



Environmental and thermodynamic evaluation of CO₂ capture, transport and storage with and without enhanced resource recovery

Diego Iribarren^{a,*}, Fontina Petrakopoulou^a, Javier Dufour^{a,b}

^a Systems Analysis Unit, Instituto IMDEA Energía, 28935 Móstoles, Spain

^b Department of Chemical and Energy Technology, ESCET, Rey Juan Carlos University, 28933 Móstoles, Spain

ARTICLE INFO

Article history:

Received 8 August 2012

Received in revised form

5 December 2012

Accepted 19 December 2012

Available online xxx

Keywords:

Carbon capture and storage

Cumulative energy demand

Exergy

Life cycle assessment

Power plant

ABSTRACT

This study evaluates the environmental and thermodynamic performance of six coal-fired power plants with CO₂ capture and storage. The technologies examined are post-combustion capture using mono-ethanolamine, membrane separation, cryogenic fractionation and pressure swing adsorption, pre-combustion capture through coal gasification, and capture performing conventional oxy-fuel combustion. The incorporation of CO₂ capture is evaluated both on its own and in combination with CO₂ transport and geological storage, with and without beneficial use.

Overall, we find that pre-combustion CO₂ capture and post-combustion through membrane separation present relatively low life-cycle environmental impacts and high exergetic efficiencies. When accounting for transport and storage, the environmental impacts increase and the efficiencies decrease. However, a better environmental performance can be achieved for CO₂ capture, transport and storage when incorporating beneficial use through enhanced oil recovery. The performance with enhanced coal-bed methane recovery, on the other hand, depends on the impact categories evaluated. The incorporation of methane recovery results in a better thermodynamic performance, when compared to the incorporation of oil recovery. The cumulative energy demand shows that the integration of enhanced resource recovery strategies is necessary to attain favourable life-cycle energy balances.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Carbon dioxide capture and storage (CCS) involves a group of technologies that can help mitigate climate change associated with the operation of facilities with high CO₂ emissions. For instance, fossil-fuelled power plants are suitable application sites for the implementation of CCS technologies [1–5].

CO₂ capture technologies are separated into three main groups: pre-combustion, oxy-fuel combustion and post-combustion [6]. Pre-combustion technology refers to the extraction of the carbon included in the fuel before the combustion, to produce a hydrogen-based fuel (e.g., integrated gasification combined-cycle power plants) [1,7]. With oxy-fuel technologies, the combustion is performed with oxygen instead of air, generating flue gases with easily separable CO₂ [1,3,8]. Finally, in post-combustion capture, the CO₂ generated is separated after the combustion of the fossil fuel. Post-combustion methods include chemical absorption,

which is the most developed technology [9,10], membrane separation, cryogenic fractionation, and pressure swing adsorption (PSA) [11].

After the CO₂ is captured, it is transported (e.g., using pipelines) and led to a storage site [11]. Geological sequestration can provide benefits by increasing oil extraction in depleted oil fields via enhanced oil recovery (EOR) [12]. Similarly, enhanced coal-bed methane recovery (ECBMR) can be performed to increase the production of methane or natural gas through the injection of CO₂ into deep unmineable coal seams [12]. Also, the recovered CO₂ can be used in technological, chemical and biological applications [2].

The present article deals with the environmental and thermodynamic evaluation of CO₂ capture, transport and storage in coal power plants. For the environmental evaluation the Life Cycle Assessment (LCA) methodology was used, which is a well-established methodology to comprehensively evaluate the potential environmental impacts associated with a product [13–16]. The thermodynamic evaluation assesses and compares the performance of the different CCS systems and it was conducted using exergetic efficiencies [4].

* Corresponding author. Tel.: +34 91 7371119.

E-mail addresses: diego.iribarren@imdea.org, diegoiribarrenlorenzo@hotmail.com (D. Iribarren).

2. Material and methods

2.1. Case studies under evaluation

The study considers the overall chain of the CCS power plants, from the mining of the coal to the geological storage of the CO₂ captured with and without enhanced resource recovery. The first CO₂ capture technology considered was post-combustion using chemical absorption with monoethanolamine (MEA). In order to incorporate different CO₂ capture systems, a number of modifications were made to this power plant (Section 2.2). Fig. 1 summarizes the cases examined. Additionally, a conventional coal-fired power plant (i.e., without CO₂ capture) is used throughout this study in order to provide a basis for comparison purposes (reference plant). The layout of each power plant differs and depends on the specific CO₂ capture method incorporated.

2.2. LCA framework and data acquisition

An LCA study was carried out to evaluate both the environmental performance and the cumulative energy demand (CED) of the case studies. The specific objectives of the LCA study are the following:

- Environmental characterization of electricity production in four coal-fired power plants with different post-combustion technologies for CO₂ capture: chemical absorption with MEA, membrane separation, cryogenic fractionation and PSA. The comparison of the environmental profiles enables the identification of the most environmentally appropriate post-combustion technology.
- Environmental characterization of pre-combustion and oxy-fuel technologies as alternatives to post-combustion recovery. The comparison of the results reveals the CO₂ capture technology with the best environmental performance.
- Environmental characterization of the power plants including CO₂ transport and geological storage, and comparison of these CCS schemes with plants incorporating only CO₂ capture.
- Modification of the environmental profiles when integrating enhanced resource recovery schemes (EOR and ECBMR), in order to determine their environmental suitability.
- Calculation of the CED indicator to estimate the life-cycle energy balance of each case.

In an LCA study a functional unit (FU) is used as a measure to quantify the performance of a system [11,12]. Here, the production of 1 kWh of net electricity (at plant) was chosen as the comparative

measure among the different cases. This FU is a common choice in LCA studies of CCS systems [1,3,9].

Fig. 2 shows the main process steps and material/energy flows involved in the present life-cycle study. All power plants included coal conditioning and power generation. It should be noted that the layout of each plant depended on the CO₂ capture method used. Thus, although a general layout for all power plants with post-combustion capture (plants A.1–4) is presented in Fig. 2, each specific post-combustion technology involves different material/energy flows.

Primary inventory data for the CCS systems were derived from a review of environmental studies in the field of CCS, as described in Sections 2.2.1 and 2.2.2. Secondary data for background processes were taken from the ecoinvent database [17], including the production of chemicals [18] and certain energy carriers [19]. Capital goods were excluded from the boundaries of the system. Additionally, zero leakage was assumed during the geological storage (based on a 100-year timeline). Inventory data for the conventional coal-fired power plant without CO₂ capture (i.e., the reference plant) were taken from specific databases [19,20].

