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Chapter 9

EXERGETIC AND EXERGOECONOMIC ANALYSES OF AN OXY-FUEL POWER PLANT WITH CO_2 CAPTURE

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ABSTRACT

The evaluation and comparison of different technologies for CO_2 capture in power plants is necessary for revealing advantages or obstacles in view of their future implementation. Oxy-fuel concepts are promising, when compared to other alternatives, because they are associated with a relatively low energy penalty and they facilitate the capture of the generated CO_2. In this paper, exergetic and exergoeconomic analyses are used to evaluate the operation of an oxy-fuel combined-cycle power plant, which is based on the principles of the S-Graz cycle. The evaluation of the plant also includes a comparison with a reference plant both without CO_2 capture and with chemical absorption.

The exergetic analysis shows a reduction of 8 percentage points in the exergetic efficiency of the plant with CO_2 capture in comparison to that of the reference plant. An economic analysis reveals an approximately 3 times higher investment cost per installed kW electricity compared with the reference plant. Specifically, 32% of the investment cost of the S-Graz plant is related to the air separation unit used for the production of the necessary oxygen, 16% of the cost is related to the high-temperature expanders and 10% is related to the CO_2 compression unit. Compared with the reference plant, the plant with CO_2 capture results in a 48% higher cost of electricity.

Keywords: Combined-cycle, CO_2 capture, exergetic analysis, exergoeconomic analysis, S-Graz cycle.

INTRODUCTION

Carbon capture and storage (CCS) is a technology with the potential to convert electricity produced by fossil fuels into clean energy, preventing the exhaust of harmful emissions to the environment by capturing them. In recent years CO_2 capture from power plants has drawn intense attention and many different alternatives have been presented in literature. This paper is part of a study analyzing different concepts of CO_2 capture from energy conversion systems generating electricity [1-5]. The power plant evaluated here is an oxy-fuel concept, based on the principles of the *S-Graz cycle*.

The *Graz cycle*, developed in 1985 by Jericha [6], was presented as a combined cycle power plant with a high-temperature steam cycle, using hydrogen as the fuel. Hydrogen and oxygen should be derived, according to the initial idea, from the splitting of water using solar energy. However, the lack of technology related to solar energy in the 1990s made the realization of the *Graz Cycle* infeasible. This led to a change in 1995, when fossil fuels were introduced to the layout of the concept [7]. The working fluid of the plant consisted of approximately 75% water vapor and 25% CO_2, while changes were also made in 2000 to include the possible use of syngas instead of methane [8]. A reduction of the steam content in favor of a higher amount of CO_2, with the intent to reduce the compression work was considered, which led to a subsequent reduction of the inlet temperature of the combustion chamber. However, in 2004 the steam content was increased back to its initial values and the name of the cycle was changed to *S-Graz Cycle* [9]. This concept considered a relevant increase in the inlet temperature of the combustion chamber and a decrease in the amount of thermal energy transferred to the combustion chamber by the recycling stream, while it also increased the mass flow rate in the cooling steam used for the high-temperature turbine of the plant.

In Ref. [10] the basic thermodynamic assumptions for component losses and efficiencies agreed with estimates from the Norwegian oil and gas company Statoil ASA for a 400 MW Graz cycle and the resulting power plant for natural gas firing was presented. The calculated net efficiency of the plant was still above most alternative CO_2 capture technologies. Because of difficulties regarding the condensation of water from a mixture of steam and incondensable gases at very low pressures, in 2006 a modified cycle configuration was presented with condensation at 1 bar [11]. With some modifications, the net cycle efficiency was found to be above 53%. In 2008 the Graz cycle turbomachinery was modified to operate under higher pressure and temperature [12]. With higher plant parameters, i.e., a maximum pressure of 50 bar and a maximum temperature of 1500°C, a net cycle efficiency above 53% is claimed.

Using exergy-based methods, the natural gas fired S-Graz cycle for CO_2 capture, presented in this paper, is compared to a power plant without CO_2 capture, referred to as the *reference plant*. The advantages of an exergetic analysis over a conventional energetic analysis are well established [13-16]. An economic analysis is used to estimate the total cost of construction, operation and maintenance associated with the power plant. The exergoeconomic analysis, an appropriate combination of an exergetic analysis with an economic analysis [13,14,16,17], can be used as a tool to guide an exergy-aided cost reduction approach. The goal is to obtain important information about trade-offs between the exergy destruction and the investment cost of the components and to propose measures for the iterative design improvements of the plant, which will be implemented and presented in a subsequent paper.

