Energy 50 (2013) 477–485

Contents lists available at SciVerse ScienceDirect

Energy

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

Environmental and thermodynamic evaluation of CO_2 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

A R T I C L E I N F O

Article history:
Received 8 August 2012
Received in revised form
5 December 2012
Accepted 19 December 2012
Available online 20 January 2013

Keywords:
Carbon capture and storage
Cumulative energy demand
Exergy
Life cycle assessment
Power plant

A B S T R A C T

This study evaluates the environmental and thermodynamic performance of six coal-fired power plants with CO_2 capture and storage. The technologies examined are post-combustion capture using monoethanolamine, membrane separation, cryogenic fractionation and pressure swing adsorption, pre-combustion capture through coal gasification, and capture performing conventional oxy-fuel combustion. The incorporation of CO_2 capture is evaluated both on its own and in combination with CO_2 transport and geological storage, with and without beneficial use.

Overall, we find that pre-combustion CO_2 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 CO_2 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.

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 CO_2 emissions. For instance, fossil-fuelled power plants are suitable application sites for the implementation of CCS technologies [1–5].

CO_2 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 CO_2 [1,3,8]. Finally, in post-combustion capture, the CO_2 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 CO_2 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 CO_2 into deep unmineable coal seams [12]. Also, the recovered CO_2 can be used in technological, chemical and biological applications [2].

The present article deals with the environmental and thermodynamic evaluation of CO_2 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).

0360-5442/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2012.12.021

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 CO_2 captured with and without enhanced resource recovery. The first CO_2 capture technology considered was post-combustion using chemical absorption with monoethanolamine (MEA). In order to incorporate different CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 capture technology with the best environmental performance.
- Environmental characterization of the power plants including CO_2 transport and geological storage, and comparison of these CCS schemes with plants incorporating only CO_2 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 CO_2 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 CO_2 capture (i.e., the reference plant) were taken from specific databases [19,20].

2.2.1. *CO_2 capture*

Inventory data were collected for each power plant, from the mining of the coal to the generation of liquid CO_2. Data for case A.1 were based on literature on post-combustion CO_2 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 CO_2 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 CO_2 capture strategy.

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

While Section 2.2.1 refers only to CO_2 recovery, the present section widens the scope of the study to include CO_2 transport and geological storage with and without enhanced resource recovery. The electricity required for the transportation of the CO_2 depends on the distance. In this specific study, 680 km pipeline transportation of supercritical CO_2 was assumed, with a preceding CO_2 compression stage. Inventory data regarding CO_2 transport and storage focus on the energy requirements of CO_2 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].

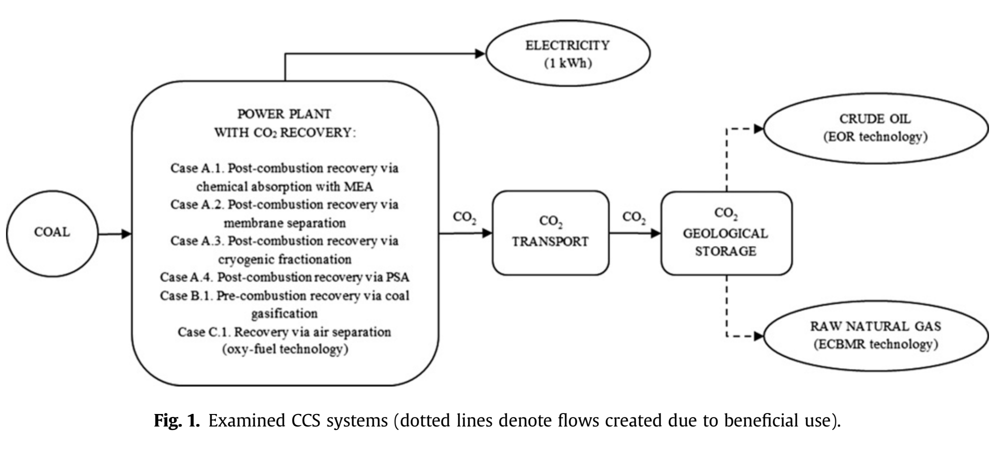

Fig. 1. Examined CCS systems (dotted lines denote flows created due to beneficial use).

