CHEMICAL ENGINEERING RESEARCH AND DESIGN 89 (2011) 1461–1469

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Exergoeconomic and exergoenvironmental evaluation of power plants including CO_2 capture

Fontina Petrakopoulou[a,*], *George Tsatsaronis*[a], *Alicia Boyano*[a], *Tatiana Morosuk*[b]

[a] *Institute for Energy Engineering, Technische Universität Berlin, Marchstr. 18, 10587 Berlin, Germany*[1]
[b] *Institute of Marine Propulsion Plants Operation, Maritime Academy of Szczecin, Waly Chrobrego 1-2, 70500 Szczecin, Poland*

ABSTRACT

CO_2 capture from power plants, combined with CO_2 storage, is a potential means for limiting the impact of fossil fuel use on the climate. In this paper, three oxy-fuel plants with incorporated CO_2 capture are evaluated from an economic and environmental perspective. The oxy-fuel plants, a plant with *chemical looping combustion* with near 100% CO_2 capture and two *advanced zero emission plants* with 100% and 85% CO_2 capture are evaluated and compared to a similarly structured reference plant without CO_2 capture. To complete the comparison, the reference plant is also considered with CO_2 capture incorporating chemical absorption with monoethanolamine. Two exergy-based methods, the exergoeconomic and the exergoenvironmental analyses, are used to determine the cost-related and the environmental impacts of the plants, respectively, and to reveal options for improving their overall effectiveness.

For the considered oxy-fuel plants, the investment cost is estimated to be almost double that of the reference plant, mainly due to the equipment used for oxygen production and CO_2 compression. Furthermore, the exergoeconomic analysis reveals an increase in the cost of electricity with respect to the reference plant by more than 20%, with the advanced zero emission plant with 85% CO_2 capture being the most economical choice. On the other hand, a life cycle assessment reveals a decrease in the environmental impact of the plants with CO_2 capture, due to the CO_2 and NO_x emission control. This leads to a reduction in the overall environmental impact of the plants by more than 20% with respect to the reference plant. The most environmentally friendly concept is the plant with chemical looping combustion.

© 2010 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

Keywords: CO_2 capture; Chemical looping combustion; Advanced zero emission plant; Exergoeconomic analysis; Exergoenvironmental analysis

1. Introduction

Carbon capture and storage (CCS) from power plants represents an option for the mitigation of anthropogenic greenhouse gas emissions caused by fossil fuel use. When evaluating options for CO_2 capture from electricity production plants, engineers are faced with a large variety of alternative approaches (Kvamsdal et al., 2007). However, dissimilar assumptions and hypotheses in evaluations make the comparison and assessment of the different concepts difficult, if not infeasible.

In this paper we examine and evaluate in detail, promising technologies proposed for CO_2 capture in power plants, using exergy-based analyses. The goal is to compare and evaluate alternative low-emission power plants from the economic and environmental viewpoints using *exergoeconomic* and *exergoenvironmental analyses*. These analyses provide information

---

Abbreviations: AR, air reactor; AZEP, advanced zero emission plant; CC, combustion chamber; CCs, carrying charges; CCS, carbon capture and storage; CLC, chemical looping combustion; COA-CO_2, cost of avoided CO_2; COE, cost of electricity; DB, duct burner; FR, fuel reactor; GT, gas turbine; HP, IP, LP, high-pressure, intermediate-pressure, low-pressure; HRSG, heat recovery steam generator; LCA, life cycle assessment; MEA, monoethanolamine; MCM, mixed conducting membrane; NG PH, natural gas preheater; OC, oxygen carrier; O&M, operating and maintenance costs; PEC, purchased equipment cost; ST, steam turbine.

[*] *Corresponding author*. Tel.: +49 30 314 22851; fax: +49 30 314 21683.

E-mail addresses: f.petrakopoulou@iet.tu-berlin.de (F. Petrakopoulou), tsatsaronis@iet.tu-berlin.de (G. Tsatsaronis), a.boyano@iet.tu-berlin.de (A. Boyano), morozyuk@iet.tu-berlin.de (T. Morosuk).

Received 31 March 2010; Received in revised form 22 July 2010; Accepted 2 August 2010

[1] www.energietechnik.tu-berlin.de.

0263-8762/$ – see front matter © 2010 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.cherd.2010.08.001

Nomenclature

b	environmental impact per unit of exergy (mPts/GJ)
$\dot{B}$	environmental impact rate associated with exergy (mPts/h)
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 (%)
f_b	exergoenvironmental factor (%)
r	relative cost difference (%)
r_b	relative environmental impact difference (%)
$\dot{Y}$	component-related environmental impact (mPts/h)
$\dot{Z}$	cost rate associated with capital investment (€/h)

Subscripts

D	exergy destruction
F	fuel (exergy)
k	component
L	loss
P	product (exergy)

Greek symbols

ε	exergetic efficiency (%)

about operational improvements and allow the detailed evaluation of energy conversion systems. Balances and relations between monetary cost and environmental impact reveal appropriate compromises between economic and environmental recommendations and considerations.

The three plants compared in this paper are a plant with *chemical looping combustion* (CLC) with 100% CO_2 capture and two *advanced zero emission plants* (AZEPs) with both 100% and 85% CO_2 capture. These three plants are oxy-fuel concepts, thus the combustion process takes place with oxygen. In the AZEP, the oxygen is separated in a mixed conducting membrane reactor and it is transferred to the combustion chamber of the process with a recycling gas. On the other hand, in the plant with CLC, a solid metal oxide is used both as the oxygen separator and carrier.

The considered oxy-fuel plants are simulated based on a reference plant and are then compared both to the reference plant without CO_2 capture and the reference plant with chemical absorption using monoethanolamine. The oxy-fuel concepts are less energy intensive, when compared to the conventional approach for CO_2 capture: post-combustion with chemical absorption using monoethanolamine. The calculated investment cost of the oxy-fuel plants with CO_2 capture is relatively high, mainly because of the high cost of the required reactors for the oxygen production and combustion. Yet the higher efficiency, in comparison to that of the plant using chemical absorption, results in a lower specific cost of electricity generation and CO_2 capture.