Methodology

Exergy-based analyses are helpful tools for evaluating energy conversion systems [13]. A useful variable for the comparison of dissimilar components is the exergy destruction ratio, defined as $y_{D,k} = \dot{E}_{D,k} \big/ \dot{E}_{F,tot}$. This ratio is a measure of the contribution of the exergy destruction within the k^{th} component to the reduction of the overall exergetic efficiency. The main sources of irreversibilities within a plant identified in the exergetic analysis are linked to economic principles in the exergoeconomic evaluation.

In an exergoeconomic analysis [13-17], a specific cost c is assigned to each exergy stream of the plant and the cost of each component's exergy destruction, $\dot{C}_{D,k}$, is calculated. The contribution of the capital investment to the total sum of costs associated with capital and exergy destruction is expressed by the exergoeconomic factor: $f_k = \dot{Z}_k \big/ \left(\dot{Z}_k + \dot{C}_{D,k}\right)$. Another variable of the exergoeconomic evaluation is the relative cost difference, $r_k = \left(c_{P,k} - c_{F,k}\right) \big/ c_{F,k}$, which shows the relative increase of the specific cost of the product of component k, $c_{P,k}$, with respect to that of the fuel of the same component, $c_{F,k}$.

The monetary impact of each component's exergy destruction and investment cost is examined. Based on the calculated exergoeconomic variables, design changes to improve the cost effectiveness are proposed.

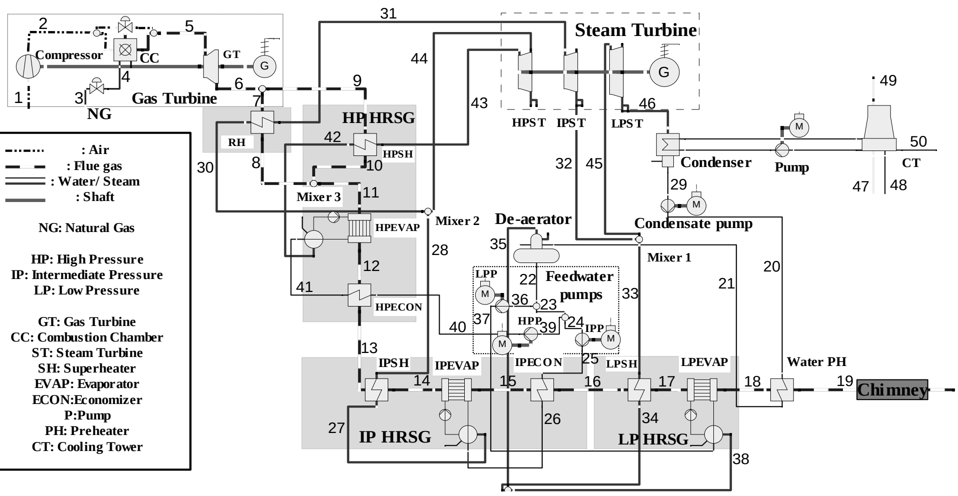

Figure 1. Reference plant without CO$_2$ capture

Description of the plants

The reference plant

The reference plant is a combined cycle power plant with a three-pressure-level *heat-recovery steam generator* (HRSG) and one reheat stage. The plant operates with methane, it does not include CO_2 capture and it is used as basis for the comparative evaluation of the S-Graz cycle. A detailed description of the plant is presented in [1] and a diagram of the process is shown in Figure 1.

The S-Graz Cycle

The structure of the plant is shown in Figure 2. Here, as for the reference plant, the fuel used is natural gas, simulated as pure methane. The CH_4 is provided with a mass flow of 14 kg/s and a pressure of 50 bar. The fuel enters the *combustion chamber* (CC) of the plant at the pressure of 40 bar, after it is preheated with extracted steam from the *high-pressure steam turbine* (HPST) of the plant. Atmospheric air is compressed to 6 bar and is then led to the air separation unit, where the necessary oxygen is obtained. The mass flow of the oxygen results from the methane mass flow and the oxidation ratio in the combustion process, which is set for nearly stoichiometric conditions (λ= 1.05). The produced outlet stream of the ASU, consisting of 95% (v/v) oxygen and 5% (v/v) argon, is compressed in an intercooled compression unit to 40 bar and it is then sent to the CC.