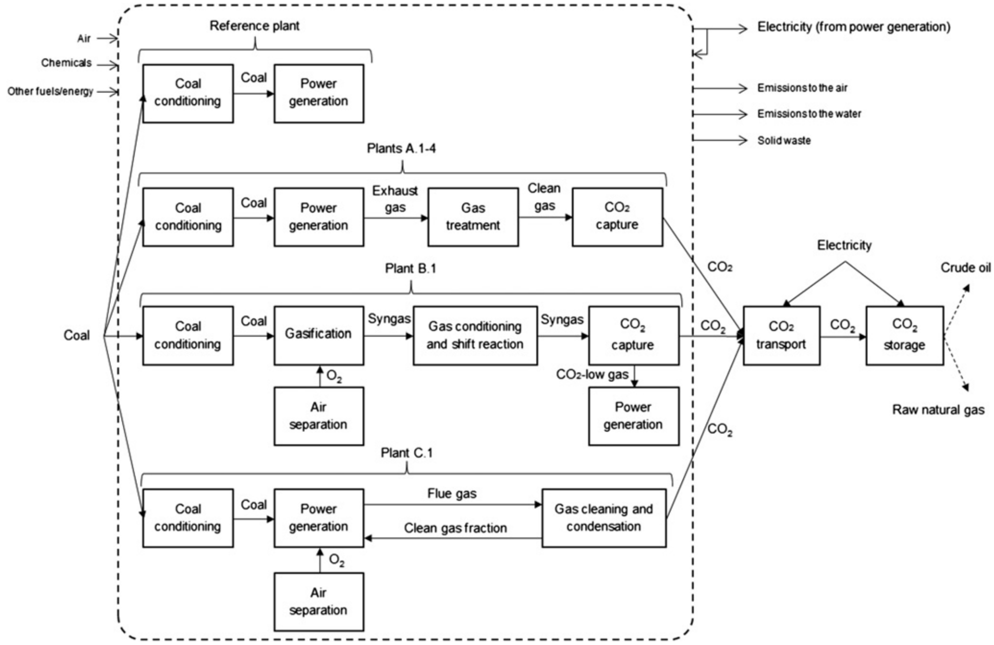

Fig. 2. Life-cycle flowchart of the evaluated systems (dotted arrows denote flows created due to beneficial use).

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 ($\varepsilon_{tot} = \dot{E}_{P,tot}/\dot{E}_{F,tot}$) [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 2
Additional data for CO_2 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)	Electricity demand[b] (kWh)	Recovered natural gas (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 CO_2 recovery. It is linked to CO_2 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.

