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Life cycle modelling of fossil fuel power generation with post combustion CO_2 capture

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Abstract

Due to its compatibility with the current energy infrastructures and the potential to reduce CO_2 emissions significantly, CO_2 capture and geological storage is recognised as one of the main options in the portfolio of greenhouse gas (GHG) mitigation technologies being developed worldwide. The CO_2 capture technologies offer a number of alternatives, which involve different energy consumption rates and subsequent environmental impacts. Life cycle assessment (LCA) not only tracks energy and non-energy related GHG releases but also tracks various other environmental releases, such as solid wastes, toxic substances and common air pollutants, as well as the consumption of other resources, such water, minerals and land use. This paper presents the principles of the LCA model developed at Imperial College and uses the post combustion capture example to demonstrate the methodology in detail.

Keywords: Life Cycle Assessment; power generation; CO_2 capture

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1. Introduction

The CO_2 capture technologies require significant amounts of energy during their implementation. The holistic perspective offered by LCA enables decision makers to quantify the trade-offs inherent in any change to the power production systems and helps to ensure that a reduction in GHG emissions does not result in increases in other environmental impacts. The other strength of LCA is that the International Organization for Standardization (ISO) has developed the ISO 14040 series of LCA standards, which provide guidance on setting appropriate system boundaries, reliable data collection, evaluating environmental impacts, interpreting results, and reporting in a transparent manner. This offers an excellent starting point for the development of measurement protocols for GHGs and other environmental impacts [1]. Finally, under the Kyoto Protocol, three flexible mechanisms (Emissions Trading, Joint Implementation (JT) and the Clean Development Mechanism (CDM)) were developed to help emitters in developed countries to meet their GHG emission targets. As a credible and internationally accepted tool, LCA offers the means to include CO_2 capture projects into the CDM framework and help the participants of flexible mechanisms to assess their proposed CO_2 capture projects and verify their emission reductions from a life-cycle perspective.

Previous LCA studies [2, 3, 4, 5, 6, 7, 8, 9] have investigated power generation plants with alternative CO_2 capture systems and concluded that CO_2 capture can reduce CO_2 emissions by around 80% throughout the life-cycle of power generation. However, with respect to other environmental impacts, such as abiotic resource depletion, acidification, human toxicity etc., previous studies report a fairly wide range of results, as they focus on specific CO_2 capture cases only. Moreover, previous studies and commercial LCA software (e.g. TEAM, GaBi 4, Ecoinvent, SimaPro 7, ETH-ESU 96, and U.S. LCI Database) have a very rigid approach to system boundaries and do not recognise the importance of the level of detail that should be included in the Life Cycle Inventory (LCI) data. So far, the LCI data considered for power generation have all been at plant level (or gate-to-gate data) rather than being at the level of unit processes inside the plants. The gate-to-gate data used in previous studies imply

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that the electricity generation systems have been largely simplified to a single black-box with constants and linear coefficients used as inputs and outputs, covering a broad range of technological and geographical differences, in which the actual variability of process technological parameters and operating conditions are implicitly neglected. In reality, the power plants with capture systems can be configured with different types of fuels fired; alternative CO_2 capture technologies use a variety of emission control devices and waste treatment methods installed, and can be located in different geographical locations in the world. Consequently, these simplifications limit the possibility of tracing emissions back to individual unit processes and restrict one's ability to represent technical and geographical differences in the environmental assessment of power generation systems.

Capture of CO_2 from the power generation process generally means that at some point in the process CO_2 needs to be separated. Three alternative approaches can integrate CO_2 capture technologies with power generation systems: post-combustion, pre-combustion and oxy-fuel combustion. The choice of specific capture method for a power generation system is determined largely by the power plant conditions. Geological storage of CO_2 can be operated in a variety of geological settings in sedimentary basins, such as depleted oil or gas fields, oil fields, unminable coal seams, and saline aquifers, where CO_2 can remain underground by a number of trapping mechanisms.