In the CC, a recycling gas consisting of water vapor and a small amount of CO_2 is used to control the temperature of the stream exiting the CC. The combustion products, at a temperature of 1400°C, have a composition of about three quarters water vapor and one quarter CO_2. A stream of water vapor used for cooling is extracted by the HPST at a temperature of about 370°C and added to the flue gas stream before this enters the *high-temperature turbine* (HTT). Before the second part of the HTT (HTT2), the gas stream is mixed with a second steam stream from the *intermediate-pressure steam turbine* (IPST). In the HTT2, the gas stream, with 87% H_2O (v/v), is expanded from 10.7 bar and 1058°C to 1.05 bar (and 615°C) and it is then led to the HRSG of the plant.

The flue gas flows through the single-pressure-level HRSG (*superheater*, SH, *evaporator*, EVAP, and *economizer*, ECON) and it is then split into three parts. 55% of the flue gas is compressed in the intercooled recycling compressors to 40 bar and sent back to the CC. The coolers of this unit are used to preheat the water used in the HRSG. Steam is mixed with the recycling stream before this enters the CC, resulting in 91% (v/v) water vapor. 45% of the remaining flue gas is led to the third expander of the plant, while the rest is used to preheat the water entering the HRSG. The condensation of most of the water included in the flue gas takes place in the condenser (COND1) after the third expander at a pressure of 0.06 bar. The water condensed in this condenser is further used in the HRSG. After the condenser, the CO_2 at 36°C and 0.06 bar is compressed in an intercooled compression unit to 100 bar and 30°C, leaving the plant at a liquid state, ready for transport and storage.

The water at the inlet of the HRSG has a pressure of 135 bar and a temperature of 316°C. The produced steam at the exit of the HRSG is at 124 bar and 560°C. In the HPST the steam is expanded from 124 bar and 560°C to 43 bar and 394°C. 84% of this steam is used to preheat the methane, 10% is mixed with the combustion gases before the HTT, and the rest is led to the IPST.

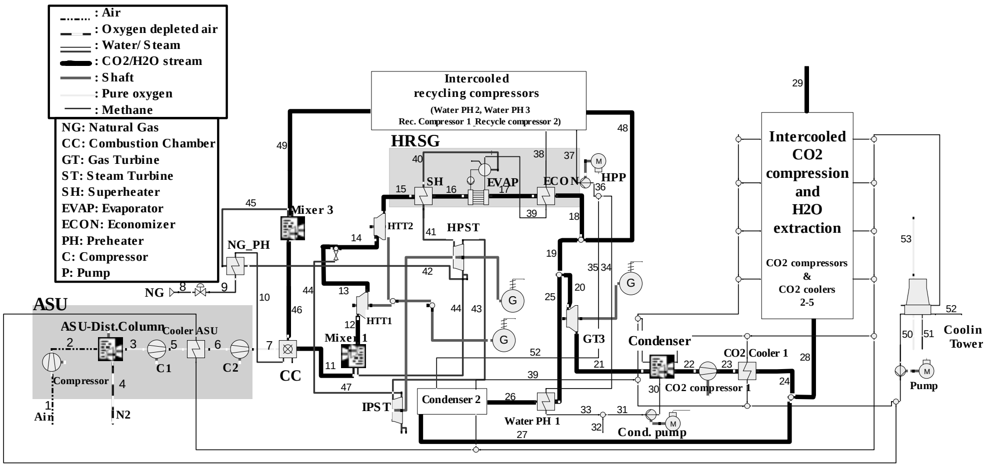

Figure 2. The S-Graz Cycle

In [11], the turbomachinery of the plant is designed so that the main components of the gas turbine system are arranged on two shafts: the compression shaft and the power shaft. The compression shaft consists of the two recycle compressors, which are driven by the first part of the HTT. This shaft has a relatively high speed, in order to obtain sufficient blade length at the outlet of the second recycle compressor and to reduce the number of stages in both of the compressors. The second part of the HTT, delivers the main power output to the generator. A further elongation of the shaft is obtained by coupling the four-flow LPST at the opposite side of the generator. The HPST can be coupled to the far end of the LPST or it can drive a separate generator. In this paper, the CO_2 compressors are assumed to be driven by steam turbines, the recycle compressors by HTT1, and the compressors of the air separation unit by HTT2.

