Exergoeconomic Analysis of an Advanced Zero Emission Plant

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In this paper, an advanced zero emission plant using oxy-fuel combustion is presented and compared with a reference plant (a) without CO_2 capture and (b) with CO_2 capture via chemical absorption. A variation of the oxy-fuel plant with a lower CO_2 capture percentage (85%) is also presented, in order to (1) evaluate the influence of CO_2 capture on the overall performance and cost of the plant and (2) enable comparison at the plant-level with the conventional method for CO_2 capture: chemical absorption with monoethanolamine. Selected results of an advanced exergetic analysis are also briefly presented to provide an overview of further development of evaluation methodologies, as well as deeper insight into power plant design. When compared with the reference case, the oxy-fuel plants with 100% and 85% CO_2 captures suffer only a relatively small decrease in efficiency, essentially due to their more efficient combustion processes that make up for the additional thermodynamic inefficiencies and energy requirements. Investment cost estimates show that the membrane used for the oxygen production in the oxy-fuel plants is the most expensive component. If less expensive materials can be used for the mixed conducting membrane reactor used in the plants, the overall plant expenditures can be significantly reduced. Using the results of the exergoeconomic analysis, the components with the higher influence on the overall plant are revealed and possible changes to improve the plants are suggested. Design modifications that can lead to further decreases in the costs of electricity and CO_2 capture, are discussed in detail. Overall, the calculated cost of electricity and the cost of avoided CO_2 from the oxy-fuel plants are calculated to be competitive with those of chemical absorption.

[DOI: 10.1115/1.4003641]

Keywords: CO_2 capture, combined cycle, advanced zero emission plant, exergetic analysis, exergoeconomic analysis

1 Introduction

The capture of CO_2 in power plants is a measure suggested to help mitigate the greenhouse effect associated with the use of fossil fuels in the energy sector. Various methods to facilitate the capture of carbon dioxide have been proposed in recent years. One approach to reduce the energy demand and simplify the CO_2 separation process is to perform combustion with pure oxygen (*oxy-fuel combustion* or *oxy-combustion*). When the combustion process is carried out with pure oxygen, the combustion products consist mainly of carbon dioxide and water vapor. In this way, the energy demand to separate the CO_2 is decreased and the main energy expense is related to the oxygen production and CO_2 compression unit.

Although, currently, oxy-fuel concepts present implementation obstacles related to technological limitations [1,2], studies, such as this one, prove these concepts as promising procedures with respect to their efficiency and their relatively low CO_2 capture cost. Many different concepts that incorporate oxy-fuel technology have been presented in literature, e.g., [3]. One of the most efficient methods is presented here.

In order to decrease the cost and energy penalty associated with the implementation of an air separation unit (ASU) in oxy-fuel combustion plants, oxygen ion transport membranes have been introduced. The power plant analyzed in this paper is an *advanced zero emission plant* (AZEP) and it incorporates such a membrane. The development of the concept was examined in a trans-European consortium and was initiated in a European project [4]. It was estimated that the technology would be available for exploitation five to seven years after completion of the first phase of the project. However, with the exception of some publications through 2007, no information about current activities based on the AZEP project has been made available [3–7]. Data used to simulate the plants in the present study are derived from small-scale or theoretical studies presented in Refs. [3–7] and the results are, therefore, associated with relatively high uncertainties.

The AZEP uses a *mixed conducting membrane* (MCM) reactor to separate the oxygen necessary for the combustion process and it performs with approximately 100% capture of the produced CO_2 (AZEP 100). A variation of the AZEP that performs with CO_2 capture close to 85% (AZEP 85) is also discussed here. This variation is used to overcome the temperature limitation related to the operation of the membrane of the plant and to allow the evaluation of possible economic trade-offs between CO_2 capture and plant efficiency. The operation and structure of the plants are based on a *reference plant* without CO_2 capture. The comparison of the plants is performed with an exergoeconomic analysis [8], which constitutes a combination of an exergetic analysis with economic principles. The exergoeconomic analysis provides information on how the structure and the operation of each plant component should be modified, in order to achieve a more cost efficient operation of the overall plant. Costs related to exergy destruction and investment are calculated and compared. Selected results of an advanced exergetic analysis are also briefly presented to provide an overview and deeper insight into the design and the improvement potential of the power plant.

This paper is part of a comprehensive study analyzing different concepts of CO_2 capture from power plants.

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Contributed by the Power Division of ASME for publication in the JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER. Manuscript received May 4, 2010; final manuscript received January 12, 2011; published online May 13, 2011. Assoc. Editor: Paolo Chiesa.

Table 1 Selected parameters and assumptions for the economic analysis

Plant economic life (yrs)	20
Levelization period (yrs)	10
Average general inflation rate (%)	3
Average nominal escalation rate for natural gas (%)	4
Average real cost of money (%)	10
Date of commercial operation	2012
Average capacity factor (%)	85
Unit cost of natural gas (€/GJ-LHV)	7

2 Methodology

2.1 Exergetic Analysis. In contrast to energy, exergy can be destroyed; thus, exergy-based methods reveal thermodynamic inefficiencies kept hidden when only energy-based methods are applied. The necessity and capabilities of exergy-based methods are well established [9,10].

The exergetic efficiency of the *k*th component ε_k and that of the overall system consisting of NC-components ε_{tot} are defined by Eqs. (1*a*) and (1*b*), respectively

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{1a}$$

$$\varepsilon_{\text{tot}} = \frac{\dot{E}_{P,\text{tot}}}{\dot{E}_{F,\text{tot}}} = 1 - \frac{\sum_{k=1}^{\text{NC}} \dot{E}_{D,k} + \dot{E}_{L,\text{tot}}}{\dot{E}_{F,\text{tot}}} \tag{1b}$$

where $\dot{E}_{P,k}$ and $\dot{E}_{F,k}$ are the exergy rates of product and fuel of component *k*, respectively, and $\dot{E}_{P,\text{tot}}$ and $\dot{E}_{F,\text{tot}}$ are the exergy rates of product and fuel of the overall system, respectively, whereas $\dot{E}_{D,k}$ is the exergy destruction within component *k* and $\dot{E}_{L,\text{tot}}$ is the exergy loss from the overall system [10].

The exergy of the product for the overall system is the net power produced in the plant, whereas the exergy of the fuel for the overall system is the sum of the fuel and the air exergy provided to the plant. General guidelines for the definition of exergetic efficiencies were given in Ref. [11].

A useful variable of the exergetic analysis is the exergy destruction ratio $y_{D,k}$. This ratio is a measure of the contribution of the exergy destruction within each component to the reduction of the overall exergetic efficiency and it is defined by Eq. (2)

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,\text{tot}}} \tag{2}$$

With an exergetic analysis, the main sources of irreversibilities within a plant are identified and are then further linked to economic principles in an exergoeconomic analysis.

2.2 Economic Analysis. For the economic analysis, the *total revenue requirement* (TRR) method has been implemented [9]. The first step of the analysis is to calculate the *fixed capital investment* (FCI) of the plants being investigated [12–17]. Costs are escalated to the reference year 2008, using the *chemical engineering plant cost index* (CEPCI), as published in *Chemical Engineering Magazine*. The main assumptions made for the economic analysis are shown in Table 1.

2.3 Exergoeconomic Analysis. The exergoeconomic analysis combines the results of the exergetic analysis with the economic data calculated in the economic analysis; it can be considered as an exergy-aided cost reduction method [8,9,18]. In an exergoeconomic analysis, specific costs are assigned to each exergy stream included in the plant. These specific costs are calculated through cost balances formulated at the component level

$$\sum_{i=1}^{i=n} \dot{C}_{i,k} - \sum_{j=1}^{j=m} \dot{C}_{j,k} + \dot{Z}_k = 0 \tag{3}$$

Here, $\Sigma_{i=1}^{i=n}\dot{C}_{i,k}$ is the sum of the cost rates associated with the *n* streams entering component *k*, $\Sigma_{j=1}^{j=m}\dot{C}_{j,k}$ represents the sum of the cost rates associated with the *m* streams leaving component *k*, and $\dot{Z}_k$ is the cost rate associated with the investment cost (including operating and maintenance expenses) of component *k*, calculated in the economic analysis.

A useful characteristic of the exergoeconomic analysis is the assignment of costs to irreversibilities. The monetary value assigned to the exergy destruction within component *k* ($\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k}$) is then compared and related to investment, operating, and maintenance costs. The contribution of the capital cost $\dot{Z}_k$ to the total sum of costs associated with capital and exergy destruction ($\dot{Z}_k + \dot{C}_{D,k}$) is expressed by the exergoeconomic factor

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{4}$$

With f_k, the relationship of the monetary impact of each component's exergy destruction and investment is revealed. If necessary, design changes to improve the overall cost effectiveness, by considering trade-offs between efficiency and investment costs, are proposed. The objective is to reduce the cost associated with the product of the overall plant.