The objective of the research described in this paper was to develop a complete and dynamic LCA model which includes fossil fuel power generation, CO_2 capture, transport and geological storage which quantifies the environmental impacts at the highest level of detail, and allow for the assessment of technical and geographical differences between the alternative CO_2 capture and storage technologies considered. The Life Cycle Inventory (LCI) database developed models the inputs and outputs of the processes at component or unit process level and aims at generating reliable and precise LCI data in a consistent and transparent manner with a clearly arranged and flexible structure for long term strategic energy system planning and decision making. The following sections present the principles of the LCA model developed and use the post combustion capture example to demonstrate the methodology followed in detail.

2. Life Cycle Assessment and its application in carbon capture and storage

Life Cycle Assessment is a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its entire life cycle, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal [10]. In order to deal with the complexity of LCA, International Standards Organisation (ISO) established a methodological framework for performing a LCA study, which comprises four phases, including Goal and Scope, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation.

Goal and Scope definition states the aim of an intended LCA study, the system boundary, the functional unit, competing systems considered, and the breadth and depth of (or level of detail) the LCA study in relation to this aim. Life Cycle Inventory Analysis is the phase to quantify the input/output relationship and to prepare an inventory of input/output data for all component processes involved in the life cycle of the system(s) under study. The aim of Life Cycle Impact Assessment is to understand and evaluate the magnitude and significance of the potential environmental impacts of a product system [10]. In this phase, impact categories (e.g. global warming, acidification, and human toxicity), category indicators, and characterisation factors are defined, and LCI results are assigned to categories and then converted into category indicators via characterisation factors. Characterisation factors can convert environmental flows into environmental impacts. Interpretation is the phase, in which the findings of either the inventory analysis or the impact assessment, or both, are analysed in relation to the defined goal and scope in order to deliver conclusions, explain limitations and provide recommendations [10].

The main objective of the research presented in this paper was to develop a comprehensive LCI database for the analysis of power generation with alternative CO_2 capture and storage options in a consistent and transparent manner. The underlying principle applied in developing this methodology can be summarised as:

1. Transparency: to show precisely how life cycle impacts are calculated and the extent to which the inputs/outputs of any unit process have been quantified.
2. Comprehensiveness: to identify all of the inputs/outputs that may give rise to significant environmental impacts.
3. Consistency of methodology: models and assumptions to allow valid comparisons to be made between technological options or operation options for a unit process.

The system boundaries of LCA in power generation with CO_2 capture, a generalised outline of which is presented in Figure 1, covers 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. In the case of the upstream processes, the LCI data are based on material from the literature. In this paper, however, only the LCA of post combustion CO_2 capture technology is presented. The functional unit was selected as 1 MW of electricity generated.

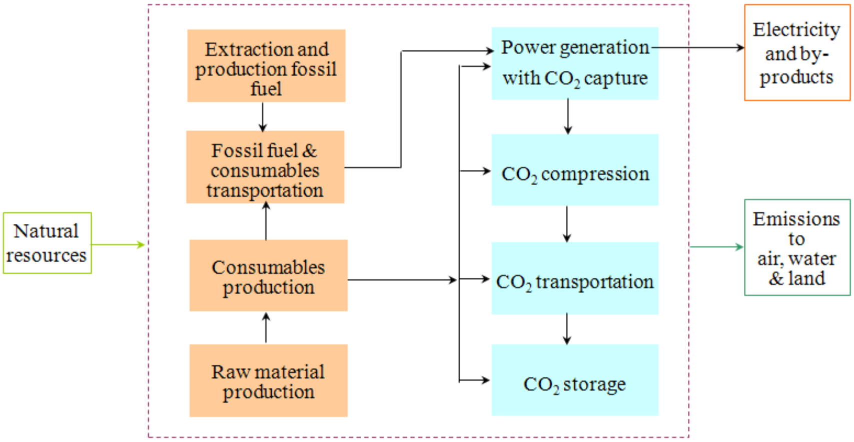


Figure 1. System boundaries of LCA in power generation with CCS.