It should be noted that in the analyses presented here, future technological advancement and operating challenges related to the large-scale realization of theoretical or small-scale units cannot be predicted and are, therefore, not considered. For this reason, a realistic overall evaluation of the feasibility of the technologies cannot be performed. This may differ among the considered plants and should be assessed separately for different concepts.

2. Applied methods

An *exergetic analysis* (Bejan et al., 1996; Tsatsaronis and Cziesla, 2002) is the first step in evaluating an energy conversion system, identifying where irreversibilities occur, and what causes them. The combination of an exergetic analysis, on one side, with an *economic analysis* and with a *life cycle assessment* (LCA) on the other side constitutes the *exergoeconomic analysis* and the *exergoenvironmental analysis*, respectively.

2.1. *Exergoeconomic analysis*

The exergoeconomic analysis is a tool used to assign specific monetary costs (estimated in a preceding economic analysis) to each exergy stream in a plant and to the exergy destruction (irreversibilities) within each plant component. The cost rate associated with investment and with operating and maintenance expenses ($\dot{Z}_k$) and the cost rate associated with the exergy destruction ($\dot{C}_{D,k}$) are calculated using Eqs. (1) and (2), respectively.

$$\dot{Z}_k = \frac{(\mathrm{CCs} + \mathrm{O\&M})}{(\mathrm{PEC}_{tot} \times \tau)} \times \mathrm{PEC}_k \tag{1}$$

where CCs, O&M, PEC and τ, are the annual carrying charges, the annual operating and maintenance costs, the purchased equipment costs and the operating hours per year, calculated in the preceding economic analysis, respectively.

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{2}$$

Thereby, the cost of exergy destruction for each component can be compared with its investment and operation costs. A detailed description of the analysis and its characteristics is provided by Bejan et al. (1996), Lazzaretto and Tsatsaronis (2006) and Tsatsaronis and Cziesla (2002).

The relationship of the monetary impact of each component's exergy destruction and investment cost is examined in detail, using the exergoeconomic factor, f_k, and the relative cost difference, r_k, shown in Eqs. (3) and (4), respectively, and described by Bejan et al. (1996). Design changes to improve the cost effectiveness of the plant being studied are then proposed based on the results from the exergoeconomic evaluation.

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{3}$$

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{4}$$

where c_F and c_P are the specific costs of the fuel and the product of component k, respectively.

2.2. *Exergoenvironmental analysis*

The exergoenvironmental analysis was developed by Meyer et al. (2009) as a tool to assess the location, magnitude, and sources of the environmental impacts associated with energy conversion systems. LCA is a technique for evaluating the environmental impact associated with a product over its life

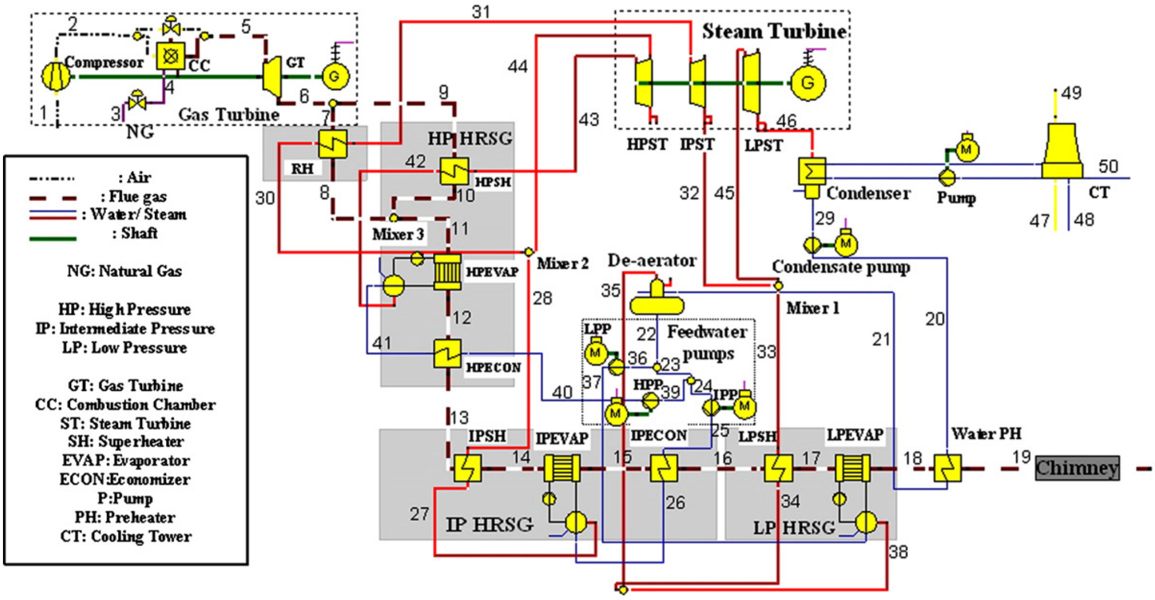

Fig. 1 – The reference plant without CO_2 capture.

cycle and it is assessed here using *ECO indicator* ‘99. ECO indicator’ 99 provides data for calculating and evaluating the impact of materials utilized in each process component. LCA is carried out following the guidelines of international standard approaches (ISO 14040, 2006) and consists of (a) a goal definition, (b) an inventory analysis, performed by identifying and quantifying the consumption and the release of materials, and (c) interpretation of the results. Because most of the provided data are functions of the size of the plant and the technology, care has been taken in sizing the system components and in collecting information about the weight, main materials, production processes and scrap outputs of all relevant equipment. From the roughly calculated amount of the main materials employed, it is possible to go back to the raw materials and to their manufacturing processes calculating the raw substances, the emissions and hence, the environmental impacts starting from the mining of the resources. In order to shift from the manufactured materials to the raw substances and emissions inventory, the software Package SimaPro 7.1 (Sima Pro user manual, 2007) was used.

Through the exergoenvironmental analysis, we assign environmental impacts to each exergy stream of a plant and to each component. The component-related environmental impact of a component k, ($\dot{Y}_k$), is calculated through the LCA. The environmental impact of the component’s exergy destruction ($\dot{B}_{D,k}$) is estimated using Eq. (5).

$$\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k} \qquad (5)$$

Analogous to the exergoeconomic analysis, an exergoenvironmental factor, $f_{b,k}$, and a relative environmental impact difference, $r_{b,k}$, calculated with Eqs. (6) and (7), respectively, guide the overall evaluation.

