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Exergy-based analyses of an advanced zero emission plant

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Abstract

CO_2 capture and storage from energy conversion systems is widely known as a potential method to reduce CO_2 emissions to the atmosphere and to limit the impact of energy use on the climate. This study uses the exergoeconomic and exergoenvironmental analyses to provide an evaluation from an economic and environmental perspective, respectively, of an advanced zero emission plant (AZEP) and to reveal possible ways to improve the overall effectiveness of the plant. The AZEP, which is an oxy-fuel power plant, is evaluated and compared with a reference plant without CO_2 capture. The exergoeconomic analysis shows a high increase in cost for the AZEP, due to the introduction of the membrane technology, while on the other hand, its environmental impact is significantly reduced. When compared with competitive alternatives, like chemical absorption—a post-combustion technology for CO_2 capture—the oxy-fuel plant achieves lower relative cost and exergy expenditures.

Keywords: AZEP; CO_2 capture; exergetic analysis; exergoeconomic analysis; exergoenvironmental analysis

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1 INTRODUCTION

The mitigation of environmental pollution through CO_2 capture in power stations has drawn great attention in recent years. Several possible alternative approaches have been proposed, but only a limited number of them seem promising from the viewpoints of efficiency, cost and environmental impact [1–3].

In this paper, a combined cycle power plant that performs CO_2 capture, the advanced zero emission plant (AZEP) [2–6], is compared with a reference plant, a power plant without CO_2 capture. The AZEP concept has the potential to become an efficient and a relatively economical technology for capturing produced CO_2 from power plants if technological challenges are addressed [2,7,8]. The idea is based on replacing the conventional combustor of a gas turbine (GT) with a mixed conducting membrane (MCM) reactor.

An economic analysis and a life cycle assessment (LCA) have been conducted to analyze the total cost and environmental impact of construction, operation and maintenance associated with the power plant. The economic analysis and the LCA are then combined with the exergetic analysis constituting the exergy-aided cost reduction and the environmental impact reduction approaches, the *exergoeconomic analysis* [9] and the *exergoenvironmental analysis* [10], respectively. In these analyses, monetary costs and environmental impacts are assigned to all energy streams of the plants, as well as to the exergy destruction incurred within each plant component. Important information about trade-offs between exergy destruction and investment cost or component-related environmental impacts will be used for iterative design improvements of the plant's configuration and operation in a subsequent paper.

2 METHODOLOGY

Exergy-based methods are powerful means for power plant evaluation [11–13]. With the exergetic analysis, the main sources of irreversibilities within a plant are identified.

A useful variable of the exergetic analysis is the exergy destruction ratio, $y_k = \dot{E}_{D,k}/\dot{E}_{F,tot}$ defined for each component k (with $\dot{E}_{D,k}$ the exergy destruction rate and $\dot{E}_{F,tot}$ the exergy rate of the fuel provided to the overall plant). This ratio is a measure of each component's exergy destruction contribution to the reduction of the overall exergetic efficiency of the plant.

The exergetic analysis is linked to investment costs and environmental impacts in the exergoeconomic and exergoenvironmental analyses, respectively.

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2.1 Exergoeconomic analysis

After completing an exergetic analysis, the first step of the exergoeconomic analysis is the *economic analysis* [14–21] performed here using the total revenue requirement (TRR) method [11]. The economic life of the plant is assumed to be 20 years and the average capacity factor of the plant is 85%. An average annual cost of money of 10% and an inflation rate of 3% were also assumed. The cost of natural gas is set at 7 €/GJ of its lower heating value (LHV) and its average annual increase is 4%. With these assumptions, the levelized TRR is calculated for a levelization period of 10 years and not 20 years, because the uncertainty related to later years is higher than in the first years.

The exergetic analysis is linked to the economic analysis in the *exergoeconomic analysis* [9,21]. Through cost balances formulated at the component level, a specific cost is assigned to each exergy stream of the plant.

A very important aspect of an exergoeconomic analysis is that irreversibilities are directly related to cost rates ($\dot{C}_{D,k}$). In this way, the estimated cost rate associated with exergy destruction is further related to and compared with the respective investment cost rate ($\dot{Z}_k$). The contribution of the capital cost to the total sum of costs ($\dot{C}_{D,k} + \dot{Z}_k$) associated with capital and exergy destruction is expressed by the exergoeconomic factor, $f_k = \dot{Z}_k/(\dot{Z}_k + \dot{C}_{D,k})$.