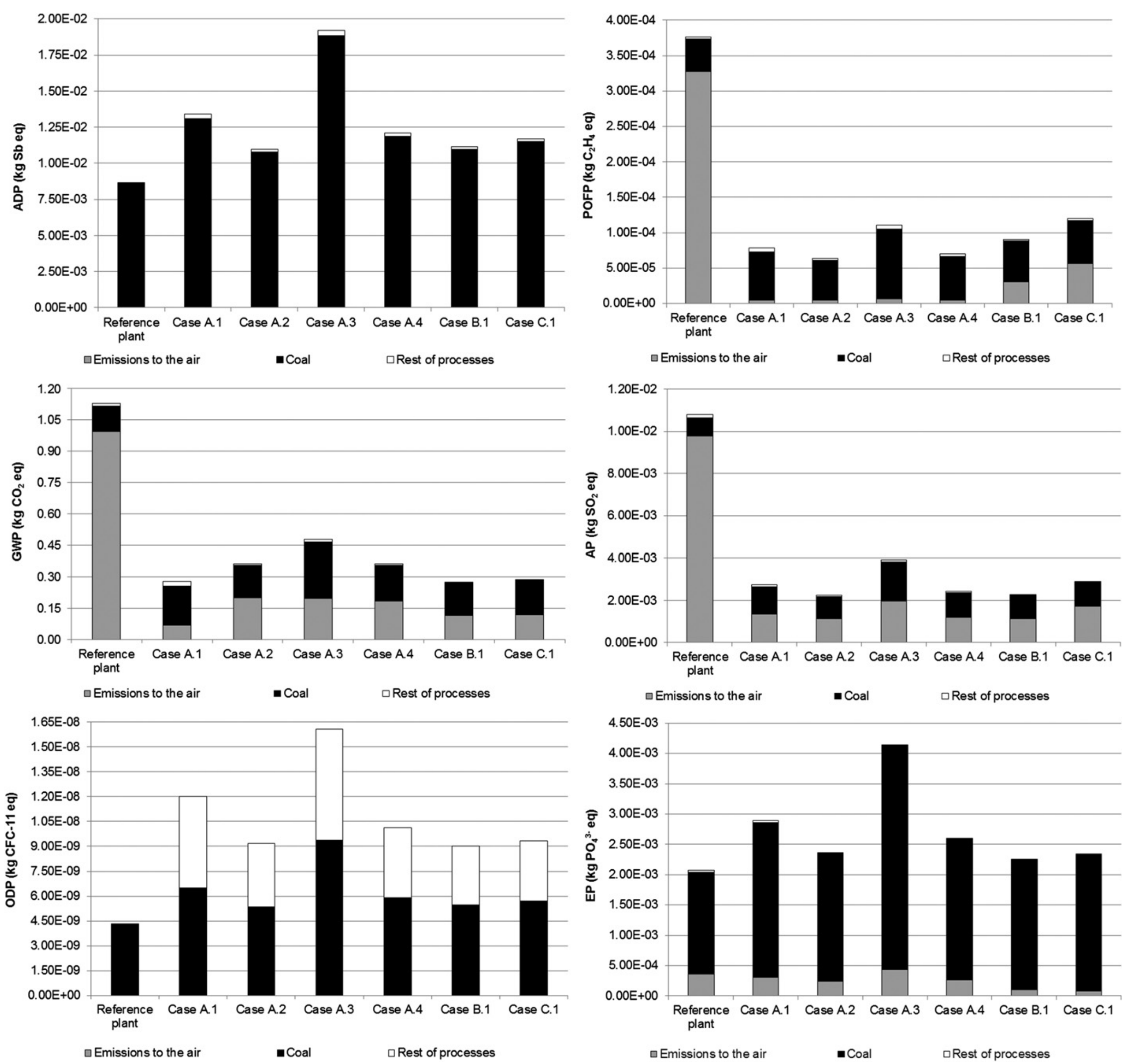

Fig. 3. Environmental impacts of the different CO_2 capture technologies.

Table 3
Environmental characterization results including CO_2 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)	$8.67\cdot10^{-3}$	$1.35\cdot10^{-2}$	$1.10\cdot10^{-2}$	$1.93\cdot10^{-2}$	$1.22\cdot10^{-2}$	$1.12\cdot10^{-2}$	$1.18\cdot10^{-2}$
GWP (kg CO_2 eq)	1.13	$2.90\cdot10^{-1}$	$3.71\cdot10^{-1}$	$4.95\cdot10^{-1}$	$3.73\cdot10^{-1}$	$2.84\cdot10^{-1}$	$2.98\cdot10^{-1}$
ODP (kg CFC-11 eq)	$4.27\cdot10^{-9}$	$1.26\cdot10^{-8}$	$9.62\cdot10^{-9}$	$1.69\cdot10^{-8}$	$1.06\cdot10^{-8}$	$9.49\cdot10^{-9}$	$9.86\cdot10^{-9}$
POFP (kg C_2H_4 eq)	$3.76\cdot10^{-4}$	$8.22\cdot10^{-5}$	$6.66\cdot10^{-5}$	$1.16\cdot10^{-4}$	$7.31\cdot10^{-5}$	$9.41\cdot10^{-5}$	$1.23\cdot10^{-4}$
AP (kg SO_2 eq)	$1.08\cdot10^{-2}$	$2.85\cdot10^{-3}$	$2.32\cdot10^{-3}$	$4.06\cdot10^{-3}$	$2.52\cdot10^{-3}$	$2.36\cdot10^{-3}$	$2.98\cdot10^{-3}$
EP (kg PO_4^{3-} eq)	$2.07\cdot10^{-3}$	$2.91\cdot10^{-3}$	$2.38\cdot10^{-3}$	$4.17\cdot10^{-3}$	$2.61\cdot10^{-3}$	$2.27\cdot10^{-3}$	$2.35\cdot10^{-3}$

