***Original* Research Article**

Life Cycle Assessment of Supercritical Coal Power Plant with Carbon Capture and Sequestration in China

ABSTRACT

Coal has been the primary source of energy in China due to its abundance, with 55 % of its consumption in power generation. Carbon capture and sequestration (CCS) presents an alternate solution as one of the clean coal utilization technologies being developed in China. This paper used life cycle assessment to compare environmental impacts of carbon capture and sequestration technology on a typical supercritical coal power plant. Results from the environmental impact assessment shows 71 % reduction in life cycle greenhouse gas emission for CCS. Also, ionization radiation and ozone depletion potentials decrease in the case of CCS as a result of emissions from ammonia production in supercritical. It was also discovered that other environmental impact categories show significant tradeoffs for CCS due to coal supply chain, energy penalty, direct emissions, waste disposal and infrastructure of capture technology. This is evidently the case as terrestrial acidification increases by 175 %, human toxicity increases by 33 % and ecotoxicity show increases of 58 % to 431 % while eutrophication show increases of 22 % to 303 %. This study therefore, contributes to carbon capture and sequestration technology on supercritical power generation plant in China.

Keywords: Life cycle assessment, supercritical, carbon capture and sequestration, greenhouse gas emission

1. INTRODUCTION

China is the world's highest producer, consumer and exporter of coal, which has been the main energy source for industrialization since the 1950's. The growing demand for coal in areas like electricity generation, steel production, cement manufacturing and as a liquid fuel causes adverse impact on the environment. Changing to other energy sources apart from coal is nearly impossible because China has the world's third highest proven coal reserves of 114.5 billion tons, making coal a cheap, accessible and dependable form of energy source (British Petroleum, 2016). Advance technology aimed at reducing emissions has yielded power plants like Integrated Gasification Combined Cycle (IGCC), Ultra super-critical and Super-critical power plants with high generation efficiencies and emission control systems. Also, steps are being taken to reduce emissions by setting up plans to cap annual coal use to five billion tons (62 %) and raise non fossil energy consumption to 15 % by 2020 to decrease heavy air pollution (International Energy Outlook, 2016). Therefore, it is fair to note that China, which is the highest greenhouse gas (GHG) emitter due to its high coal consumption contributes significantly to global climate change. Renewable energy source is the long-term solution to tackle the GHG emission problem but it is not cost competitive at the present. For the interim, carbon capture and sequestration is an alternative solution (CCS). CCS is the process of capturing waste carbon dioxide from large point source like fossil fuel power plant, transport to storage site and depositing it where it would not enter the atmosphere, normally underground in geological formations.

It is significant to note that, there have been many studies conducted on life cycle analysis on coal fired plant with CCS. Most of these studies carried out comparative assessment of post combustion

coal, IGCC and NGCC (Natural Gas Combined Cycle) power plant with CCS. In addition, comparative studies of CCS with renewable energy technology have been done. These information were evident from studies such as Rubin and Rao (2005), Viebahn et al. (2007), Odeh and Cockerill (2008). However, it was uncovered that these research works mainly focused on GHG emission reduction. Other studies such as Nie et al. (2011), Koornneef et al. (2008), Korre et al. (2009), Pent and Henkel (2008) performed life cycle modelling and conducted detailed environmental impact assessment of coal power plants for different CO_2 capturing systems. Furthermore, studies such as Xiao et al. (2011) and Cui et al. (2012) performed life cycle assessment on pulverized coal power generation in China without considering CCS technology. Liang et al. (2013) conducted a complete life cycle assessment on China's clean coal power generation technologies. Wu et al. (2014) carried out life cycle analysis of coal fired power plants with CCS in China. The authors only considered CO_2 capture system for IGCC and ultra-supercritical power plants, which are commercially few in operation. Viebahn et al. (2015) performed environmental impact assessment on supercritical power plant with CCS in China, however, some impact categories like human toxicity, ecotoxicity, ionization radiation etc. were not discussed.