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}} \qquad (6)$$

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \qquad (7)$$

where b_F and b_P are the specific environmental impact of the fuel and the product of component k, respectively.

A detailed description of the analysis can be found in Meyer et al. (2009) and Tsatsaronis and Morosuk (2008). The total impact of a plant is calculated and ways to decrease the environmental consequences of its construction and operation can be suggested.

3. The plants

3.1. *The reference plant*

To facilitate the comparison of alternative CO_2 capture methods, a reference plant without CO_2 capture was used as the base case for the simulation and evaluation of the new plants incorporating CO_2 capture. This reference plant is a natural gas-fired, combined cycle power plant with only one product: electricity (Fig. 1). When feasible, important parameters of this plant were kept constant in the simulation of the plants with integrated CO_2 capture. The fuel input is kept the same in all cases, in order to assume similar, thus comparable, technology (particularly for the gas turbine systems) for all plants compared in the paper.

3.2. *The reference plant with chemical absorption using monoethanolamine*

Chemical absorption with *monoethanolamine* (MEA) is the most mature and easily implemented method for CO_2 capture. The structural differences in the plant with post-combustion capture compared to the reference plant without CO_2 capture are the absorption unit added at the outlet of the exhaust gases, the steam extraction used to produce the required thermal energy for complete regeneration of the chemical solvent and the steam turbine added to drive the CO_2 compressors. Computational calculations are based on Rubin and Rao (2002). Solvent losses of the plant with post-combustion, represented by the lean sorbent CO_2 loading, have been varied from 0.0–0.3 mol CO_2/mol MEA. The influence of this variation on the exergetic efficiency and on the energy requirement of the plant is shown in Fig. 2. Hereafter, a comparison is made between the minimal case (0.0 mol CO_2/mol MEA) and a mean value (0.2 mol CO_2/mol MEA) to further evaluate the effect

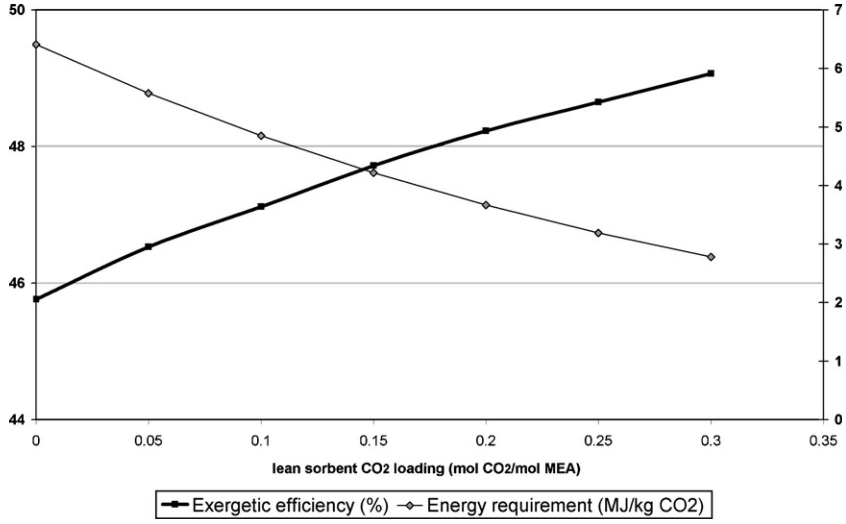

Fig. 2 – Exergetic efficiency (thick black line) and energy requirement (thin grey line) relative to the lean sorbent CO_2 loading.

of this variable. With zero solvent losses, the electricity production and the *cost of electricity* (COE) of the plant are found to be 334 MW and 95.5 €/MWh, respectively. With losses of 0.2 mol CO_2/mol MEA, the electricity production and the COE of the plant are calculated to be 352 MW and 92.1 €/MWh, respectively. From these values, the cost of avoided CO_2 for the plant using MEA is calculated to be 65.0–78.3 €/t of separated CO_2. With lean sorbent CO_2 loading equal to zero, the investment cost of the plant is increased by 20%, while with the lean sorbent CO_2 loading equal to 0.2 mol CO_2/mol MEA, the investment cost is increased by 30% (always with respect to the reference plant). This difference in the investment cost is related to the different sizes of the components used in each case. Post-combustion capture is still one of the most energy-intensive methods available today and it has not yet been possible to decrease the large energy requirement related to this technology. The plant with post-combustion is not one of the main focus points of this paper, but it is introduced and referred to here as an alternative CO_2 capture technique and as the standard for comparison purposes. It is simulated with close to 85% CO_2 capture.

3.3. *Plant with chemical looping combustion, CLC*

In the plant with CLC, shown in Fig. 3, the *combustion chamber* (CC) of a conventional *Gas Turbine* (GT) is replaced by two reactors, an *air reactor* (AR) and a *fuel reactor* (FR) (Fig. 4). A metal oxide is recycled between the two reactors, transferring oxygen extracted from ambient air in the AR to the FR. There, the combustion of the fuel takes place (Abad et al., 2006, 2007; Hossain and de Lasa, 2008; Klara, 2007; Knoche and Richter, 1968; Lewis and Gilliland, 1954; Lyngfelt et al., 2001; Mattison and Lyngfelt, 2001; Richter and Knoche, 1983; Wolf et al., 2005). A detailed diagram of the overall plant is presented by Petrakopoulou et al. (2009a).