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. CO_2 capture

Fig. 3 shows the results of the environmental characterization of the six CO_2 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 CO_2 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 CO_2 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. CO_2 capture, transport and storage with and without enhanced resource recovery

Table 3 presents the environmental impacts calculated for each case study when CO_2 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 CO_2 compression, transportation and injection lead to an increase in all impact categories. Table 3 also includes the

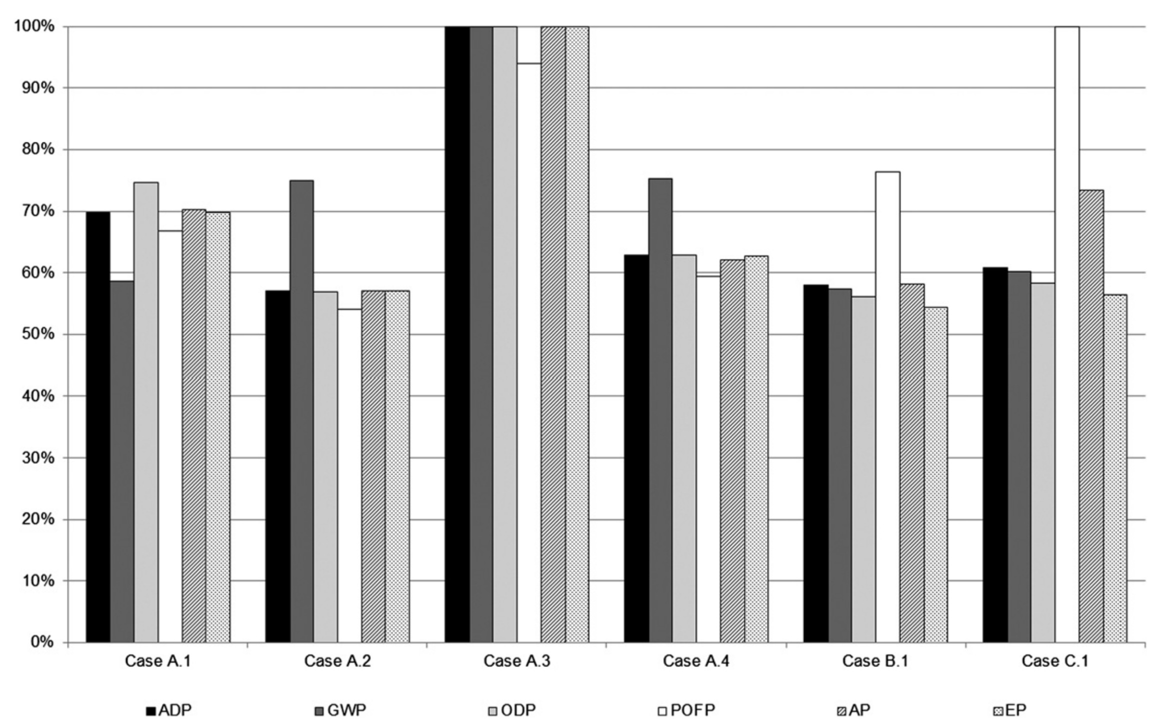

Fig. 4. Environmental comparison of the case studies including CO_2 transport (680 km) and geological storage without enhanced resource recovery.