Another variable of the exergoeconomic evaluation is the relative cost difference, $r_k = (c_{P,k} - c_{F,k})/c_{F,k}$ that shows the relative increase of the specific cost of the product, $c_{P,k}$ with respect to that of the fuel, $c_{F,k}$.

The relationship of the monetary impact of each component's exergy destruction and investment is examined. When necessary, design changes to improve the cost-effectiveness of the plant are proposed.

2.2 Exergoenvironmental analysis

The *exergoenvironmental analysis* is conducted analogously to the exergoeconomic analysis. It consists of three steps: exergetic analysis, environmental analysis (LCA) and exergoenvironmental analysis. The environmental impact analysis is conducted at the component level and is determined through an LCA, which is carried out following the guidelines of international standard approaches [21] and measured in Eco-indicator 99 points. The specific environmental impacts of each energy stream are determined by a system of environmental impact balances formulated at the component level.

Analogous to the exergoeconomic analysis, in an exergoenvironmental analysis, the environmental impact of the exergy destruction ($\dot{B}_{D,k}$) is calculated and is further compared with the component-related environmental impact ($\dot{Y}_k$). At the component level, the contribution of the component-related environmental impact to the total environmental impact, $\dot{Y}_k + \dot{B}_{D,k}$, is expressed by the exergoenvironmental factor, $f_{b,k} = \dot{Y}_k/(\dot{Y}_k + \dot{B}_{D,k})$.

An important variable of the exergoenvironmental evaluation is the environmental impact difference, $r_{b,k} = (b_{P,k} - b_{F,k})/b_{F,k}$, where b denotes the environmental impact per unit of exergy. This ratio depends on the environmental impact of the exergy destruction and the component-related environmental impact.

Each component's environmental impact is then examined, allowing suggestions for design changes to improve the overall environmental impact effectiveness. The objective is to reduce the environmental impact associated with the product of the overall plant.

3 DESCRIPTION OF THE PLANTS

3.1 The reference plant

The reference plant, a 411-MW power plant, includes no CO_2 emission control and it is used as the basis for the evaluation of the AZEP presented here. The reference plant is a combined cycle with a three-pressure-level heat-recovery steam generator (HRSG) and one reheat stage; it has only one product—electricity—and works with natural gas that was assumed to be pure methane. The CO_2 emission rate of the plant is 339 g/kW h. A simplified diagram of the process is shown in Figure 1.

3.2 The AZEP

The AZEP, Figure 2, an oxy-fuel plant, is based on the replacement of the combustion chamber (CC) of a conventional GT system by an MCM reactor.

The key processes used in this technology, explained in refs. [2–6], are the following: (a) O_2 is separated from air in the MCM, (b) the combustion of the natural gas (NG) occurs in an N_2-free environment, (c) a recycling gas is used as oxygen carrier and combustion temperature controller and (d) the heat of combustion is transferred to the oxygen-depleted air in a high temperature heat exchanger (HTHX).

The MCM reactor, shown in Figure 3, consists of the CC, a low-temperature heat exchanger, the air separation membrane, a high-temperature heat exchanger and a bleed gas heat exchanger. The reactor can be integrated into a conventional GT system in the place of the CC. In Figure 2, the heat exchangers of the reactor cannot be distinguish. The purchased equipment cost of the MCM reactor was chosen to be 50 k€/MW based on estimates provided in [4]. This cost was then scaled by a factor of 3 to represent the fixed capital investment associated with the MCM reactor.

In the MCM reactor, 90% of the incoming air, compressed in the air compressor of the plant at 17 bar, is preheated and sent to the membrane. There, 38% of the oxygen included in the air permeates the membrane. This percentage of the oxygen membrane permeation is determined by predefining the compositions of the incoming and outgoing recycling gas stream [5]. The oxygen-depleted air (14% v/v O_2) exits the MCM at 1000°C, is heated in the high-temperature heat exchanger to