3 Description of the Plants

3.1 The Reference Plant. The reference plant, a combined cycle power plant without CO_2 capture, has been used as the base case for the simulation of the plants that incorporate CO_2 capture. The configuration of the reference power plant is shown in Fig. 1. The plant uses methane, has one product (electricity), and includes a three-pressure level *heat-recovery steam generator* (HRSG) with one reheat stage. Calculated variables of the operation of the plant are provided in Table 2.

Flue gas exiting the *combustion chamber* (CC) at 628 kg/s is expanded in the *gas turbine* (GT) of the plant and it is then led to the HRSG. The combustion products enter the HRSG with a pressure of 1.058 bars at 580°C. In the HRSG, the gas provides thermal energy to produce steam at three pressure levels, 124/22/4.1 bars, and is then exhausted to the atmosphere at 95°C. High-pressure (HP) steam produced at 560°C is expanded to 23 bars in the *high-pressure steam turbine* (HPST) and returns to the HRSG, where it is reheated to 560°C. The reheated steam is sent to the *intermediate-pressure steam turbine* (IPST), where it is expanded to 4.1 bars. This low-pressure steam is mixed with low-pressure superheated steam from the low-pressure level HRSG and is led to the *low-pressure steam turbine* (LPST), where it is expanded to 0.05 bar. The steam is condensed in the condenser, preheated, led to the de-aerator of the plant, and further conveyed to the feed water pumps to continue the cycle.

3.2 The AZEP. The structure and operating conditions of the plants with CO_2 capture are similar to those of the reference plant. The majority of the differences are related to structural requirements of the plants, i.e., additional processes such as oxygen production or CO_2 treatment. Variables related to the operation and the performance of the plants are shown in Table 3.

The combustion process in the AZEP is performed with pure oxygen, which causes a large temperature increase in the CC of the reactor. To keep the combustion temperature within acceptable limits, a part of the flue gas is recycled back to the CC to be used

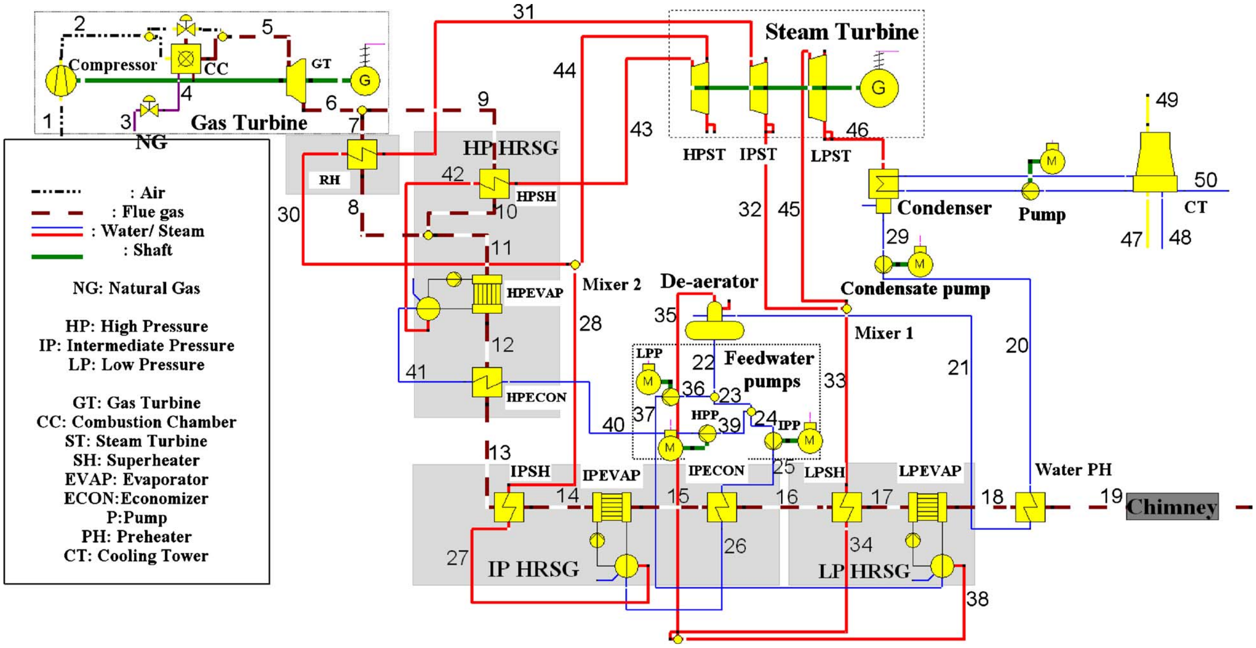

Fig. 1 Structure of the reference plant

as cooling medium. In oxy-fuel concepts, CO_2 separation is facilitated because the combustion products consist mainly of carbon dioxide and water vapor. The CO_2 is freed from the condensed water and it is then compressed and liquefied. The oxygen necessary for the combustion process in the AZEP [5–7] is produced in the MCM reactor.

3.3 The MCM Reactor. The MCM reactor, shown in Fig. 2, can be integrated into a conventional gas turbine system; it consists of a mixed conducting membrane, one high- and one low-temperature heat exchanger, a bleed gas heat exchanger, and a combustion chamber. The main component of the MCM reactor, the membrane, consists of complex crystalline structures, which incorporate oxygen ion vacancies. The operation of the membrane is based on oxygen adsorption. Oxygen atoms of the incoming air are adsorbed onto the surface of the membrane. The atoms are then decomposed into ions and occupy the oxygen vacancies of the membrane. The transfer of the oxygen ions is counterbalanced by an opposite electron flow. The selectivity of the membrane is infinite as long as its surface is perfect, i.e., no crack or pore is present. For the purpose of this paper, the mixed conducting membrane is simulated as a black box using data provided in Ref. [7].

Air is compressed in the compressor of the main GT of the plant to 17 bars. 90% of the air enters the MCM reactor and is heated to 900°C in the low-temperature heat exchanger of the reactor. Close to 38% of the oxygen included in the air is separated in the MCM and it is transferred at a temperature of 490°C to the reactor's combustion chamber with the help of a recycling gas. This circulated sweep gas that consists of 33.5% v/v CO_2, 66% v/v H_2O, and 0.5% v/v O_2 is also used to keep the temperature of the combustion process within acceptable limits. In the CC, the oxygen reacts with the provided fuel (methane) in nearly stoichiometric conditions ($\lambda = 1.05$). The oxygen-depleted air (14% v/v O_2) exits the MCM at 1000°C; it is then heated to 1250°C in the high-temperature gas-gas heat exchanger of the MCM reactor, mixed with 10% of the incoming air and it exits the reactor.

3.4 The AZEP 100. The *AZEP* with near 100% CO_2 capture will be referred to here as the *AZEP 100*. The plant produces electricity, using pure methane, and its structure is based on the reference plant described previously. Its configuration is shown in Fig. 3.

In this plant, the methane is preheated to 250°C in a gas-gas heat exchanger and it is then led to the CC of the MCM reactor. The oxygen-depleted air exiting the MCM reactor is expanded in the main GT of the plant to 1.058 bars and 497°C and it is then sent to the steam cycle of the plant. There, the heat provided by the gas is used to produce steam at three pressure levels: 124 bars, 22 bars, and 4.1 bars (as in the reference plant). The condenser at the lower level of the *steam turbine* (ST) operates at 0.05 bar. In the *high-pressure superheater* (HPSH) and the *reheater* (RH) of the plant, the steam is heated to a temperature not higher than 477°C (see streams 31 and 44 in Table 3), a temperature that results from the minimum temperature difference defined in the heat exchangers ($\Delta T_{min} = 20°C$) and the temperature of the flue gas entering the HRSG (497°C). Intermediate-pressure steam is expanded down to 0.1 bar to produce the necessary power to drive the CO_2 compression unit, as well as the recycling compressor that is used to cover the pressure drop within the MCM reactor. The turbine-driven CO_2 compression unit has been chosen in order to decrease the fuel consumption in the overall plant, by decreasing losses in equipment that would have to be used in the case of a motor-driven unit.

The combustion products, consisting of carbon dioxide and water vapor, are expanded in a secondary expander to 1.051 bars and are driven to the secondary HRSG of the plant. There, thermal energy from the gas is used to produce high-pressure steam. After the secondary HRSG, the water vapor is condensed in a flue gas condenser and the CO_2 is further compressed and liquefied. The CO_2 compression unit consists of four intercooled stages.

3.5 The AZEP 85. The AZEP 85 (Fig. 4) operates in the same way as the AZEP 100. The mass flow of the provided fuel is the same in both plants and the main difference between the two AZEP concepts is the addition of a supplementary firing (duct burner (DB)) at the exit of the MCM reactor in the AZEP 85. The DB is used to increase the, otherwise materially limited, exit temperature of the MCM reactor. The outlet gas temperature of this secondary combustion is 1300°C while the cooling of the turbine blades has not been taken into account in this simulation.

