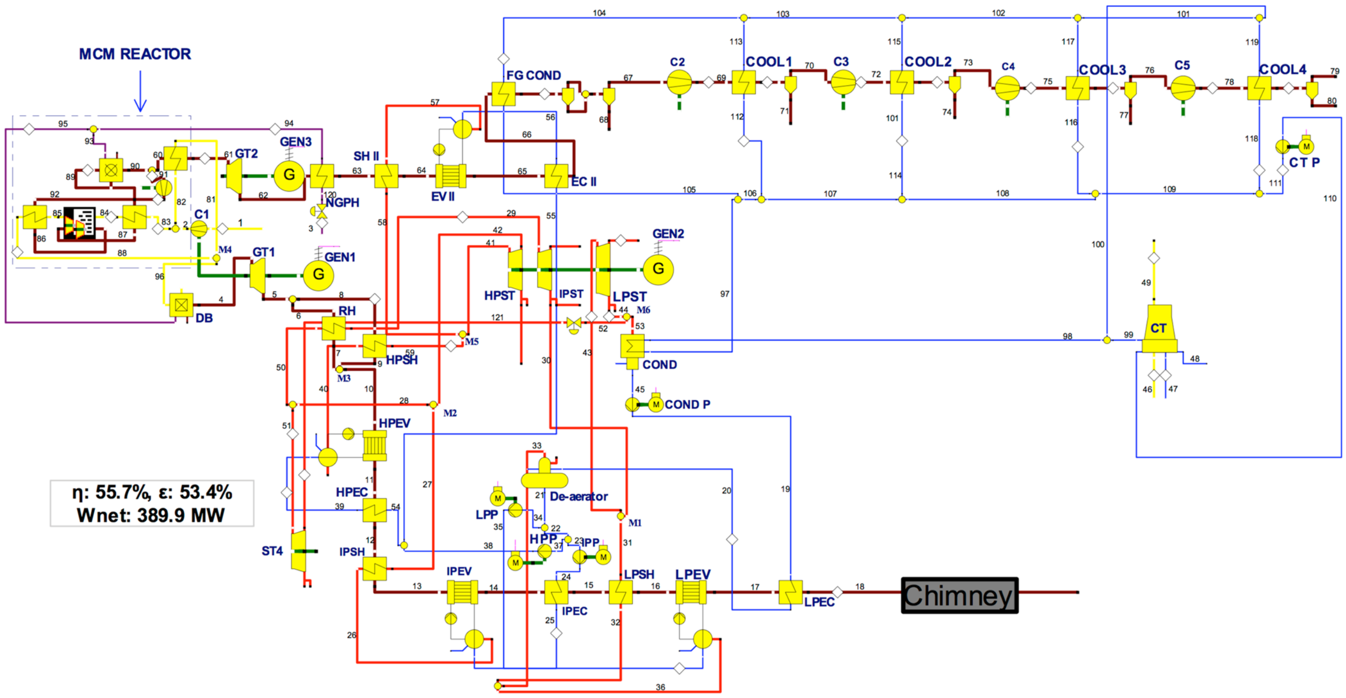

Figure 1. Structure of the considered advanced zero emission plant (AZEP 85).

turbine (GT) system is replaced by a mixed conducting membrane reactor, in which the necessary oxygen for the oxy-fuel combustion is produced.[21] The concept was introduced in a trans-European consortium and was initiated in a European project.[23] It is not yet a commercially available technology, which means that technological challenges may increase the uncertainty of the realization of the concept. However, these considerations are out of the scope of this work. Here, we investigate its best possible application, assuming that the technological problems associated with its realization have already been addressed. The overall power plant structure considered here is shown in Figure 1.

For the purpose of this paper, the MCM is simulated as a black box using embedded data provided by Jordal et al. (2004).[24] The MCM reactor consists of a mixed conducting membrane, one high- and one low-temperature heat exchanger (HTHX MCM and LTHX MCM), a bleed gas heat exchanger (Air HX), and a CC. The membrane is based on oxygen adsorption and consists of complex crystalline structures that incorporate oxygen ion vacancies. Oxygen atoms of the incoming air are adsorbed onto the surface of the membrane and decomposed into ions. The ions occupy the oxygen vacancies of the membrane, and their transport is counter-balanced by an opposite electron flow. Because the operation of the membrane is based on ion diffusion and not molecular sieving, the selectivity of the membranes is infinite as long as the membrane surface is perfect; that is, no cracks or pores are present. The main operational features of the plant can be found in Table 1, while the results from the conventional exergy-based analyses of the plant can be found in refs 6 and 25.

Close to 38% of the oxygen included in the air is separated in the MCM and is transferred at a temperature of 490 °C to the reactor's CC with the help of recycled sweep gas. The circulated sweep gas entering the CC (Stream 89 with 60% v/v H_2O, 30% v/v CO_2, 10% v/v O_2) is also used to control the temperature of the combustion process. By specifying the mass flow of this gas and setting the appropriate air ratio (λ) of the CC, the mass flow of the methane is determined.