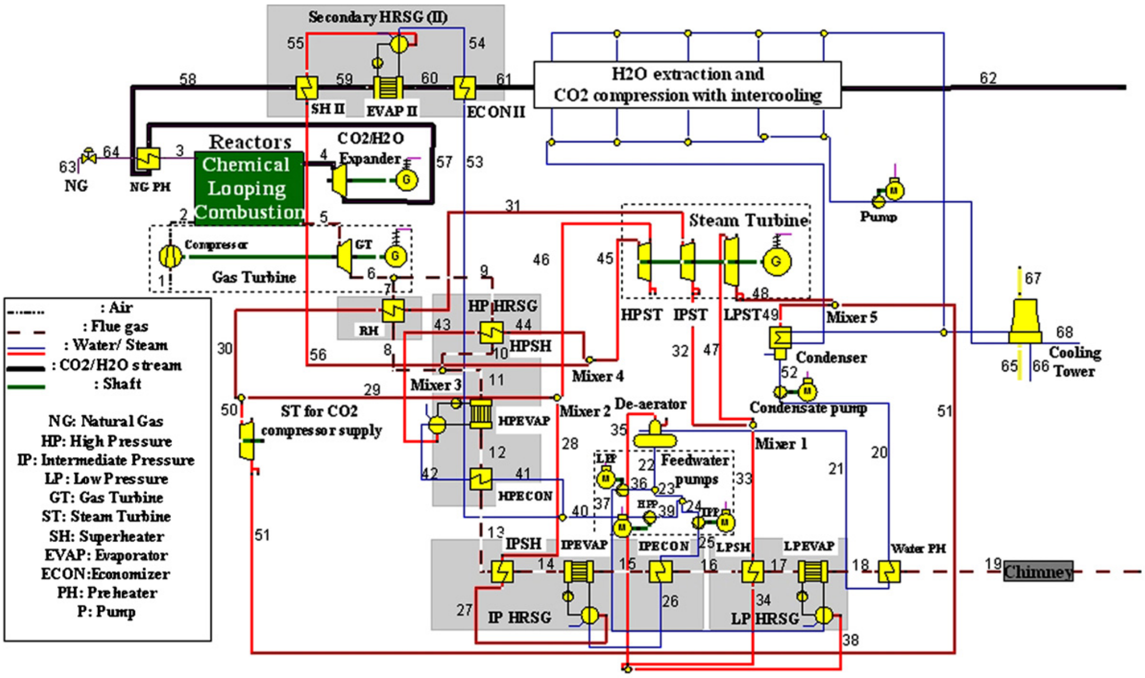

Fig. 3 – The plant with chemical looping combustion.

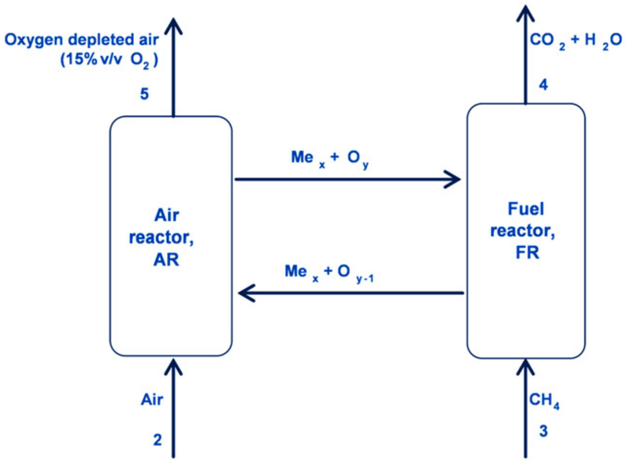

Fig. 4 – Configuration of chemical looping combustion (the numbering of the streams agrees with Fig. 3).

3.4. *The advanced zero emission plants, AZEPs*

In the AZEPs, shown in Fig. 5, the CC of the GT system is replaced by a *mixed conducting membrane* (MCM) reactor (Griffin et al., 2005; Moeller et al., 2006; Sundkvist et al., 2001, 2007). The reactor consists of the mixed conducting membrane, a high-temperature heat exchanger, a low-temperature heat exchanger, a bleed gas heat exchanger and the CC (Fig. 6). The oxygen separation occurs in the membrane and a sweep gas is used to transfer this, almost pure, oxygen to the CC of the reactor. The membrane oxygen separation is driven by the partial pressure difference of the oxygen between the ambient air and the sweep gas. A detailed diagram of the plant is provided by Petrakopoulou et al. (2009b).

In this paper, we analyze an AZEP with near 100% CO_2 capture (AZEP 100), as well as a variation with near 85% CO_2 capture (AZEP 85). The latter uses a supplementary firing after the MCM reactor, in order to increase the, otherwise limited, inlet temperature of the GT. In this way, the efficiency of the plant is enhanced, but the CO_2 produced by this added combustion is not further treated. This leads to an overall CO_2 capture of close to 85%. Due to its lower CO_2 capture effectiveness, this plant can be more accurately compared to the conventional approach of chemical absorption using MEA, since the latter also operates with close to 85% CO_2 capture.

4. Results and discussion

The oxy-fuel plants are analyzed and compared with both the reference plant without CO_2 capture, and the reference plant with chemical absorption. The methods used for the evaluation of the plants are the *exergy-based analyses* described previously, the results of which are presented below.

4.1. *Exergetic analysis*

The results of the exergetic analysis for the overall plants are shown in Table 1. The three oxy-fuel plants are characterized by a relatively low decrease in the exergetic efficiency, when compared to the reference plant, and by an increase in the overall efficiency by three percentage points, when compared to the plant with chemical absorption. Among all plants with CO_2 capture, the plant with CLC has the lowest exergy destruction and the highest exergy loss.

The lower efficiency penalty for the oxy-fuel plants is due to the more efficient combustion process, the additional power produced by the GT (CO_2/H_2O GT), and the secondary *heat recovery steam generator* (HRSG) added to better use the energy-supply potential of the separated CO_2 stream.

4.2. *Economic and exergoeconomic analyses*

The *investment cost*, *operation and maintenance* expenses, and *fuel costs* were estimated in a detailed economic analysis conducted for each plant separately using available data (EPRI

