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Life cycle modelling and comparative assessment of the environmental impacts of oxy-fuel and post-combustion CO_2 capture, transport and injection processes

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Abstract

The oxy-fuel combustion CO_2 capture route and post-combustion CO_2 capture route involve different energy consumption rates and subsequent environmental impacts. The holistic perspective offered by Life Cycle Assessment (LCA) can help decision makers to compare alternative CO_2 capture and storage technologies in a life cycle perspective. This paper, at first, introduces the principles of the dynamic LCA model developed for oxy-fuel combustion and post-combustion power generation with CO_2 capture, transport and injection processes. Next, a comparative life cycle assessment of alternative CO_2 capture technologies is presented. Results show that, at life-cycle level, the post-combustion and oxy-fuel combustion CCS cases can reduce the life-cycle Global Warming Potential (GWP) by 78.8% and 80.0% respectively compared to conventional power plant without CCS. Other environmental impacts, such as Ecotoxicity, Human toxicity and Acidification, vary significantly with the different CO_2 capture routes employed. Finally, by comparing the results obtained with the most recent LCA studies of post-combustion power generation with CO_2 capture and storage, it is shown that the plant level, gate-to-gate studies provide significantly variable results and generally overestimate life cycle environmental impacts.

Keywords: Life cycle assessment; Oxy-fuel combustion; Post-combustion; CO_2 capture and storage

1. Introduction

The CO_2 capture technologies offer a number of alternatives, which involve different power generation and capture routes with varied energy consumption rates and subsequent environmental impacts. The holistic perspective offered by Life Cycle Assessment (LCA) can help decision makers to quantify the trade-offs inherent in any change to the power production systems and ensure that a reduction in greenhouse gas (GHG) emissions would not cause increases in other environmental impacts. The life cycle performance of various power generation plant configurations with alternative CO_2 capture systems, transport and injection scenarios have been investigated by previous LCA studies [1, 2, 3, 4, 5, 6, 7]. However, since these studies are based on a low resolution analysis (plant level analysis or gate-to-gate data from generic databases), these studies report wide ranging results for climate change impacts and other impact categories such as abiotic resource depletion, acidification, human toxicity, etc. which cannot be adequately characterised in coarse resolution LCA studies. The use of gate-to-gate data implies that the electricity generation systems have been largely simplified to a single blackbox with constants and linear coefficients used to assign inputs and outputs, covering a broad range of technological and geographical differences, in which the actual variability of process parameters and operating conditions are implicitly neglected. In addition, plant level analysis limits the capacity of such studies to quantify the trade-offs inherent in any change to the power production systems and restrict the ability to identify design options that eliminate highly polluting emissions.

In this respect, the dynamic LCA model developed at Imperial College incorporates fossil fuel power generation, CO_2 capture, CO_2 conditioning, pipeline transportation and injection and storage, and quantifies the environmental impacts at the highest level of detail, allowing for the assessment of technical and geographical differences between the alternative power

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generation, CO_2 capture, transport and storage technologies considered. An earlier paper by the authors [8] presents the post-combustion life cycle model developed while this paper presents the principles of the LCA models developed for the oxy-fuel power generation and CO_2 capture system and discusses, in detail, the comparative assessment carried out between the post-combustion and oxy-fuel capture options modelled.

2. The life cycle assessment model developed

The system boundaries of LCA in power generation with CO_2 capture and storage, a generalised outline of which is presented in Figure 1, cover power generation, alternative CO_2 capture options, and upstream processes such as extraction and production of fossil fuels, raw materials production, as well as gas compression, transport and storage. The functional unit selected is 1 MWh of electricity generated. The LCA model for the CO_2 storage system processes is not reported here due to the complexity of the model that cannot be adequately presented in a short manuscript.

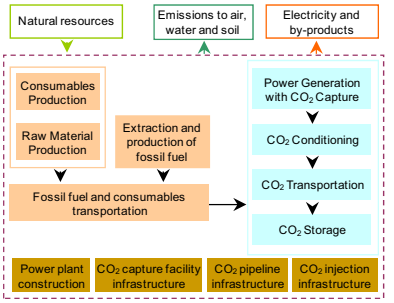


Figure 1. Generalised outline of the power generation with CCS LCA system and boundaries.