Table 1. Operational Parameters

Ambient Air
15 °C, 1.013 bar, 60% relative humidity
composition (mol %): N_2 (77.3), O_2 (20.73), CO_2 (0.03), H_2O (1.01), Ar (0.93)
Fuel
14 kg/sec, 15 °C, 50 bar, LHV = 50.015 kJ/kg
natural gas composition (mol %): CH_4 (100.0)
Gas Turbine System and CO_2/H_2O Gas Turbine
compressor: polytropic efficiency, 94.0%; mechanical efficiency, 99%; pressure ratio, 16.8
air turbine: polytropic efficiency, 91%; mechanical efficiency, 99%
CO_2/H_2O turbine: polytropic efficiency, 91%
generators: electrical efficiency, 98.5%
Steam Cycle
HRSG: 1 reheat stage; 3-pressure-levels,: HP (124 bar), IP (22 bar), LP (4.1 bar)
HRSG pressure drop: hot side, 30 mbar; cold side, 10%
SHs, ECONs (HP, IP, LP): ΔT_{min}, 20 °C
EVAPs (HP, IP, LP): approach temperature, 6 °C; pinch point, 10 °C
live steam temperature: (ref.plant) 559 °C
steam turbine polytropic efficiency: HP (90%), IP (92%), LP (87%)
condenser operating pressure: 0.05 bar
pumps: efficiency, 62–86% (incl. motors and mechanical efficiency, 98%)
CO_2 Compression Unit (4 intercooled stages)
compressors polytropic efficiency (4 stages): 80%, 79%, 78%, 77%
CO_2 end pressure: 103 bar
cooling water: inlet/outlet temperature, 15 °C/25 °C
CO_2 condenser exit temperature: 30 °C
coolers exit temperature: 40 °C
Overall Plant
plant exergetic efficiency of the reference plant without CO_2 capture: 56.5%
plant exergetic efficiency of the AZEP 85%: 53.4%

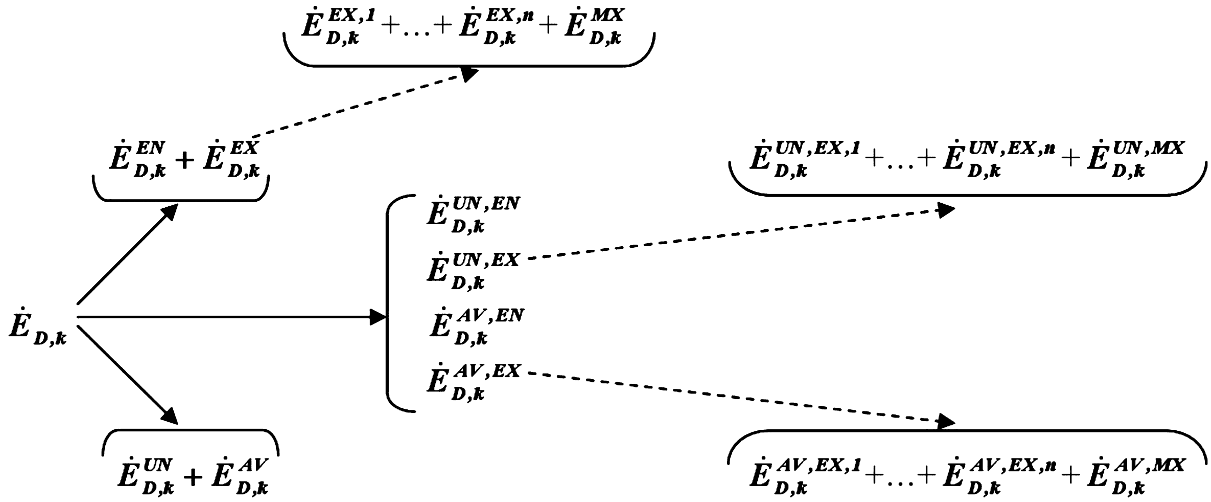

Figure 2. Options for splitting the exergy destruction in an advanced exergetic analysis.[14]

Table 2. Assumptions Related to the Ideal Operation and Unavoidable Exergy Destruction of the Components[a]

component, k	ideal operation	$E_{D,k}^{UN}$	component, k	ideal operation	$E_{D,k}^{UN}$
GT1	η_{is} = 100%	η_{is} = 96%	C2−C5	η_{is} = 100%	η_{is} = 94%
	η_{mech} = 100%	η_{mech} = 100%		η_{mech} = 100%	η_{mech} = 100%
GT2	η_{is} = 100%	η_{is} = 96%	C6	η_{is} =100%	η_{is} =94%
	η_{mech} = 100%	η_{mech} = 100%		η_{mech} = 100%	η_{mech} = 100%
C1	η_{is} = 100%	η_{is} = 94%	SH/RH	ΔT_{min} = 0	ΔT_{min} = 4
	η_{mech} = 100%	η_{mech} = 100%		ΔP = 0	ΔP = 0
DB	Q_{loss} =0	Q_{loss} = 0			
	ΔP = 0	ΔP = 0	EV	ΔT_{min} = 0	ΔT_{min} = 1
	λ = 10	λ = 1		appr. T = 0	appr. T = 0
STs	η_{is} = 100%	η_{is} = 95% HP, IP 92% LP		ΔP = 0	ΔP = 0
	η_{mech} = 100%	η_{mech} = 100%			
	Q_{loss} = 0	Q_{loss} = 0	EC	ΔT_{min} = 0	ΔT_{min} = 1
MCM	ΔP = 0	ΔP = 0		ΔP = 0	ΔP = 0
	ΔT_{min} = dependent[b]	ΔT_{min} =20			
CC MCM	Q_{loss} = 0	Q_{loss} = 0	NGPH	ΔT_{min} = dependent[b]	ΔT_{min} = 20
	ΔP = 0	ΔP = 0		ΔP = 0	ΔP = 0
	λ = 1.05	λ = 1			
MCM HTHX	ΔT_{min} = dependent[b]	ΔT_{min} = 20	Air HX	ΔT_{min} = dependent[b]	ΔT_{min} = 20
	ΔP = 0	ΔP = 0		ΔP = 0	ΔP = 0
MCM LTHX	ΔT_{min} = dependent[b]	ΔT_{min} = 20			
	ΔP = 0	ΔP = 0	COOL	ΔT_{min} = 0	ΔT_{min} = 1
				ΔP = 0	ΔP = 0
			pumps	η_{is} = 100%	η_{is} = 95%
				η_{mech} = 100%	η_{mech} = 100%
			motors	η_{el} = 100%	η_{el} = 98%
			generators	η_{el} = 100%	η_{el} = 99.5%