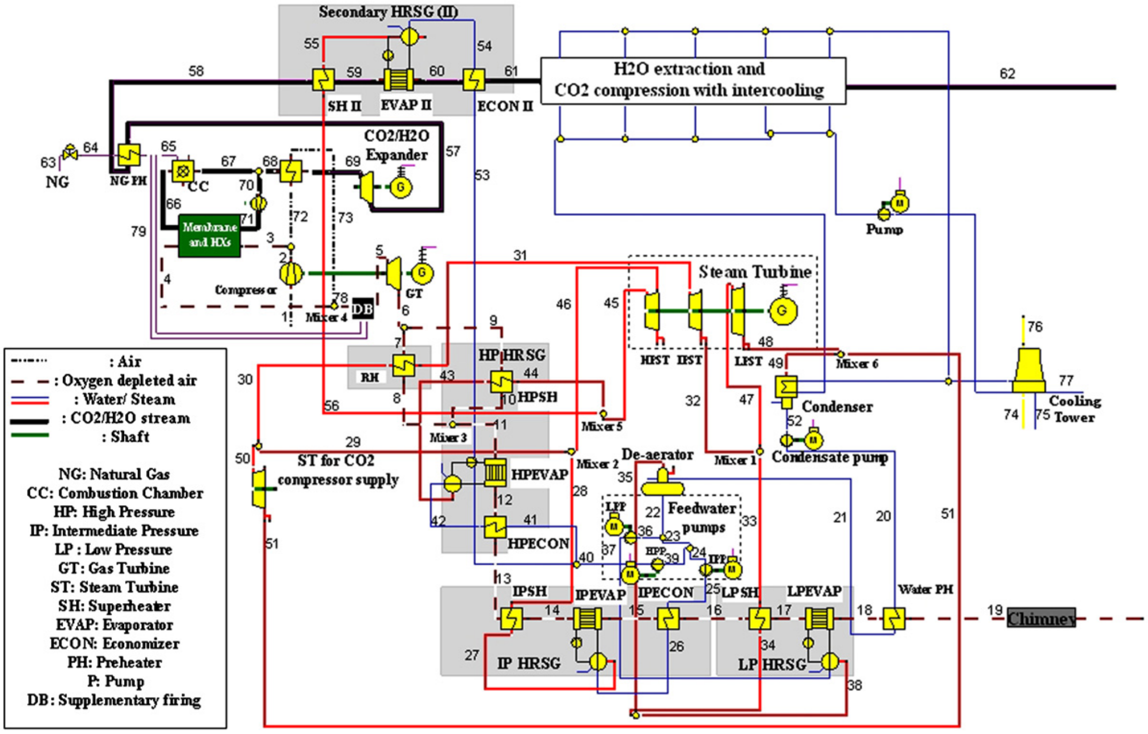

Fig. 5 – Structure of the advanced zero emission plants (additions for the variation AZEP 85: streams 78, 79 and DB).

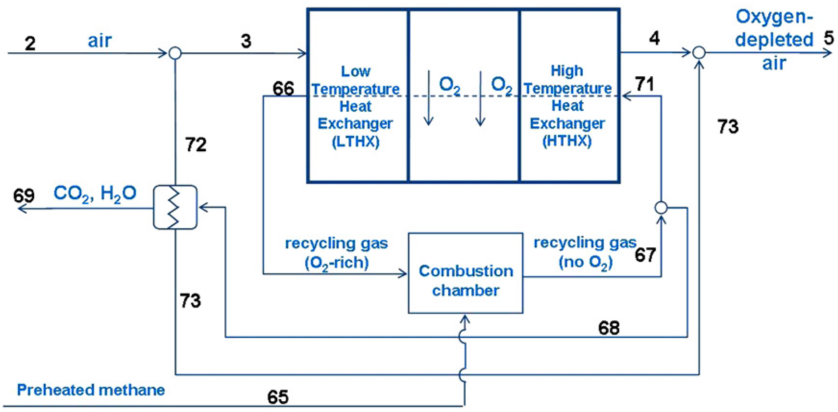

Fig. 6 – The mixed conducting membrane reactor (the numbering of the streams agrees with Fig. 5).

Table 1 – Overview of the analyses for the overall plants.

	Base case	CLC	AZEP 100	AZEP 85	MEA[c]
Exergetic efficiency (%)	56.3	51.3	51.5	53.2	45.8–48.2
Exergy of the product (MW)	411.4	374.8	376.2	388.7	334.1–352.1
Exergy destruction (MW)	305.2	312.9	326.5	319.0	368.7–350.6
Exergy loss (MW)	14.0	43.0	28.0	22.9	27.3–27.4
COE (€/MWh)[a]	73.9	91.7	94.9	91.3	92.1–95.5
COA-CO_2 (€/t)[a]	N/A	53.1	62.7	61.6	65.0–78.3
Environmental impact (mPts/kWh)[b]	31.9	23.1	24.2	25.8	28.1–31.2

[a] COA-CO_2, cost of avoided CO_2; COE, cost of electricity.

[b] Not including sequestration.

[c] Lean sorbent CO_2 loading: 0.0–0.2 mol CO_2/mol MEA.

report, 2000; Framer, 2006; Tsatsaronis and Winhold, 1984; Tsatsaronis et al., 1990; Turton et al., 2002). Table 2 shows the main assumptions made for the economic analysis.

When compared to the reference plant, the investment cost increases by 71% for the plant with CLC, by 96% for the AZEP 100 and by 86% for the AZEP 85. The respective increase for the plant with MEA was assumed to be close to 20% and 30%, with lean sorbent CO_2 loading equal to zero and 0.2 mol CO_2/mol MEA, respectively, considering a relatively low-cost chemical absorption unit.

Results at the stream level for the oxy-fuel plants are presented by Petrakopoulou et al. (2009a,b). The main results of the exergoeconomic analysis at the component level are shown in Table 3. The total cost of a component consists of its investment cost rate ($\dot{Z}_k$) and the cost rate associated with its exergy destruction ($\dot{C}$). From a cost perspective, the higher a component's total cost, the more significant the component is. The exergoeconomic factor, f_k, is an indicator of the influence of the investment cost on the total cost associated with the component being considered. The higher the exergoeconomic factor, the higher the effect of the investment cost on the total cost. To improve the operation of a component with a high exergoeconomic factor and to potentially improve the overall plant, we should reduce its investment cost. On the other hand, a low f_k value suggests that a decrease in the exergy destruction should be considered, even if this would increase the investment cost of the component being considered.

Table 2 – Selected parameters and assumptions for the economic analysis.