2.2.1. CO₂ capture

Inventory data were collected for each power plant, from the mining of the coal to the generation of liquid CO₂. Data for case A.1 were based on literature on post-combustion CO₂ recovery through chemical absorption with MEA [1,3,9,11]. These data were modified according to Khoo and Tan [11] in order to include alternative post-combustion technologies (cases A.2, A.3 and A.4). Adjustments for pre-combustion CO₂ recovery with Selexol (case B.1; negligible solvent loss) and oxy-fuel technology (case C.1) were based on Singh et al. [3]. Table 1 presents the main inventory data of each CO₂ capture strategy.

2.2.2. Transport and geological storage with and without enhanced resource recovery

While Section 2.2.1 refers only to CO₂ recovery, the present section widens the scope of the study to include CO₂ transport and geological storage with and without enhanced resource recovery. The electricity required for the transportation of the CO₂ depends on the distance. In this specific study, 680 km pipeline transportation of supercritical CO₂ was assumed, with a preceding CO₂ compression stage. Inventory data regarding CO₂ transport and storage focus on the energy requirements of CO₂ compression, pipeline transportation and injection for geological storage [11]. Table 2 shows the additional energy required due to these processes (with respect to the demand of the first scenario in Section 2.2.1), as well as the additional energy requirement to recover crude oil or raw natural gas [12].

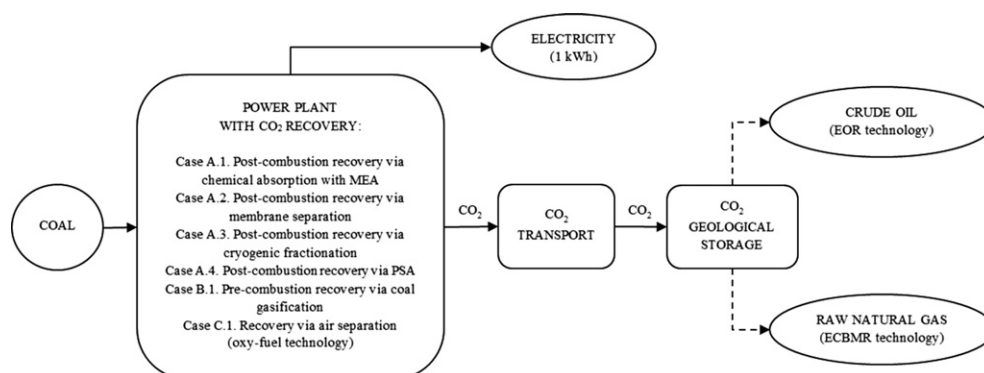


Fig. 1. Examined CCS systems (dotted lines denote flows created due to beneficial use).

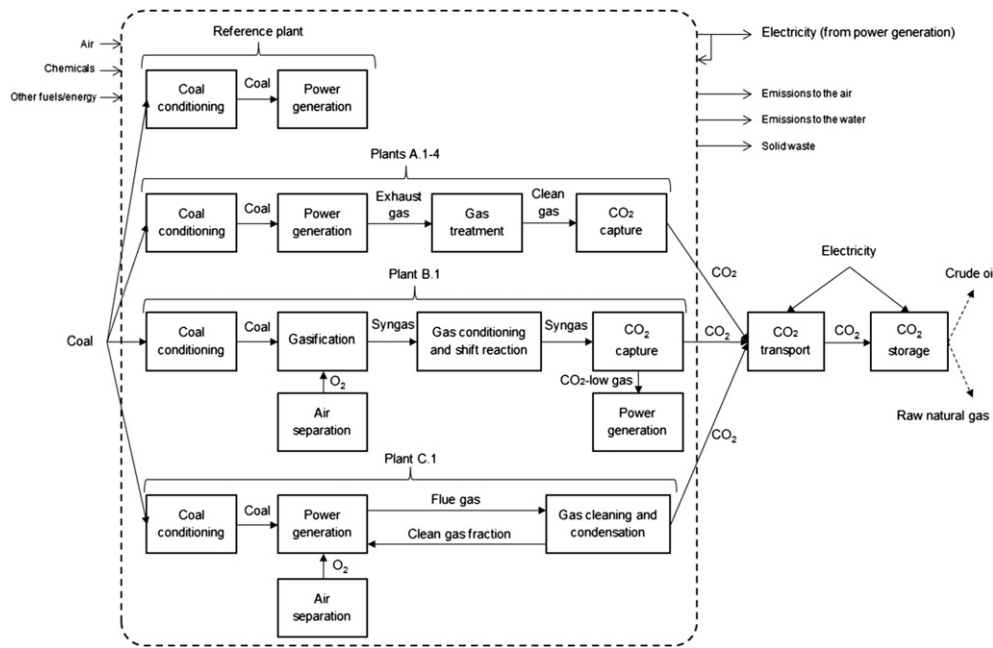


Fig. 2. Life-cycle flowchart of the evaluated systems (dotted arrows denote flows created due to beneficial use).

2.3. Exergetic analysis

In contrast to energy that must be always conserved, in real processes exergy is destroyed. Thus, an exergetic analysis is a convenient way to identify sources of irreversibilities within energy conversion systems, while also allowing the definition of operating efficiencies that facilitates the evaluation of the different processes. Here, we use exergetic efficiencies to compare the thermodynamic performance of the different CCS power plants. The exergetic efficiency of the overall system, ϵ_{tot} , is defined as the ratio between the exergy of the product and the exergy of the fuel of the plant ($\epsilon_{\text{tot}} = \dot{E}_{P,\text{tot}}/\dot{E}_{F,\text{tot}}$) [21]. The exergy of the product is defined as the exergy of the desired output resulting from the operation of the plant, while the exergy of the fuel is defined as the

expense in exergetic resources for the generation of this desired output [22–24].

In the present work, the exergetic efficiency of the plants is calculated for three different conditions: (i) operation with CO_2 capture, (ii) operation with CO_2 capture, transport and storage, and (iii) operation with CO_2 capture, transport and storage with beneficial use. In case (iii) we assume that the recovered fuels are not used in the plants and they only result in economic benefits through their sale. Thus, they were not considered as products of the power plants and were not incorporated into the calculated overall efficiencies of the plants. The energy requirement for CO_2 capture was assumed to be covered by the internal operation of the plant, while the power needed to transfer and store the captured CO_2 was considered to be covered with electricity from the grid.

Table 1

Main inventory data of the CO_2 recovery alternatives (FU: 1 kWh of net electricity at plant).