In the supplementary firing component, part of the fuel is burned with the remaining oxygen included in the oxygen-

Table 2 Calculated variables for selected streams of the reference case without CO_2 capture

Stream j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_{\text{tot},j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)
1	614.5	15.0	1.01	0.96	0.0	0
2	614.5	392.9	17.00	232.25	19.0	15,860
3	14.0	15.0	50.00	729.62	9.2	24,037
5	628.5	1264.0	16.49	741.01	15.3	40,824
6	628.5	580.6	1.06	189.87	15.3	10,460
7	268.5	580.6	1.06	81.11	15.3	4,469
8	268.5	447.6	1.05	54.64	15.3	3,010
9	360.0	580.6	1.06	108.75	15.3	5,991
10	360.0	449.3	1.05	73.68	15.3	4,059
11	628.5	448.6	1.05	128.33	15.3	7,070
12	628.5	341.2	1.04	84.69	15.3	4,666
13	628.5	257.9	1.04	55.77	15.3	3,073
14	628.5	257.3	1.04	55.59	15.3	3,063
15	628.5	237.6	1.04	49.49	15.3	2,727
16	628.5	234.1	1.04	48.43	15.3	2,668
17	628.5	229.3	1.04	47.01	15.3	2,590
18	628.5	156.4	1.03	27.98	15.3	1,542
19	628.5	95.3	1.03	16.49	0.0	0
20	94.6	32.9	3.73	0.47	25.6	44
21	94.6	135.6	3.62	8.18	30.2	889
22	95.4	140.0	3.62	8.79	30.7	973
23	72.4	140.0	3.62	6.67	30.7	739
24	7.2	140.0	3.62	0.67	30.7	74
25	7.2	140.5	25.13	0.68	33.8	83
26	7.2	216.6	24.38	1.56	27.2	153
27	7.2	222.6	24.38	7.23	21.8	568
28	7.2	237.9	23.16	7.35	22.0	583
29	94.6	32.9	0.05	0.44	21.2	33
30	72.4	305.1	23.16	79.53	20.3	5,814
31	72.4	560.6	22.00	103.42	20.0	7,459
32	72.4	317.2	4.10	66.03	20.0	4,762
33	22.1	214.1	4.10	18.01	25.0	1,623
34	22.1	146.4	4.32	16.96	24.8	1,514
35	0.8	146.4	4.32	0.63	24.8	56
36	23.0	140.0	3.62	2.12	30.7	234
37	23.0	140.0	4.32	2.12	31.1	237
38	23.0	146.4	4.32	17.60	24.8	1,570
39	65.2	140.0	3.62	6.01	30.7	665
40	65.2	141.8	134.56	6.96	31.4	788
41	65.2	325.2	130.53	31.88	22.6	2,596
42	65.2	331.2	130.53	71.79	20.5	5,302
43	65.2	560.6	124.00	103.51	20.1	7,489
44	65.2	313.2	23.16	72.22	20.1	5,226
45	94.6	293.0	4.10	83.86	21.2	6,386
46	94.6	32.9	0.05	12.87	21.2	980
47	19,004.1	15.0	1.01	29.58	0.0	0
48	370.3	15.0	1.01	0.93	0.0	0
49	19,103.0	15.3	1.01	27.30	0.0	0
50	271.5	21.0	1.01	0.75	0.0	0

depleted air. The gas emissions from this supplementary burning process are not treated, decreasing the CO_2 capture of the plant by almost 15%. Since the mass flow of the separated CO_2 in the AZEP 85 is smaller than in the AZEP 100, the power input needed for its compression also decreases accordingly.

Although the structure of the AZEP 85 is similar to that of the AZEP 100, the temperature profiles in the heat exchangers are different, due to the higher inlet temperature of the main GT in the former. The inlet flue gas temperature of the main HRSG is increased to 580°C and the HPSH heats the steam to 560°C. In this way, the steam cycle works more efficiently in the AZEP 85 than in the AZEP 100.

The simulation of the different processes has been performed using EBSILONPROFESSIONAL [19]. MATLAB [20] is the programming language used to perform the exergetic analysis. In MATLAB, exergy balances are stated both for the component level and for the overall plant, i.e., balances regarding the rate of product exergy, the rate of fuel exergy, and the rate of exergy destruction for each component and for the overall system. The exergetic analysis is based on the specific exergy costing (SPECO) approach [11]. To calculate the (physical and chemical) exergies of streams, in order to use them in the exergy balances of the analysis, the software THESIS [21], originally developed at the RWTH Aachen in Germany, has been used. The main thermodynamic values of the streams (mass flow, temperature, and pressure) and their composition are exported from EBSILONPROFESSIONAL and are supplied as input to the exergy calculation software. The respective enthalpies, the entropies, and, lastly, the exergy values are then calculated.

4 Results and Discussion

The AZEP concepts have the advantage of relatively low CO_2 capture energy demand, due to the relatively clean combustion

Table 3 Calculated variables for selected streams of the AZEP 100 and the AZEP 85