Power generation with CO_2 capture involves a set of inter-related components and the relationships between them. Here, the systems are broken down or modularised into subsystems or component unit processes connected by flows of intermediate products or emissions. The purpose of modularisation is to make complex systems more easily understood and more accurately modelled. Through modularisation, the LCI models quantify flows of materials, natural resources, energy, intermediate products or emissions at component or 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 allows plant operators and designers to model and compare different technical and engineering scenarios from a life cycle perspective. Ultimately, modularisation eliminates the limitations introduced by the use of 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 [11]. The ISO LCA methodology focuses on the LCA study of existing plants and does not offer methods for novel systems that are not commercially operated. Therefore, the modularisation methodology presented in this paper provides an approach to conduct LCA by configuring virtual systems of power generation with CO_2 capture, based on the best available technology and component unit processes of the system. This research employed the CML 2001 [12] baseline impact categories, category indicators, and characterisation methods for the LCIA. The CML 2001 baseline impact categories include: Global Warming, Stratospheric Ozone Depletion, Acidification, Eutrophication, Photo-oxidant formation, Ecotoxicity, Human toxicity, Depletion of abiotic resources, and Land Use.

3. Life Cycle modelling of power generation with post combustion CO_2 capture

A post combustion CO_2 capture system includes component unit processes of coal combustion, particulate matter removal, flue gas desulphurisation, CO_2 capture and CO_2 compression. In this section, coal combustion LCI model and chemical absorption CO_2 capture LCI model are given as examples to demonstrate the methodology used in quantifying the inputs and outputs at unit process level. The interpretation of LCI and LCIA results at unit process level and the LCIA results of power generation systems with post combustion CO_2 capture are discussed in detail.

3.1. Coal combustion LCI model development and LCIA results

The coal combustion LCI model calculates mass flows (including coal, CO_2, N_2, O_2, and H_2O), energy consumption and heat (steam) output using stoichiometric reactions and engineering models which are based on chemical and physical principles and estimates emissions (CO, SO_2, SO_3, NOx, acids, PM and trace metals) using the US EPA AP-42 emission factors [13]. In order to characterise the technological and geographical differences that exist between various coal combustion processes considered, the LCI model developed allows for the use of different coal characteristics and 6 types of boilers as input. A schematic representation of the coal combustion LCI model is shown in Figure 2.

A fixed plant size of 500 MW was used throughout the case studies implemented. Plant efficiency of conventional power plants at subcritical steam conditions is around 40% [14]. Advanced supercritical steam plants can attain efficiencies that exceed 45% and, as further developments take place the ultra-supercritical plants may ultimately achieve efficiencies of 50-55% [15]. Research considered the internationally quoted efficiency ratings from the literature, at the same time, allowance was made for geographical differences in gross efficiencies of existing plants and the average regional gross efficiencies of subcritical plants in various regions across the world were taken as reference. The average regional gross efficiency of individual subcritical plants ranges from 27% in Eastern Europe to 40% in the Middle East with Western European plants running at 39% regional gross efficiency [14].

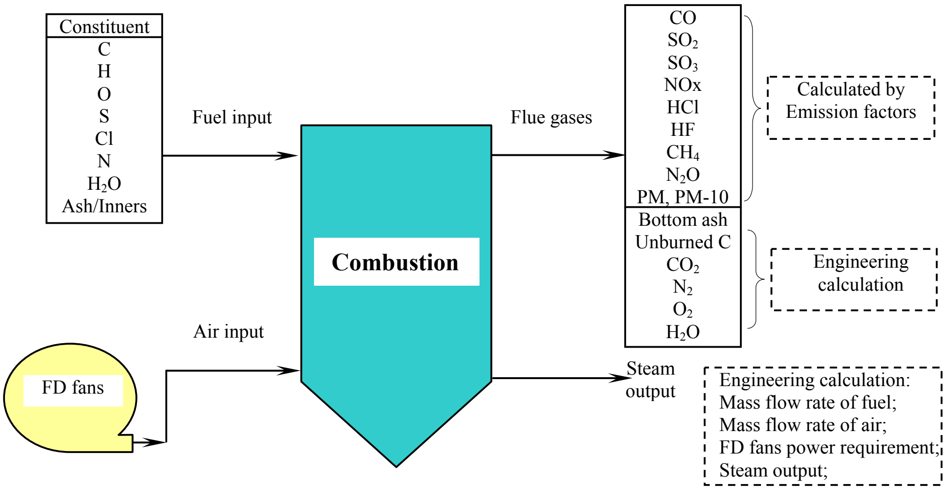


Figure 2. The schematic representation of a coal combustion process LCI model

Boiler operation conditions used in this research include availability and capacity utilisation rate of the plant, which also influence the plant efficiency. In this research, it was assumed that the availability of a power plant is 90%. Based on the analysis carried out by the IEA [14], it was assumed that plants with CCS will be for base load operation and a utilisation rate of 75% and 80% can be assumed for industrialised countries and the developing countries respectively.