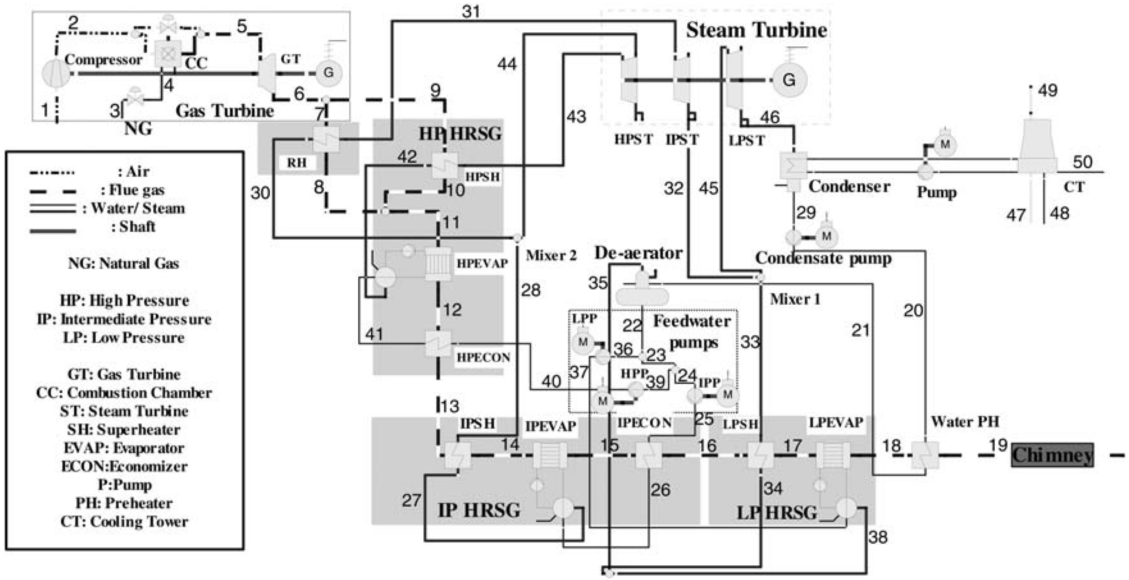

Figure 1. *Reference plant without CO_2 capture.*

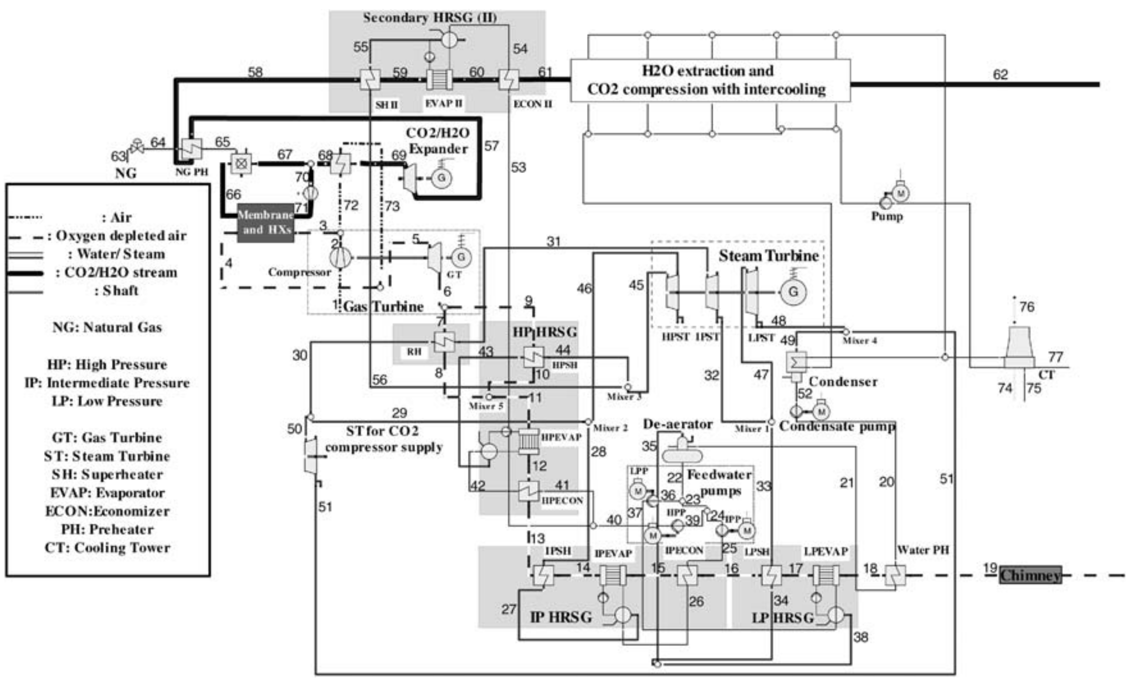

Figure 2. *Structure of the advanced zero emission plant (AZEP).*

1250°C and mixed with 10% of the incoming air. The thermal energy of the oxygen-depleted air is then used to produce steam at three different pressure levels (124, 22 and 4.1 bar) in the main HRSG of the plant. A circulating sweep gas, used as the oxygen carrier, exits the CC of the reactor with a composition of 33.5% CO_2, 66% H_2O and 0.5% v/v O_2. The thermal energy of this stream is then used to preheat the air in the high- and low-temperature heat exchangers and to sweep the oxygen separated in the membrane. The enriched gas, with 10% v/v O_2, is then led to the CC. There, the oxygen reacts with the provided fuel (methane), in nearly stoichiometric conditions (excess air fraction: $\lambda = 1.05$). In the oxy-fuel concepts we can control the outlet temperature of the CC by the recycling gas and in this way λ can be kept at low levels. Usually, the air used in the combustion process is also used as a means to control the outlet temperature of the combustion products. However, in the AZEP, the temperature control comes from the recirculation gas, facilitating minimum levels of λ.

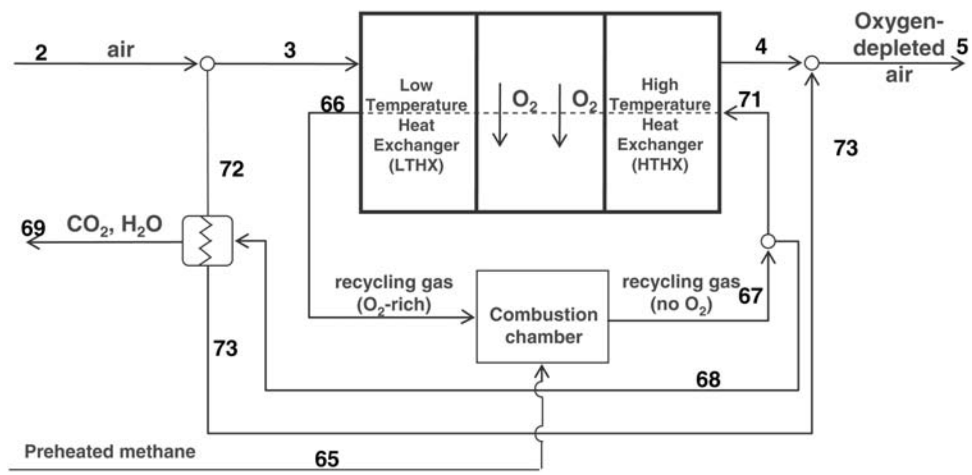

Figure 3. *The MCM reactor (the numbering of the streams agrees with Figure 2).*

Table 1. *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)	$\dot{E}_{tot,j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)	Stream, j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_{tot,j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)