Advanced zero emission plant 100							Advanced zero emission plant 85						
Stream j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_{\text{tot},j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)	Stream j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_{\text{tot},j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)
1	710.1	15.0	1.01	1.11	0.0	0	1	603.6	15.0	1.01	0.94	0.0	0
2	710.1	393.0	17.01	268.43	22.3	21,537	2	603.6	392.8	16.99	228.07	21.9	17,970
3	639.1	393.0	17.01	241.58	22.3	19,383	3	543.2	392.8	16.99	205.26	21.9	16,173
4	583.2	1250.0	17.00	644.71	18.6	43,219	4	495.7	1250.0	16.98	547.97	18.5	36,555
5	654.2	1174.6	17.00	673.85	18.9	45,765	5	558.2	1301.9	16.81	650.87	18.2	42,601
6	654.2	497.0	1.06	141.74	18.9	9,627	6	558.2	578.7	1.06	155.21	18.2	10,158
7	299.2	497.0	1.06	64.83	18.9	4,403	7	218.2	578.7	1.06	60.67	18.2	3,971
8	299.2	431.9	1.05	51.71	18.9	3,512	8	218.2	467.0	1.05	43.15	18.2	2,824
9	355.0	497.0	1.06	76.91	18.9	5,224	9	340.0	578.7	1.06	94.54	18.2	6,188
10	355.0	417.4	1.05	58.09	18.9	3,945	10	340.0	447.8	1.05	62.89	18.2	4,116
11	654.2	424.0	1.05	109.80	18.9	7,458	11	558.2	455.3	1.05	106.03	18.2	6,941
12	654.2	341.2	1.05	76.84	18.9	5,219	12	558.2	341.2	1.04	66.21	18.2	4,334
13	654.2	277.4	1.04	54.31	18.9	3,689	13	558.2	252.7	1.04	40.03	18.2	2,621
14	654.2	275.0	1.04	53.51	18.9	3,634	14	558.2	252.3	1.04	39.92	18.2	2,613
15	654.2	232.6	1.04	40.22	18.9	2,732	15	558.2	232.6	1.04	34.76	18.2	2,275
16	654.2	225.0	1.04	37.97	18.9	2,579	16	558.2	229.1	1.04	33.86	18.2	2,217
17	654.2	221.3	1.04	36.89	18.9	2,506	17	558.2	224.9	1.04	32.80	18.2	2,147
18	654.2	156.4	1.03	20.16	18.9	1,369	18	558.2	156.4	1.03	17.55	18.2	1,149
19	654.2	92.0	1.03	8.10	0.0	0	19	558.2	84.7	1.03	6.35	0.0	0
20	99.3	32.9	3.73	0.50	29.1	52	20	95.0	32.9	3.73	0.48	28.3	48
21	99.3	136.4	3.62	8.68	35.4	1,107	21	95.0	136.4	3.62	8.31	33.4	1,000
22	100.0	140.0	3.62	9.21	36.0	1,193	22	95.7	140.0	3.62	8.82	34.1	1,082
23	79.6	140.0	3.62	7.33	36.0	950	23	77.1	140.0	3.62	7.11	34.1	872
24	15.5	140.0	3.62	1.43	36.0	185	24	6.2	140.0	3.62	0.57	34.1	70
25	15.5	140.4	25.13	1.47	38.0	201	25	6.2	140.5	25.13	0.59	37.6	79
26	15.5	216.6	24.38	3.34	31.4	377	26	6.2	216.6	24.38	1.34	30.8	148
27	15.5	222.6	24.38	15.49	25.8	1,438	27	6.2	222.6	24.38	6.19	25.6	570
28	15.5	257.4	23.16	16.12	26.0	1,508	28	6.2	232.7	23.16	6.26	25.9	582
29	79.6	265.7	23.16	83.65	23.5	7,076	29	77.1	307.1	23.16	84.88	22.7	6,941
30	44.0	265.7	23.16	46.30	23.5	3,917	30	48.4	307.1	23.16	53.21	22.7	4,351
31	44.0	477.0	22.00	57.69	23.7	4,923	31	48.4	558.7	22.00	68.91	22.7	5,627
32	44.0	253.4	4.10	37.36	23.7	3,188	32	48.4	315.7	4.10	44.00	22.7	3,594
33	19.7	205.0	4.10	15.87	29.7	1,694	33	17.9	209.1	4.10	14.45	28.7	1,494
34	19.7	146.4	4.32	15.09	29.3	1,594	34	17.9	146.4	4.32	13.68	28.4	1,400
35	0.7	146.4	4.32	0.55	29.3	58	35	0.7	146.4	4.32	0.53	28.4	54
36	20.4	140.0	3.62	1.88	36.0	244	36	18.5	140.0	3.62	1.71	34.1	210
37	20.4	140.0	4.32	1.88	36.3	246	37	18.5	140.0	4.32	1.71	34.5	212
38	20.4	146.4	4.32	15.64	29.3	1,653	38	18.5	146.4	4.32	14.21	28.4	1,454
39	64.1	140.0	3.62	5.90	36.0	765	39	71.0	140.0	3.62	6.54	34.1	802
40	64.1	141.7	134.56	6.84	36.3	895	40	71.0	141.7	134.56	7.57	34.6	942
41	49.8	141.7	134.56	5.32	36.3	696	41	59.3	141.7	134.56	6.33	34.6	788
42	49.8	325.2	130.53	24.36	27.5	2,410	42	59.3	325.2	130.53	28.98	25.9	2,702
43	49.8	331.2	130.53	54.86	24.8	4,903	43	59.3	331.2	130.53	65.27	23.8	5,593
44	49.8	477.0	124.00	72.01	24.5	6,352	44	59.3	558.7	124.00	93.92	23.4	7,905
45	64.1	501.5	124.00	95.32	22.9	7,859	45	71.0	561.9	124.00	112.79	22.4	9,114
46	64.1	267.8	23.16	67.53	22.9	5,567	46	71.0	314.2	23.16	78.67	22.4	6,358
47	63.7	238.3	4.10	53.19	25.5	4,884	47	66.2	286.9	4.10	58.30	24.3	5,093
48	63.7	32.9	0.05	8.41	25.5	772	48	66.2	32.9	0.05	8.98	24.3	784
49	99.3	32.9	0.05	12.91	24.8	1,153	49	95.0	32.9	0.05	12.73	23.8	1,091
50	35.5	265.7	23.16	37.35	23.5	3,159	50	28.8	307.1	23.16	31.68	22.7	2,590
51	35.5	32.9	0.05	4.49	23.5	380	51	28.8	32.9	0.05	3.75	22.7	307
52	99.3	32.9	0.05	0.46	24.8	41	52	95.0	32.9	0.05	0.44	23.8	38
53	14.3	141.7	134.56	1.52	36.3	199	53	11.7	141.7	134.56	1.25	34.6	155
54	14.3	325.2	130.53	6.97	20.9	526	54	11.7	325.2	130.53	5.70	20.7	424
55	14.3	331.2	130.53	15.70	18.5	1,045	55	11.7	331.2	130.53	12.85	18.4	849
56	14.3	592.5	124.00	23.40	17.9	1,504	56	11.7	578.6	124.00	18.87	17.8	1,209
57	69.9	685.0	1.05	60.25	13.0	2,830	57	59.4	684.1	1.04	51.12	13.1	2,408
58	69.9	612.5	1.05	54.43	13.0	2,556	58	59.4	598.6	1.04	45.32	13.1	2,135
59	69.9	495.8	1.04	45.82	13.0	2,152	59	59.4	490.2	1.04	38.58	13.1	1,817
60	69.9	341.2	1.04	36.08	13.0	1,694	60	59.4	341.2	1.03	30.63	13.1	1,443
61	69.9	217.6	1.03	30.02	13.0	1,410	61	59.4	222.3	1.02	25.65	13.1	1,208
62	38.9	30.0	103.09	22.12	0.0	0	62	33.1	30.0	103.09	18.81	0.0	0
63	14.0	15.0	50.00	729.62	9.2	24,037	63	14.0	15.0	50.00	729.62	9.2	24,037
65	14.0	250.0	16.99	729.72	9.3	24,315	65	11.9	250.0	17.0	620.3	9.3	20,668
66	473.0	488.7	16.99	390.97	13.5	19,035	66	402.0	487.8	16.99	331.99	13.6	16,219
67	487.0	1276.2	16.48	940.04	13.0	44,144	67	413.9	1275.6	16.48	798.60	13.1	37,614
68	69.9	1276.2	16.48	134.85	13.0	6,332	68	59.4	1275.6	16.48	114.56	13.1	5,396
69	69.9	1200.0	16.47	126.64	13.0	5,947	69	59.4	1200.0	16.47	107.65	13.1	5,070
70	417.1	1276.2	16.48	805.20	13.0	37,812	70	354.5	1275.6	16.48	684.04	13.1	32,218

Table 3 (*Continued.*)

Advanced zero emission plant 100							Advanced zero emission plant 85						
Stream j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_{\text{tot},j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)	Stream j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_{\text{tot},j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)
71	417.1	1286.9	17.10	813.51	13.5	39,607	71	354.5	1286.2	17.10	691.11	13.6	33,763
72	71.0	393.0	17.01	26.84	22.3	2,154	72	60.4	392.8	16.99	22.81	21.9	1,797
73	71.0	523.8	17.00	32.96	21.5	2,546	73	60.4	522.5	16.98	27.96	21.1	2,129
							78	556.1	1174.5	16.98	572.67	18.8	38,683
							79	2.1	250.0	16.98	109.46	9.3	3,647

products obtained through oxy-combustion. The main part of the energy use within these plants is related to the oxygen production necessary for the combustion process.

The results of the exergetic and exergoeconomic analyses at the component level for the reference plant, the AZEP 100 and the AZEP 85, are shown in Tables 4–6. Specific monetary values of all streams of the plants are given in Tables 2 and 3.

4.1 Exergetic Analysis. The calculated exergy loss of the AZEP 85 is lower than that of the AZEP 100. This happens because in the AZEP 85, (1) the mass flow rates of the captured CO_2, as well as those of the working fluids of the MCM reactor and the GT system, are smaller and (2) the exhaust gas of the plant has a lower temperature and a smaller mass flow rate. When compared with the conventional combustion process of the reference plant, combustion in both of the oxy-fuel plants is realized more efficiently; the exergy destruction ratio $y_{D,\text{CC}}$ is calculated to be 18–30% lower and the exergetic efficiency ε_{CC} about 8% higher than in the reference plant. This is essentially due to the preheating of the reactants taking part in the combustion. Through the preheating of the gases, the thermodynamic inefficiencies connected to the combustion process decrease significantly. Furthermore, in the AZEP 100, the exergy destruction ratio of the combustion process is lower than that of the AZEP 85, which includes both the CC and the supplementary firing. This is a result of the lower exergetic efficiency of the supplementary firing component.

The combination of lower exergy destruction and lower loss in the AZEP 85 results in a higher power output. Since the same amount of fuel is provided to both plants, the exergetic efficiency of the overall plant is higher for the AZEP 85 by 1.7 percentage points. Compared with the reference plant that does not include CO_2 capture, the AZEP concepts suffer from a reduction of 3–5 percentage points in exergetic efficiency. This reduction is relatively small, when compared with chemical absorption with monoethanolamine (MEA) (ε_{tot}=45.8%) [22]. This indicates that these methods can be promising for CO_2 capture, as long as current implementation challenges are met.

4.2 Exergoeconomic Analysis. An important outcome of the exergoeconomic analysis is the ranking of the components included in a plant, based on the sum of their investment and exergy destruction cost rates ($\dot{C}_D+\dot{Z}$). This ranking reveals which components should have priority for improvement, with the main objective being the enhancement of the cost effectiveness of the plant as a whole.

When comparing the sums of the costs of the components of the oxy-fuel plants, the CC and the expander of the GT system receive the highest priority. In the AZEP 100, the next highest priorities are given to the MCM and the compressor. In the AZEP 85, these two components trade places. This happens because the mass flow rates of the AZEP 100 are higher and, therefore, the size of the membrane is larger. The higher mass flows result in higher cost rates $\dot{C}_{D,\text{MCM}}$ and $\dot{Z}_{\text{MCM}}$. The LPST has a higher sum of cost rates in the AZEP 85 than in the AZEP 100. Moreover, the higher steam mass flow and the higher inlet temperature increase the priority of the *HP* HRSG in the AZEP 85. This results in a higher improvement priority for the HP HRSG than for the steam turbine used to drive the CO_2 compressors (ST for CO_2 supply). The other two pressure levels of the HRSG in the AZEP 85 are of lower priority, mainly due to their smaller steam flow rates and, therefore, their lower exergy destruction and investment cost. Lastly, the high- and low-temperature heat exchangers of the MCM reactor are of lower priority in the AZEP 85, due to the lower mass flow rate and, thus, their smaller size, compared with AZEP 100.