In many parts of the world, the choice of coal is limited to that produced locally. This results in a geographical difference in emissions from power generation. For instance, in China coal fired power plants almost entirely depend on indigenous coals with an average sulphur content of 1.3%. On the other hand, power plants in Germany still fire on lignite or brown coal. In order to represent the characteristics of the coal at a regional level, the model developed considers the composition and heating value of coal when calculating the mass flow of coal, air requirements and environmental emissions. Trace metals are also emitted during coal combustion. The quantity of any given metal emitted depends on the physical and chemical properties of the metal, the concentration of the metal in the coal, and the combustion conditions. Emissions of 9 trace metals are calculated using emission factor equations proposed by US EPA [16]. Figure 3 presents the LCI results for 1MW electricity generated from a wall-fired dry bottom pulverised coal (PC) boiler burning bituminous coal and demonstrate the level of detail achieved in the inputs and outputs. Figure 4 presents the LCIA results of a combustion process using different types of coals as inputs or with different types of boilers used.

The LCIA results show that, in general, coal type is the dominant factor in determining the environmental impact potential. The Global Warming Potential (GWP) is mainly influenced by the type of coal used, and lignite combustion has the highest value in GWP, due to the low heating value of lignites. Five combustion alternatives have the same value in depletion of abiotic resources since the boilers used had the same energy efficiency and consume same amount of energy for the generation of 1MW electricity. Human toxicity and Ecotoxicity are mainly caused by trace metals in particulate matters or bottom ash, which depend on the type of coal burnt, and sub-bituminous coal combustion has the highest value in these impact categories because of its highest particulate matter emission factor and low heating value, therefore, its combustion generates more particulate matters and bottom ash. Sub-bituminous coal combustion and lignite combustion have the lowest values in Photo-oxidant formation and Acidification than bituminous coal combustion, because they have lower sulphur contents. Eutrophication impact is dependent on the type of boiler used. Cyclone boilers and wall-fired wet bottom PC boilers have the highest Eutrophication values, due to their higher NOx emission factors compared to other types of boilers.