1	614.5	15.0	1.01	0.96	0.0	0	24	7.2	140.0	3.62	0.67	30.7	74
2	614.5	392.9	17.00	232.25	19.0	15 860	25	7.2	140.5	25.13	0.68	33.8	83
3	14.0	15.0	50.00	729.62	9.2	24 037	26	7.2	216.6	24.38	1.56	27.2	153
5	628.5	1264.0	16.49	741.01	15.3	40 824	27	7.2	222.6	24.38	7.23	21.8	568
6	628.5	580.6	1.06	189.87	15.3	10 460	28	7.2	237.9	23.16	7.35	22.0	583
7	268.5	580.6	1.06	81.11	15.3	4469	29	94.6	32.9	0.05	0.44	21.2	33
8	268.5	447.6	1.05	54.64	15.3	3010	30	72.4	305.1	23.16	79.53	20.3	5814
9	360.0	580.6	1.06	108.75	15.3	5991	31	72.4	560.6	22.00	103.42	20.0	7459
10	360.0	449.3	1.05	73.68	15.3	4059	32	72.4	317.2	4.10	66.03	20.0	4762
11	628.5	448.6	1.05	128.33	15.3	7070	33	22.1	214.1	4.10	18.01	25.0	1623
12	628.5	341.2	1.04	84.69	15.3	4666	34	22.1	146.4	4.32	16.96	24.8	1514
13	628.5	257.9	1.04	55.77	15.3	3073	35	0.8	146.4	4.32	0.63	24.8	56
14	628.5	257.3	1.04	55.59	15.3	3063	36	23.0	140.0	3.62	2.12	30.7	234
15	628.5	237.6	1.04	49.49	15.3	2727	37	23.0	140.0	4.32	2.12	31.1	237
16	628.5	234.1	1.04	48.43	15.3	2668	38	23.0	146.4	4.32	17.60	24.8	1570
17	628.5	229.3	1.04	47.01	15.3	2590	39	65.2	140.0	3.62	6.01	30.7	665
18	628.5	156.4	1.03	27.98	15.3	1542	40	65.2	141.8	134.56	6.96	31.4	788
19	628.5	95.3	1.03	16.49	0.0	0	41	65.2	325.2	130.53	31.88	22.6	2596
20	94.6	32.9	3.73	0.47	25.6	44	42	65.2	331.2	130.53	71.79	20.5	5302
21	94.6	135.6	3.62	8.18	30.2	889	43	65.2	560.6	124.00	103.51	20.1	7489
22	95.4	140.0	3.62	8.79	30.7	973	44	65.2	313.2	23.16	72.22	20.1	5226
23	72.4	140.0	3.62	6.67	30.7	739	45	94.6	293.0	4.10	83.86	21.2	6386
							46	94.6	32.9	0.05	12.87	21.2	980