The CCS value chain comprises inter-linked component unit processes that are closely dependent upon each other. In the methodology the authors developed, the systems were broken down or modularised into subsystems or component unit processes connected by flows of intermediate products or emissions as illustrated in Figure 2 for the oxy-fuel combustion CCS system. Through modularisation, the Life Cycle Inventory (LCI) models developed quantify flows of materials, natural resources, energy, intermediate products and emissions at component unit process level. This approach makes sure that the technical, spatial and temporal differences that exist between different industrial sites and operations can be accounted for by modifying certain parameters of the component unit processes as necessary. Furthermore, modularisation eliminates the limitations introduced by the linear input/output coefficients used by conventional LCI models. The flexible structure of the LCI database provided through modularisation enables the practitioner to choose component unit processes so that different technological options can be considered without the need for redesign or loss of information [8].

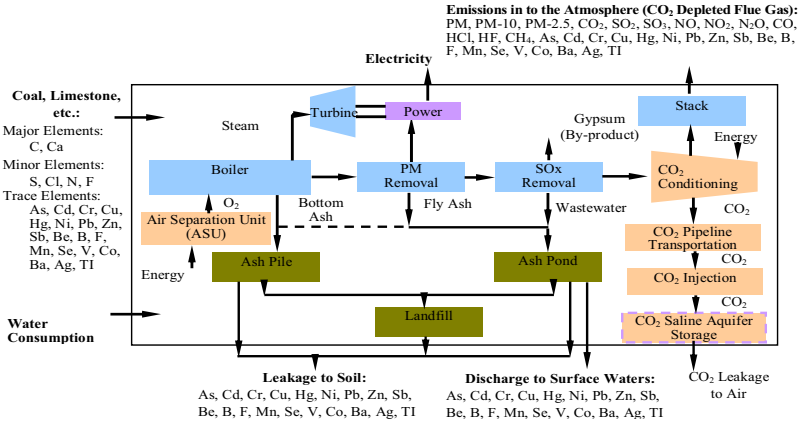


Figure 2. The level of detail involved in the LCA of oxy-fuel-combustion CCS system.

The oxy-fuel LCI model reported here was developed in collaboration with Vattenfall AB and includes the oxy-fuel combustion unit, air separation unit, particulate matter (PM) removal unit, SOx removal unit and the CO_2 conditioning unit. The LCA model is able to quantify the fate of elements including C, S, N, Cl, and F, which form CO_2, CO, SOx, NOx, N_2O, HCl and HF during the combustion processes respectively, and trace elements such as As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, Sb, Be, B, F, Mn, Se, V, Co, Ba, Ag and Ti, across the unit processes involved. In addition, the LCI models developed are able to quantify the removal rate of air emissions of concern across the flue gas treatment processes, with the knowledge that these pollution control

units have interactions with and impacts upon each other. For instance, the coal combustion (by using almost pure oxygen) unit process LCI model quantifies mass flows of inputs and outputs, based on either basic chemical and physical principles or empirical relationships of coal combustion by using almost pure oxygen, accounting for the operating parameters of oxygen purity, excess oxygen ratio, flue gas recycling ratio, air leakage level and boiler efficiency; aiming at incorporating more parameters into the LCI models and reducing the uncertainty of LCI results. A summary of input flows, output flows and parameters modelled or considered for LCI models related to the oxy-fuel combustion CCS system are listed in Table 1. The LCI model of post-combustion CO_2 capture was developed at the same level of detail including the component unit processes of coal combustion, particulate matter (PM) removal, NOx removal, desulphurisation, solid waste disposal, CO_2 capture, compression, transportation and injection. The details of this model can be found in earlier publications by the authors [8].

Table 1. Input flows, output flows and parameters modelled or considered in LCI models developed for oxy-fuel combustion CO_2 capture related unit processes.