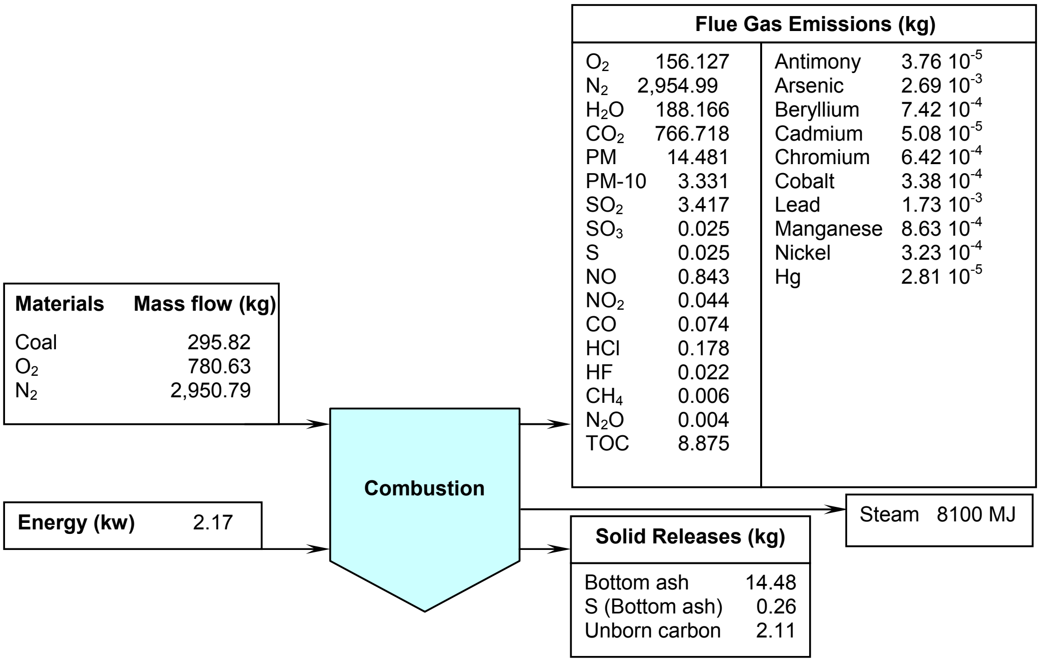


Figure 3. LCI results of coal combustion in a wall-fired dry bottom PC boiler per 1 MW electricity generated.

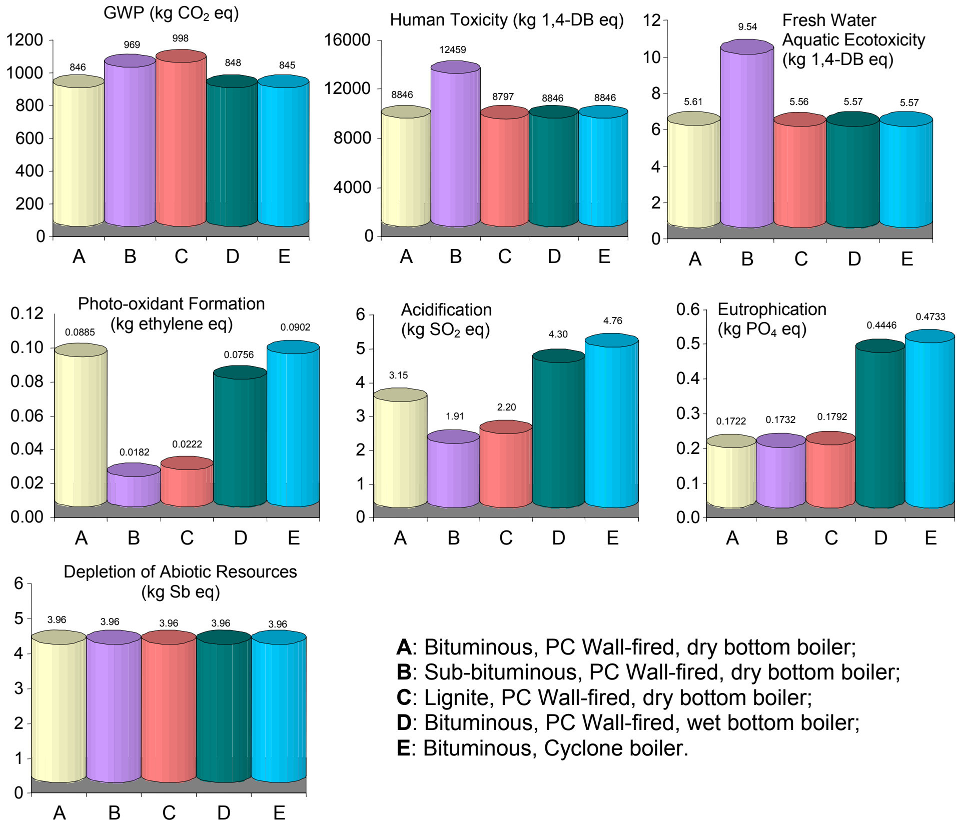


Figure 4. LCIA results of coal combustion with alternative coal types and boilers (per 1 MW electricity generated).

3.2. Chemical absorption CO_2 capture LCI model development and LCIA results

In the chemical absorption CO_2 capture LCI model, the inputs and outputs are calculated using engineering models. The schematic representation of the LCI model is shown in Figure 4. In order to account for the technological differences that exist between alternative chemical absorption CO_2 capture processes, the model developed was set up for 8 different solvents (Table 1). The energy consumption value used for alternative solvent regeneration processes was taken from the literature [17, 18].