		Case A.1	Case A.2	Case A.3	Case A.4	Case B.1	Case C.1
Inputs							
Coal	g	672.20	554.00	969.20	609.90	564.18	591.26
Natural gas	g	1.06	0.88	1.53	0.97	0.89	0.94
Ammonia	g	1.48	1.22	2.15	1.31	—	—
Limestone	g	55.63	46.10	80.44	49.59	—	—
NaOH	g	0.16	—	—	—	—	—
Solvent	g	1.99 (MEA)	—	—	—	$7.15 \cdot 10^{-3}$ (Selexol)	—
Fuel oil	g	8.03	6.62	11.58	7.29	6.74	7.07
Outputs							
Products							
Net electricity (at plant)	kWh	1.00	1.00	1.00	1.00	1.00	1.00
CO_2 (l)	kg	1.29	0.91	1.76	1.04	1.02	1.07
Wastes to treatment							
Hazardous waste	g	2.93	—	—	—	—	—
Municipal waste	g	2.34	1.94	3.39	2.09	0.01	0.01
Emissions to air							
Carbon dioxide	g	67.65	200.71	195.07	184.13	113.55	119.00
Sulphur dioxide	g	0.09	0.09	0.13	0.09	0.64	1.18
Nitrogen oxides	g	1.37	1.13	1.97	1.22	0.73	0.56
Ammonia	g	0.35	0.28	0.51	0.30	$3.57 \cdot 10^{-3}$	$3.48 \cdot 10^{-3}$
Particulates	g	0.14	0.12	0.19	0.12	0.09	0.19
Solvent	g	0.11	—	—	—	—	—

Table 2Additional data for CO₂ transport (680 km) and geological storage with and without enhanced resource recovery (FU: 1 kWh of net electricity at plant).

	Geological storage		EOR		ECBMR	
	Additional electricity demand ^a (kWh)		Electricity demand ^b (kWh)		Recovered crude oil (kg)	
Case A.1	0.023		0.035	0.373	0.024	0.643
Case A.2	0.016		0.025	0.265	0.017	0.457
Case A.3	0.031		0.048	0.509	0.033	0.878
Case A.4	0.019		0.028	0.303	0.020	0.522
Case B.1	0.018		0.028	0.296	0.019	0.511
Case C.1	0.019		0.029	0.311	0.020	0.536

^a Additional electricity requirement relative to the electricity demand of liquid CO₂ recovery. It is linked to CO₂ compression, pipeline transportation and injection for geological storage. It was assumed to be satisfied by the electrical grid.

^b Electricity requirement due to resource recovery. It was assumed to be satisfied by the electrical grid.

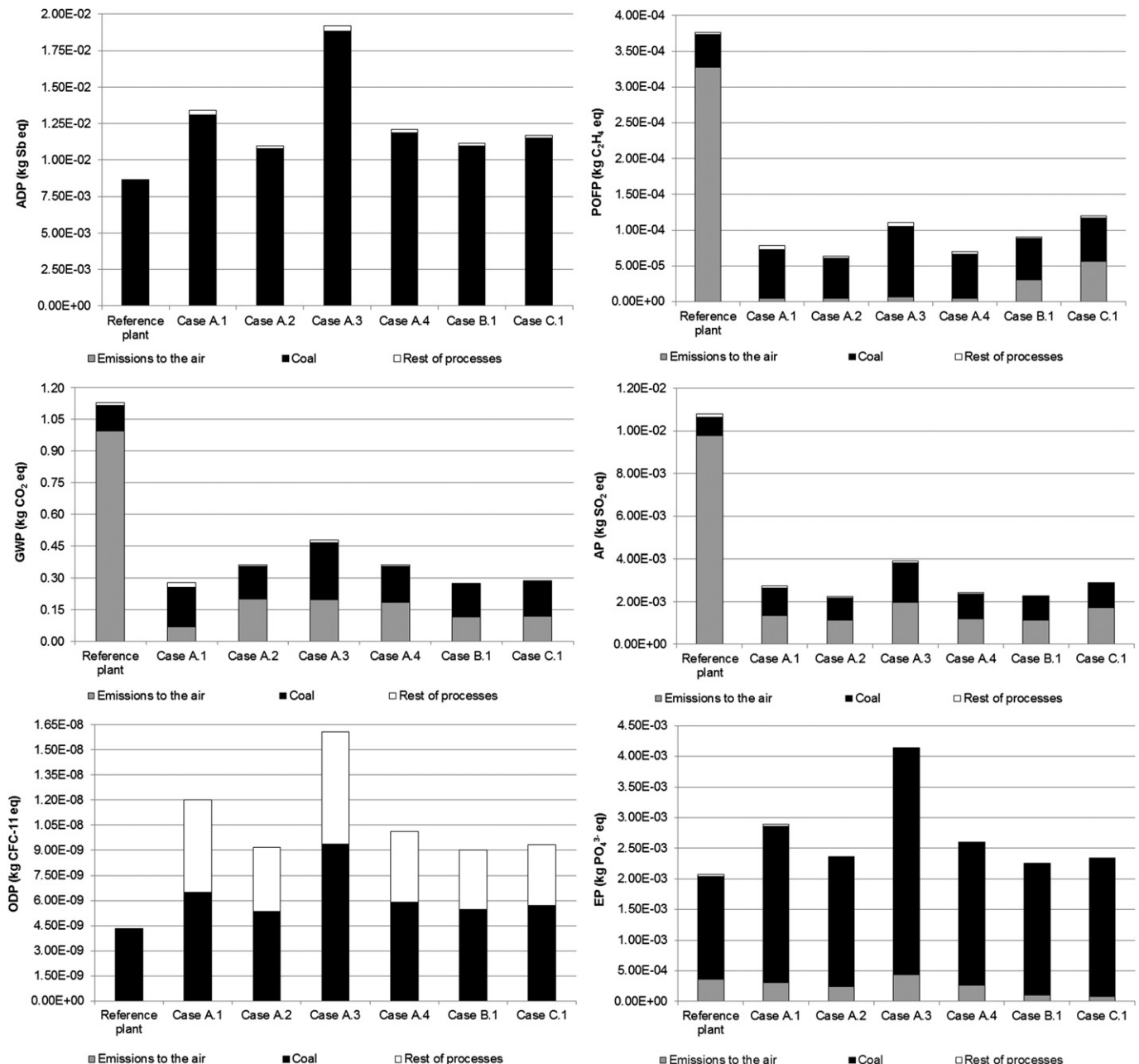
**Fig. 3.** Environmental impacts of the different CO₂ capture technologies.