[a]HS = hot side; CS = cold side. [b]Depends on the operation of other components.

The methane is preheated to 250 °C in a gas−gas heat exchanger (NG PH) before it is sent to the CC of the reactor. The combustion products that consist of 33.5% v/v CO_2, 66% v/v H_2O, and 0.5% v/v O_2, expand in a CO_2/H_2O expander (GT2) to 1.051 bar and are then driven to the secondary, single-pressure-level heat recovery steam generator (HRSG II) of the plant. The oxygen-depleted air (14% v/v O_2) exits the MCM at 1000 °C, and it is heated up to 1200 °C (due to material and reactor design constraints) in the HTHX of the reactor. All design materials for the different plant components can be found in ref 2. The stream is then mixed with 10% of the incoming air, exits the reactor, and is sent to a supplementary firing (duct burner, DB). In this supplementary firing, part of the provided fuel is burned with the oxygen left in the oxygen-depleted air to increase the exit temperature of the MCM reactor. The outlet gas temperature of this secondary combustion is near 1300 °C, a relatively high temperature that increases the power output of the gas turbine and enhances the overall efficiency of the plant.[2] After passing thought the DB, the stream is expanded in the main GT of the plant to 1.058 bar and 579 °C, and it is sent to the main, three-pressure-level HRSG of the plant. There, the heat provided by the gas is used to produce steam at three pressure levels that is expanded in the steam turbine (ST) of the plant to generate electricity. In

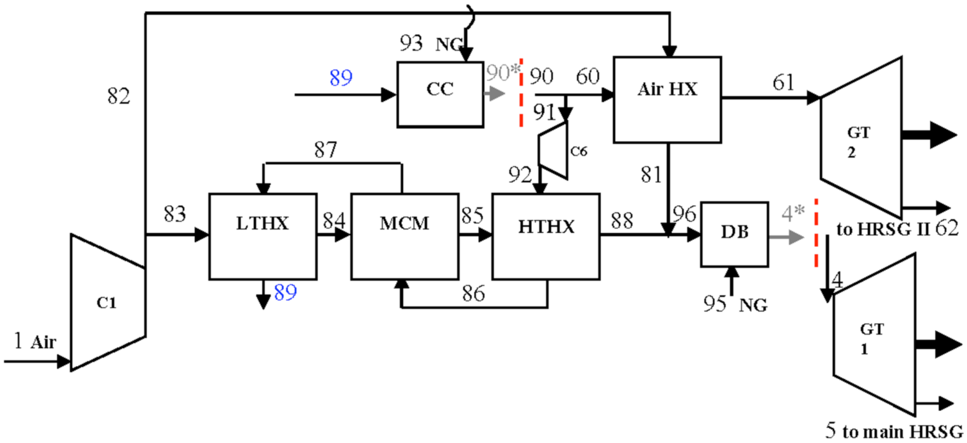

Figure 3. MCM reactor as part of the GT system of the AZEP 85 (Stream 89 exits the LTHX and enters the CC of the plant).

the high-pressure (HP) superheater (SH) and the reheater (RH) of the plant, the produced steam is heated to a temperature of 559 °C. Additional steam is generated in the secondary HRSG of the plant (HRSG II). Extracted LP steam expanded in an additional ST (ST4) of the power plant is also used to drive the CO_2 capture unit.

3. METHODOLOGY

The presented analysis constitutes a tool to detect deficiencies of complex energy conversion systems and to reveal effective ways of improving them. This analysis aims to evaluate energy conversion systems, which do not yet exist but may be constructed in the future, and allows the investigation of their performance under various operating conditions and structural modifications. Part of the exergy destruction of a system can be avoided with structural modifications and efficiency improvements of individual components. Exergy destruction that can be avoided through technically feasible design and/or operational improvements is called *avoidable* (AV). Here, we refer to the best technology that could become available in the foreseeable future. AV exergy destruction plays the main role in the determination of improvement steps, as well as in the estimation of the improvement potential of a system. The remaining exergy destruction, which is associated with physical, technological, and economic constraints, and cannot be avoided in the foreseeable future, is called *unavoidable* (UN). Exergy destruction can also be separated depending on its source: If it is caused by component interactions, it is *exogenous* (EX), while if it stems from the operation of the component itself, it is *endogenous* (EN). With the endogenous and exogenous quantities, interactions among components are identified. Furthermore, the avoidable and unavoidable estimates are split into their endogenous and exogenous parts. A schematic example of the paths to split the exergy destruction is shown in Figure 2.