Table 1: Solvent alternatives used in the LCI model

Solvent types	Solvent Alternatives
Primary Amine	MEA, DGA
Second Amine	DEA, DIPA
Tertiary Amine	MDEA, TEA
Hindered Amine	KS-1
Promoted Potassium Carbonate	K^+/PZ

Figure 5 presents the LCI results obtained for a MEA CO_2 capture system with reference to 1MW electricity produced, using the LCI model described above. To complete the LCI data for the chemical absorption capture process, the LCI emissions corresponding to electricity consumption are added as upstream LCI data. These are calculated using the in-house LCA model for power generation without capture. The solvent production LCI emissions are neglected according to the LCA 1% cut-off rule, as the consumption of solvent is small.

The LCIA results (not shown here) illustrate that CO_2 capture processes can significantly reduce the life-cycle GWP impact, and the KS-1 process compares favourably with other alternatives, because it consumes less energy and hence causes less greenhouse gas emissions related to energy production. Since CO_2 capture processes can remove particulate matters and acid gases from the flue gas, they result in reduced values of life-cycle Human toxicity and Photo-oxidant formation impacts. The removal of acid gases also reduces Acidification and Eutrophication and results in reduced values for Acidification and Eutrophication impacts for MEA and K+/PZ processes when the capture process is considered alone. The KS-1 process generates more NH_3, which contributes to increased Acidification and Eutrophication impacts. Depletion of abiotic resources and Ecotoxicity impacts are increased for all capture processes and are related to energy consumption, which in turn results in increased fossil fuel consumption and higher Ecotoxicity related emissions.

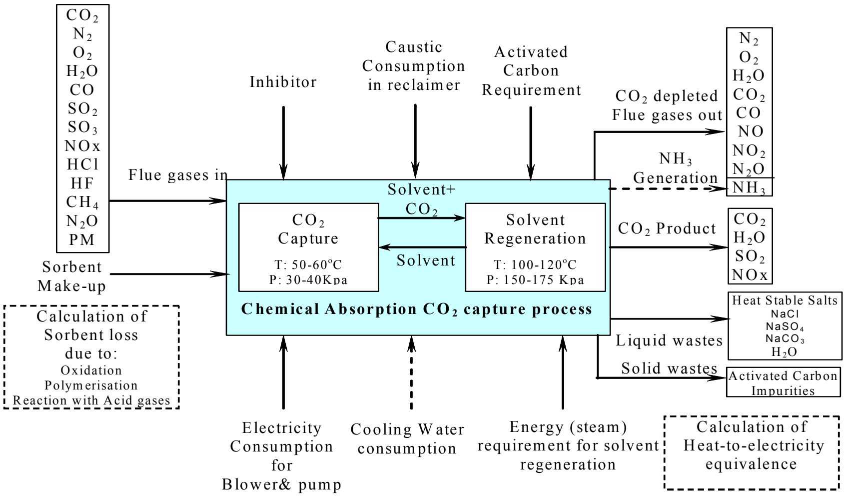
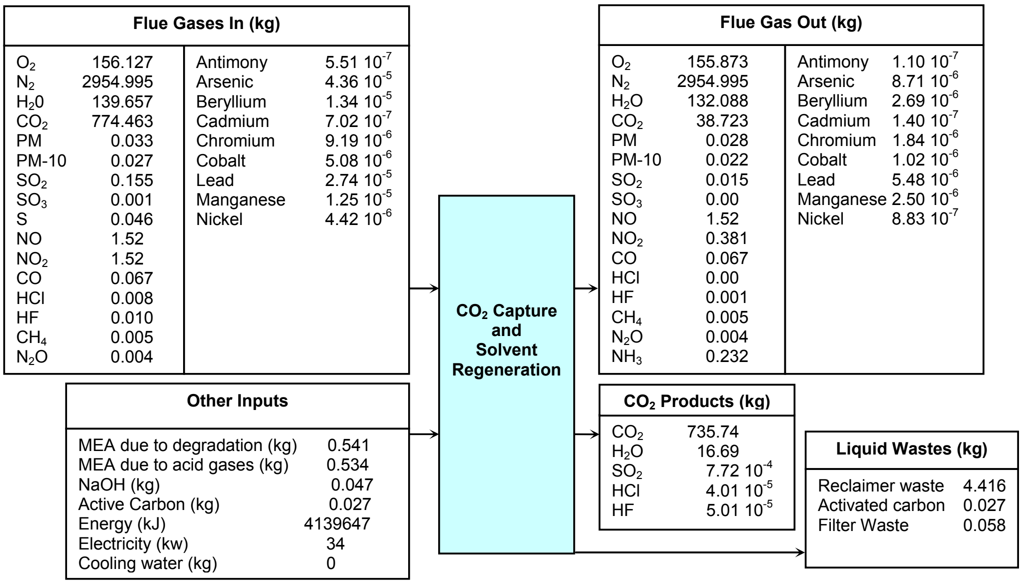


Figure 4. A schematic representation of chemical absorption CO_2 capture processes LCI model.