On the basis of literature reviewed pertaining to this study, it was noticed that little studies has been done in China on life cycle assessment of supercritical coal power plant with CCS. It is worth stating that supercritical coal power plant currently represent the dominant raw coal-based power generation technology in China (Cui et al., 2012). This paper aimed to bridge the gap by evaluating the potential environmental impacts of a typical supercritical coal power plant with CCS in China using life cycle assessment.

2. METHODOLOGY

2.1 Life cycle assessment

Life cycle assessment is the compilation and evaluation of the inputs and outputs of a product system and their potential environmental impacts during its lifetime (ISO 14040). LCA consists of the following steps; (1) Goal and Scope (2) Inventory Analysis (3) Impact Assessment and (4) Interpretation.

2.2 Goal and Scope

The objective of this study is to carry out life cycle assessment on a typical supercritical power generation plant and conduct comparative studies with carbon capture and sequestration technology.

2.3 Functional unit

The functional unit provides a reference where inputs and outputs are standardized (ISO 2006). The functional unit considered for this study is 1 MWh of generated electricity.

2.4 System boundary

The system boundary defines which processes will be included in, or excluded from the life cycle assessment. The life cycle analysis tracked inputs and outputs from each unit process of power production; from coal mining to transportation and to emission control measures. This study also considered transport of CO_2 and sequestration process. It is important to note that end of life stage of products and by-products from various stages were considered in the life cycle analysis.

2.5 General framework of life cycle inventory (LCI) modeling

When conducting life cycle assessment, some parameters must be the same in order to achieve a consistent inventory model. A net generation capacity of 600 MWh is assumed for both scenarios (Liang et al., 2014). Power plant construction and decommissioning data for China is acquired from Ecoinvent Database (Ecoinvent, 2007). Type of coal used for power production is a dominant factor in determining environmental impacts (Korre at al., 2010). Therefore, for geographical relevance, coal mix was assumed to be obtained from China and supplied to both power plants. Data on the average chemical composition and net caloric value of coal from China was obtained from Wang and Li (2001), as shown in Table 1. Coal mining and washing data was from Ecoinvent database (Ecoinvent, 2007). Mined coal was assumed to be transported a distance of 1880 km (Liang et al., 2014) by a 1000 ton

capacity diesel powered cargo train to each power plant site. Solvent production, waste disposal and use of byproducts were taken into consideration during life cycle inventory modeling. Emission data from coal combustion is estimated from mass flow calculations using stoichiometric reactions based on chemical and physical principles. Emission reduction factors from varying technologies for each scenario were derived from literature (Liang et al., 2014; Korre at al., 2010; Pent and Henkel, 2009; Singh et al., 2011)

Table 1. Chemical composition and heating values of coal used for life cycle inventory (Wang and Li, 2001)

Chemical Composition	Weight Percent (%)
Carbon	65.84
H_2O content	8.4
Sulphur	1.01
Nitrogen	0.9
Ash	23.85
Heating Value (MJ/kg)	22.54

2.5.1 Supercritical power plant

A typical supercritical power plant in China has a net generation efficiency of 40.8 %. (Liang et al., 2014). During operation, pollutants such as SO_2, NO_x, NH_3, HCl and particulate matter are removed from flue gas with the help of varying emission control measures such as Electrostatic Precipitator (ESP), Flue Gas Desulphurization (FGD) and Selective Catalytic Reduction (SCR) as illustrated in figure 1. Flue gas desulphurization has a removal efficiency of 95 % as shown in Table 2. Flue gas rich in SO_2 reacts with lime in a scrubbing unit to produce gypsum. Gypsum is further processed into wall board which is used in construction. With the help of electrostatic precipitator (99.9 % efficient), particulate matter in flue gas is removed, collected and disposed at landfill. Selective catalytic reduction with an efficiency of 85 % uses ammonia to convert NO_x into nitrogen gas. Nitrogen gas is then harmlessly released into the environment.