RESULTS AND DISCUSSION

Tables 1-4 show the results of the exergoeconomic analysis for the reference plant and the S-Graz cycle at the stream-level (Tables 1,2) and at the component-level (Tables 3,4). The S-Graz plant produces a power output of approximately 352 MW with an exergetic efficiency of 48% (8 percentage points lower than that of the reference plant) and approximately 30 MW of exergy loss. The reference plant produces a power output of about 411 MW, with an exergetic efficiency of about 56%. The specific investment cost of the reference plant is approximately 522 €/kW, while the S-Graz cycle has a specific investment cost of 1,456 €/kW.

This increase in the investment cost of the oxy-fuel plant is mainly due to the ASU added for the oxygen production, the relatively expensive HTT, the recycle compressors, and the CO_2 compression unit.

As expected, the main source of the cost of exergy destruction in both plants is the CC. However, in the S-Graz cycle, the component with the second highest exergy destruction is the distillation column of the ASU, followed by the expanders of the plant. In general, the distillation column of the ASU is one of the most influential components with the highest investment cost ($\dot{Z}_k$) and the second highest cost of exergy destruction ($\dot{C}_{D,k}$). This ranks this component in second place in terms of the sum of costs ($\dot{C}_{D,k} + \dot{Z}_k$), with a resulting value very similar to that calculated for the CC of the plant. The compressors used for the recycling of the flue gas (rec. compressors 1 and 2) are economically important, mainly because of their high investment cost. The expanders of the plant (HTT1, HTT2, GT3) result in a relatively high sum of costs, which is approximately equally shared between investment cost and the cost of exergy destruction.

Two important indicators used to distinguish between the most influential components, the exergoeconomic factor, f_k, and the relative cost difference, r_k, are shown in Tables 3 and 4. Low values of the exergoeconomic factor suggest a reduction in the cost of exergy destruction, while high values of the factor suggest a reduction in the investment cost of the respective component [13]. Additionally, high values of the relative cost difference show a high difference between the specific cost of fuel and the specific cost of product in a component, and presumably a high potential for improvement.

Low values of the exergoeconomic factor are calculated for the two compressors (C1 and C2) of the ASU, and for water preheater PH1. The preheaters PH2 and PH3 are considered together with the compressors they serve, resulting overall in reasonable exergoeconomic factors. Thus, to improve the cost effectiveness of the overall plant an increase in the efficiency of these components is suggested. For the coolers (including the coolers of the CO_2 compression unit) and PH1, an immediate decrease of the exergy destruction can be achieved by integrating the components with the water preheating system of the plant, thus using a part of the thermal energy to preheat the water. High values of the relative cost difference are found for the HTT1 and the distillation column of the ASU. For this reason, the operating conditions of these components should be re-evaluated and possibly modified. The exergoeconomic factor of the overall plant is 55% revealing roughly equal contributions between investment cost and cost of exergy destruction. However, the relative cost difference for the overall plant has a relatively high value that suggests a high increase in the cost of the product of the plant. To decrease this value, the individual values of the components should be considered for minimization.

The economic parameters considered when evaluating the plant are the *cost of electricity* (COE) and the *cost of avoided CO_2* (COA-CO_2) The COA-CO_2 [18] shows the added cost of electricity per metric ton of CO_2 avoided based on net plant capacity:

$$\mathrm{COA} - \mathrm{CO_2} = \frac{\left(€ / kWh\right)_{capture} - \left(€ / kWh\right)_{reference}}{\left(ton_{CO_2} / kWh\right)_{reference} - \left(ton_{CO_2} / kWh\right)_{capture}}$$

The reference plant operates with 3×10^{-4} t of CO_2/kWh. The COE for the S-Graz cycle, is found to be 109 €/MWh and its COA-CO_2 is 104 €/t (with zero CO_2 emissions).

To objectively evaluate the oxy-fuel plant, the reference plant with chemical absorption has also been taken into consideration [4]. Chemical absorption is the most conventional and easily applicable way to capture CO_2 and it should, therefore, be considered as the basic CO_2

capture technology for comparison purposes. The COE and the COA-CO_2 of the reference plant with chemical absorption is 96 €/MWh and 78 €/t, respectively [3]. Thus, these high costs calculated for the oxy-fuel plant can make this technology less appealing, when other options easier to be implemented exist.