4 RESULTS AND DISCUSSION

4.1 Exergoeconomic evaluation

Table 1 shows important variables for selected streams of the reference case. The respective values for the AZEP are shown in Table 2. The cost of the air and water provided is considered to be zero. The highest values of the cost rate, $\dot{C}_j$, are reached in both plants in streams 2–6, which have high physical and/or chemical exergy. The results of the exergetic and exergoeconomic analyses at the component level for the reference case and the AZEP are presented in Tables 3 and 4, respectively.

Compared with the reference plant that includes no CO_2 capture, the AZEP concept shows a relatively small reduction in exergetic efficiency (4.8 percentage-points). It should be noted that in other energy-intensive CO_2 capture technologies, such as chemical absorption with monoethanolamine (MEA), the overall penalty in the exergetic efficiency is found to be ~11 percentage-points. This indicates that this oxy-fuel method is promising for CO_2 capture, as long as current implementation challenges, related to the oxy-fuel operation and membrane feasibility, are met. As expected, the main exergy destruction in both plants occurs within the CC, due to the chemical reaction.

Table 2. *Calculated variables for selected streams of the AZEP.*

Stream, j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_{tot,j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)	Stream, j	$\dot{m}_j$ (kg/s)	T_j (°C)	p_j (bar)	$\dot{E}_{tot,j}$ (MW)	c_j (€/GJ)	$\dot{C}_j$ (€/h)
1	710.1	15.0	1.01	1.11	0.0	0	37	20.4	140.0	4.32	1.88	36.3	246
2	710.1	393.0	17.01	268.43	22.3	21 537	38	20.4	146.4	4.32	15.64	29.3	1653
3	639.1	393.0	17.01	241.58	22.3	19 383	39	64.1	140.0	3.62	5.90	36.0	765
4	583.2	1250.0	17.00	644.71	18.6	43 219	40	64.1	141.7	134.56	6.84	36.3	895
5	654.2	1174.6	17.00	673.85	18.9	45 765	41	49.8	141.7	134.56	5.32	36.3	696
6	654.2	497.0	1.06	141.74	18.9	9627	42	49.8	325.2	130.53	24.36	27.5	2410
7	299.2	497.0	1.06	64.83	18.9	4403	43	49.8	331.2	130.53	54.86	24.8	4903
8	299.2	431.9	1.05	51.71	18.9	3512	44	49.8	477.0	124.00	72.01	24.5	6352
9	355.0	497.0	1.06	76.91	18.9	5224	45	64.1	501.5	124.00	95.32	22.9	7859
10	355.0	417.4	1.05	58.09	18.9	3945	46	64.1	267.8	23.16	67.53	22.9	5567
11	654.2	424.0	1.05	109.80	18.9	7458	47	63.7	238.3	4.10	53.19	25.5	4884
12	654.2	341.2	1.05	76.84	18.9	5219	48	63.7	32.9	0.05	8.41	25.5	772
13	654.2	277.4	1.04	54.31	18.9	3689	49	99.3	32.9	0.05	12.91	24.8	1153
14	654.2	275.0	1.04	53.51	18.9	3634	50	35.5	265.7	23.16	37.35	23.5	3159
15	654.2	232.6	1.04	40.22	18.9	2732	51	35.5	32.9	0.05	4.49	23.5	380
16	654.2	225.0	1.04	37.97	18.9	2579	52	99.3	32.9	0.05	0.46	24.8	41
17	654.2	221.3	1.04	36.89	18.9	2506	53	14.3	141.7	134.56	1.52	36.3	199
18	654.2	156.4	1.03	20.16	18.9	1369	54	14.3	325.2	130.53	6.97	20.9	526
19	654.2	92.0	1.03	8.10	0.0	0	55	14.3	331.2	130.53	15.70	18.5	1045
20	99.3	32.9	3.73	0.50	29.1	52	56	14.3	592.5	124.00	23.40	17.9	1504