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 CO_2 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.

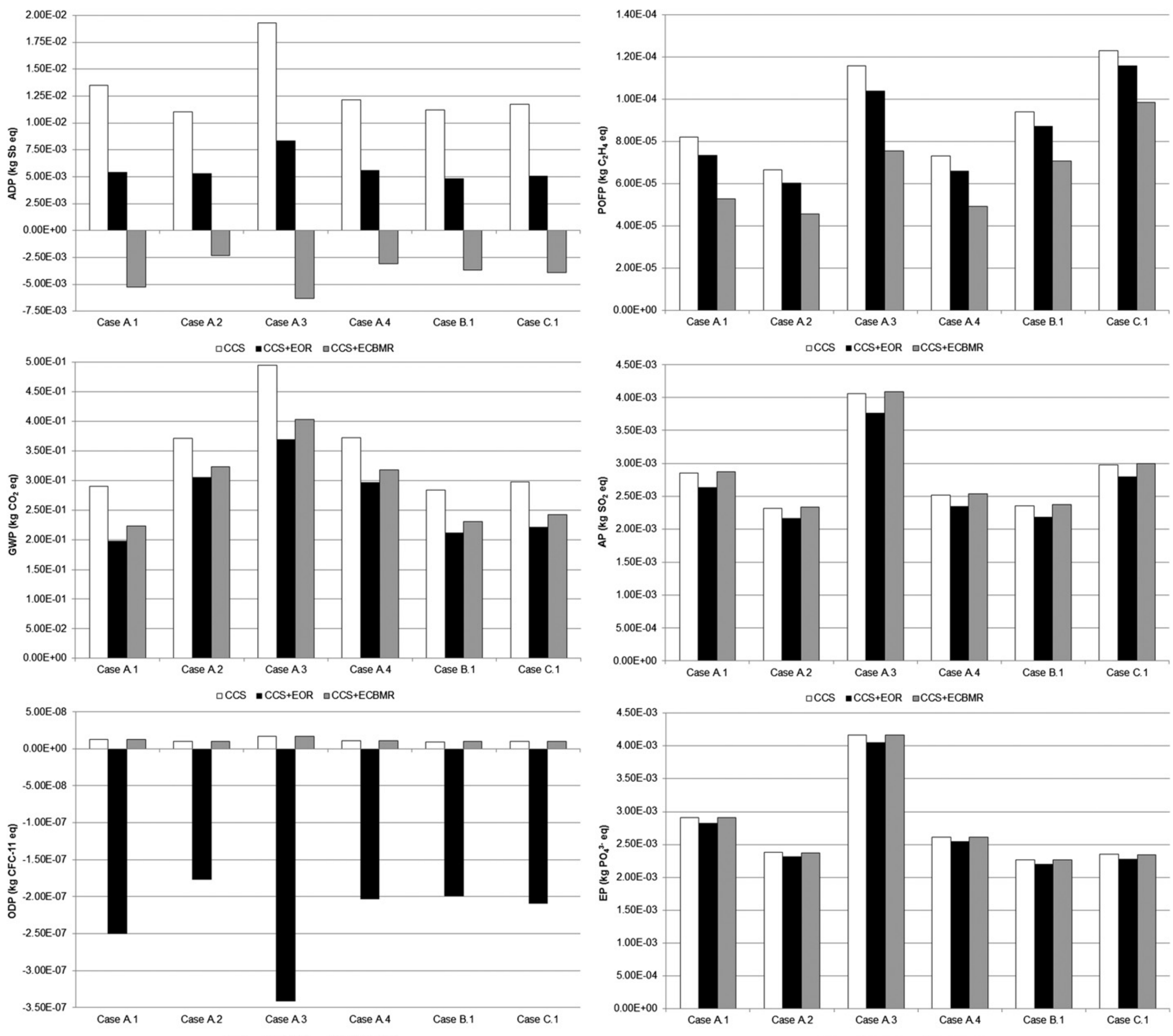

Fig. 5. Modification of the environmental profile of different CCS strategies due to the integration of EOR and ECBMR (impacts per FU allocated to the electricity output).