Table 3Environmental characterization results including CO₂ transport (680 km) and geological storage without enhanced resource recovery (FU: 1 kWh of net electricity at plant).

	Reference plant	Case A.1	Case A.2	Case A.3	Case A.4	Case B.1	Case C.1
ADP (kg Sb eq)	$8.67 \cdot 10^{-3}$	$1.35 \cdot 10^{-2}$	$1.10 \cdot 10^{-2}$	$1.93 \cdot 10^{-2}$	$1.22 \cdot 10^{-2}$	$1.12 \cdot 10^{-2}$	$1.18 \cdot 10^{-2}$
GWP (kg CO ₂ eq)	1.13	$2.90 \cdot 10^{-1}$	$3.71 \cdot 10^{-1}$	$4.95 \cdot 10^{-1}$	$3.73 \cdot 10^{-1}$	$2.84 \cdot 10^{-1}$	$2.98 \cdot 10^{-1}$
ODP (kg CFC-11 eq)	$4.27 \cdot 10^{-9}$	$1.26 \cdot 10^{-8}$	$9.62 \cdot 10^{-9}$	$1.69 \cdot 10^{-8}$	$1.06 \cdot 10^{-8}$	$9.49 \cdot 10^{-9}$	$9.86 \cdot 10^{-9}$
POFP (kg C ₂ H ₄ eq)	$3.76 \cdot 10^{-4}$	$8.22 \cdot 10^{-5}$	$6.66 \cdot 10^{-5}$	$1.16 \cdot 10^{-4}$	$7.31 \cdot 10^{-5}$	$9.41 \cdot 10^{-5}$	$1.23 \cdot 10^{-4}$
AP (kg SO ₂ eq)	$1.08 \cdot 10^{-2}$	$2.85 \cdot 10^{-3}$	$2.32 \cdot 10^{-3}$	$4.06 \cdot 10^{-3}$	$2.52 \cdot 10^{-3}$	$2.36 \cdot 10^{-3}$	$2.98 \cdot 10^{-3}$
EP (kg PO ₄ ³⁻ eq)	$2.07 \cdot 10^{-3}$	$2.91 \cdot 10^{-3}$	$2.38 \cdot 10^{-3}$	$4.17 \cdot 10^{-3}$	$2.61 \cdot 10^{-3}$	$2.27 \cdot 10^{-3}$	$2.35 \cdot 10^{-3}$

3. Results and discussion

3.1. Environmental evaluation

The life-cycle inventories were implemented into the software SimaPro 7 [25]. A total of six environmental impact potentials were evaluated: abiotic depletion (ADP), global warming (GWP), ozone layer depletion (ODP), photochemical oxidant formation (POFP), acidification (AP) and eutrophication (EP). These impact categories were evaluated using the CML method [26]. This study considers only the environmental characterization of the proposed systems and it does not include optional elements of the life cycle impact assessment step, such as normalization and weighting [14]. This is an attempt to generate more objective results for the comparative environmental assessment of the systems [27,28]. Nevertheless, in order to explore the relative importance of each indicator, the results included could be easily normalized and aggregated using normalization/weighting sets, which adds subjectivity to the study [29].

3.1.1. CO₂ capture

Fig. 3 shows the results of the environmental characterization of the six CO₂ capture strategies considered. When more than one product is generated, allocation is necessary to distribute the inventory data and the environmental burdens among the products of the multifunctional system [30]. In this study, the environmental burdens were assigned only to the electricity produced.

As seen from the results plotted in Fig. 3, among the capture alternatives, post-combustion CO₂ recovery via membrane separation (case A.2) presents the lowest impacts for ADP, POFP and AP, while pre-combustion capture via coal gasification (case B.1) has the lowest values of GWP, ODP and EP. Hence, the choice of the most environmentally appropriate technology for CO₂ recovery depends on the selected impact categories. In this respect, it should be noted that the inclusion of six impact categories – instead of only the GWP category – leads to a more comprehensive evaluation of the environmental performance of these alternative technologies. This facilitates a more concrete decision-making process towards environmental sustainability [31].

As also observed in Fig. 3, coal supply is identified as the main source of environmental impact in each category. Direct emissions to the air also play an important role, especially concerning GWP and AP. Other processes contribute significantly to ODP, which is linked to fuel oil production.

3.1.2. CO₂ capture, transport and storage with and without enhanced resource recovery

Table 3 presents the environmental impacts calculated for each case study when CO₂ transport and geological storage without enhanced oil recovery are included in the system boundaries. When compared to the results of Fig. 3, additional energy requirements for CO₂ compression, transportation and injection lead to an increase in all impact categories. Table 3 also includes the