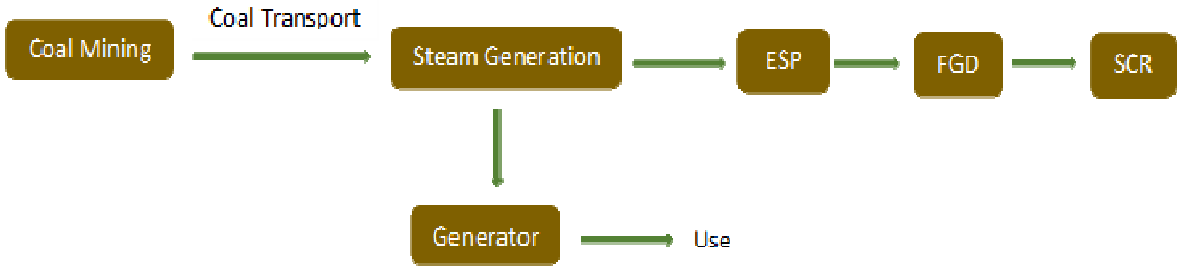

Fig. 1. Process flow chart of a typical supercritical power plant showing the system boundary considered for life cycle assessment

2.5.2 Supercritical with CCS

CO_2 capture commercially used in post combustion power plant is absorption capture process. Hence, this study assumed monoethanolamine (MEA) absorption capture having a 90 % capture efficiency (Table 2). Capture efficiency can be higher than 90 %, however, this will correspond to higher energy penalty, which is undesirable in supercritical coal power plants. Capture process requires energy for solvent regeneration, pump and gas blower action and CO_2 compression, hence a 10.2 % energy penalty (Singh et al., 2011) was assumed for this study.

Furthermore, MEA removes other pollutants from flue gas like particulate matter, SO_2, and NO_x. MEA reacts with SO_2 and NO_x to produce heat stable salts. Heat stable salts are removed in stripping unit using activated carbon in the form of charcoal. The amount of charcoal used is 0.05 kg per ton of CO_2 captured. This study considered a removal efficiency of 99.9 % for both particulate matter and SO_2 as

shown in Table 2. During NO_x reduction, only NO_2 reacts with MEA. This results in NO passing out of the exhaust stack as an inert gas. Total NO_x reduction was assumed to be 37.7 % (Korre et al., 2010).

MEA is lost during capture process as a result of evaporation, oxidation, and carbonate polymerization. Thus, 1.5 kg of MEA per 1 ton of CO_2 captured was assumed to be lost during operation. Caustic soda was used in MEA regeneration for a repeated capture process. Formation of ammonia gas as a result of MEA degradation is assumed to be negligible.

Table 2. Main performance specifications for supercritical power plant with and without CCS

Parameter	Supercritical	Supercritical with CCS	Reference
Net generation capacity (MWh)	600	600	[12]
Net generating efficiency (%)	40.8	30.6	[12/calculated]
Mass of coal (kg)	391.46	522.27	[calculated]
Coal transport distance (km)	1880	1880	[12]
Heating value (MJ/kg)	22.54	22.54	[16]
PM removal efficiency (%)	99.9	99.9	[9]
SO_2 removal efficiency (%)	95	99.995	[12/9]
NO_x removal efficiency (%)	85	37.7	[12/8]
CO_2 removal efficiency (%)	-	90	[9]
Limestone consumption (kg/kg SO_2 removed)	1.6	-	[calculated]
Ammonia consumption (kg/kg NO_x removed)	0.4	-	[calculated]
MEA for CO_2 capture (kg/kg CO_2 captured)	-	1.35	[calculated]
MEA for SO_2 capture (kg/kg SO_2 captured)	-	0.95	[calculated]
Energy for MEA regeneration (MJ)	-	4200	[8]
CO_2 transport distance (km)	-	500	[17]

2.5.2. CO_2 compression and transport

Captured CO_2 is compressed at the power plant to a pressure of 15 MPa and transported through a 0.4 mm diameter pipe to a distance of 500 km for sequestration (figure 2). It is important to note that CO_2 experience a pressure drop of 1 MPa every 100 km when it is being transported through pipes (Singh et al., 2011).