Splitting the exergy destruction into avoidable/unavoidable parts is performed by considering each component in isolation. The assumptions for the calculation of the unavoidable exergy destruction assumed here are shown in Table 2.[2] To estimate each component's endogenous exergy destruction, the examined component operates under real conditions, while all remaining components operate ideally (Table 2). Thus, if the overall system consists of n components, we perform n new simulations. To estimate the effect that each component has on each of the remaining ones, the exogenous exergy destruction of each component must be split into its specific sources. With this splitting, individual component interactions are revealed that might cancel each other out in the overall exogenous value. During this procedure, the components are further examined in pairs. In each case, two components of interest operate under real conditions and the remaining components operate ideally. In this way, we eliminate the effect of the remaining ideally operating components on the two components of interest, and we see how the two components interact with one another. This is repeated until all possible component combinations have been performed. Splitting the exogenous exergy destruction of a component into its specific sources (contributions by other components) requires additional simulations, with the components operating under real conditions in pairs.[2] The operating assumptions lead to a total of $(n^2 + n)/2$ simulations, with n being the number of the components in the plant. Since the plant presented here includes 51 components, we end up with 1326 simulations.

Although in each considered simulation the $n - 2$ components operate ideally, their operating conditions may somewhat alter the real operation of the two components of interest. The difference between the exogenous exergy destruction calculated in the beginning and the sum of the individual exogenous exergy destruction values calculated in these detailed simulations is called mexogenous (from mixed exogenous) exergy destruction (MX).

As already mentioned, to realize the endogenous/exogenous splitting, the ideal operation of each plant component must be defined. Ideal conditions involve operation with exergetic efficiencies equal to unity and temperature differences and pressure drops equal to zero. Exceptions to these assumptions are applied only when the complexity of the plant and the interconnections among the components do not allow such an operation. In such cases, conditions closest to the ideal ones are selected. Because most of these adjustments do not affect the analysis or the conclusions obtained from it, they are only mentioned when they are of relatively high importance. For example, an adiabatic expander will operate with an exergetic efficiency (and consequently an isentropic efficiency) of 1.0. Similar assumptions are made for all different components within the plant. The calculation of the endogenous exergy destruction for chemical reactors is relatively complex, since ideal conditions cannot be easily defined. To overcome this problem, different methods have been proposed.[26] In the exergy balance method, also applied here, an ideal reactor is defined when its exergy destruction is zero, while its mass and energy balances are not fulfilled. To maintain the same composition, temperature, and specific exergy of the flue gases exiting the combustor, the air−fuel ratio of the reactor is maintained as in the real case and a fictitious mass flow rate is calculated at the outlet that satisfies the requirement of zero exergy destruction within the component ($\dot{E}_{in} = \dot{m}^*_{fict} e_{out}$). The newly calculated mass flow rate then replaces that of the real case in all downstream components of the plant and represents the effect of the implementation of an ideal reactor.

When reactors operate ideally, their exergy balances are maintained by separating the system (the flow diagram) into two parts after each reactor: One subsystem consists of the components upstream to the reactor, whereas the second subsystem contains the components downstream the reactor (see Figure 3). The net power output of the overall plant and the excess air fractions of the CC and the DB are kept constant throughout the analysis. When the CC operates as in the real case, its exergetic efficiency matches that of the real case ($\dot{E}_{21}$ +

Table 3. Selected Results at the Component Level of the Advanced Exergetic Analysis (MW)

	$E_{D,k}^{real}$	$E_{D,k}^{UN}$	$E_{D,k}^{EX}$	$E_{D,k}^{AV}$	$E_{D,k}^{UN}$	$E_{D,k}^{UN,EN}$	$E_{D,k}^{UN,EX}$	$E_{D,k}^{AV,EN}$	$E_{D,k}^{UN,EX}$	E_{P}^{real}	E_{P}^{EN}
C1	11.17	7.39	3.78	5.02	6.15	4.06	2.09	3.33	1.69	227.13	149.88
CC	153.65	120.57	33.09	13.56	140.10	109.81	30.29	10.76	2.80	466.61	365.73
GT2	1.98	2.73	−0.75	1.31	0.66	0.92	−0.25	1.81	−0.50	53.73	75.26
MCM	5.62	3.41	2.21	1.40	4.23	1.45	2.78	1.96	−0.57	77.03	26.35
MCM LTHX	9.55	4.58	4.97	4.90	4.65	3.54	1.11	1.05	3.86	211.51	160.99
DB	31.26	20.16	11.10	16.74	14.52	9.43	5.08	10.73	6.01	78.20	50.82
GT1	14.16	10.64	3.53	7.11	7.06	5.12	1.94	5.52	1.59	481.50	349.47
NGPH	5.70	3.72	1.98	5.66	0.05	0.01	0.04	3.71	1.95	0.10	0.02
HPEC	3.52	1.72	1.79	1.04	2.48	1.33	1.15	0.39	0.65	22.65	12.18
LPST	6.05	4.65	1.40	2.51	3.54	2.72	0.82	1.93	0.58	43.27	33.26
ST4	6.78	4.53	2.25	5.78	1.01	0.67	0.34	3.87	1.91	21.14	14
C5	0.66	0.91	−0.25	0.53	0.13	0.17	−0.04	0.74	−0.20	2.85	3.85
FG COND	13.52	18.21	−4.69								
GEN1	3.65	3.39	0.26	−1.24	4.89	4.54	0.35	−1.15	−0.09	239.55	222.58