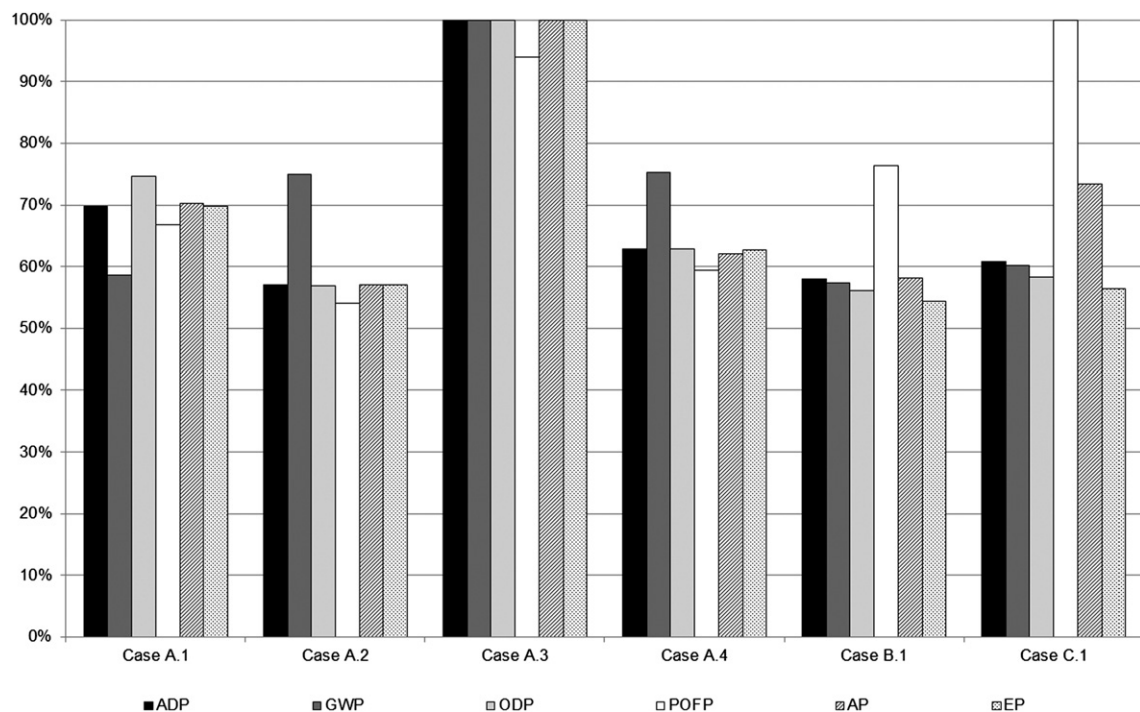


Fig. 4. Environmental comparison of the case studies including CO₂ transport (680 km) and geological storage without enhanced resource recovery.

environmental impacts associated with the reference plant. In comparison with this conventional facility, plants incorporating CCS strategies result in lower impacts of GWP, POFP and AP, but higher impacts of ADP, ODP and EP.

Fig. 4 provides a comparison among the different case studies including CO₂ transport and geological storage without beneficial use. Cases A.2, B.1 and A.4 are generally found to perform environmentally better than cases A.1 and A.3. In particular, case A.3 (which involves post-combustion capture via cryogenic fractionation) generally shows the highest environmental impacts.

When geological storage is used with EOR or ECBMR, the environmental profile of the CCS strategies changes, due to additional energy requirements. In this study, an allocation procedure based on avoided burdens was used, in order to take into account the environmental benefits of recovered crude oil or raw natural gas (avoided products) [27]. Thus, an environmental credit was applied to the system, deducting the impacts

associated with the conventional production of these products (crude oil/raw natural gas). Fig. 5 shows how the environmental profile of the different CCS schemes changes due to the incorporation of EOR and ECBMR.

The integration of EOR results in lower impacts for all categories, in comparison with the CCS systems without recovery. In particular, desirable impacts (i.e., negative characterized results) are obtained for ODP, due to the partial avoidance of the conventional production of crude oil.

When compared to the CCS systems without beneficial use, the implementation of an ECBMR scheme leads to lower impacts of ADP (desirable impact due to the partial avoidance of the conventional production of raw natural gas), GWP and POFP. Moreover, slightly lower values are obtained for EP. On the other hand, slightly increased impacts are found for ODP and AP due to additional power requirements for the recovery of the raw natural gas.

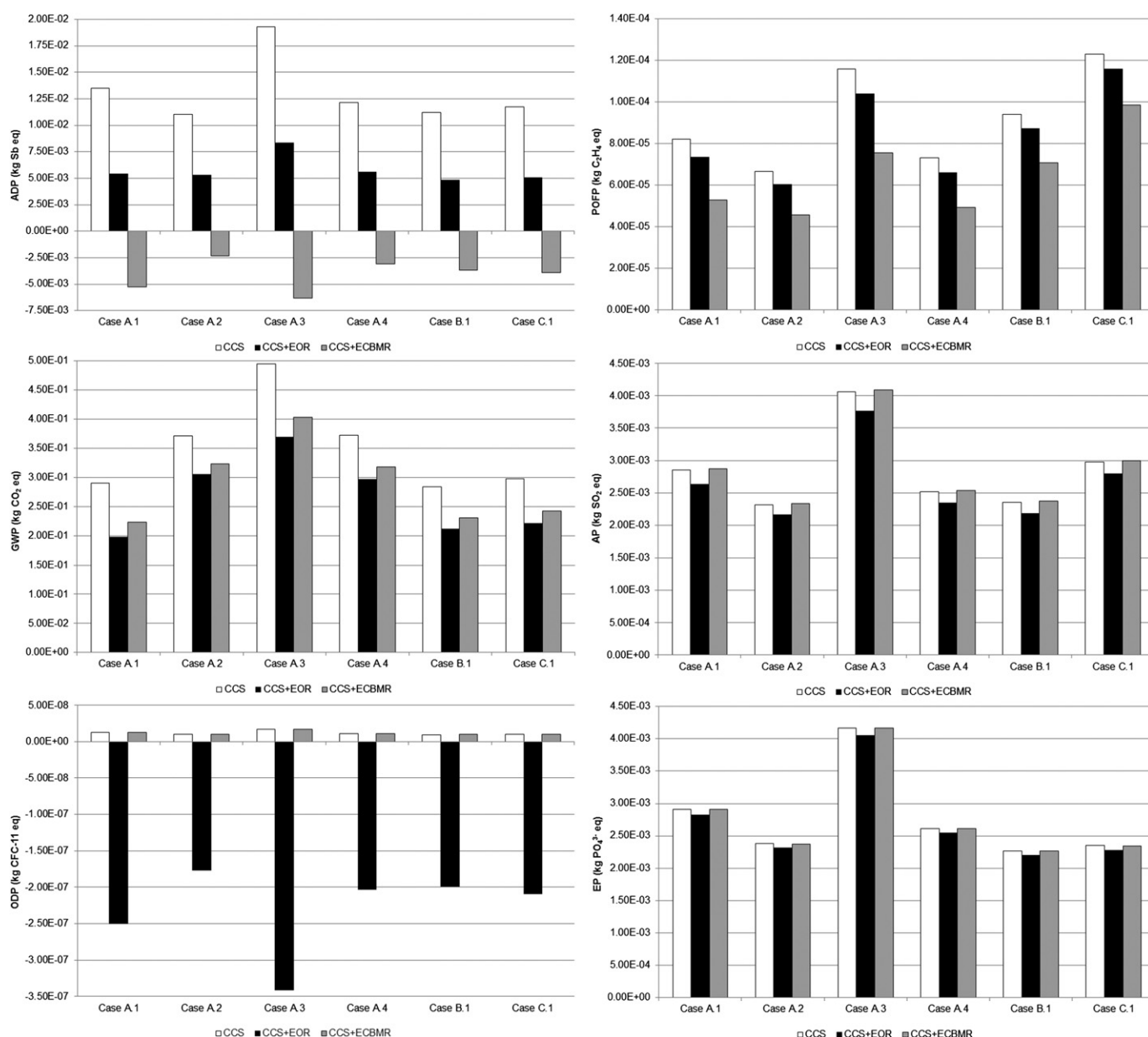


Fig. 5. Modification of the environmental profile of different CCS strategies due to the integration of EOR and ECBMR (impacts per FU allocated to the electricity output).