The AZEPs and their components can also be compared and evaluated with the aid of the exergoeconomic factor. When this

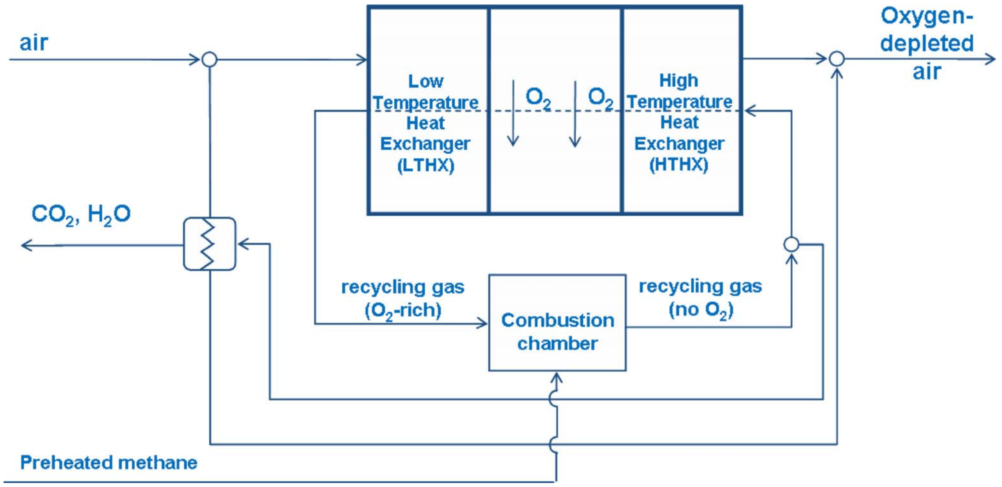

Fig. 2 The MCM reactor

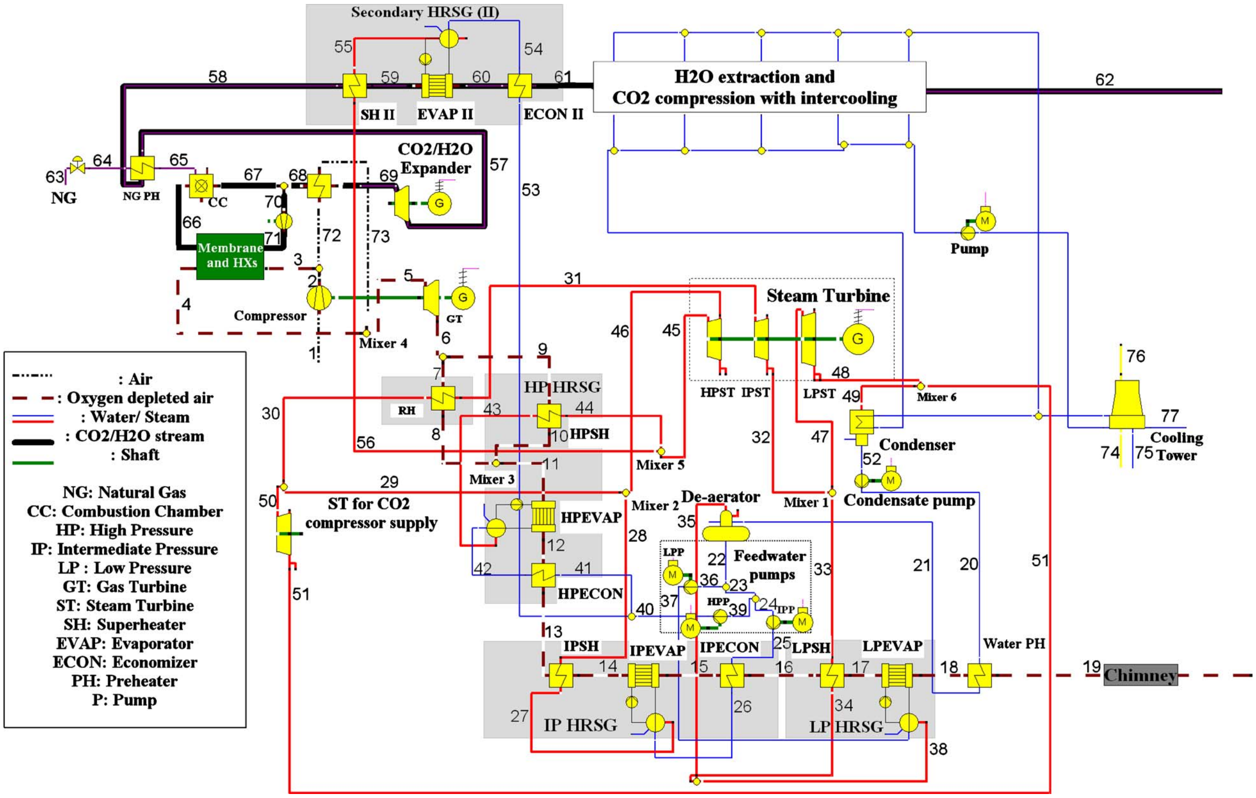

Fig. 3 Structure of the AZEP 100

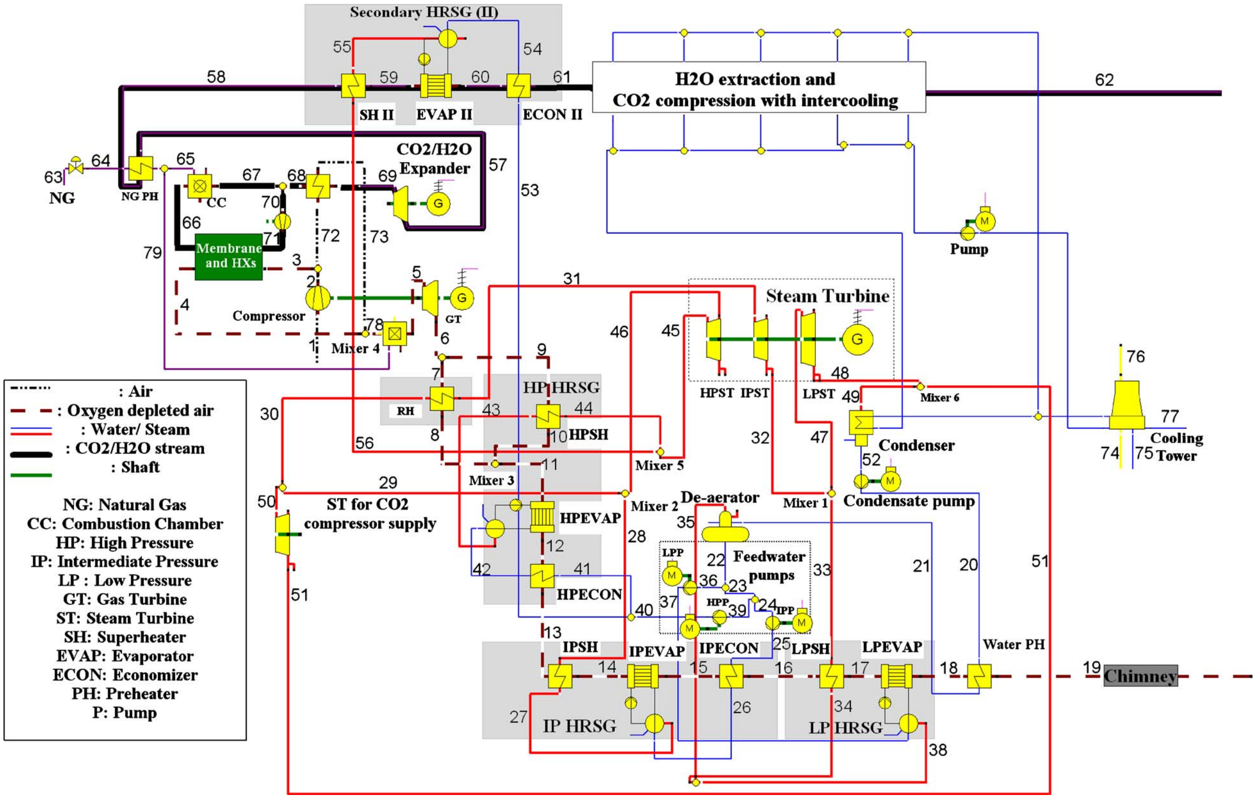

Fig. 4 Structure of the AZEP 85

Table 4 Results of the exergetic and exergoeconomic analyses at the component level for the reference case