$\varepsilon_{CC}\dot{E}_{22} = \dot{m}^{*}_{fict,CC}e_{13}$ with $\varepsilon_{CC} = \varepsilon_{CC}^{real}$). When the CC operates ideally, its exergy destruction is set equal to zero ($\dot{E}_{D,CC} = 0 \Rightarrow \varepsilon_{CC} = 1 \Rightarrow \dot{E}_{21} + \dot{E}_{22} = \dot{m}^{*}_{fict,CC}e_{13}$). The same conditions apply for the DB of the plant: When it operates as in the real case, its efficiency is kept constant ($\dot{E}_6 + \varepsilon_{DB}\dot{E}_{23} = \dot{m}^{*}_{fict,DB}e_8$ with $\varepsilon_{DB} = \varepsilon_{DB}^{real}$), while the ideal DB has no exergy destruction ($\dot{E}_{D,DB} = 0 \Rightarrow \varepsilon_{DB} = 1 \Rightarrow \dot{E}_6 + \dot{E}_{23} = \dot{m}^{*}_{fict,DB}e_8$). The exergies of streams 89 and 96 (Figures 1 and 3) at the inlet of the CC and the DB, depend on the operation of the components that can cause a change to their pressure and/or temperature. For example, the exergy of Stream 89 depends on the MCM LTHX, the MCM, the MCM HTHX, and the CC (4^2 = 16 possible combinations), while the exergy of Stream 96 depends on the MCM LTHX, the MCM, the MCM HTHX, and the C1 (4^2 = 16 possible combinations). When the pressures of streams 83 and 96 are defined, the pressures of Streams 82 and 81 are adjusted accordingly. Because the predefinition of this many different exergy values is not recommended, a routine for the calculation of the physical exergy of streams has been incorporated in EbsilonProfessional.[27] Because the fuel−air ratio of both reactors has been kept constant, the composition of the outgoing streams is always the same as in the real case; that is, the specific chemical exergy of the streams is the same as in the real case.

The assumed restrictions that are related to the operation of the MCM inevitably lead to strong interactions between the MCM and the MCM LTHX. When the LTHX is real, the inlet temperature of Stream 87 must be high enough to achieve a minimum temperature difference (ΔT_{min}, determined by Streams 87 and 84) as close as possible to the real case. The minimum inlet temperature of the MCM is 900 °C and the minimum temperature of stream 87 would, in this case, be 964 °C. When the LTHX or the MCM operate ideally, the temperatures of Streams 85 and 87 are decreased to lower the ΔT_{min} of the components. Lastly, the inlet pressures of both gas turbines must agree with those of the real case and any pressure variations must be accounted for.

4. RESULTS AND DISCUSSION

The main variable used to evaluate the potential for improvement of a plant in an advanced exergetic analysis is the avoidable exergy destruction, E_D^{AV}. Larger values of avoidable exergy destruction indicate high improvement potential. A second variable for consideration is the endogenous part of the exergy destruction, E_D^{EN}. Endogenous exergy destruction is usually easier to manipulate than exogenous (E_D^{EX}), because the former depends on the operation of the component itself and not on component interactions that are more difficult to affect. Nonetheless, a change in the endogenous exergy destruction can alter component interactions as well. Thus, these two parts of the exergy destruction should be examined in parallel.

In a conventional exergetic analysis, the larger the absolute value of the exergy destruction within a component, the higher its improvement priority must be, whereas in an advanced exergetic analysis this value is scaled to refer to the component's avoidable part of exergy destruction. To identify the real improvement potential of a component, we calculate the total avoidable exergy destruction caused by it to both itself (endogenous, avoidable) and to the operation of the remaining components of the plant (exogenous, avoidable).[14] Although a high avoidable-exergy-destruction value reveals high improvement potential for the component being considered, it is possible that such a component has relatively low endogenous avoidable exergy destruction but relatively high exogenous avoidable exergy destruction. Thus, an evaluation should take into account all data available and the conclusions should be adjusted accordingly.

In general, reactors are components with high exergy destruction.[2,16] However, the results related to the reactors of the AZEP 85 show some particularities (see Table 3). Although the CC has a rate of exergy destruction almost five times higher than the DB of the plant, the latter results in a 23% higher avoidable value. In this way, the DB has the highest improvement priority, followed by the CC, GT1, ST4, and C1. This is a result of the high unavoidable exergy destruction of the CC (91%). Ninety one percent is a relatively high percentage when compared to results obtained for a combustion chamber in other energy conversion systems. For example, the unavoidable exergy destruction of the CC in a conventional combined-cycle power plant is approximately 78%,[16] a value much lower than that obtained here. Additionally, the chemical looping reactor of a plant with CO_2 capture studied by Petrakopoulou (2010),[2] presented unavoidable exergy destruction of approximately 66%, a value even lower than that of the conventional plant. Thus, the behavior of the CC of the AZEP diverges from the expected behavior. This difference exists because the exergy destruction of the CC in the AZEP is decreasing slower with decreasing excess air (in comparison to a conventional CC). Since preheated gases of high physical exergy enter the component, there is a small margin for reducing the exergy destruction in the CC of the AZEP system.