Table 4

CED of the different case studies (MJ per FU allocated to the electricity output).

	Case A.1	Case A.2	Case A.3	Case A.4	Case B.1	Case C.1
<i>From coal mining to CO₂ recovery</i>						
CED (MJ)	19.99	16.31	28.53	17.95	16.54	17.34
<i>From coal mining to CO₂ geological storage without enhanced resource recovery</i>						
CED (MJ)	20.20	16.45	28.81	18.12	16.71	17.51
<i>From coal mining to CO₂ geological storage with EOR</i>						
CED (MJ)	1.91	3.46	3.85	3.26	2.19	2.26
<i>From coal mining to CO₂ geological storage with ECBMR</i>						
CED (MJ)	−18.22	−10.86	−23.66	−13.07	−13.83	−14.52

CED of the reference plant: 12.80 MJ.

3.2. Cumulative energy analysis

The life-cycle energy balance of each case study was calculated as the difference between the energy output (i.e., 1 kWh = 3.6 MJ) and the life-cycle energy input. The use of a life-cycle approach in the calculation of the energy input differentiates between conventional and life-cycle energy balances. Positive balances are desired, as they indicate feasible energy conversion systems [32,33].

The life-cycle energy input of the case studies was calculated as their CED. Here, CED refers to the cumulative (non-renewable) fossil and nuclear energy demand as defined by Hischier et al. [34], it includes coal as raw material and it is calculated through the implementation of the life-cycle inventories into SimaPro 7 [25]. As seen in Table 4, the lowest CED values are obtained when enhanced resource recovery strategies are implemented. This result is linked to the selected allocation approach, which considers crude oil and raw natural gas as avoided products. Specifically, the incorporation of ECBMR strategies shows negative CED values in all cases, indicating potential energy savings.

In Fig. 6, the life-cycle energy balances are presented, which were calculated by deducting the CED values from the electricity output (3.6 MJ). All examined strategies involving only CO₂ recovery are found to be energetically detrimental, while the scenarios including carbon capture and geological storage without enhanced resource recovery perform energetically worse. The integration of enhanced resource recovery generally results in positive energy balances, with the ECBMR strategies resulting in the highest life-cycle energy balances. Taking into account the environmental

assessment presented in Section 3.1, it should be noted that, overall, both environmental and energy results encourage the use of enhanced resource recovery strategies.

3.3. Exergetic analysis

The overall thermodynamic performance of the plants was evaluated based on their exergetic efficiencies. The exergy of the fuel of the reference plant [11] was calculated to be 12,287 kJ, while the exergy of the product was 3600 kJ. Therefore, the exergetic efficiency of the reference plant is found to be 29.30%.

The exergy of the product for all of the plants was kept the same as for the reference plant (1 kWh or 3600 kJ), while the exergy of the fuel was calculated for each plant individually and it depended on the specific operation of each plant. For each of the plants, the additional energy requirement for capturing the CO₂ generated is correlated to additional fuel input. On the other hand, the transport and storage of the CO₂ are correlated to additional power input that is provided by booster stations connected to the electrical grid. These two points lead to differences in the exergy of the fuel, and consequently, in the efficiencies of the plants. If the electricity required for transport and storage of the CO₂ would be covered by electricity generated in the power plants and not from the grid, the overall efficiencies of the plants would naturally decrease. However, such assumption can only be made when relatively short transport distances are examined. For distances of over 100–150 km, such as in the present study, booster stations are required for the recompression of the stream [35].

The operation of the plants was first evaluated when CO₂ capture is incorporated (Table 5). In this case, the energy penalty depends on the energy requirement of the capture technology used [36]. The best option is found to be the plant that includes membrane separation (case A.2), which presents a penalty of 4.3 percentage points with respect to the conventional plant without CCS, followed closely by the plant with pre-combustion technology (case B.1). Moderate results are obtained for the plants with oxy-fuel technology (case C.1) and PSA (case A.4), while a high penalty is found for the plant using MEA (case A.1). Lastly, the plant that includes the cryogenic unit (case A.3) presents the lowest efficiency among the six alternatives, due to the high energy requirements of its operation.

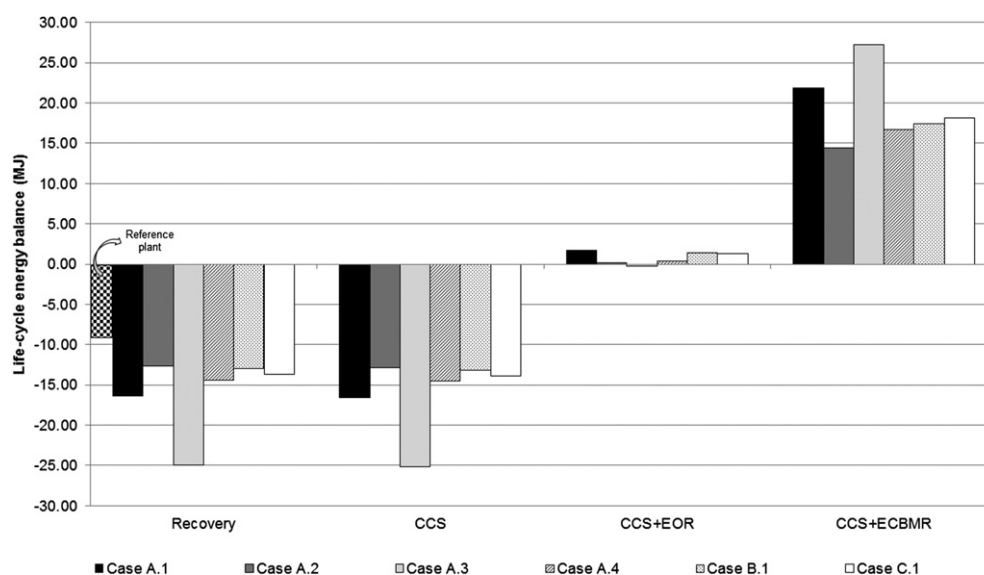
**Fig. 6.** Life-cycle energy balance of each strategy under evaluation (MJ).

Table 5

Exergetic efficiencies of the power plants incorporating CO₂ capture and CO₂ capture, transport (680 km) and storage.