21	99.3	136.4	3.62	8.68	35.4	1107	57	69.9	685.0	1.05	60.25	13.0	2830
22	100.0	140.0	3.62	9.21	36.0	1193	58	69.9	612.5	1.05	54.43	13.0	2556
23	79.6	140.0	3.62	7.33	36.0	950	59	69.9	495.8	1.04	45.82	13.0	2152
24	15.5	140.0	3.62	1.43	36.0	185	60	69.9	341.2	1.04	36.08	13.0	1694
25	15.5	140.4	25.13	1.47	38.0	201	61	69.9	217.6	1.03	30.02	13.0	1410
26	15.5	216.6	24.38	3.34	31.4	377	62	38.9	30.0	103.09	22.12	0.0	0
27	15.5	222.6	24.38	15.49	25.8	1438	63	14.0	15.0	50.00	729.62	9.2	24 037
28	15.5	257.4	23.16	16.12	26.0	1508	65	14.0	250.0	16.99	729.72	9.3	24 315
29	79.6	265.7	23.16	83.65	23.5	7076	66	473.0	488.7	16.99	390.97	13.5	19 035
30	44.0	265.7	23.16	46.30	23.5	3917	67	487.0	1276.2	16.48	940.04	13.0	44 144
31	44.0	477.0	22.00	57.69	23.7	4923	68	69.9	1276.2	16.48	134.85	13.0	6332
32	44.0	253.4	4.10	37.36	23.7	3188	69	69.9	1200.0	16.47	126.64	13.0	5947
33	19.7	205.0	4.10	15.87	29.7	1694	70	417.1	1276.2	16.48	805.20	13.0	37 812
34	19.7	146.4	4.32	15.09	29.3	1594	71	417.1	1286.9	17.10	813.51	13.5	39 607
35	0.7	146.4	4.32	0.55	29.3	58	72	71.0	393.0	17.01	26.84	22.3	2154
36	20.4	140.0	3.62	1.88	36.0	244	73	71.0	523.8	17.00	32.96	21.5	2546

Table 3. *Main results of the exergetic and exergoeconomic analyses for selected components of the reference plant.*

Component, k	$\dot{E}_{D,k}$ (MW)	ε_k (%)	y_k (%)	$\dot{C}_{D,k} + \dot{Z}_k$ (€/h)	f_k (%)
HP HRSG	11.08	89.7	1.52	1032	40.9
IP HRSG	3.25	90.4	0.44	358	50.0
LP HRSG	7.71	75.9	1.06	709	40.1
HPST	2.11	93.2	0.29	318	52.0
IPST	2.18	94.2	0.30	457	65.6
LPST	9.64	86.4	1.32	1431	48.7
Compressor	11.38	95.3	1.56	1980	65.5
CC	220.87	69.7	30.23	8203	11.3
GT	20.47	96.3	2.80	2610	56.8
Total	305.15	56.3	41.77	16 513	39.1

HP HRSG, high-pressure heat recovery steam generator; IP HRSG, intermediate-pressure heat-recovery steam generator; LP HRSG, low-pressure heat recovery steam generator; HPST, high-pressure steam turbine; IPST, intermediate-pressure steam turbine; LPST, low-pressure steam turbine; CC, combustion chamber; MCM, mixed conducted membrane; GT, gas turbine; HX, heat exchanger; NG PH, natural gas preheater.

The combustion process in the AZEP, however, is performed more efficiently. y_{cc}, which reveals the percentage of exergy destruction taking place in the CC, is thus 18% lower.

Taking into account the overall results of the exergoeconomic analysis, the most important components are those with the highest sum of costs $\dot{C}_{D,k} + \dot{Z}_k$. Thus, the three main components are constituting the GT system: the CC, the GT and the compressor. However, the exergoeconomic factor, f_k, of these components, which is a second indicator of the direction the improvement trials should follow, is considered to be within acceptable limits. High values of the exergoeconomic factor indicate relatively high investment cost and suggest a reduction of this cost, while low values indicate high exergy destruction and suggest a reduction of the irreversibilities.