Unit Process	Technology options	Input flows modelled or calculated	Output flows or parameters modelled or calculated
Oxy-fuel Combustion	PC wall fired, dry bottom boiler	Oxygen Input; FD Fans Power Requirement; Recycled Flue Gas Input; Oxygen Purity; Excess Oxygen; Flue Gas Recycle Ratio; Air Leakage Level; Boiler Efficiency	Air Emissions: CO, SO_2, SO_3, NOx, HCl, HF, CH_4, N_2O, CO_2, N_2, O_2, and H_2O Solid Emissions: PM, PM-10, Bottom Ash, and Unburned Carbon; Emissions of trace metals; Heat Output
CO_2 Conditioning	CO_2 conditioning for oxy-fuel combustion	Cooling Water; Electricity Consumption; Natural Gas Input for Drier; Adsorbent Consumption	Vent Gas Composition; CO_2 Product Composition; CO_2 Product Pressure; SOx Removal Rate; NOx Removal Rate; Mercury Removal Rate; HCl Removal Rate; HF Removal Rate; H_2S Removal Rate; Other Impurities Removal Rate; CO_2 Recovery Rate; Emissions from Natural Gas Combustion; Waste Water Discharge
Air Separation Process	Cryogenic distillation process	Air input; Electricity Input; Cooling Water Input; Absorbent Consumption	Oxygen Product Flow Rate; Oxygen Product Purity; Removal Rate of Impurities in the Pre-purification Unit; Emissions from Refrigeration; Wastes from Pre-purification
CO_2 transportation	CO_2 pipeline transportation	Energy Required for Recompression;	CO_2 Density and Viscosity; CO_2 Pipeline Diameter; CO_2 Pressure Drop in Pipeline; Emissions from Recompression Stations; Fugitive Emissions from Recompression Stations
CO_2 injection	CO_2 injection to saline aquifer	Energy Requirement by the Injection Pumps; Energy Requirement by the CO_2 Heater; Fugitive Emissions from the Injection Facilities	Bottomhole Injection Pressure; CO_2 Injectivity; Number of Injection Wells; CO_2 Surface Injection Pressure

This research employed the CML 2001 baseline impact categories, category indicators, and characterisation methods for Life Cycle Impact Assessment (LCIA) [9]. The CML 2001 baseline impact categories include: Global Warming Potential (GWP), Ozone Layer Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photo-oxidant Formation Potential (POCP), Ecotoxicity Potential (EP), Human Toxicity potential (HTP), and Abiotic Resources Depletion Potential (ADP).

Table 2. Description of base case scenario for a conventional 500 MW power plant, a 500 MW power plant with post-combustion CO_2 capture, conditioning, transport and injection and a 500 MW power plant with oxy-fuel combustion CO_2 capture, conditioning, transport and injection.

	Conventional power plant	Power plant with post-combustion CO_2 capture, conditioning, transport and injection	Power plant with oxy-fuel combustion CO_2 capture, conditioning, transport and injection
Boiler output capacity (MW)	500	500	500
Boiler type	PC wall fired, dry bottom		
Chemical absorption CO_2 capture technology	-	MEA	-
Power plant gross energy efficiency (%)	-	45%	45%
SOx removal rate	95%	95%	-
NOx removal rate (NH_3 to NO ratio)	0.8	0.8	-
CO_2 capture rate	-	95%	-
O_2 purity at the air separation unit	-	-	95%
CO_2 purity at CO_2 conditioning unit	-	-	95%
Compression pressure (MPa)	-	13.8	13.8
Pipeline distance (Km)	-	300	300
Storage formation depth (m)	-	1,000	1,000
Coal type	US Appalachian (bituminous)		

3. Comparative assessment of life cycle environmental impacts

3.1 The description of base case scenarios

This section presents a comparison of the life cycle environmental impacts of oxy-fuel combustion CCS, post-combustion capture CCS and coal fired power generation with no CCS first. It then presents a sensitivity study evaluating the effects of process parameters on the LCA impact indicator results based on the characteristics of the same oxy-fuel combustion CCS system used in the above comparative study. Therefore, base case scenarios for oxy-fuel combustion, post-combustion CO_2

capture and conventional power generation with no CCS were first defined as presented in Table 2. The upstream processes considered include coal production (underground coal mining), coal transportation, limestone production, limestone transport by truck, MEA production, MEA transport by truck, ammonia production, ammonia transport by truck, power plant infrastructure, air separation unit infrastructure, CO_2 pipeline infrastructure, CO_2 capture facility infrastructure, and compressor infrastructure. The upstream LCI data were either calculated using the GaBi (v.4) LCA software or collected from literature [5, 10, 11, 12].