In general, most of the exergy destruction within the components of the examined plant was found to be unavoidable. Exceptions are the CO_2 compressors, the HXs

Table 4. Splitting the Exogenous Rate of Exergy Destruction (MW)[a]

component, k	$\dot{E}_{D,k}^{EX}$	component, r	$\dot{E}_{D,k}^{EX,r}$	component, k	$\dot{E}_{D,k}^{EX}$	component, r	$\dot{E}_{D,k}^{EX,r}$
CC	33.09	DB	0.05	GT1	3.53	CC	2.21
		MCM LTHX	0.06			DB	0.01
		C1	3.44			MCM LTHX	0.01
		GT1	5.13			C1	0.15
		MCM	0.06			MCM	0.02
		ST4	0.81			ST4	0.10
		LPST	1.66			LPST	0.16
		SUM	24.68 (−5.86)			SUM	3.34 (11.78)
		MX	8.41			MX	0.19
DB	11.10	CC	4.27	MCM	2.21	CC	0.66
		MCM LTHX	0.01			DB	0.03
		C1	0.46			MCM LTHX	−0.02
		GT1	0.71			C1	0.07
		MCM	0.01			GT1	0.19
		ST4	0.18			ST4	0.03
		LPST	0.35			LPST	0.07
		SUM	8.18 (0.26)			SUM	1.65 (0.57)
		MX	2.92			MX	0.56
MCM LTHX	4.97	CC	0.76	ST4	2.25	CC	−1.17
		DB	0.04			DB	0.01
		C1	−0.27			MCM LTHX	0.07
		GT1	0.23			C1	0.31
		MCM	−0.20			GT1	0.14
		ST4	0.11			MCM	0.16
		LPST	−0.10			LPST	0.05
		SUM	2.84 (0.24)			SUM	1.85 (1.77)
		MX	2.13			MX	0.40
C1	3.78	CC	1.59	LPST	1.40	CC	0.39
		DB	0.03			DB	0.04
		MCM LTHX	0.01			MCM LTHX	−0.10
		GT1	0.27			C1	0.14
		MCM	0.01			GT1	0.82
		ST4	0.07			MCM	0.00
		LPST	0.10			ST4	−0.25
		SUM	2.88 (6.98)			SUM	0.93 (0.54)
		MX	0.91			MX	0.47

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

that operate with high minimum temperature differences due to design requirements, and the components ST4, DB, and GT1.

Most of the total exergy destruction within the plant is found to be endogenous (77%). However, analyzing the endogenous values, we find that in the reactors, the components C1, IPST, LPST, and the majority of the HXs, most of the endogenous exergy destruction is unavoidable ($E_{D,k}^{UN,EN}$). On the other hand, more than half of the exergy destruction within the DB of the plant is avoidable ($E_{D,k}^{AV,EN}$), while GT1, the HPST, and the CO_2 compressors also present relatively high values of avoidable endogenous exergy destruction. The high endogenous values show that component interactions, represented by the exogenous exergy destruction, play a secondary role, and focus should be placed more on the improvement of internal component inefficiencies. The results also show that the exogenous values are mainly unavoidable for the majority of the components.

When dealing with a power plant with a large number of interrelated components, it can be expected that improving one component might lead to a deterioration in the performance of others (opposing effects). If the deterioration in the other components leads to higher thermodynamic inefficiencies than the gain in the component improved in the first place, we might end up decreasing the overall efficiency of the power plant. These effects can be quantified using advanced exergy-based analyses and can imply the deterioration of a component to achieve an improvement of the overall process. Negative values calculated for the exogenous exergy destruction and presented in Table 3 show such opposing effects and result from differences in the mass flow rates between the real and the endogenous cases. When the conditions of the ideally operating components result in increased mass flows, the endogenous exergy destruction is higher than in the real case, E_D^{real}, and the E_D^{EX} is, therefore, negative. For example, in the calculation of the E_D^{EN} of GT2, the power output of the steam cycle and of GT1 is decreased, due to the lower temperature of the combustion products entering the HRSG—a result of the high isentropic efficiency of the ideal expander. In order to keep the overall power output of the process constant, the power output of GT2 must increase. Since the inlet temperature of GT2 remains constant, the power output is determined by the mass flow. With increased mass flow, the E_D^{EN} of GT2 surpasses the E_D^{real} resulting in a negative E_D^{EX}. Similar explanations can be given for the negative values of the $E_D^{UN,EX}$, since their calculation