3.3. Life Cycle Impact Assessment results for power generation with CO_2 capture

The LCIA results reported in Figure 6 were calculated for coal power generation systems utilising alternative post-combustion CO_2 capture technologies using the LCI models developed. The results show that post-combustion CO_2 capture with different solvents (MEA, KS-1 and K+/PZ) can achieve 80% reduction in greenhouse gas emissions, without a significant increase in other environmental burdens throughout the whole power generation life cycle, compared to power generation without CO_2 capture. Power generation with CO_2 capture systems yield higher values for Depletion of Abiotic resources and Ecotoxicity since



Flue Gases In (kg)

O_2	156.127	Antimony	5.51 10^{-7}
N_2	2954.995	Arsenic	4.36 10^{-5}
H_20	139.657	Beryllium	1.34 10^{-5}
CO_2	774.463	Cadmium	7.02 10^{-7}
PM	0.033	Chromium	9.19 10^{-6}
PM-10	0.027	Cobalt	5.08 10^{-6}
SO_2	0.155	Lead	2.74 10^{-5}
SO_3	0.001	Manganese	1.25 10^{-5}
S	0.046	Nickel	4.42 10^{-6}
NO	1.52		
NO_2	1.52		
CO	0.067		
HCl	0.008		
HF	0.010		
CH_4	0.005		
N_2O	0.004		

Other Inputs

MEA due to degradation (kg)	0.541
MEA due to acid gases (kg)	0.534
NaOH (kg)	0.047
Active Carbon (kg)	0.027
Energy (kJ)	4139647
Electricity (kw)	34
Cooling water (kg)	0

Flue Gas Out (kg)

O_2	155.873	Antimony	1.10 10^{-7}
N_2	2954.995	Arsenic	8.71 10^{-6}
H_2O	132.088	Beryllium	2.69 10^{-6}
CO_2	38.723	Cadmium	1.40 10^{-7}
PM	0.028	Chromium	1.84 10^{-6}
PM-10	0.022	Cobalt	1.02 10^{-6}
SO_2	0.015	Lead	5.48 10^{-6}
SO_3	0.00	Manganese	2.50 10^{-6}
NO	1.52	Nickel	8.83 10^{-7}
NO_2	0.381		
CO	0.067		
HCl	0.00		
HF	0.001		
CH_4	0.005		
N_2O	0.004		
NH_3	0.232		

CO_2 Products (kg)

CO_2	735.74
H_2O	16.69
SO_2	7.72 10^{-4}
HCl	4.01 10^{-5}
HF	5.01 10^{-5}

Liquid Wastes (kg)

Reclaimer waste	4.416
Activated carbon	0.027
Filter Waste	0.058

Figure 5. LCI results of a MEA CO_2 capture system (per 1 MW electricity generated).