3.2 Fate of air emissions and trace metals across power generation with CO_2 capture and conditioning

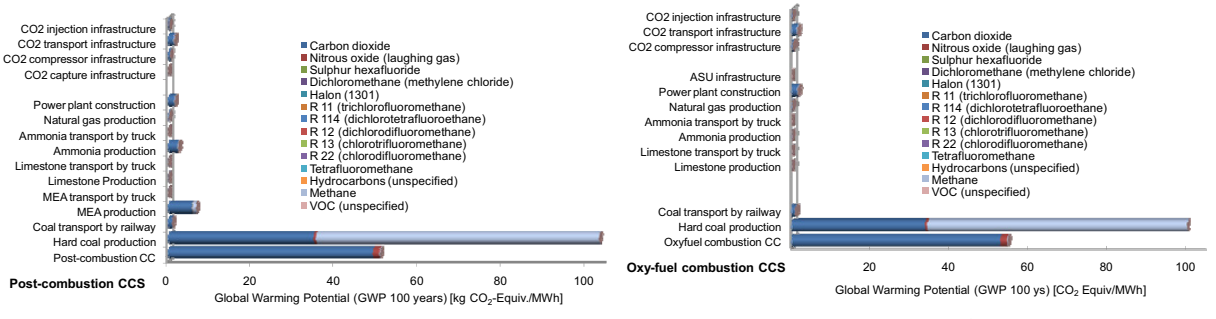
In both oxy-fuel combustion and post-combustion CO_2 capture power plants air emissions are originally generated by the coal combustion process and then totally or partially removed by the pollution control units such as selective catalyst reduction (SCR), electrostatic precipitator (ESP), flue gas desulphurisation (FGD) and the CO_2 capture unit. The LCI models developed quantify the fate of these air emissions while they pass through individual units along the power generation system with CO_2 capture and conditioning chain. Compared with post-combustion systems, oxy-fuel combustion power generation systems have less air emissions of NOx, SOx HCl, HF and vapour mercury as state of the art oxy-fuel CO_2 conditioning units are designed such that they separate or remove most or all the NOx, SOx, HCl, HF, vapour mercury and other impurities that exist in the CO_2 concentrated flue gas [13]. It is noted, however, that in the oxy-fuel power generation systems these air emissions are converted to liquid emissions contained in the discharged water from the CO_2 conditioning unit. This implies the need to use a discharged water treatment method for the oxy-fuel combustion CO_2 conditioning unit.

The trace metals that are found in power generation system emissions originate from coal. After coal combustion, the trace metals are partitioned and released to the environment through different routes: with air emissions, MEA capture solid wastes, FGD wastes, gypsum, fly ash or bottom ash. The majority of Antimony (Sb), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Lead (Pb), Manganese (Mn), Nickel (Ni), Copper (Cu), Thallium (Tl), Vanadium (V), Barium (Ba) and Silver (Ag) emissions show up in bottom ash, because they do not volatilise during combustion and distribute more or less equally over bottom ashes and fly ashes. Because most of the Arsenic (As), Beryllium (Be), and Zinc (Zn) are vaporised during combustion, they are mainly found in the fly ash after combustion. Mercury (Hg) and Selenium (Se) are volatilised and leave the combustion unit in a vapour phase. It is worth noting that 3.95% of Mercury is emitted to atmosphere in vapour form. Around 51.40% of mercury goes with gypsum as the by-product of the FGD process, 12.52% of it shows in the MEA capture solid wastes and 31.08% is in the fly ash. The scattering of mercury emissions across the pollution control chain increases the difficulty to mitigate the environmental impacts of mercury emissions.

In oxy-fuel combustion power generation with CO_2 capture and conditioning, following coal combustion, trace metals are partially captured by the pollution control units and are discharged as air emissions, FGD wastes, gypsum, fly ash, bottom ash and CO_2 conditioning wastes. The pattern of trace metal partitioning is very similar to that of the post-combustion capture power generation. It is worth noting that a small portion of the trace metals accompany the CO_2 product into the storage site in the case of oxy-fuel combustion system. There are no emissions of Mercury (Hg) to air, as this is totally removed by the CO_2 conditioning unit.

3.4 Life cycle greenhouse gas (GHG) emissions

Figure 3a illustrates that the total GWP of the 500 MW power generation unit with post-combustion capture, transport and injection is 167.121 kg CO_2 equivalent. The majority of this impact is from hard coal production which accounts for 61.71% of the GWP. Other upstream processes including MEA production, ammonia production, power plant construction, and transport infrastructure account for 3.90%, 1.38%, 0.87% and 0.82% of the GWP respectively. Emissions from power generation with capture, transport and injection make up 30.32% of the GWP. Figure 3a also shows that CO_2, methane and nitrous oxide are the main emissions contributing to GWP. Carbon dioxide emissions (95.50 kg) mainly come from power generation with CO_2 capture (48.96 kg), hard coal production (34.72 kg), and MEA production (5.66 kg). Methane emissions (69.30 kg CO_2 equiv) are mainly due to coal production, which accounts for 97.76% of the total methane emissions.