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

Table 2. Calculated variables for selected streams of the S-Graz Cycle

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	256.1	15.0	1.01	0.40	0.0	0	26	13.1	338.2	1.03	8.06	17.0	493
2	256.1	218.9	6.00	51.24	20.9	3,858	27	13.1	89.2	1.02	2.48	17.0	152
3	62.0	15.0	1.01	7.40	20.9	557	28	44.5	313.2	1.01	0.04	12.3	13
5	194.1	15.0	1.01	4.06	0.0	7,045	29	44.5	30.0	100.00	23.79	0.0	0
6	62.0	297.2	6.80	21.13	22.6	1,719	30	117.1	36.1	0.06	0.64	17.0	39
7	62.0	60.0	6.79	16.31	29.3	1,719	31	117.1	36.1	1.05	0.66	19.2	45
8	62.0	359.6	40.00	31.24	30.1	3,381	32	31.5	36.1	1.05	0.18	0.0	0
9	14.1	15.0	50.00	732.76	9.2	24,141	33	85.6	36.1	1.05	0.48	19.2	33
10	14.1	15.0	40.02	732.30	0.0	0	34	85.6	95.0	1.01	3.59	30.2	390
11	14.1	330.0	40.00	736.37	9.3	24,690	35	9.6	30.0	1.01	0.04	17.0	2
12	369.1	1,401.3	38.80	969.77	16.8	58,781	36	95.3	88.4	1.01	3.44	31.7	393
13	379.1	1,373.1	38.80	980.02	16.9	59,740	37	95.3	89.4	143.02	4.84	31.8	554
14	379.1	1,069.7	10.71	715.40	16.9	43,609	38	95.3	316.4	134.56	43.82	23.6	3,726
15	384.3	1,057.8	10.71	719.17	17.0	43,980	39	95.3	325.1	130.53	46.57	23.3	3,914
16	384.3	615.2	1.05	357.90	17.0	21,887	40	95.3	331.1	130.53	104.87	21.5	8,107
17	384.3	505.4	1.04	305.13	17.0	18,660	41	95.3	560.0	124.00	151.12	21.1	11,452
18	384.3	346.1	1.03	239.31	17.0	14,634	42	80.0	393.8	42.96	101.19	21.1	7,669
19	384.3	338.2	1.03	236.42	17.0	14,458	43	5.3	393.8	42.96	6.66	21.1	505
20	171.3	338.2	1.03	105.39	17.0	6,445	44	10.0	393.8	42.96	12.65	21.1	959
21	9.6	30.0	1.01	0.04	17.0	2	45	80.0	331.6	40.81	94.14	21.1	7,134
22	158.2	71.6	0.06	19.12	17.0	1,169	46	293.0	547.5	40.00	386.71	21.6	30,128
23	41.1	36.1	0.06	4.88	17.0	298	47	5.3	220.3	10.71	4.89	21.1	371
24	41.1	353.3	1.03	15.99	38.8	2,232	48	213.0	338.2	1.03	131.03	17.0	8,013
25	41.1	40.8	1.01	11.41	38.8	1,592	49	213.0	646.9	40.00	294.90	21.7	22,994