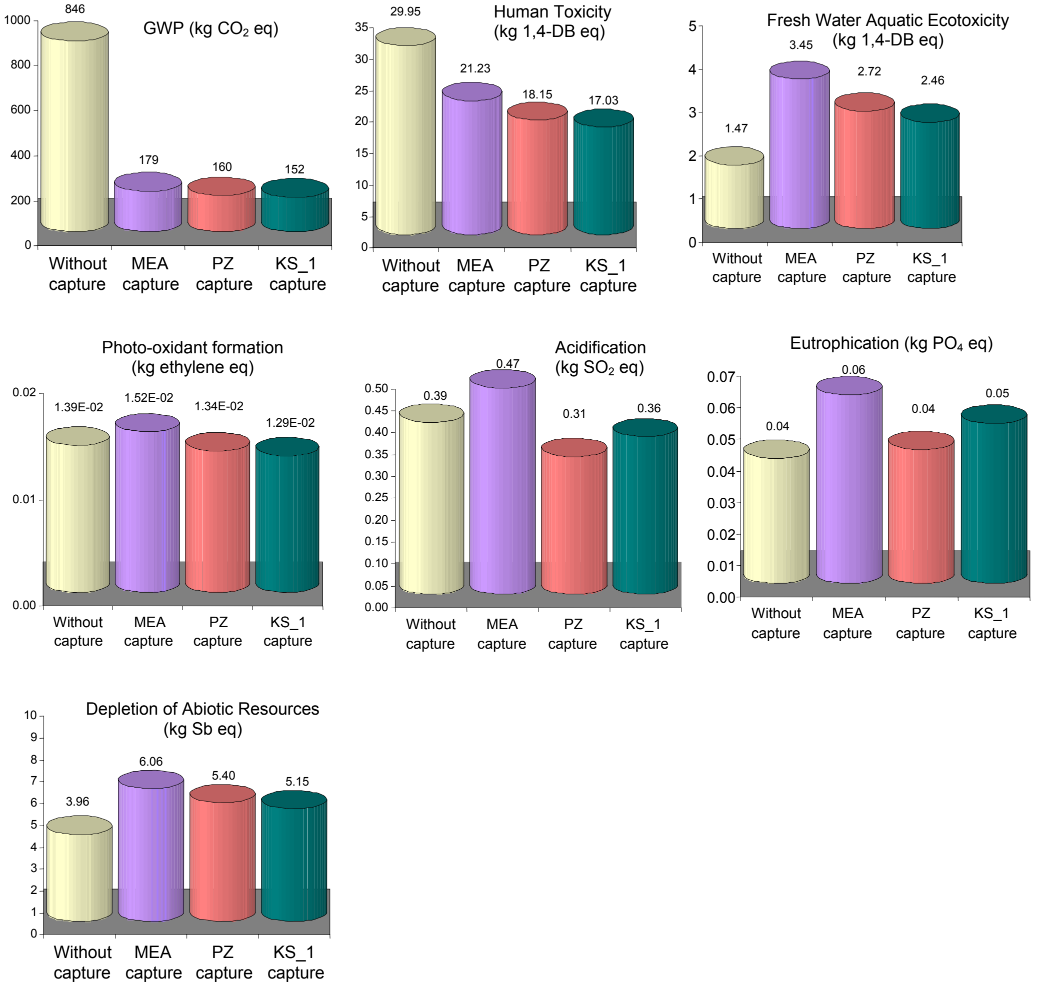


Figure 6. LCIA results for alternative power generation systems with/without CO_2 capture (per 1 MW electricity generated).

these plants require more coal and limestone for the same amount of energy produced and generate more bottom ash, fly ash and solid wastes. The disposal of ash and solid wastes cause Ecotoxicity impacts. With respect to Human toxicity, power generation with CO_2 capture systems have lower values, because CO_2 capture process can further reduce fly ash in the flue gas after the Flue Gas Desulphurisation (FGD) process and this reduce the emissions of trace metals in the fly ash.

However, captured fly ash will be discharged in water or soil, and this shifts Human toxicity impacts to Ecotoxicity impacts. CO_2 capture process can also further reduce the acid gases such as SOx, NOx, HCL and HF in flue gases after the FDG process, and hence power generation with CO_2 capture systems do not increase the impacts of Acidification, Eutrophication, and Photo-oxidant formation considerably throughout the life cycle. MEA capture system has the highest values in these three impact categories since the MEA capture processes consume more coal and the upstream processes of coal mining contribute to these three impacts. KS-1 capture has more benefits in most impact categories than MEA and K+/PZ, but KS-1 has a slightly higher value for Acidification and Eutrophication than K+/PZ, as KS-1 capture process generates more NH_3.

4. Conclusions

This paper described the methodological framework developed for life-cycle modelling of CO_2 capture in power generation using the post-combustion capture example. The LCIA results obtained for this power generation system have demonstrated that emissions from power generation plants have a significant variability due to geographical and technical differences. The models developed can identify these geographical and technical differences at unit process level and generate reliable emission data and potential environmental impact results.

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