	Capture of CO ₂			Capture and storage of CO ₂			
	$\dot{E}_{F,tot}$ (kJ)	$\dot{E}_{P,tot}$ (kJ)	ϵ_{tot} (%)	$\dot{E}_{F,tot}$ (kJ)	$\dot{E}_{P,tot}$ (kJ)	ϵ_{tot} (%)	Reduction in ϵ_{tot} (%points)
Case A.1	17,499	3600	20.57	17,582	3600	20.48	0.10
Case A.2	14,422	3600	24.96	14,481	3600	24.86	0.10
Case A.3	25,231	3600	14.27	25,345	3600	14.20	0.06
Case A.4	15,877	3600	22.67	15,945	3600	22.58	0.10
Case B.1	14,687	3600	24.51	14,753	3600	24.40	0.11
Case C.1	15,392	3600	23.39	15,461	3600	23.28	0.10

ϵ_{tot} of the reference plant: 29.30%.

Transport and storage are found to affect the overall efficiency of the plants marginally, with the operating efficiencies of the plants decreasing by a maximum of 0.11 percentage points with respect to the efficiencies of the plants incorporating only CO₂ capture (Table 5). The minimum decrease is found for the plant including cryogenic fractionation (case A.3), while the maximum decrease is calculated for the pre-combustion plant (case B.1). In all cases, 100% of the CO₂ captured was considered to be stored. As mentioned earlier, if the electricity of transport and storage were covered by the plant itself, the overall operating efficiencies would decrease. For example, for the plant with membrane separation, the overall efficiency of the plant would be approximately 0.4 percentage points lower than that reported in Table 5.

Lastly, the exergetic efficiencies of the plants were recalculated when CO₂ storage is combined with beneficial use of the CO₂. As mentioned, the two paths of beneficial use considered were ECBMR and EOR. It was assumed that 0.5 t of natural gas and 0.3 t of oil are recovered with each tonne of CO₂ injected [12]. When compared to the plants incorporating CO₂ capture, transport and storage without enhanced resource recovery, beneficial use is found to be associated with an additional, relatively small, penalty related to the extraction of the fuels (Table 6). On the other hand, recovering oil and natural gas increases the availability in fuels and the revenue of the facility. Thus, the incorporation of beneficial use slightly decreases the efficiency of the plants, but it recovers raw natural gas or crude oil.

The total exergy of the recovered fuels is shown in Table 6. Although the difference among the efficiencies calculated when beneficial use is performed is small, independent of the CO₂ capture technology used, ECBMR shows better results. Additionally, the exergy of the natural gas recovered during ECBMR is higher than

Table 6

Exergetic efficiencies of the power plants incorporating capture, transport (680 km) and geological storage with beneficial use of CO₂.

	$\dot{E}_{F,tot}$ (kJ)	$\dot{E}_{P,tot}$ (kJ)	ϵ_{tot} (%)	Reduction in ϵ_{tot} (%points)	Exergy of recovered resource (kJ)
ECBMR					
Case A.1	17,587	3600	20.47	0.01	26,737
Case A.2	14,485	3600	24.85	0.01	19,018
Case A.3	25,351	3600	14.20	0.00	36,517
Case A.4	15,949	3600	22.57	0.01	21,703
Case B.1	14,757	3600	24.40	0.01	21,257
Case C.1	15,465	3600	23.28	0.01	22,277
EOR					
Case A.1	17,625	3600	20.43	0.05	9244
Case A.2	14,512	3600	24.81	0.05	6576
Case A.3	25,403	3600	14.17	0.03	12,627
Case A.4	15,980	3600	22.53	0.05	7504
Case B.1	14,787	3600	24.35	0.06	7350
Case C.1	15,497	3600	23.23	0.05	7703

ϵ_{tot} of the reference plant: 29.30%.

that of the oil recovered during EOR. Thus, overall, post-combustion capture using membrane separation with transport and storage including ECBMR appears to be the most promising alternative. When compared to the plant with pre-combustion, the plant with membrane separation presents here a slightly lower penalty of storage due to the smaller mass flow of CO₂ captured and stored.

When ECBMR is performed, the plant with MEA, which is the most conventional post-combustion capture, presents an efficiency penalty of 8.8 percentage points (with respect to the reference power plant without CCS) that increases to approximately 8.9 percentage points when EOR is considered. Nevertheless, we should mention that when beneficial use is performed, the benefit of the additional fuel was not included in the efficiencies but it was considered as additional available exergy produced, presented as a separate value in Table 6.

4. Conclusions

Six case studies involving different CO₂ capture technologies for coal-fired power plants were assessed from both environmental and thermodynamic perspectives. We found that among the capture technologies, post-combustion capture with membrane separation and pre-combustion capture through coal gasification result in the lowest environmental impacts and the highest efficiencies. Coal supply and direct emissions to the air were identified as the main sources of environmental impact.

Transport and geological storage without enhanced resource recovery increase the environmental impacts and decrease the efficiency of the plants, due to the additional energy requirements for CO₂ compression, transportation and injection. Although additional energy is required to recover crude oil when storing CO₂ in depleted oil fields, the integration of an EOR scheme was shown to be an environmentally friendly alternative. In the case of ECBMR, the environmental results of the plants depend on the impact categories evaluated. A relevant difference between the two beneficial uses considered stems from the exergy of the recovered fuel; the exergy of the natural gas recovered during ECBMR exceeds that of the oil recovered during EOR.

Based on the life-cycle energy balances, the strategies considering only carbon capture, as well as those considering carbon capture and geological storage without enhanced resource recovery are energetically ineffective, independent of the capture technology used. However, favourable life-cycle energy balances can be achieved when incorporating enhanced resource recovery strategies.

Overall, post-combustion capture (through membrane separation) and pre-combustion capture (via coal gasification), coupled with CO₂ transport and geological storage with EOR or ECBMR, were found to be the CCS technologies with the most promising performance.

Acknowledgements

Dr. Fontina Petrakopoulou would like to thank the AMAROUT Action (PEOPLE-COFUND) funded by the 7th Framework Programme.

References

- [1] Peht M, Henkel J. Life cycle assessment of carbon dioxide capture and storage from lignite power plants. *Int J Greenh Gas Con* 2009;3:49–66.
- [2] Vega LF. El CO₂ como recurso. 1st ed. Barcelona: gasNatural Foundation; 2010.
- [3] Singh B, Strømman AH, Hertwich EG. Comparative life cycle environmental assessment of CCS technologies. *Int J Greenh Gas Con* 2011;5:911–21.
- [4] Petrakopoulou F. Comparative evaluation of power plants with CO₂ capture: thermodynamic, economic and environmental performance. Doctoral thesis, Technische Universität Berlin; 2010.