Plant economic life (years)	20
Levelization period (years)	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

For example, the exergoeconomic factor of the CC in the reference plant shows that only 11.3% of the component's total cost is related to its investment cost, with the remaining 88.7% related to its exergy destruction. This low exergoeconomic factor, however, is common for combustion reactors, due to the high level of irreversibilities present there. These high irreversibilities rank this component first in terms of cost of exergy destruction. The exergoeconomic factor of the MCM reactors of the AZEP concepts and the reactors of the plant with CLC is substantially higher than that of the CC of the reference plant. In the case of the AZEP concepts, the MCM reactor includes two expensive heat exchangers and the membrane, all of which increase the investment cost significantly and, at the same time, the exergoeconomic factor of the overall reactor. In the case of the plant with CLC, the large size of the two reactors increases the investment cost of the CLC unit, also resulting in a relatively high exergoeconomic factor. The values of the exergoeconomic factor are within the expected value ranges for the majority of the components. An exception could be the *steam turbine* (ST) used to drive the CO_2 compression unit (ST for CO_2 supply). The low exergoeconomic factor here shows relatively high exergy destruction, both on its own and when it is compared to the other steam turbines of the plants. This indicates that to improve the operation, we should increase the efficiency of this ST. Another

Table 3 – Main results of the exergoeconomic analysis at the component level.

Component, k	Base case			Plant with CLC			AZEP 100			AZEP 85		
	$\dot{Z}_k$ (€/h)	$\dot{C}+\dot{Z}_k$ (€/h)	f_k (%)	$\dot{Z}_k$ (€/h)	$\dot{C}+\dot{Z}_k$ (€/h)	f_k (%)	$\dot{Z}_k$ (€/h)	$\dot{C}+\dot{Z}_k$ (€/h)	f_k (%)	$\dot{Z}_k$ (€/h)	$\dot{C}+\dot{Z}_k$ (€/h)	f_k (%)
Compressor	1,297	1,980	65.5	904	1,813	49.8	1,083	2,042	53.0	1,141	1,930	59.1
CC/reactors	926	8,203	11.3	4,823	11,214	43.0	794	11,123	36.5	728	9,572	37.3
GT	1,482	2,610	56.8	1,033	2,299	44.9	1,238	2,569	48.2	1,304	2,470	52.8
HP HRSG	422	1,032	40.9	303	846	35.8	348	866	40.2	400	1,058	37.8
IP HRSG	179	358	50.0	161	399	40.4	198	429	46.1	153	305	50.2
LP HRSG	284	709	40.1	225	684	32.9	288	774	37.2	278	698	39.9
HPST	166	318	52.0	96	237	40.4	138	300	45.9	177	363	48.8
IPST	300	457	65.6	138	255	54.2	153	261	58.6	196	315	62.3
LPST	696	1,431	48.7	361	944	38.2	413	972	42.5	475	1,060	44.8
HRSG II	–	–	–	17	35	49.0	72	191	37.7	62	158	39.1
ST for CO_2 supply	–	–	–	146	566	25.8	274	952	28.7	249	804	31.0
CO_2 Compression unit	–	–	–	1,230	1,991	61.8	1,512	2,648	58.8	1,430	2,362	60.5
CO_2/H_2O Expander	–	–	–	202	321	63.1	312	467	67.0	241	373	64.7
NG PH	–	–	–	7	227	3.20	4	273	1.6	5	273	1.7
Compressor recycle	–	–	–	–	–	–	645	682	94.6	593	623	95.1
DB	–	–	–	–	–	–	–	–	–	270	1,312	20.6
Total	6,460	16,513	39.1	10,423	20,731	50.3	11,790	22,504	52.4	11,572	22,042	52.5

component that exhibits high exergy destruction is the *natural gas preheater* (NG PH). This is justified, by the high-pressure losses in the valve prior to the heat exchanger. Lastly, the CO_2 compression unit and the recycling compressor of the MCM reactor in the AZEPs exhibit relatively high values of the exergoeconomic factor. It is thus likely that less expensive compressors and coolers (if possible) would be more cost effective for the overall plant, even if the overall plant efficiency decreases.

The COE and the *cost of avoided CO_2* (COA-CO_2) are considered for the comparison and evaluation of the plants (Table 1). The cost of avoided CO_2 capture shows the added cost of electricity per ton of avoided CO_2 based on net plant capacity (Rubin and Rao, 2002). Although the COE of the plant with MEA is comparable to that of the oxy-fuel concepts, a difference in the energy penalty of the plants is revealed by the cost of avoided CO_2. The relatively high penalty of avoided CO_2 in the plant with chemical absorption (65.0–78.3 €/t of CO_2 with $5.9–6.3 \times 10^{-5}$ t of CO_2/kWh exhausted) is related to the high energy demand of MEA regeneration.

4.3. *Life cycle assessment and exergoenvironmental analysis*

Table 4 shows the main results of the exergoenvironmental analysis, at the component level, for the reference plant and the three oxy-fuel plants. More detailed tables are provided by Petrakopoulou et al. (2010a,b). The oxy-fuel plants show a decrease in the environmental impact associated with the final product with respect to the reference plant (Table 1). The component-related environmental impact ($\dot{Y}_{tot}$) differs among the plants, but in the end, the total environmental impact ($\dot{B}+\dot{Y}_{tot}$) of the reference and oxy-fuel plants reach comparable values. This fact indicates that the construction phase is not the key area for reducing the environmental impact of these plants. For example, the component-related environmental impact of the reference plant with post-combustion is almost three times lower than that of the reference plant without CO_2 capture, due to the smaller size of common equipment. However, depending on the lean sorbent CO_2 loading (0.0–0.2 mol CO_2/mol MEA), the plant using MEA results in an overall environmental impact of 28.1–31.2 mPts/kWh (Table 1)—values marginally lower than those of the reference plant. It should be noted that the component-related environmental impact of the plant using MEA is higher when solvent losses are assumed, due to the higher environmental impact of larger equipment, even though the chemical absorption unit gets smaller. Nonetheless, the difference in the resulting overall impact is relatively small since, as already discussed, the component-related environmental impact is low when compared to the environmental impact of the plant operation.

In the reference plant, the highest environmental impact ($\dot{B}+\dot{Y}_k$) corresponds to the CC, the GT, the *low-pressure* (LP) ST, and the compressor. On the other hand, in the two AZEP concepts and the plant with CLC, the highest environmental impact is caused by the reactors, the GT and the compressor.