Component k	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$c_{F,k}$ (€/GJ)	$c_{P,k}$ (€/GJ)	$\dot{C}_{D,k}$ (€/h)	$\dot{Z}_k$ (€/h)	$\dot{C}_{D,k}+\dot{Z}_k$ (€/h)	f_k (%)	r_k (%)
Compressor	242.68	231.30	11.38	95.3	1.56	16.7	19.0	683	1297	1,980	65.5	14
CC	729.62	508.76	220.87	69.7	30.23	9.2	13.6	7,276	926	8,203	11.3	49
Expander GT	551.15	530.67	20.47	96.3	2.80	15.3	16.7	1,128	1482	2,610	56.8	9
Reheater RH	26.47	23.89	2.58	90.3	0.35	15.3	19.1	142	105	247	42.6	25
HPSH	35.07	31.72	3.35	90.5	0.46	15.3	19.2	184	149	334	44.8	25
HPEVAP	43.64	39.91	3.73	91.5	0.51	15.3	18.8	205	184	389	47.2	23
HPECON	28.92	24.91	4.00	86.2	0.55	15.3	20.2	220	89	309	28.7	32
IPSH	0.18	0.12	0.06	69.0	0.01	15.3	34.6	3	4	7	55.2	126
IPEVAP	6.10	5.67	0.43	92.9	0.06	15.3	20.3	24	65	89	73.2	33
IPECON	1.06	0.87	0.19	82.5	0.03	15.3	22.1	10	5	15	33.5	44
LPSH	1.43	1.04	0.38	73.3	0.05	15.3	29.0	21	18	39	46.6	89
LPEVAP	19.03	15.48	3.55	81.4	0.49	15.3	23.9	195	173	368	46.9	56
LPECON	11.49	7.71	3.78	67.1	0.52	15.3	30.5	209	93	301	30.8	99
HPST	31.29	29.18	2.11	93.2	0.29	20.1	23.8	153	166	318	52.0	18
IPST	37.39	35.21	2.18	94.2	0.30	20.0	24.2	157	300	457	65.6	21
LPST	70.99	61.35	9.64	86.4	1.32	21.2	29.0	734	696	1,431	48.7	37
Condensate pump	0.04	0.04	0.01	78.8	0.00	19.6	80.5	1	7	7	91.0	310
HP pump	1.12	0.96	0.17	85.3	0.02	19.6	35.6	12	38	50	76.6	81
IP pump	0.03	0.02	0.01	65.3	0.00	19.6	140.4	1	7	8	91.0	615
LP pump	0.00	0.00	0.00	67.2	0.00	19.6	384.6	0	2	2	97.3	1858
De-aerator	0.56	0.53	0.03	95.4	0.00	24.8	40.0	2	26	28	92.0	62
Mixer 1	1.81	1.63	0.18	90.1	0.02	20.0	22.5	13	0	13	0.0	12
Mixer 2	0.63	0.58	0.04	92.9	0.01	20.1	24.3	3	0	3	0.0	21
Mixer 3	0.18	0.18	0.00	99.9	0.00	15.3	15.3	0	0	0	0.0	
Condenser	12.43	-	7.53	-	1.70	21.2	-	946	86	1,032	8.3	-
Total (E_L=14.0 MW)	730.58	411.40	305.15	56.3	41.77	9.2	20.5	10,053	6460	16,513	39.1	124

factor is high, a decrease in the investment cost of the component should take place. On the other hand, when this factor is low, an improved design of the component from the thermodynamic viewpoint (a design with lower exergy destruction) should be considered. The mass flows are larger in the MCM reactor of the AZEP 100 than in the AZEP 85 since the total amount of the fuel provided to the AZEP 100 plant is combusted there. For this reason, most of the cost rates $\dot{C}_{D,\mathrm{CC}}$ and $\dot{Z}_{\mathrm{CC}}$, associated with exergy destruction and investment costs, respectively, are higher in this plant than in AZEP 85. However, although the exergy destruction in the GT system of the AZEP 85 is lower than in the AZEP 100, the investment cost of the unit is higher, due to the larger power output. This results in higher exergoeconomic factors for these components in this plant, when compared with the respective components in the AZEP 100. Nonetheless, f_k still lies within acceptable limits (lower than 55% for heat exchangers, 35–75% for compressors/turbines, and higher than 90% for pumps [9]) for both plants and, therefore, no change in the GT system is suggested. Relatively low exergoeconomic factors are calculated for the steam turbines of the plants, especially in the AZEP 100, where the inlet temperatures of the turbines are limited by the low inlet temperature of the gas turbine. Moreover, low values of the exergoeconomic factor are calculated for the *air heat exchanger* (HX air) and the *natural gas preheater* (NG PH). This, however, is justified by the high-temperature difference caused by design requirements, in the first case, and a pressure drop (valve), in the second case. The relatively high values of f_k of the heat exchangers in the MCM reactor (HTHX and LTHX) indicate that these components have relatively high investment costs and could be candidates for improvement, if less expensive materials could be considered.

The overall values of the two oxy-fuel plants (shown under *total* in Tables 5 and 6) are at similar levels, with the overall exergoeconomic factors having a negligible difference. On the other hand, when comparing the exergoeconomic factors of these plants with that of the reference plant, a difference of approximately 34% is noted. While the common components in all of the plants discussed here have similar values, the MCM reactor contributes significantly to an increase in the investment cost and, consequently, the exergoeconomic factor.

To compare the costs calculated for the plants, the *cost of electricity* (COE) and the *cost of avoided* CO_2 (COA-CO2) are considered. The cost of avoided CO_2, defined in Ref. [23], shows the added cost of electricity per ton of CO_2 avoided based on net plant capacity. To evaluate the costs, the most known and commonly proposed method for CO_2 capture, chemical absorption with *MEA*, is used [22,23]. For this plant, the structure of which is similar to the reference plant with an additional chemical absorption unit, the COE is found to be 95.5 €/MW h and the COA-CO_2 78.3 €/t [22].

For the AZEP 100, the COE is calculated to be 94.9 €/MW h and the cost of avoided CO_2 is 62.7 €/t. For the AZEP 85, these values are 91.3 €/MW h and 61.6 €/t, respectively. The oxy-fuel plants have lower costs in comparison to the MEA plant. Both the COE and the COA-CO_2 are higher for the plant with chemical absorption because of its high energy demand of the solvent regeneration.

Investment costs related to not commercially available components of the plants should be treated with caution, due to implementation challenges and uncertainties that are not easily quantifiable. Therefore, a sensitivity analysis of the investment cost of the MCM reactor (from −50% to +100%) has been performed here, in order to evaluate its influence on the COE and the COA-CO2 of the AZEPs. Figure 5 shows that variations of the investment cost of the MCM reactor influence the COA-CO2 more than the COE. For example, a 50% decrease in the cost of the reactor decreases the COE of the plant by approximately 5–6 percentage points and the COA-CO2 by 29 percentage points for both AZEPs. Moreover, the COE of the AZEP 100 and the AZEP 85 surpass that of the MEA plant with an increase in their investment cost of 1% and 13%, respectively, while the COA-CO2 of the AZEPs surpass that of the MEA plant after an increase of 23%.

The two oxy-fuel plants perform CO_2 capture in a relatively efficient way. Some of the differences in the costs and the general results of the plants are based on calculation assumptions and requirements. The choice of a plant can differ depending on the

Table 5 Results of the exergetic and exergoeconomic analyses at the component level for the AZEP 100