Table 3. 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_k [%]		$c_{F,k}$ [€/GJ]	$c_{P,k}$ [€/GJ]	$\dot{C}_{D,k}$ [€/h]	$\dot{Z}_k$ [€/h]	f_k [%]	r_k [%]
Compressor	242.68	231.30	11.38	95.3	1.56		16.67	19.05	682.8	1,297.0	65.5	14.3
CC	729.62	508.76	220.87	69.7	30.23		9.15	13.63	7,276.3	926.5	11.3	48.9
GT	551.15	530.67	20.47	96.3	2.80		15.30	16.67	1,127.9	1,482.3	56.8	8.9
Reheater	26.47	23.89	2.58	90.3	0.35		15.30	19.13	141.9	105.4	42.6	25.0
HPSH	35.07	31.72	3.35	90.5	0.46		15.30	19.16	184.5	149.5	44.8	25.2
HPEVAP	43.64	39.91	3.73	91.5	0.51		15.30	18.83	205.3	183.6	47.2	23.1
HPECON	28.92	24.91	4.00	86.2	0.55		15.30	20.16	220.5	88.6	28.7	31.8
IPSH	0.18	0.12	0.06	69.0	0.01		15.30	34.61	3.1	3.8	55.2	126.1
IPEVAP	6.10	5.67	0.43	92.9	0.06		15.30	20.32	23.8	65.0	73.2	32.8
IPECON	1.06	0.87	0.19	82.5	0.03		15.30	22.06	10.2	5.2	33.5	44.2
LPSH	1.43	1.04	0.38	73.3	0.05		15.30	28.97	21.0	18.3	46.6	89.3
LPEVAP	19.03	15.48	3.55	81.4	0.49		15.30	23.93	195.4	172.8	46.9	56.4
LPECON	11.49	7.71	3.78	67.1	0.52		15.30	30.48	208.5	92.7	30.8	99.2
HPST	31.29	29.18	2.11	93.2	0.29		20.10	23.77	152.9	165.6	52.0	18.3
IPST	37.39	35.21	2.18	94.2	0.30		20.03	24.19	157.4	299.7	65.6	20.7
LPST	70.99	61.35	9.64	86.4	1.32		21.15	29.01	734.3	696.3	48.7	37.2
Condensate Pump	0.04	0.04	0.01	78.8	0.00		19.64	80.52	0.7	6.7	91.0	310.0
Condenser	12.43	–	7.53	–	1.70		21.15	–	946.4	85.7	8.3	–
Total (E_L=14 MW)	**730.58**	**411.40**	**305.15**	**56.3**	**41.77**		**9.15**	**20.53**	**10,053.1**	**6,459.9**	**39.1**	**124.4**

Table 4. Results of the exergetic and exergoeconomic analyses at the component level for the S-Graz cycle

Component, k	$\dot{E}_{F,k}$ [MW]	$\dot{E}_{P,k}$ [MW]	$\dot{E}_{D,k}$ [MW]	ε_k [%]	y_k [%]	$c_{F,k}$ [€/GJ]	$c_{P,k}$ [€/GJ]	$\dot{C}_{D,k}$ [€/h]	$\dot{Z}_k$ [€/h]	f_k [%]	r_k [%]
CC	736.4	551.8	184.6	74.9	25.2	9.3	12.7	6,188	582	8.6	36.6
Compressor	53.8	50.8	2.9	94.6	0.4	18.6	21.1	195	259	57.0	13.3
C1	16.4	13.7	2.7	83.5	0.4	18.6	23.5	181	62	25.5	26.4
C2	17.7	14.9	2.8	84.2	0.4	18.6	30.9	187	67	26.3	66.3
HTT1	264.6	253.4	11.3	95.7	1.5	16.9	34.8	686	690	50.1	105.4
HTT2	361.3	344.2	17.1	95.3	2.3	17.0	18.6	1,047	947	47.5	9.5
GT3	78.2	69.5	8.7	88.9	1.2	17.0	23.6	533	1,118	67.7	38.8
SH	52.8	46.2	6.5	87.6	0.9	17.0	20.1	399	117	22.7	18.3
EVAP	65.8	58.3	7.5	88.6	1.0	17.0	20.0	460	168	26.7	17.6
ECON	2.9	2.8	0.1	95.5	0.0	17.0	19.0	8	12	60.3	12.0
NG_PH	7.1	3.6	3.4	51.2	0.5	21.1	42.3	261	15	5.4	100.8
HPST	30.6	28.7	1.9	93.8	0.3	21.1	25.0	145	264	64.6	18.8
IPST	1.8	1.7	0.1	93.6	0.0	21.1	27.2	9	28	76.2	29.0
HPP	1.7	1.4	0.3	84.7	0.0	19.8	31.9	18	43	70.5	61.5
Cond. Pump	0.0	0.0	0.0	76.1	0.0	19.8	140.0	0	5	94.8	607.4
ASU-dist.column	51.2	11.5	39.8	22.4	5.4	20.9	184.3	2,996	3,744	55.6	781.4
Cooler ASU	4.8	-	4.8	-	0.7	10.0	-	173	12	6.3	-
Condenser	13.6	-	13.6	-	1.9	10.0	-	489	78	13.7	-
Condenser 2	1.5	-	1.5	-	0.2	10.0	-	54	24	30.6	-
Rec. Compressor 1	92.2	85.9	6.3	93.2	0.9	18.4	24.2	416	1,369	76.7	31.3
Rec. Compressor 2	132.4	124.7	7.6	94.2	1.0	18.4	23.5	507	1,755	77.6	27.3
Water PH1	5.6	3.1	2.5	55.7	0.3	17.0	31.9	151	16	9.8	88.1
Water PH2	31.0	24.8	6.2	80.0	0.8	17.0	22.2	380	83	17.9	30.5
Water PH3	15.8	14.2	1.6	89.9	0.2	20.3	23.4	117	38	24.7	14.9