The components that follow the GT system in order of importance are the low-pressure steam turbine (LPST) and the high-pressure (HP) HRSG in the reference plant, while, in the AZEP, the components that follow the GT system in order of

Table 4. *Main results of the exergetic and exergoeconomic analyses for selected components of the AZEP.*

Component, k	$\dot{E}_{D,k}$ (MW)	ε_k (%)	y_k (%)	$\dot{C}_{D,k} + \dot{Z}_k$ (€/h)	f_k (%)
HP HRSG	7.63	89.7	1.04	866	40.2
IP HRSG	3.41	88.4	0.47	429	46.1
LP HRSG	7.15	76.1	0.98	774	37.2
HPST	1.97	92.9	0.27	300	45.9
IPST	1.27	93.8	0.17	261	58.6
LPST	6.08	86.4	0.83	972	42.5
Compressor	13.15	95.3	1.80	2042	53.0
CC	180.65	75.2	24.72	6813	11.7
GT (air)	19.60	96.3	2.68	2569	48.2
MCM	6.75	93.1	0.92	2080	84.2
MCM HTHX	1.43	99.0	0.20	650	89.3
MCM LTHX	11.22	95.7	1.54	1479	63.0
CO_2/H_2O GT	3.28	95.1	0.45	467	67.0
Compr. rec.	0.28	96.8	0.04	682	94.6
HX air	2.09	74.6	0.29	105	6.5
NG PH	5.72	1.7	0.78	273	1.6
HRSG II	2.54	89.6	0.35	191	37.7
ST/CO_2 supply	8.02	75.6	1.10	952	28.7
CO_2 compr.	2.85	82.4	0.39	1894	79.8
Total	326.48	51.5	44.68	22 504	52.4

HP HRSG, high-pressure heat-recovery steam generator; IP HRSG, intermediate-pressure heat-recovery steam generator; LP HRSG, low-pressure heat-recovery steam generator; HPST, high-pressure steam turbine; IPST, intermediate-pressure steam turbine; LPST, low-pressure steam turbine; CC, combustion chamber; MCM, mixed conducted membrane; GT, gas turbine; HX, heat exchanger; NG PH, natural gas preheater.

importance are the MCM, the CO_2 compressor unit, the low-temperature heat exchanger of the MCM reactor (MCM LTHX) and the added steam turbine used to drive the CO_2 compression unit (ST/CO_2 supply). As expected, the CC has a low exergoeconomic factor due to the high irreversibilities of the chemical reactions. However, most of these irreversibilities are unavoidable and, thus, the improvement trials should not focus on this component. Relatively low exergoeconomic factors, indicating high irreversibilities, are also found for the air preheater (HX Air) and the natural gas preheater (NG PH), but they are justified by the valves prior to the heat exchangers used to indicate the design-required pressure drops. The valves are considered together with the preheaters. Moreover, the low value of f_k of the steam turbine that drives the CO_2 compressors suggests an increase in the turbines efficiency, in order to decrease its irreversibilities. On the other hand, high values of the exergoeconomic factor are calculated for the MCM and the MCM HTHX. Thus, ways to decrease the investment cost of these components should be considered in an attempt to improve the cost-effectiveness of the overall plant.

The economic parameters considered here are the cost of electricity (COE) and the *cost of avoided CO_2*. The cost of avoided CO_2 [22] shows the added COE per metric ton of CO_2 avoided based on net plant capacity: $[(€/\mathrm{kWh})_{\mathrm{capture}} - (€/\mathrm{kWh})_{\mathrm{reference}}]/[(t_{CO_2}/\mathrm{kWh})_{\mathrm{reference}} - (t_{CO_2}/\mathrm{kWh})_{\mathrm{capture}}]$. The reference plant operates with 3×10^{-4} tons of CO_2/kWh.

To compare and evaluate the costs, the most mature and commonly proposed method for CO_2 capture, chemical absorption with MEA, is also briefly evaluated here. For this method, the COE and cost of avoided CO_2 are calculated approximately to simplify the comparison for the purpose of this paper.