The exergoenvironmental analysis not only identifies the components with the highest environmental impact, but it also reveals the possibilities and trends for improvement, in order to decrease the environmental impact of the overall system. The exergoenvironmental factor is calculated analogously to the exergoeconomic factor. The higher the

Table 4 – Main results of the exergoenvironmental analysis at the component level.

Component, k	BASE CASE			PLANT WITH CLC			AZEP 100			AZEP 85		
	$\dot{Y}_k$ (mPts/h)	$\dot{B}+\dot{Y}_k$ (mPts/h)	$f_{b,k}$ (%)	$\dot{Y}_k$ (mPts/h)	$\dot{B}+\dot{Y}_k$ (mPts/h)	$f_{b,k}$ (%)	$\dot{Y}_k$ (mPts/h)	$\dot{B}+\dot{Y}_k$ (mPts/h)	$f_{b,k}$ (%)	$\dot{Y}_k$ (mPts/h)	$\dot{B}+\dot{Y}_k$ (mPts/h)	$f_{b,k}$ (%)
Compressor	236	228,731	0.10	190	272,672	0.07	184	277,994	0.07	194	231,901	0.08
CC/reactors	381	2,861,944	0.01	2,537	2,529,633	0.10	154,055	2,899,588	5.31	154,027	2,487,036	6.19
GT	1,126	396,957	0.28	906	391,525	0.23	880	399,705	0.22	926	356,994	0.26
HP HRSG	1,472	215,658	0.68	1,126	168,722	0.67	1,024	156,201	0.66	1201	202,147	0.59
IP HRSG	898	63,709	1.41	613	73,876	0.83	527	69,900	0.75	606	47,092	1.29
LP HRSG	338	149,465	0.23	303	141,695	0.21	315	145,891	0.22	301	128,501	0.23
HPST	276	49,507	0.56	229	41,105	0.56	231	46,907	0.49	278	54,149	0.51
IPST	317	50,800	0.62	234	33,845	0.69	215	30,677	0.7	247	34,313	0.72
LPST	493	232,052	0.21	375	165,280	0.23	356	153,623	0.23	383	164,085	0.23
HRSG II	–	–	–	30	5,881	0.51	172	44,636	0.39	136	35,899	0.38
ST for CO_2 supply	–	–	–	185	120,320	0.15	243	191,757	0.13	215	159,181	0.14
CO_2 compression unit	–	–	–	260	192,284	0.14	260	257,888	0.10	254	217,779	0.12
CO_2/H_2O expander	–	–	–	192	39,367	0.49	204	57,761	0.35	193	49,220	0.39
NG PH	–	–	–	3	72,648	0.00	1	100,371	0.00	1	99,982	0.00
Compressor recycle	–	–	–	–	–	–	596	10,154	5.87	596	8,593	6.94
DB	–	–	–	–	–	–	–	–	–	53	409,328	0.01
Total	48,422	3,958,548	0.12	51,937	4,105,798	1.26	206,404	4,436,365	4.65	11,572	4,339,010	4.74

exergoenvironmental factor ($f_{b,k}$), the higher the influence of the component-related environmental impact to the total environmental impact associated with the component being considered. For example, the total environmental impact of the reference plant could be decreased by decreasing the component-related environmental impact of the *intermediate-pressure* (IP) and/or the *high-pressure* (HP) HRSG. However, the analysis shows that it would be more effective to increase the exergetic efficiency of the individual processes, and especially that of the CC, if this would be possible. In general, a decrease in the irreversibilities present in reactors is difficult, because the inefficiencies are unavoidable, for the most part. However, preheating of the air and the natural gas, as well as use of different GT systems (e.g., steam-cooled expander) would lead to better efficiencies and would decrease the incurred exergy destruction. In the case of the oxy-fuel plants, a reduction of the overall environmental impact could be achieved by decreasing the component-related environmental impact of the reactors (e.g., by replacing the construction materials assumed here, with materials of lower environmental impact), or by increasing the exergetic efficiency of the remaining components.

The value ranges of the exergoeconomic and exergoenvironmental factors differ significantly. In general, the component-related environmental impact is almost negligible, when compared to the environmental impact related to the operation of the plant (represented by the environmental impact of the exergy destruction, $\dot{B}$). For this reason, and in order to reduce the overall environmental impact associated with these plants, we should pay more attention to the effectiveness of the component operation, and should try to increase the exergetic efficiencies of the components.

5. Conclusions

In this paper three oxy-fuel plants were analyzed and compared using exergy-based methods. To aid the comparison, these plants were based on a reference plant, without CO_2 capture, of similar configuration and operational conditions. The reference plant has also been considered with chemical absorption using MEA in the exergetic and exergoeconomic analyses.

The three oxy-fuel plants are significantly more expensive, when compared to the reference plant without CO_2 capture, resulting in almost double the investment cost. Moreover, they result in an increase in the cost of electricity by a minimum of 23%. Nonetheless, they are more efficient and less costly when compared to the conventional alternative for CO_2 capture, i.e. the reference plant with chemical absorption. As far as the environmental impact is concerned, the construction of the oxy-fuel plants has a similar environmental impact to that of the reference plant without emission treatment. However, the overall environmental impact of the oxy-fuel plants is lower by 19–27%.

The choice of the best option for CO_2 capture depends on the results of both the exergoeconomic and the exergoenvironmental analyses. In our evaluation, the exergoeconomic analysis showed the AZEP 85 as the most economical solution with a slightly lower cost of electricity, in comparison to the plant with CLC, but at the same time with a much higher cost of avoided CO_2. If the environmental impact is of greater importance for the decision-maker, then preference should be given to the plant with CLC, although it results in a higher cost of electricity.

Acknowledgments

This research was funded by the European Commission's Marie Curie 6th Framework Programme, and is a part of the MRTN CT-2005-019296—INSPIRE.

References

Abad, A., Mattisson, T., Lyngfelt, A., Rydén, M., 2006. Chemical-looping combustion in a 300 W continuously operating reactor system using a manganese-based oxygen carrier. Fuel 85, 1174–1185.

Abad, A., Mattisson, T., Lyngfelt, A., Johansson, M., 2007. The use of iron oxide as oxygen carrier in a chemical-looping reactor. Fuel 86, 1021–1035.