(a) (b)

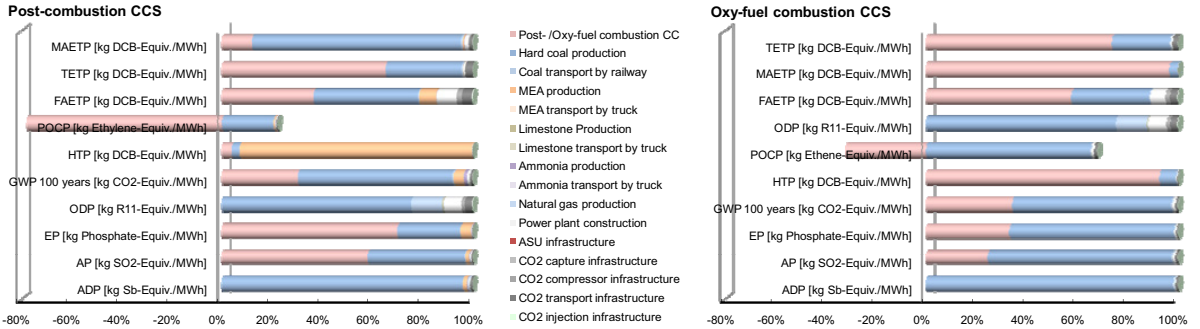
Figure 3. (a) Global warming potential for the base case 500 MW coal fired power plant with post-combustion capture, transport and injection; (b) Global warming potential for the base case 500 MW oxy-fuel combustion CO_2 capture plant, transport and injection.

In the case of the 500 MW oxy-fuel combustion CO_2 capture with transport and injection scenario, Figure 3b, the total GWP is 158.46 kg CO_2 equivalent. At 63.11%, the majority of the GWP is due to hard coal production. Emissions from power generation with CO_2 capture make up 34.08% of the GWP. Other upstream processes account for 2.81% of the GWP. Figure 3b also shows that CO_2, methane and nitrous oxide are the main substances contributing to GWP. Carbon dioxide emissions (90.35 kg) mainly come from power generation with CO_2 capture (52.68 kg) and hard coal production (33.67 kg). Methane emissions from coal production (65.70 kg CO_2 equiv) account for 99.12% of the total methane emissions.

3.5 Life cycle impacts in all environmental impact categories

Figure 4a illustrates that life-cycle environmental impacts of post-combustion CCS system are dominated by the emissions from power plants with CO_2 capture and coal production in all impact categories, except for HTP which is dominated by the MEA production. Other upstream processes, including coal transportation, limestone production, limestone transport, MEA production, MEA transport, ammonia production, ammonia transport, power plant infrastructure, CO_2 pipeline infrastructure, CO_2 capture facility infrastructure, and compressor infrastructure have minor environmental impacts in a life-cycle perspective. The AP, EP, GWP, HTP, MAETP and POCP are caused primarily by air emissions. The FAETP and TETP are mainly due to trace metal emissions to air or soils. In every environmental impact category, the resultant impact is dominated by several key substances. The contribution of power generation with CO_2 capture to the environmental impact categories AP, EP, GWP100, HTP and POCP is due to its air emissions. On the other hand, its contribution to the environmental impact categories FAETP, MAETP and TETP is due to trace metal emissions to air or soils.

Figure 4b demonstrates that life-cycle environmental impacts of oxy-fuel combustion CCS systems are dominated by the emissions from the oxy-fuel combustion CO_2 capture plant and coal production in all impact categories, except for the ODP which is dominated by coal production, coal transportation and power plant infrastructure. Other upstream processes, such as limestone production, limestone transport, CO_2 pipeline infrastructure, ASU facility infrastructure and the compressor infrastructure have minor environmental impacts. The AP, EP, GWP, HTP, MAETP and POCP are primarily due to air emissions. The FAETP and TETP mainly come from trace metal emissions to air or soils. Similar to post-combustion, each environmental impact category is dominated by several key substances. Air emissions from the oxy-fuel combustion capture plant contribute to the AP, EP, GWP, HTP and POCP. Trace metal emissions to air or soils contribute to the FAETP, MAETP and TETP.