Component k	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$c_{F,k}$ (€/GJ)	$c_{P,k}$ (€/GJ)	$\dot{C}_{D,k}$ (€/h)	$\dot{Z}_k$ (€/h)	$\dot{C}_{D,k}+\dot{Z}_k$ (€/h)	f_k (%)	r_k (%)
Compressor	280.47	267.32	13.15	95.3	1.80	20.3	22.4	959	1,083	2,042	53.0	10
CC	729.72	549.07	180.65	75.2	24.72	9.3	12.7	6,019	794	6,813	11.7	37
MCM	97.30	90.54	6.75	93.1	0.92	13.5	19.9	329	1,751	2,080	84.2	47
MCM reactor HTHX	142.04	140.61	1.43	99.0	0.20	13.5	14.8	70	581	650	89.3	9
MCM reactor LTHX	260.08	248.86	11.22	95.7	1.54	13.5	15.2	546	932	1,479	63.0	12
Expander (air) GT	532.11	512.51	19.60	96.3	2.68	18.9	20.3	1,331	1,238	2,569	48.2	7
CO_2/H_2O expander	66.39	63.11	3.28	95.1	0.45	13.0	15.1	154	312	467	67.0	16
Compressor recycle	8.59	8.31	0.28	96.8	0.04	37.2	60.0	37	645	682	94.6	61
HX air	8.20	6.12	2.09	74.6	0.29	13.0	17.8	98	7	105	6.5	36
NG PH	5.82	0.10	5.72	1.7	0.78	13.0	785.4	269	4	273	1.6	5921
Reheater RH	13.12	11.38	1.73	86.8	0.24	18.9	24.6	118	56	174	32.4	30
HPSH	18.82	17.15	1.68	91.1	0.23	18.9	23.5	114	113	227	49.8	24
HPEVAP	32.96	30.50	2.46	92.5	0.34	18.9	22.7	167	171	338	50.6	20
HPECON	22.53	19.04	3.49	84.5	0.48	18.9	25.0	237	65	302	21.5	33
IPSH	0.80	0.63	0.17	79.0	0.02	18.9	31.2	11	11	22	48.9	65
IPEVAP	13.29	12.15	1.14	91.4	0.16	18.9	24.2	78	119	196	60.5	28
IPECON	2.24	1.88	0.37	83.6	0.05	18.9	26.2	25	12	37	32.1	39
LPSH	1.08	0.78	0.31	71.8	0.04	18.9	35.7	21	16	37	43.2	89
LPEVAP	16.73	13.76	2.97	82.2	0.41	18.9	28.4	202	169	370	45.5	50
LPECON	12.06	8.19	3.87	67.9	0.53	18.9	35.8	263	103	366	28.2	90
SH II	8.61	7.70	0.91	89.4	0.12	13.0	16.6	43	23	66	35.5	27
EVAP II	9.74	8.73	1.02	89.6	0.14	13.0	16.5	48	27	75	36.2	27
ECON II	6.06	5.45	0.61	90.0	0.08	13.0	16.7	29	22	50	43.0	28
HPST	27.79	25.82	1.97	92.9	0.27	22.9	26.9	162	138	300	45.9	17
IPST	20.33	19.06	1.27	93.8	0.17	23.7	28.1	108	153	261	58.6	19
LPST	44.78	38.70	6.08	86.4	0.83	25.5	34.0	558	413	972	42.5	33
ST for CO_2 supply	32.85	24.83	8.02	75.6	1.10	23.5	37.2	678	274	952	28.7	58
Condensate pump	0.05	0.04	0.01	79.4	0.00	21.6	82.4	1	7	8	90.4	281
HP pump	1.10	0.94	0.16	85.3	0.02	21.6	38.4	13	38	51	75.3	77
IP pump	0.06	0.04	0.02	69.9	0.00	21.6	109.6	1	11	12	88.9	406
LP pump	0.00	0.00	0.00	66.3	0.00	21.6	429.4	0	2	2	97.3	1884
CO_2 compressor 1	3.96	3.31	0.66	83.4	0.09	37.2	166.2	88	369	457	80.7	347
CO_2 compressor 2	4.08	3.39	0.69	83.0	0.10	37.2	84.0	93	380	473	80.3	126
CO_2 compressor 3	4.07	3.35	0.72	82.2	0.10	37.2	88.5	97	379	476	79.6	138
CO_2 compressor 4	4.13	3.36	0.78	81.2	0.11	37.2	90.4	104	384	488	78.7	143
De-aerator	0.48	0.46	0.02	95.6	0.00	29.3	47.8	2	28	30	92.6	63
Mixer 4	43.99	40.18	3.82	91.3	0.52	18.6	20.4	256	0	256	0.0	9
Condenser flue gas	17.60	-	14.25	-	1.95	13.1	-	832	110	942	11.6	-
Cooler 1	0.80	-	0.64	-	0.09	45.6	-	131	11	142	7.6	-
Cooler 2	0.95	-	0.77	-	0.11	52.8	-	180	11	190	5.7	-
Cooler 3	0.90	-	0.74	-	0.10	58.5	-	189	10	199	5.0	-
Cooler 4	0.92	-	0.76	-	0.10	63.2	-	210	13	223	5.7	-
Condenser	12.45	-	7.55	-	1.03	24.8	-	1,112	87	1,199	7.3	-
Total (E_L=28.0 MW)	730.73	376.27	326.48	51.5	44.68	9.2	26.4	10,715	11,790	22,504	52.4	188

expectations and priorities of the decision-maker.

The results obtained from the conventional exergetic and exergoeconomic analyses show that the AZEP 85 is favorable from both thermodynamic and cost perspectives. In order to determine the improvement potential of a plant and to pinpoint design and operating changes for the improvement of the process, the avoidable exergy destruction, as well as component interactions, must be estimated (e.g., Ref. [24]). In general, part of the exergy destruction of a system can be avoided with structural modifications or efficiency improvements in individual components. Exergy destruction that can be avoided through technically feasible design and/or operating improvement is considered *avoidable* (E_D^{AV}). Larger values of avoidable exergy destruction indicate significant improvement potential. The exergy destruction that cannot be avoided in any feasible way is associated with physical, technological, and economic constraints and it is called *unavoidable* (E_D^{UN}). Additionally, the exergy destruction within one component can be separated depending on its source: If it is incurred by component interactions, it is *exogenous* (E_D^{EX}) while if it stems only from the operation of the component itself, it is *endogenous* (E_D^{EN}). Selected results for the most important components of the AZEP 85 are shown in Table 7.

The reactors in the AZEP 85 are the components with the highest absolute value of exergy destruction. However, although the CC has a rate of exergy destruction almost 5 times higher than the DB, the DB results in a 23% higher value of avoidable exergy destruction E_D^{AV}. Thus, it has the highest improvement priority, followed by the CC, the expander (GT), the ST used to drive the CO_2 compressors (ST for CO_2 supply), the NG PH, and the compressor. Moreover, 91% of the exergy destruction in the CC of the AZEP 85 is unavoidable. This high unavoidable exergy destruction of the CC is justified by its operation. Because preheated gases of high physical exergy are used, the reduction of the exergy destruction by decreasing the excess air in the combustion is small. While most of the exergy destruction within the compressor and the combustion chamber is unavoidable, the opposite is true for the other three components of Table 7. In general, most of the total exergy destruction of the plant is endogenous (77%). This shows that component interactions, represented by the exogenous exergy destruction, do not play a significant role. Therefore, improvement strategies should mainly focus on the reduction of internal component inefficiencies.

Table 6 Results of the exergetic and exergoeconomic analyses at the component level for the AZEP 85

Component k	$\dot{E}_{F,k}$ (MW)	$\dot{E}_{P,k}$ (MW)	$\dot{E}_{D,k}$ (MW)	ε_k (%)	$y_{D,k}$ (%)	$c_{F,k}$ (€/GJ)	$c_{P,k}$ (€/GJ)	$\dot{C}_{D,k}$ (€/h)	$\dot{Z}_k$ (€/h)	$\dot{C}_{D,k}+\dot{Z}_k$ (€/h)	f_k (%)	r_k (%)
Compressor	238.30	227.13	11.17	95.3	1.53	19.6	22.0	789	1,141	1,930	59.1	12
CC	620.26	466.61	153.65	75.2	21.03	9.3	12.7	5,120	728	5,848	12.4	38
MCM	82.65	77.03	5.62	93.2	0.77	13.6	19.9	275	1,481	1,756	84.4	47
MCM reactor HTHX	120.72	119.49	1.24	99.0	0.17	13.6	14.9	60	522	582	89.6	10
MCM reactor LTHX	221.06	211.51	9.55	95.7	1.31	13.6	15.3	467	834	1,301	64.1	13
DB	109.46	78.20	31.26	71.4	4.28	9.3	13.9	1,042	270	1,312	20.6	50
Expander (air) GT	495.66	477.85	17.81	96.4	2.44	18.2	19.6	1,166	1,304	2,470	52.8	8
CO_2/H_2O expander	56.53	53.73	2.80	95.1	0.38	13.1	15.0	132	241	373	64.7	15
Compressor recycle	7.31	7.07	0.24	96.8	0.03	36.2	60.7	31	593	623	95.1	68
HX air	6.91	5.15	1.76	74.5	0.24	13.1	17.9	83	6	89	6.7	37
NG PH	5.80	0.10	5.70	1.7	0.78	13.1	790.5	269	5	273	1.7	5942
Reheater RH	17.52	15.70	1.82	89.6	0.25	18.2	22.6	119	71	190	37.3	24
HPSH	31.65	28.65	3.00	90.5	0.41	18.2	22.4	196	143	340	42.2	23
HPEVAP	39.82	36.29	3.54	91.1	0.48	18.2	22.1	231	170	401	42.3	22
HPECON	26.17	22.65	3.52	86.6	0.48	18.2	23.5	230	87	317	27.4	29
IPSH	0.11	0.07	0.05	57.5	0.01	18.2	50.1	3	3	6	46.8	175
IPEVAP	5.16	4.85	0.31	94.0	0.04	18.2	24.2	20	74	94	78.6	33
IPECON	0.90	0.75	0.15	83.5	0.02	18.2	25.5	10	5	15	35.3	40
LPSH	1.06	0.77	0.29	72.5	0.04	18.2	34.0	19	15	34	44.5	87
LPEVAP	15.25	12.50	2.75	81.9	0.38	18.2	27.6	180	154	334	46.1	52
LPECON	11.20	7.83	3.37	69.9	0.46	18.2	33.7	220	109	329	33.1	85
SH II	6.74	6.03	0.71	89.5	0.10	13.1	16.6	33	20	53	37.6	27
EVAP II	7.95	7.14	0.81	89.8	0.11	13.1	16.5	38	24	62	38.4	26
ECON II	4.98	4.46	0.52	89.5	0.07	13.1	16.8	25	18	42	42.1	28
HPST	34.12	31.81	2.30	93.3	0.31	22.4	26.3	186	177	363	48.8	17
IPST	24.90	23.45	1.45	94.2	0.20	22.7	27.0	119	196	315	62.3	19
LPST	49.32	42.62	6.70	86.4	0.92	24.3	32.6	585	475	1,060	44.8	34
ST for CO_2 supply	27.92	21.14	6.78	75.7	0.93	22.7	36.2	555	249	804	31.0	59
Condensate pump	0.04	0.04	0.01	78.9	0.00	21.4	84.7	1	7	8	90.6	296
HP pump	1.21	1.04	0.17	86.0	0.02	21.4	37.6	13	42	55	76.3	76
IP pump	0.03	0.02	0.01	64.3	0.00	21.4	157.4	1	7	8	90.9	636
LP pump	0.00	0.00	0.00	65.7	0.00	21.4	470.6	0	2	2	97.5	2101
CO_2 compressor 1	3.38	2.81	0.57	83.3	0.08	36.2	169.0	74	339	413	82.2	367
CO_2 compressor 2	3.48	2.88	0.60	82.8	0.08	36.2	85.6	78	350	427	81.8	136
CO_2 compressor 3	3.47	2.85	0.62	82.2	0.08	36.2	90.1	81	348	429	81.2	149
CO_2 compressor 4	3.52	2.85	0.66	81.2	0.09	36.2	92.0	86	353	440	80.4	154
De-aerator	0.46	0.44	0.02	95.6	0.00	28.4	47.2	2	27	29	93.0	66
Mixer 4	37.46	34.20	3.26	91.3	0.45	18.5	20.3	217	0	217	0.0	9
Condenser flue gas	15.09	-	12.23	-	1.67	13.2	-	716	96	812	12	-
Cooler 1	0.68	-	0.55	-	0.07	46.3	-	114	10	123	8	-
Cooler 2	0.81	-	0.66	-	0.09	53.6	-	156	10	165	6	-
Cooler 3	0.76	-	0.63	-	0.09	59.5	-	163	9	172	5	-
Cooler 4	0.79	-	0.65	-	0.09	64.2	-	182	11	193	6	-
Condenser	12.29	-	7.45	-	1.02	23.8	-	1,053	88	1,142	8	-
Total (E_L=22.9 MW)	730.56	388.67	319.01	53.2	43.67	9.2	25.4	10,470	11,572	22,042	52.5	177