Bejan, A., Tsatsaronis, G., Moran, M., 1996. Thermal Design and Optimization. Wiley, New York.

EPRI report, 2000. Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal, Palo Alto, CA, U. S. Department of Energy—Office of Fossil Energy, Germantown, MD and U. S. Department of Energy/NETL, Pittsburgh, PA, 1000316.

Framer, R., 2006. Gas Turbine World 2006 Handbook. Pequot Publishing, Fairfield, CT.

Griffin, T., Sundkvist, S.G., Asen, K., Bruun, T., 2005. Advanced zero emissions gas turbine power plant. Journal of Engineering for Gas Turbines and Power 127, 81–85.

Hossain, M.M., de Lasa, H.I., 2008. Chemical-looping combustion (CLC) for inherent CO_2 separation – a review. Chemical Engineering Science 63, 4433–4451.

ISO 14040, 2006. Environmental Management, Life Cycle Assessment, Principles and Framework.

Klara, J.M., 2007. Chemical-Looping Process in a Coal-to-Liquids, Independent Assessment of the potential of the OSU Chemical Looping Concept, U.S. Department of Energy, National Energy Technology Laboratory, DOE/NETL-2008/1307.

Knoche, K.F., Richter, H., 1968. Verbesserung der Reversibilität von Verbrennungs-Prozessen. Brennstoff-Wärme-Kraft 5, 205–210.

Kvamsdal, H., Jordan, K., Bolland, O., 2007. A quantitative comparison of gas turbine cycles with CO_2 capture. Energy 32 (1), 10–24.

Lazzaretto, A., Tsatsaronis, G., 2006. SPECO: a systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy 31, 1257–1289.

Lewis, W.K., Gilliland, E.R., 1954. Production of pure carbon dioxide, US Patent No. 2,665,972.

Lyngfelt, A., Leckner, B., Mattisson, T., 2001. A fluidized-bed combustion process with inherent CO_2 separation; application of chemical-looping combustion. Chemical Engineering Science 56, 3101–3113.

Mattison, T., Lyngfelt, A., 2001. Applications of chemical-looping combustion with capture of CO_2. In: 2nd Nordic Minisymposium on CO_2 Capture and Storage, Göteborg, Sweden.

Meyer, L., Tsatsaronis, G., Buchgeister, J., Schebek, L., 2009. Exergoenvironmental analysis for evaluation of the environmental impact of energy conversion systems. Energy 34, 75–89.

Moeller, B., Torisson, T., Assadi, M., Sundkvist, S.G., Asen, K.I., 2006. AZEP gas turbine combined cycle power plants—thermo-economic analysis. International Journal of Thermodynamics 9, 21–28.

Petrakopoulou, F., Tsatsaronis, G., Morosuk, T., 2009. Exergoeconomic analysis of a power plant with Chemical Looping Combustion. In: ECOS 2009 Proceedings, Foz do Iguacu, Brazil.

Petrakopoulou, F., Tsatsaronis, G., Morosuk, T., 2009. Exergoeconomic analysis of an advanced zero emission plant. In: Proceedings of the ASME IMECE, Florida, USA, CD-ROM, pp. 2009–11015.

Petrakopoulou, F., Boyano, A., Cabrera, M., Tsatsaronis, G., 2010. Exergoeconomic and exergoenvironmental analyses of the AZEP concept, a combined cycle power plant with CO_2 capture. International Journal of Low-Carbon Technology, IJLCT-2010-008.R2, ID: CTQ028.

Petrakopoulou, F., Boyano, A., Cabrera, M., Tsatsaronis, G., 2010b. Exergoeconomic and exergoenvironmental analyses of a combined cycle power plant with chemical looping technology. The International Journal of Greenhouse Gas Control, doi:10.1016/j.ijggc.2010.06.008.

Richter, H.J., Knoche, K.F., 1983. Reversibility of combustion processes. In: ACS Symposium Series, 235, pp. 9971–9985.

Rubin, E.S., Rao, A.B., 2002. A Technical, Economic and Environmental Assessment of Amine-based CO_2 Capture Technology for Power Plant Greenhouse Gas Control, Technical report DOE/DE-FC26-00NT40935, U.S. DOE/NETL.

Sima Pro user manual, 2007. Pre Consultants BV, Amersfoort (NL).

Sundkvist, S.G., Griffin, T., Thorshaug, N.P., 2001. AZEP—development of an integrated air separation membrane—gas turbine. In: 2nd Nordic Minisymposium on CO_2 Capture and Storage, Göteborg, Sweden.

Sundkvist, S.G., Julsrud, S., Vigeland, B., Naas, T., Budd, M., Leistner, H., Winkler, D., 2007. Development and testing of AZEP reactor components. International Journal of Greenhouse Gas Control I, 180–187.

Tsatsaronis, G., Winhold, M., 1984. Thermoeconomic Analysis of Power Plants, Final Report, AP-3651, Research Project 2029-8, EPRI, Palo Alto.

Tsatsaronis, G., Tawfik, T., Lin, L., 1990. Assessment of Coal Gasification/Hot gas cleanup based advanced Gas Turbine Systems, Exergetic and Thermoeconomic Evaluation, Final Report submitted to Southern Company Services and the U.S. DOE, DE_FC21_89MC26019, Center for Electric Power, Tennessee Technological University.

Tsatsaronis, G., Cziesla, F., 2002. Encyclopedia of Physical Science and Technology, vol. 16., 3rd ed. Academic Press, pp. 659–680.

Tsatsaronis, G., Morosuk, T., 2008. A general exergy-based method for combining a cost analysis with an environmental impact analysis. Part I – Theoretical Development; Part II – Application to a cogeneration system. In: Proceedings of the ASME International Mechanical Engineering Congress and Exposition, IMECE November 2–6, Boston, Massachusetts, USA, IMECE2008-67218-9.

Turton, R., Bailie, R.C., Whiting, W.B., Shaeiwitz, J.A., 2002. Analysis, Synthesis and Design of Chemical Processes, 2nd ed. Prentice Hall, Upper Saddle River, NJ, USA.

Wolf, J., Anheden, M., Yan, J., 2005. Comparison of nickel- and iron-based oxygen carriers in chemical looping combustion for CO_2 capture in power generation. Fuel 84, 993–1006.