(a) (b)

Figure 4. (a) Life cycle environmental impact results for the base case 500 MW coal fired power plant with post-combustion capture, transport and injection; (b) Life cycle environmental impact results for the base case 500 MW oxy-fuel combustion CO_2 capture, transport and injection system.

Figure 5 presents the comparison of alternative power generation systems with CCS against conventional power generation without CCS at plant direct emissions level (Figure 5a), that is only power generation with CCS processes are included and upstream processers are not counted, and at life cycle level (Figure 5b). Figure 5a shows that compared to power generation without CO_2 capture, power plants with post-combustion and oxy-fuel combustion CO_2 capture can reduce the GWP by 92.8% and 92.4% respectively. The power plant with post-combustion CO_2 capture shows a relative increase in the ADP, AP and EP compared to conventional power generation, which is due to the incremental use of coal and resultant NOx and NH_3 emissions to air, and trace metal emissions to soils. Since MEA CO_2 capture can remove atmospheric emissions of trace metals further after the FGD, the FAETP, HTP, TETP and MAETP are decreased relative to the conventional power plant without CCS scenario. Incremental emissions of NO cause a reduction in the POCP. The plant with oxy-fuel combustion CO_2 capture shows a relative increase in ADP, FAETP, HTP, MAETP and POCP and a decrease in AP and EP, compared to conventional power generation. The increase in the ADP is because of the incremental use of coal; the increase of FAETP, HTP and MAETP is as a result of HF emissions to freshwater; the increase in POCP is because of the removal of NO emissions in the CO_2 conditioning unit after leaving the FGD. On the other hand, the AP and EP are decreased since the CO_2 conditioning unit can remove air emissions of NOx, SOx, HCl and HF further after the FGD.

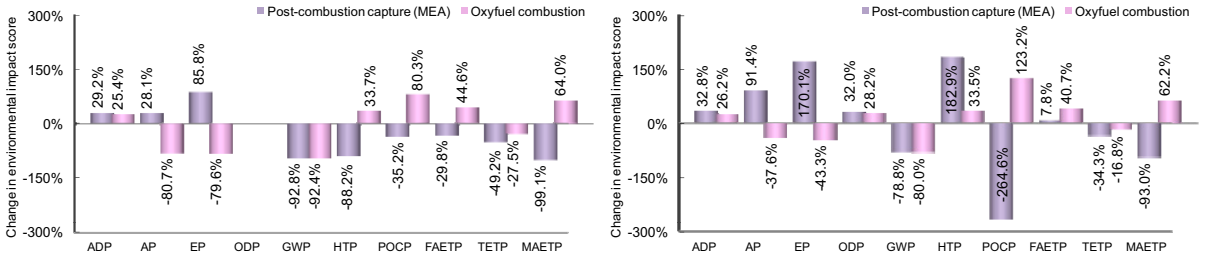


Figure 5. (a) LCIA results for alternative power generation systems with CO_2 capture against conventional power generation without CCS at plant direct emissions level (per 1 MW electricity generated); (b) LCIA results for alternative power generation systems with CO_2 capture against conventional power generation without CCS at life-cycle level (per 1 MWh electricity generated).

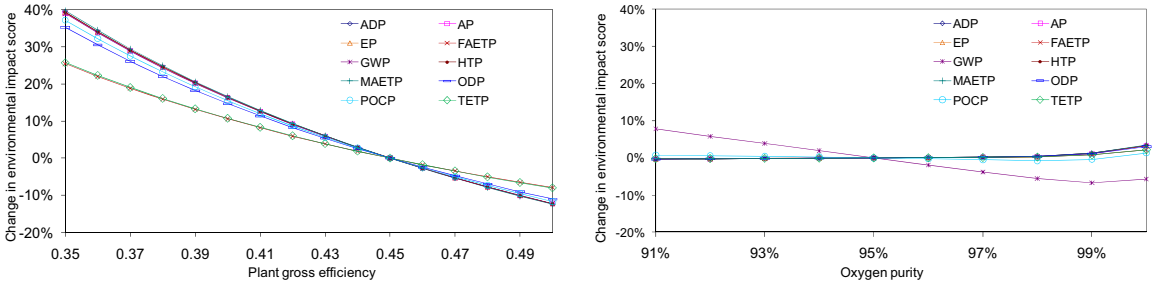
Figure 5b presents the comparison of the environmental impacts of alternative power generation systems with CO_2 capture against conventional power generation without CCS at life cycle level. The comparison can be summarised as follows:

- Compared to the power plant without capture, the post-combustion and oxy-fuel combustion CO_2 capture cases can reduce the life-cycle GWP by 78.8% and 80.0% respectively. Due to its higher energy efficiency, the oxy-fuel combustion case results in a slightly larger GWP reduction from both power plant and upstream processes, especially coal mining.
- Both post-combustion and oxy-fuel combustion cases have a larger ADP value than the plant without CCS since capture, transport and injection require additional energy which results in an increase of coal use and upstream processes of coal mining results in a lager ADP values.
- The post-combustion case has a 91.4% higher AP value than the plant without CCS as this option uses more coal and consequently causes an increase of NOx emissions from the power plant and an increase of SO_2 and NOx emissions from the upstream process (mainly coal mining). On the other hand, the post-combustion case has lower SOx emissions than the plant without CCS as the MEA CO_2 capture unit can further reduce SOx emissions. The MEA capture unit generates NH_3 emissions, which makes a considerable contribution to AP. The CO_2 conditioning unit in the oxy-fuel plant can completely remove the emissions of NOx, SOx, HCl and HF, which are the main AP contributors. Therefore, the oxy-fuel combustion case has a lower AP value (37.6% lower) than the plant without CCS.
- The post-combustion plant uses more coal and cause an increase in the NOx emissions from both power plant and the upstream processes (mainly coal mining and MEA production). This system also generates NH_3 emissions, which contribute to EP from the MEA CO_2 capture unit. Therefore, the post-combustion case has a significantly higher EP value (170.1% higher) than the plant without CCS. Since the CO_2 conditioning unit can totally remove emissions of NOx, the oxy-fuel combustion case has a lower EP value (43.3% lower) than the plant without CCS.
- The post-combustion case consumes MEA and the MEA production causes significantly high HTP. Therefore, the post-combustion case has a very high HTP value (182.9% higher) compared to the plant without CCS. The HTP caused by MEA production accounts for 92.5% of the life-cycle HTP. The CO_2 conditioning unit in oxy-fuel combustion removes atmospheric HF emissions and convert them to HF emissions to freshwater, which increases the overall life-cycle HTP.
- The MEA CO_2 capture unit in post-combustion capture can further remove 95% of the HF emissions to air in the flue gas leaving the FGD and this significantly reduces the MAETP. On the other hand, the oxy-fuel combustion has a larger MAETP value than the plant without CCS case due to the conversion of atmospheric HF emissions to HF emissions to freshwater.
- Removal of trace metals at the MEA CO_2 capture unit and the CO_2 conditioning unit in the two capture plants reduces the TETP compared to the power plant without CCS.
- Because of the emissions of HF to freshwater from the CO_2 conditioning unit the oxy-fuel combustion case increases the FAETP compared to power plant without CCS. Post-combustion case has slightly higher FAETP than power plant without CCS as post-combustion case generates more trace metal emissions to soil from coal production.
- The POCP of the post-combustion case has a significantly lower value (264.6% lower) than the plant without CCS case as the MEA CO_2 capture unit removes the NO emissions, which reduces the POCP. The increased use of coal due to CO_2 capture results in increased R11 (trichlorofluoromethane), R114 (dichlorotetrafluoroethane) and R12 (dichlorodifluoromethane) emissions which increases the ODP of both post-combustion and oxy-fuel combustion cases.

3.6 Sensitivity analysis and comparison of LCA results with values from the literature

An obvious benefit of developing the LCI model of power generation systems at unit process level is that it is possible to account for technical, operational and geographical differences by choosing appropriate LCI model parameters. This flexibility also allows to run sensitivity studies evaluating the influence of the chosen parameters on the LCA impact indicator results. Figure 6a illustrates the effect of oxy-fuel capture plant energy efficiency on environmental impacts which is not linear and not the same for all impact categories. The reason behind this is that an increase of energy efficiency reduces the coal consumption and hence reduces emissions from both the power plant and upstream processes. For the oxy-fuel combustion capture illustrated here, TETP and FAETP are less sensitive to the change of plant gross efficiency, since a significant proportion of TETP and

FAETP originate from trace metal emissions to soil, which are mainly determined by the solid waste disposal method. In oxy-fuel combustion CO_2 capture, the power plant can choose to operate at different O_2 product purities. Figure 6b illustrates that an increase in O_2 product purity can decrease GWP but does not cause an increase in other environmental impacts as long as the O_2 product purity is less than 98%. This is because the use of higher O_2 purity in the system increases the CO_2 concentration in flue gas and consequently decreases the rate of CO_2 vented to the atmosphere in the CO_2 conditioning unit. If O_2 product purity is larger than 98%, this will increase the energy consumption of the ASU significantly and consequently increase the life-cycle environmental impacts. From LCA point of view, O_2 product purity at 98% is the optimum value, at which GWP is reduced by 5% compared to O_2 product purity at 95%.