- [5] Romeo LM, Calvo E, Valero A, De Vita A. Electricity consumption and CO₂ capture potential in Spain. *Energy* 2009;34:1341–50.
- [6] Mondal MK, Balsora HK, Varshney P. Progress and trends in CO₂ capture/separation technologies: a review. *Energy* 2012;46:431–41.
- [7] Petrakopoulou F, Tsatsaronis G. Production of hydrogen-rich fuels for pre-combustion carbon capture in power plants: a thermodynamic assessment. *Int J Hydrogen Energ* 2012;37:7554–64.
- [8] Petrakopoulou F, Tsatsaronis G, Piancanstelli C, Gallio I, Morosuk T. Exergetic and exergoeconomic analyses of an oxy-fuel power plant with CO₂ capture. In: Acosta MJ, editor. *Advances in energy research*, vol. 6. New York: Nova Publishers; 2011. p. 229–42.
- [9] Schreiber A, Zapp P, Kuckshinrichs W. Environmental assessment of German electricity generation from coal-fired power plants with amine-based carbon capture. *Int J Life Cycle Ass* 2009;14:547–59.
- [10] Petrakopoulou F, Tsatsaronis G, Morosuk T, Boyano A. Thermodynamic, economic and environmental performance of a power plant with post-combustion CO₂ capture using monoethanolamine. In: Liu G, editor. *Greenhouse gases – emission, measurement and management*. Rijeka: InTech; 2012. p. 463–84.
- [11] Khoo HH, Tan RBH. Life cycle investigation of CO₂ recovery and sequestration. *Environ Sci Technol* 2006;40:4016–24.
- [12] Khoo HH, Tan RBH. Environmental impact evaluation of conventional fossil fuel production (oil and natural gas) and enhanced resource recovery with potential CO₂ sequestration. *Energ Fuel* 2006;20:1914–24.
- [13] ISO 14040:2006. Environmental management – life cycle assessment – principles and framework. International Organization for Standardization; 2006.
- [14] ISO 14044:2006. Environmental management – life cycle assessment – requirements and guidelines. International Organization for Standardization; 2006.
- [15] Strube R, Pellegrini G, Manfrida G. The environmental impact of post-combustion CO₂ capture with MEA, with aqueous ammonia, and with an aqueous ammonia-ethanol mixture for a coal-fired power plant. *Energy* 2011;36:3763–70.
- [16] Singh B, Strømman AH, Hertwich EG. Scenarios for the environmental impact of fossil fuel power: co-benefits and trade-offs of carbon capture and storage. *Energy* 2012;45:762–70.
- [17] Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Heck T, Hellweg S, et al. Overview and methodology. ecoinvent report No. 1, v2.0. Dübendorf: Swiss Centre for Life Cycle Inventories; 2007.
- [18] Althaus HJ, Chudacoff M, Hirschier R, Jungbluth N, Osses M, Primas A. Life cycle inventories of chemicals. ecoinvent report No. 8, v2.0. Dübendorf: Swiss Centre for Life Cycle Inventories; 2007.
- [19] Dones R, Bauer C, Bolliger R, Burger B, Faist Emmenegger M, Frischknecht R, et al. Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. ecoinvent report no. 5, v2.0. Dübendorf: Swiss Centre for Life Cycle Inventories; 2007.
- [20] US Life Cycle Inventory Database [Internet]. National renewable energy laboratory [cited 2012 Mar 4]. Available from: <http://www.nrel.gov/lci>.
- [21] Tsatsaronis G. Strengths and limitations of exergy analysis. In: Bejan A, Mamut E, editors. *Thermodynamic optimization of complex energy systems*. Dordrecht: Kluwer Academic Publishers; 1998. p. 93–100.
- [22] Tsatsaronis G, Winhold M. Exergoeconomic analysis and evaluation of energy-conversion plants—I. A new general methodology. *Energy* 1985;10:69–80.
- [23] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: Wiley-Interscience; 1995.
- [24] Lazzaretto A, Tsatsaronis G. Speco: a systematic and general methodology for calculating efficiencies and costs in thermal systems. *Energy* 2006;31:1257–89.
- [25] Goedkoop M, de Schryver A, Oele M, Durksz S, de Roest D. Introduction to LCA with SimaPro 7. the Netherlands: PRé Consultants; 2010.
- [26] Guinée JB, Gorrié M, Heijungs R, Huppes G, Kleijn R, de Koning A, et al. Life cycle assessment – an operational guide to the ISO standards. Leiden: Centre of Environmental Science; 2001.
- [27] Iribarren D, Dufour J, Serrano DP. Preliminary assessment of plastic waste valorization via sequential pyrolysis and catalytic reforming. *J Mater Cycles Waste Manag* 2012;14:301–7.
- [28] Iribarren D, Peters JF, Dufour J. Life cycle assessment of transportation fuels from biomass pyrolysis. *Fuel* 2012;97:812–21.
- [29] Reap J, Roman F, Duncan S, Bras B. A survey of unresolved problems in life cycle assessment – part 2: impact assessment and interpretation. *Int J Life Cycle Ass* 2008;13:374–88.
- [30] Ekvall T, Finnveden G. Allocation in ISO 14041 – a critical review. *J Clean Prod* 2001;9:197–208.
- [31] Dufour J, Iribarren D. Life cycle assessment of biodiesel production from free fatty acid-rich wastes. *Renew Energ* 2012;38:155–62.
- [32] González-García S, Iribarren D, Susmozas A, Dufour J, Murphy RJ. Life cycle assessment of two alternative bioenergy systems involving *Salix* spp. biomass: bioethanol production and power generation. *Appl Energ* 2012;96:111–22.
- [33] Serrano DP, Dufour J, Iribarren D. On the feasibility of producing hydrogen with net carbon fixation by the decomposition of vegetable and microalgal oils. *Energ Environ Sci* 2012;5:6126–35.
- [34] Hirschier R, Weidema B, Althaus HJ, Bauer C, Doka G, Dones R, et al. Implementation of life cycle impact assessment methods. ecoinvent report No. 3, v2.1. Dübendorf: Swiss Centre for Life Cycle Inventories; 2009.
- [35] Bachu S, Chalaturnyk R, Gerbis M, Gunter B, Harwood J, Keith D, et al. Building capacity for CO₂ capture and storage in the APEC region – a training manual for policy makers and practitioners. Singapore: APEC Secretariat; 2009.
- [36] Hammond GP, Ondo Akwe SS, Williams S. Techno-economical appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage. *Energy* 2011;36:975–84.