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
From coal mining to CO_2 recovery						
CED (MJ)	19.99	16.31	28.53	17.95	16.54	17.34
From coal mining to CO_2 geological storage without enhanced resource recovery						
CED (MJ)	20.20	16.45	28.81	18.12	16.71	17.51
From coal mining to CO_2 geological storage with EOR						
CED (MJ)	1.91	3.46	3.85	3.26	2.19	2.26
From coal mining to CO_2 geological storage with ECBMR						
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 CO_2 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 CO_2 generated is correlated to additional fuel input. On the other hand, the transport and storage of the CO_2 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 CO_2 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 CO_2 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.

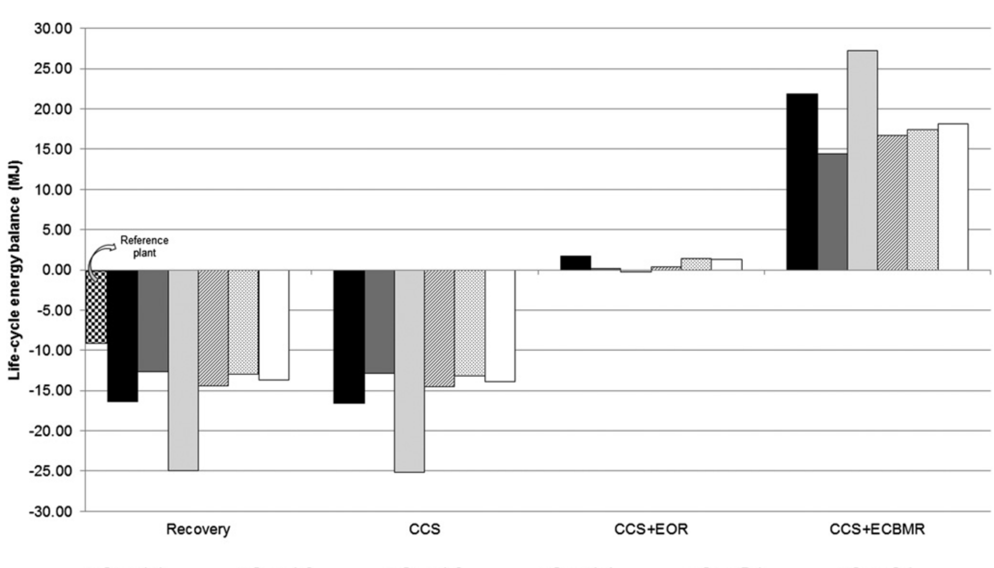

Fig. 6. Life-cycle energy balance of each strategy under evaluation (MJ).

Table 5
Exergetic efficiencies of the power plants incorporating CO_2 capture and CO_2 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 CO_2 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 CO_2 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 CO_2 storage is combined with beneficial use of the CO_2. 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 CO_2 injected [12]. When compared to the plants incorporating CO_2 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 CO_2 capture technology used, ECBMR shows better results. Additionally, the exergy of the natural gas recovered during ECBMR is higher than 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 CO_2 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.

Table 6
Exergetic efficiencies of the power plants incorporating capture, transport (680 km) and geological storage with beneficial use of CO_2.

	$\dot{E}_{F,tot}$ (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%.

4. Conclusions

Six case studies involving different CO_2 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 CO_2 compression, transportation and injection. Although additional energy is required to recover crude oil when storing CO_2 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 CO_2 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] Pehnt 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 CO_2 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 CO_2 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 CO_2 capture potential in Spain. Energy 2009;34:1341–50.
[6] Mondal MK, Balsora HK, Varshney P. Progress and trends in CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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, Hischier 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, Gorrée 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] Hischier 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 CO_2 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.