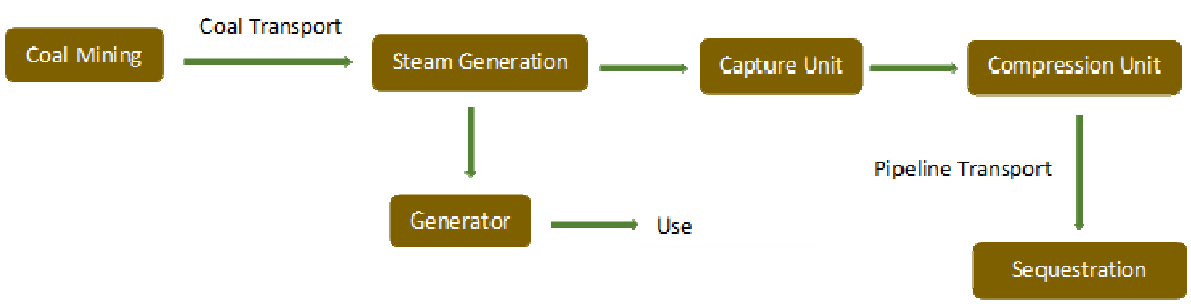

Fig. 2. Process flow chart of a supercritical power plant with CCS, showing the system boundary considered for life cycle assessment

2.5.3 Sequestration

CO_2 is assumed to be sequestrated at a pressure of 11 MPa. Sequestration data is obtained from Ecoinvent Database (Ecoinvent, 2007) for a single CO_2 injection well. The study considered CO_2 injection into saline aquifer. Monitoring of storage site was not included in the life cycle assessment. Here, CO_2 leakage is assumed to be negligible.

2.6 Environmental Impact Assessment

This study used ReCiPe methodology to perform life cycle environmental impact assessment on supercritical power plant with and without CCS. ReCiPe is based on the CML 2000 and the Eco-Indicator 99 methodologies. The CML 2000 emphasizes on midpoint indicators, whereas the Eco-Indicator 99 focus on endpoint indicators. Impact categories for ReCiPe include global warming, terrestrial acidification, ionization radiation, human toxicity, eutrophication, ecotoxicity, particulate matter formation, ozone depletion, photochemical oxidant formation and resource depletion as indicated in Table 3.

Table 3. Life cycle impact categories and characterization factor (AL Torp, Norwegian University of Science and Technology, Norway, unpublished results)

Impact category	Unit	Scale	Characterization factor
Global Warming	kg (CO_2 to air)	Global	Converts LCI data on GHGs like CO_2, NO_2, CH_4, CFCs, HCFCs, CH_3Br to carbon dioxide (CO_2) equivalents
Resource depletion	kg of water, metal and fossil	Global, Regional, Local	Converts LCI data on water, metals and fossil fuels used to a ratio of quantity of resource used versus quantity of resource left in reserve.
Ecotoxicity	kg (14DCB to soil or water)	Global, Regional, Local	Converts LC50 data on toxins to equivalents using multimedia exposure pathways.
Eutrophication	kg (N or P to water)	Local	Converts LCI data on PO_4^{3-}, NO, NO_2, Nitrates and NH_4^+ to phosphate (PO_4^{3-}) equivalents
Terrestrial Acidification	kg (SO_2 to air or water)	Regional, Local	Converts LCI data on acids like SO_2, NO_x, HCL, HF, and NH_4^+ to hydrogen (H^+) ion equivalents.
Human toxicity	kg (14DCB to urban air)	Global, Regional, Local	Converts LC50 data on toxins to equivalents using multimedia exposure pathways.
Ionizing Radiation	kg (U_{235} to air)	Local	Converts LCI data on radioactive substances to ^{235}U equivalents.
Ozone depletion	kg(CFC_{115} to air)	Global	Converts LCI data on halons, CH_3Br, chlorofluorocarbons and hydrochlorofluorocarbons to trichlorofluoromethane (CFC-11) equivalents.
Particulate matter formation	kg (PM_{10} to air)	Global, Regional, Local	Converts LCI data on TOC (Total Organic Carbon), heavy metals, smoke, dust and spores to PM10 equivalents.
Photochemical oxidant formation	kg ($NMVOC_6$ to air)	Regional, Local	Converts LCI data on substances like benzene, ethanol, cyclohexane and acetone to NMVOC (Non Methane Volatile Organic Compounds) equivalents.