(a) (b)

Figure 6. (a) The effect of power plant gross efficiency on life cycle impact indicator scores in comparison to a power plant of 45% gross efficiency (oxy-fuel combustion CO_2 capture, transport and injection); (b) The effect of ASU oxygen product purity on life cycle impact indicator scores in comparison to a plant operating at 95% O_2 purity (oxy-fuel combustion CO_2 capture, transport and injection).

Table 4 compares the LCA results presented in the paper with that reported in recent literature in order to reflect upon the benefits of the detailed LCI models developed by the authors. A comparison with similar results on oxy-fuel combustion CO_2 capture, transport and injection is not possible as there are no other publications available at this time. It is clear that for each impact category the results reported by different authors vary significantly, as different coal and plant operation parameters are employed in different studies. Table 4 also shows that for each impact category the results presented in this paper indicate lower impacts than other studies, however, it is encouraging that the results are of the same order of magnitude, except for FAETP. The FAETP impact is dominated by the emission of metals to water and to the air, and these emissions are due to leaching from landfills filled with solid waste generated by power generation and upstream processes. Knoorneef et al. [5] reported much larger FAETP values for a generic landfill, while this paper considers a well managed landfill (a landfill with composite liner) and used a model that accounts for precipitation, water infiltration through a composite liner, water infiltration through solid waste, and concentration of leachate constituents. All the trace metals leaching to underground waters can be traced back to their origin in coal.

Table 4. Comparison of life cycle impact results with literature (based on 1 MWh electricity generated)

Impact category	**Power generation without CCS**	**Post-combustion CCS**						**Oxyfuel combustion CCS**
	This paper	This paper	Knoorneef et al. [5]	Pehnt and Henkel [6]			Viebahn et al. [13]	This paper
				Case 1	Case 2	Case 3		
GWP [kg CO_2-Equiv.]	786.52	167.12	243	200	195	180	280	157.59
ADP [kg Sb-Equiv.]	3.72	4.94	8.45	N/A	N/A	N/A	N/A	4.70
AP [kg SO_2-Equiv.]	0.97	1.85	2.10	1.35	0.59	0.5	1.1	0.60
EP [kg Phosphate-Equiv.]	0.11	0.30	0.29	230	90	70	0.09	0.07
ODP [kg R11-Equiv.]	1.33E-06	1.76E-06	9.93E-06	N/A	N/A	N/A	N/A	1.71E-06
POCP [kg Ethene-Equiv.]	-0.10	-0.37	0.06	25	24	20	0.062	0.02
HTP [kg DCB-Equiv.]	32.07	90.79	164	N/A	N/A	N/A	N/A	42.83
MAETP [kg DCB-Equiv.]	2.62E+05	1.83E+04	5.50E+04	N/A	N/A	N/A	N/A	4.25E+05
FAETP [kg DCB-Equiv.]	0.44	0.48	13.40	N/A	N/A	N/A	N/A	0.62
TETP [kg DCB-Equiv.]	0.20	0.13	0.511	N/A	N/A	N/A	N/A	0.16

"N/A": data are not available.

4. Conclusions

The LCA models developed by the authors are detailed at unit process level and account for geographical differences and operational parameters. Therefore, their use can reduce the uncertainty in the life cycle impact assessments carried out and help to quantify the variability in these estimates by accounting for operational and spatial differences involved in different operations. The comparative assessment of different CCS options investigated has indicated that the life cycle environmental impacts of oxy-fuel combustion CCS systems are slightly better than post-combustion CCS systems. However, for both CO_2

capture systems, the reduction of CO_2 emissions results in an increased abiotic resource depletion (dominantly fossil fuels) from a life-cycle perspective. Post-combustion CCS or oxy-fuel combustion CCS also increase some categories of life cycle impacts, such as AP, EP, etc. These increases of impacts are mainly from upstream processes. This implies that the increase of other categories of environmental impacts caused by CCS can be offset by reducing emissions from other industries, where advanced pollution control technologies can be readily applied at much lower costs.

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