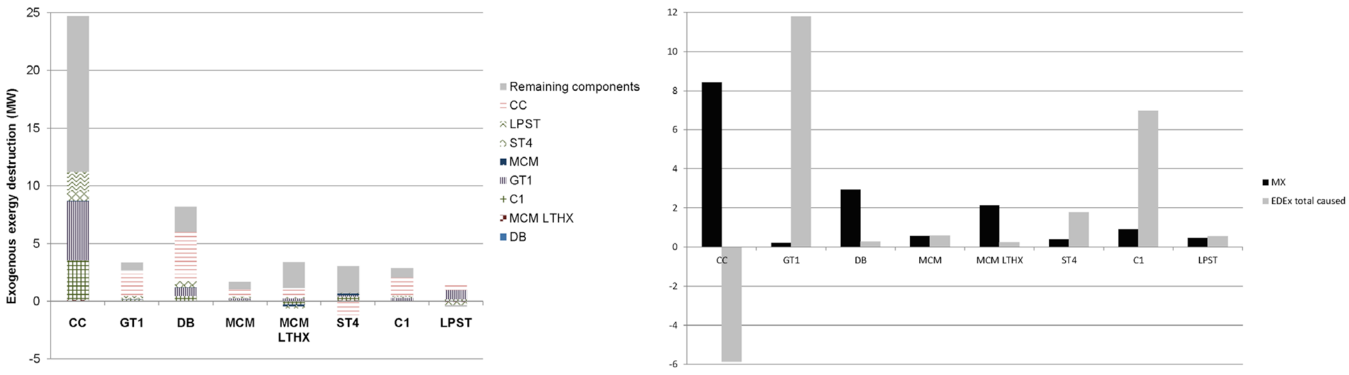

Figure 4. Defining the sources of exogenous rate of exergy destruction within each component (MW).

depends on the calculation of the $\dot{E}_{D}^{UN,EN}$, which is a function of the $\dot{E}_{P}^{EN}$. With the exception of the generators and motors that are influenced only by the components to which they are directly connected, it is unclear whether a reduction in the efficiency of the components with negative exergy destruction (e.g., some HXs and the CO_2 compressors, e.g., C5) could lead to an improvement of the overall system.

Although the exogenous exergy destruction accounts for a relatively small amount of the exergy destruction within the components, the determination of its specific sources can shed light onto improvement options (see Table 4 and Figure 4).[14]

As mentioned previously, the difference between the sum of the individual exogenous values of a component and its initial exogenous value is called mexogenous exergy destruction (MX, $\dot{E}_{D,k}^{MX}$). The results for the components with the highest exogenous exergy destruction of the plant and their mexogenous values are shown in Table 4 and Figure 4. Eight components are presented here, while the complete results can be found in ref 2.

In general, the mexogenous values have been found to be relatively low for all components. The highest mexogenous value is calculated for the reactors. The relative high value calculated for the CC reveals strong component interactions. As shown in Table 4, 26% of the exogenous exergy destruction in the CC stems from GT1 and C1, a small part of which is avoidable.[2] Similarly, in GT1 and C1, the exogenous exergy destruction is mainly imposed by the CC. Nonetheless, a large part of the exogenous exergy destruction stemming from the CC is avoidable (52% for GT1 and 44% for C1). These results show that by decreasing the exergy destruction of the CC we can eventually improve the performance of C1 and GT1. Actions to improve reactors include increasing the temperature level of the reaction process by increasing the temperatures of the incoming streams (fuel and air), decreasing pressure losses, and decreasing the air−fuel ratio. It should be noted, however, that the overall exogenous exergy destruction caused by the CC is found to be negative. This is a result mainly determined by the components of the CO_2 compression unit and GT2 and shows that higher inefficiencies in the CC can result in a thermodynamic improvement of the mentioned components. This contradicts the results of plants that have been examined previously,[2,16] where, overall, more predictable component interactions were revealed. The results obtained here reflect the more complex structure of the considered plant and the stronger interrelations of its components.

Adding a component's avoidable endogenous and avoidable exogenous exergy destruction (caused by this component to the remaining components of the plant), we obtain its total avoidable exergy destruction. This value is very useful for the evaluation of the components, as well as for more robust comparisons among different components. When the total avoidable exergy destruction is high, the component has a large influence on the overall system. As seen in Table 5 and Figure 5, both the CC and the DB have negative avoidable exogenous values. This is associated with the opposing effect that the two components have on a number of other plant components and shows that higher irreversibilities within the two reactors result in better operation of a number of components. This can stem from changes in temperatures and mass flows, which affect the exergy destruction within components significantly. The endogenous avoidable exergy destruction of the CC is relatively low and similar to that of the DB, while its exogenous exergy destruction is highly negative. The ideal CC decreases the mass flow of the compression unit, increasing the energy requirements of the plant and decreasing its overall efficiency. Therefore, the total avoidable exergy destruction of the CC is low (1.61 MW). Because the avoidable exogenous value of the DB is only slightly negative, the DB results in the largest total avoidable exergy destruction among the plant components, closely followed by GT1. When comparing GT1 with C1, GT1 causes higher avoidable exogenous exergy destruction. Furthermore, due to its much higher avoidable endogenous exergy destruction, its total avoidable exergy destruction is found to be 54% higher than that of C1. Thus, improvement efforts should mainly focus on the DB and GT1.