The COE for a plant with chemical absorption, the structure of which is similar to the reference plant with an additional chemical absorption unit, is found to be 95.5 €/MWh; the cost of avoided CO_2 for the same plant is 78.3 €/t (with 60 g CO_2/kWh exhausted). The COE for the AZEP is calculated to be 94.9 €/MWh, whereas the cost of avoided CO_2 is found to be 62.7 €/t (with 3 g CO_2/kWh exhausted). These costs are lower when compared with the plant with chemical absorption. The differences are mainly due to the high energy demand of the solvent regeneration in the plant utilizing chemical absorption and the relatively low percentage of CO_2 capture (85%), in comparison with the close to 100% capture of the AZEP presented here.

4.2 Exergoenvironmental evaluation

Table 5 shows the main results of the exergoenvironmental analysis at the component level for the reference plant and the AZEP concept. In the reference plant, the highest environmental impact corresponds to the GT system (mainly due to the CC). On the other hand, in the AZEP, the highest

Table 5. *Main results of the exergoenvironmental analysis.*

Component, k	Ref. Plant		AZEP	
	$\dot{B}_{D,k} + \dot{Y}_k$ (Pts/h)	$f_{b,k}$ (%)	$\dot{B}_{D,k} + \dot{Y}_k$ (Pts/h)	$f_{b,k}$ (%)
HP HRSG	216	1.26	156	0.66
IP HRSG	64	2.59	70	0.75
LP HSRG	150	0.42	146	0.22
HPST	50	1.03	47	0.49
IPST	51	1.15	31	0.70
LPST	232	0.39	154	0.23
Compressor	229	0.19	278	0.07
CC/MCM reactor	2862	0.02	2900	5.31
GT (air)	397	0.53	340	0.22
CO_2/H_2O GT	–	–	58	0.35
Compr. rec.	–	–	10	5.87
NG PH	–	–	100	0.00
HRSG II	–	–	45	0.39
ST/CO_2 supply	–	–	192	0.13
CO_2 compr.	–	–	99	0.23
Total	39 585	0.12	4436	4.65

HP HRSG, high-pressure heat-recovery steam generator; IP HRSG, intermediate-pressure heat-recovery steam generator; LP HRSG, low-pressure heat-recovery steam generator; HPST, high-pressure steam turbine; IPST, intermediate-pressure steam turbine; LPST, low-pressure steam turbine; CC, combustion chamber; MCM, mixed conducted membrane; GT, gas turbine; NG PH, natural gas preheater.

environmental impact is caused by the MCM reactor, the GT system and the compression of the separated CO_2.

The environmental impact of a kWh of electricity is 31.9 mPts/kWh for the reference plant and 24 mPts/kWh for the AZEP. These values are in agreement with the average environmental impact values calculated for some European countries [10]. However, it should be mentioned that the values given here for the environmental impact of electricity from the AZEP do not consider transportation and storage of CO_2. Assuming 4.4 mPts/kg needed for sequestration [23], the overall environmental impact of the AZEP is found to be 26 mPts/kWh.

The exergoenvironmental analysis does not only identify the components with the highest environmental impact, but also the possibilities and trends for improvement, in order to decrease the environmental impact of the overall system. The higher the exergoenvironmental factor ($f_{b,k}$), the higher the influence of the component-related environmental impact to the overall performance of the plant.

The total environmental impact of the reference plant can be decreased by decreasing the component-related environmental impact of the IP HRSG and the HP HRSG or that of the HP and IP steam turbines and/or by increasing the exergetic efficiency of the components with a low $f_{b,k}$ value, such as the CC. In the case of the AZEP, a reduction of the overall environmental impact could be achieved by decreasing the component-related environmental impact of the recycling compressor, the MCM reactor and that of the IP HRSG.

5 CONCLUSIONS

In this paper, a combined cycle oxy-fuel plant, the AZEP concept with $\sim$100% CO_2 capture, is compared with a reference plant—a combined cycle without CO_2 capture.

An exergetic analysis showed lower irreversibilities in the combustion process for the AZEP concept compared with the conventional CC of the reference plant. Moreover, the oxy-fuel plant results in a decrease of the exergetic efficiency by less than 5 percentage-points, with respect to the reference case without CO_2 capture. The added components in the oxy-fuel plant do not reduce the overall efficiency as much as in the plant with chemical absorption using MEA (with $\sim$11 percentage-point penalty for the latter). The exergy and cost penalties noted for the AZEP process are mainly due to the production of the oxygen necessary for the combustion process.

The investment cost of the AZEP results in a significant increase in the COE, due to the high cost of the MCM reactor. However, the environmental impact of the produced electricity also decreases significantly thanks to the implementation of the AZEP technology.

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