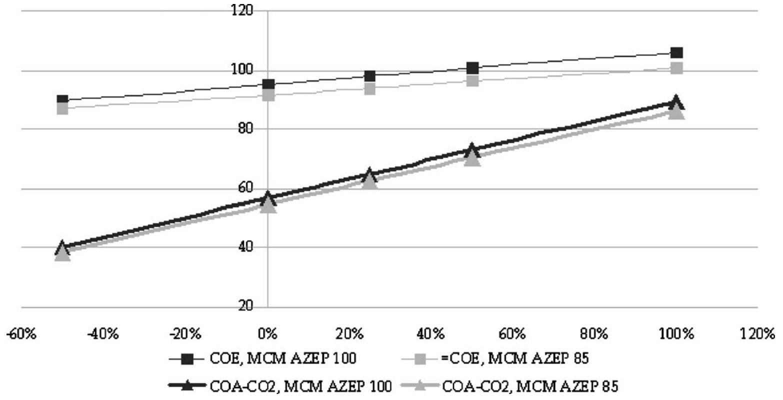

Fig. 5 Sensitivity analysis of the investment cost of the MCM reactor

Table 7 Results of the advanced exergetic analysis for selected components of the AZEP 85 (MW)

Component k	$E_{D,k}^{\mathrm{real}}$	$E_{D,k}^{\mathrm{EN}}$	$E_{D,k}^{\mathrm{EX}}$	Component r	$E_{D,k}^{\mathrm{EX},r}$	$E_{D,k}^{\mathrm{AV}}$	$E_{D,k}^{\mathrm{UN}}$	$E_{D,k}^{\mathrm{UN,EN}}$	$E_{D,k}^{\mathrm{UN,EX}}$	$E_{D,k}^{\mathrm{AV,EN}}$	$E_{D,k}^{\mathrm{AV,EX}}$
Compressor	11.17	7.39	3.78	CC	1.59	5.02	6.15	4.06	2.09	3.33	1.69
				DB	0.03						
				MCM LTHX	0.01						
				GT	0.27						
				MEXO	0.91						
CC	153.65	120.57	33.09	DB	0.05	13.56	140.10	109.81	30.29	10.76	2.80
				MCM LTHX	0.06						
				Compressor	3.44						
				GT	5.13						
				MEXO	8.41						
MCM LTHX	9.55	4.58	2.21	CC	0.76	4.90	4.65	3.54	1.11	1.05	3.86
				DB	0.04						
				Compressor	−0.27						
				GT	0.23						
				MEXO	2.13						
DB	31.26	20.16	4.97	CC	4.27	16.74	14.52	9.43	5.08	10.73	6.01
				MCM LTHX	0.01						
				Compressor	0.46						
				GT	0.71						
				MEXO	2.92						
GT	14.16	10.64	11.10	CC	2.21	7.11	7.06	5.12	1.94	5.52	1.59
				DB	0.01						
				MCM LTHX	0.01						
				Compressor	0.15						
				MEXO	0.19						
Total		77%	23%								

Although the exogenous exergy destruction accounts for a relatively small amount of the exergy destruction in the plant, the determination of its specific sources can shed light onto improvement options as well. The results for the components with the highest exogenous exergy destruction of the plants are also shown in Table 7. The mexogenous exergy destruction (MEXO) is caused by simultaneous interactions of more than two components [24]. The mexogenous exergy destruction is somewhat high for the CC, revealing more intense component interactions. As shown in Table 7, 26% of the exogenous exergy destruction in the CC of the AZEP stems from the GT and the compressor, a small part of which, is avoidable. Similarly, in the GT and the compressor, the exogenous exergy destruction is mainly due to the CC. Nonetheless, a large part of the exogenous exergy destruction stemming from the reactors is avoidable (32–33% for the compressor and approximately 44% for the GT).

With conventional exergy-based analyses, the main sources of irreversibilities and costs are identified in a plant. Nonetheless, specific insights about component interactions and the improvement potential of a plant are revealed by the advanced exergetic analysis, briefly described above.

5 Conclusions

In this paper, two versions of an advanced zero emission plant with 100% and 85% CO_2 captures (AZEP 100 and AZEP 85) have been analyzed, compared, and evaluated. The performance of the plants has been compared with the performance of similarly operating reference plants (1) without CO_2 capture and (2) with CO_2 capture through chemical absorption using monoethanolamine (MEA plant). In the AZEPs, the added components that are associated with the CO_2 capture unit do not consume high amounts of energy and the energy and cost penalties are mainly related to the production of the oxygen necessary for oxy-combustion. The cost of electricity, relative to the reference plant without CO_2 capture, is 28% higher for the AZEP 100 and 24% higher for the AZEP 85. The difference in the cost of electricity is mainly due to the higher cost of the MCM reactor and, in particular, to the larger size of the included membrane (especially in the AZEP 100). When compared with the MEA plant, the AZEP 100 has a lower cost of avoided CO_2 and cost of electricity by 20% and 0.6%, respectively, while the same values for the AZEP 85 are lower by 21% and 4%, respectively. However, the additional relative investment cost (per ton of CO_2) related to the CO_2 capture unit is lower in the AZEP 100 than in the AZEP 85.

CO_2 capture from power plants is a costly process. However, if this procedure is deemed necessary, the most cost effective solutions should be improved using both conventional and advanced exergy-based methods and further promoted for large-scale implementation. Oxy-fuel appears to be a promising, relatively economical technology that keeps the energy penalty of CO_2 capture in power plants at relatively low levels.

Acknowledgment

This research was funded by the European Commission's Marie Curie Sixth 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

c = cost per unit of exergy (€/GJ)
$\dot{C}$ = cost rate associated with an exergy stream (€/h)
$\dot{E}$ = exergy rate (MW)
f = exergoeconomic factor (%)
$\dot{m}$ = mass flow rate (kg/s)
p = pressure (bar)
r = relative cost difference (%)
T = temperature (°C)
y = exergy destruction ratio (%)
$\dot{Z}$ = cost rate associated with capital investment (€/h)

Subscripts

D = exergy destruction
F = fuel (exergy)

k = component
L = loss
P = product (exergy)

Abbreviations

HX air = air heat exchanger
AZEP = advanced zero emission plant
CC = combustion chamber
COE = cost of electricity
DB = duct burner
FCI = fixed capital investment
GT = gas turbine
HRSG = heat-recovery steam generator
HP, IP, and LP = high-pressure, intermediate-pressure, and low-pressure
LHV = lower heating value
MCM = mixed conducted membrane
MEXO = mexogenous exergy destruction
NGHX = natural gas heat exchanger
SPECO = specific exergy costing
ST = steam turbine
TRR = total revenue requirement

Greek Symbols

ε = exergetic efficiency (%)
λ = excess air fraction

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