Table 5. Splitting the Rate of Exergy Destruction Caused by Each Component (MW)

component, *k*	$\Sigma_{r=1\, r\neq k}^{n} \dot{E}_{D,r}^{AV,EX,k}$	$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,\Sigma}$
DB	−0.09	10.73	10.64
GT1	3.76 (41%)	5.52 (59%)	9.28
C1	2.68 (45%)	3.33 (55%)	6.02
MCM	0.63 (24%)	1.96 (76%)	2.60
LPST	0.63 (25%)	1.93 (75%)	2.56
CC	−9.15	10.76	1.61
MCM LTHX	0.10 (9%)	1.05 (91%)	1.15

As mentioned before, a reactor can be improved by increasing the temperature level of the reaction process. However, in the case of the DB, the temperature of the inlet air is already high and the incoming natural gas is already preheated to 250 °C. Thus, a temperature increase in this case would likely not be a priority, although some further preheating of the natural gas could be considered. Another measure that can increase the efficiencies of both the DB and GT1

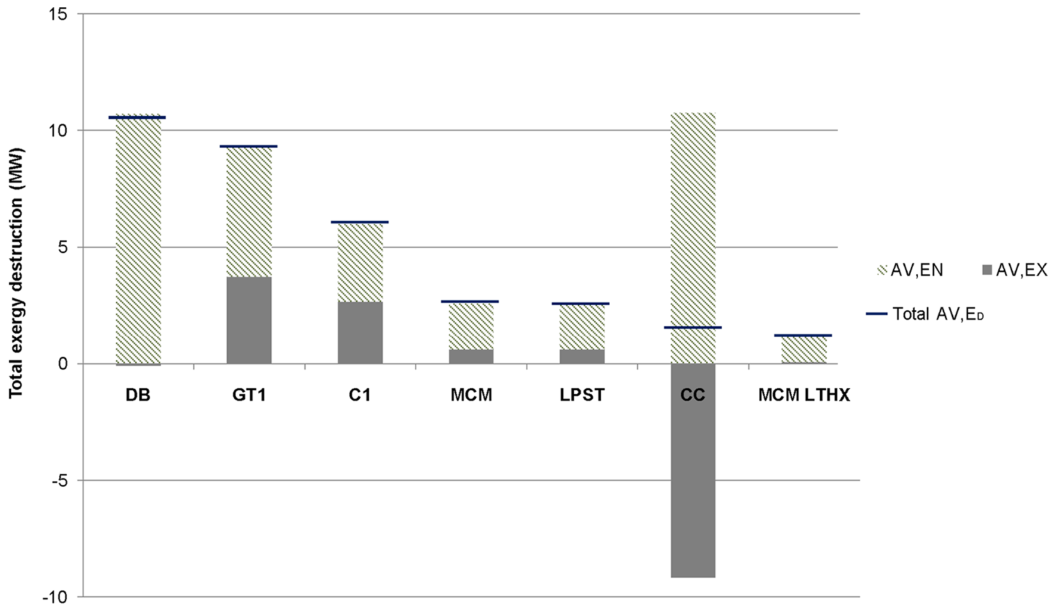

Figure 5. Total avoidable exergy destruction caused by each component (MW).

simultaneously is the decrease of the air−fuel ratio of the reactor. This measure would improve the efficiency of the reaction process and would increase the temperature of the combustion products. The higher temperature of the combustion products would, subsequently, lead to a higher efficiency of GT1. We should mention that such measures would need to be balanced with further actions, since they would lead to higher amounts of produced CO_2 and would, most probably, increase the cost of downstream components and the cooling systems.

5. CONCLUSIONS

In this paper, an oxy-fuel combined cycle power plant with CO_2 capture was examined using an advanced exergetic analysis. Although relatively time-consuming and complex, the analysis quantifies the potential for improvement for each plant component and the overall plant, as well as the component interactions. In general, the overall potential for improvement of the plant was found to be relatively low, due to high unavoidable exergy destruction values. Additionally, the improvement potential is mainly associated with the internal operational conditions of the components.

The origin of the exogenous exergy destruction can only be revealed by splitting it into its sources. During this process, which is currently only possible when applying an advanced exergetic analysis, we find relatively intense interactions among some components that should be accounted for in an optimization scenario. A very interesting finding, for example, is that the combustion chamber affects several plant components in different ways and its opposing and concurrent effects can only be revealed through this splitting process.

To examine the total significance of the different plant components, the total avoidable exergy destruction caused by each component was calculated. Because of the complexity of the effect of the combustion chamber on the remaining plant components, it results in a negative value of avoidable exogenous exergy destruction, while it has an overall low potential for improvement since 91% of its irreversibilities are unavoidable. As a result, it is placed in the sixth position regarding the priority for improvement (after the duct burner, the expander, and the compressor of the main gas turbine system, the mixed conducting membrane, and the low-pressure steam turbine). The duct burner, which appears to be the most significant component in the plant, results in a very similar avoidable endogenous value to that of the combustion chamber, but it prevails over all the other plant components due to its lower negative exogenous exergy destruction in comparison with the combustion chamber.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: f.petrakopoulou@iet.tu-berlin.de.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was funded by the European Commission's Marie Curie 6th Framework Programme as part of the Research Training Network, INSPIRE. The authors would like to thank Evonik Energy Systems GmbH for their support with the software EbsilonProfessional.

■ NOMENCLATURE

$\dot{E}$ = exergy rate (MW)
T = temperature (°C)

Subscripts

D = exergy destruction
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 = carbon capture and storage
DB = duct burner
EC = economizer
EV = evaporator
FCI = fixed capital investment
GT = gas turbine
HP = high pressure
HRSG = heat recovery steam generator
HT = high temperature
HX = heat exchanger
IP = intermediate pressure
LHV = lower heating value
LP = low pressure
LT = low temperature
MCM = mixed conducting membrane
MX = mexogenous
NG = natural gas
PH = preheater
RH = reheater
SH = superheater
ST = steam turbine

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