Table 4. (Continued)

Component, k	$\dot{E}_{F,k}$ [MW]	$\dot{E}_{P,k}$ [MW]	$\dot{E}_{D,k}$ [MW]	ε_k [%]	y_k [%]	$c_{F,k}$ [€/GJ]	$c_{P,k}$ [€/GJ]	$\dot{C}_{D,k}$ [€/h]	$\dot{Z}_k$ [€/h]	f_k [%]	r_k [%]
CO_2 compressor 1	12.5	11.1	1.4	88.7	0.2	18.6	48.3	95	739	88.7	159.9
CO_2 compressor 2	4.6	3.9	0.7	84.1	0.1	25.0	114.7	66	335	83.5	358.6
CO_2 compressor 3	4.7	3.9	0.8	83.5	0.1	25.0	94.6	70	336	82.8	278.4
CO_2 compressor 4	4.7	3.9	0.8	82.9	0.1	25.0	99.7	72	334	82.3	298.6
CO_2 compressor 5	4.8	3.9	0.9	81.9	0.1	25.0	85.9	78	340	81.4	243.6
CO_2 Cooler 1	4.6	-	4.6	-	0.6	10.0	-	165	11	6.2	-
CO_2 Cooler 2	1.0	-	1.0	-	0.1	10.0	-	36	9	19.3	-
CO_2 Cooler 3	1.0	-	1.0	-	0.1	10.0	-	37	9	19.0	-
CO_2 Cooler 4	1.0	-	1.0	-	0.1	10.0	-	37	9	19.2	-
CO_2 Cooler 5	19.2	-	1.1	-	0.1	10.0	-	39	11	22.2	-
Total (E_L=29.7 MW)	**733.2**	**351.9**	**351.6**	**48.0**	**48.0**	**9.2**	**30.3**	**11,582**	**14,152**	**55.0**	**231.0**

CONCLUSION

An oxy-fuel power plant with CO_2 capture in the form of the S-Graz cycle, has been presented and evaluated using exergetic and exergoeconomic analyses. The plant has been compared to a reference plant that does not employ CO_2 capture and briefly to the reference plant with chemical absorption. The S-Graz cycle results in an exergetic efficiency of 48%, which is 8 percentage points lower than that of the reference plant without CO_2 capture. The cost of exergy destruction is similar in both plants. However, the investment cost of the oxy-fuel plant results in a significant increase in the total costs and thus in the cost of electricity. Main contributors to this are the air separation unit, the expensive high-temperature expanders, the recycling compressors and the CO_2 compressors. Nevertheless, the cost of electricity of the oxy-fuel plant is higher when compared to the reference plant with chemical absorption.

Although the plant only suffers a relatively low decrease in the exergetic efficiency, when compared to other conventional alternatives for CO_2 capture [1,18], the total cost expenditure is significantly high. Nonetheless, the S-Graz plant should also be compared to other similar technologies for CO_2 capture using exergoeconomics, as well as through an exergoenvironmental impact analysis, in order to obtain enough data for possible realization options of the concept.

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)
i, j	entering and exiting exergy streams
k	component
L	loss
P	product (exergy)

ABBREVIATIONS

ASU	Air separation unit
CC	Combustion chamber
CCS	Carbon capture and sequestration
COE	Cost of electricity
COND	Condenser
ECON	Economizer
EVAP	Evaporator
GT	Gas turbine
HP, IP,LP	High-pressure, intermediate-pressure, low-pressure
HRSG	Heat recovery steam generator
HTT	High-temperature turbine
NG	Natural gas
PH	Preheater
SH	Superheater
ST	Steam turbine

Greek symbols

ε	exergetic efficiency (%)
λ	oxidation ratio

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