3. RESULTS AND DISCUSSION

Global warming potential in Table 4 indicates a significant decrease of 71 % in CO_2 equivalents for CCS. It was observed that the main contributing factor for total GHG emission for supercritical is coal combustion. However, the main cause of total GHG emission for CCS turns out to be coal supply chain. CO_2 leakage after sequestration is considered as negligible due to the short term impact assessed by this study.

From Table 4, application of CCS technology reduces ionization radiation and ozone depletion potentials. It is quite clear that the use of ammonia during NO_x reduction is the cause of comparatively higher ionization radiation and ozone depletion potentials in supercritical. Here, waste tailings from

ammonia production contains radioactive and organic compounds, which are released into the environment.

With regards to eutrophication, CCS experienced an increase of 22 % and 303 % for freshwater and marine eutrophication respectively (Table 4). Comparatively, it is evident that CCS which used more coal, will have high amounts of phosphor or phosphate leaching into water bodies from processes such as coal mining, ash and reclaimer waste disposal. Thus, contributing to CCS recording a higher freshwater eutrophication value. On the other hand, the 303 % increase in marine eutrophication could be attributed to MEA having the least NO_x reduction factor as compared to supercritical's selective catalytic reduction.

Analysis of results from Table 4 indicates a 175 % increase for terrestrial acidification potential for CCS. This is a surprising phenomenon because CCS has an improved SO_2 reduction efficiency (99.995 %) over supercritical. However, SO_2 emission from coal supply chain and MEA production evidently increase terrestrial acidification potential for CCS.

Various toxicity potentials for CCS record increases of 33 % to 431 % as shown in Table 4. It is observed that human toxicity increases by 33 %, while freshwater, marine and terrestrial ecotoxicity increase by 431 %, 58 % and 427 % respectively. The increase in toxicity potentials can be attributed to CCS infrastructure and heavy metal emission during coal supply chain and solvent production. CCS infrastructure and heavy metal emission from solvent production are the contributing factors to high freshwater and terrestrial ecotoxicity potentials. Moreover, heavy metal emission from coal supply chain is the leading cause of increased marine ecotoxicity and human toxicity values for CCS.

It can also be noted from Table 4 that particulate matter formation potential for CCS increases by 209 %. This is evidently caused by burning more coal for electricity production. In addition to that, SO_2 and methane emissions during coal supply chain are the main factors for a 286 % increase of photochemical oxidant formation potential for CCS.

Furthermore, coal supply chain and solvent production are the factors for high fossil, water and metal depletion potentials for CCS. As indicated in Table 4, fossil depletion potential increases by 32 % while water and metal depletion increase by 18 % and 15 % respectively. Results in Table 4 can further be viewed in Figure 3.

Table 4. Results for environment impact assessment

Impact Category	Supercritical	Supercritical with CCS	Change in Impact
Global Warming	961	276	-71
Terrestrial Acidification	1.47	4.04	175
Freshwater Eutrophication	8.46E-05	1.03E-04	22
Ozone Depletion	1.38E-10	8.70E-11	-37
Fossil Depletion	269	356	32
Freshwater Ecotoxicity	0.0125	0.0664	431
Human Toxicity	5.17	6.86	33
Ionization Radiation	0.212	0.174	-18
Marine Ecotoxicity	0.0120	0.019	58
Marine Eutrophication	0.675	2.72	303
Metal Depletion	0.0473	0.0542	15
Particulate Matter Formation	0.524	1.62	209
Photochemical Oxidant Formation	1.84	7.1	286
Terrestrial Ecotoxicity	2.79E-03	1.47E-02	427
Water Depletion	15	17.7	18

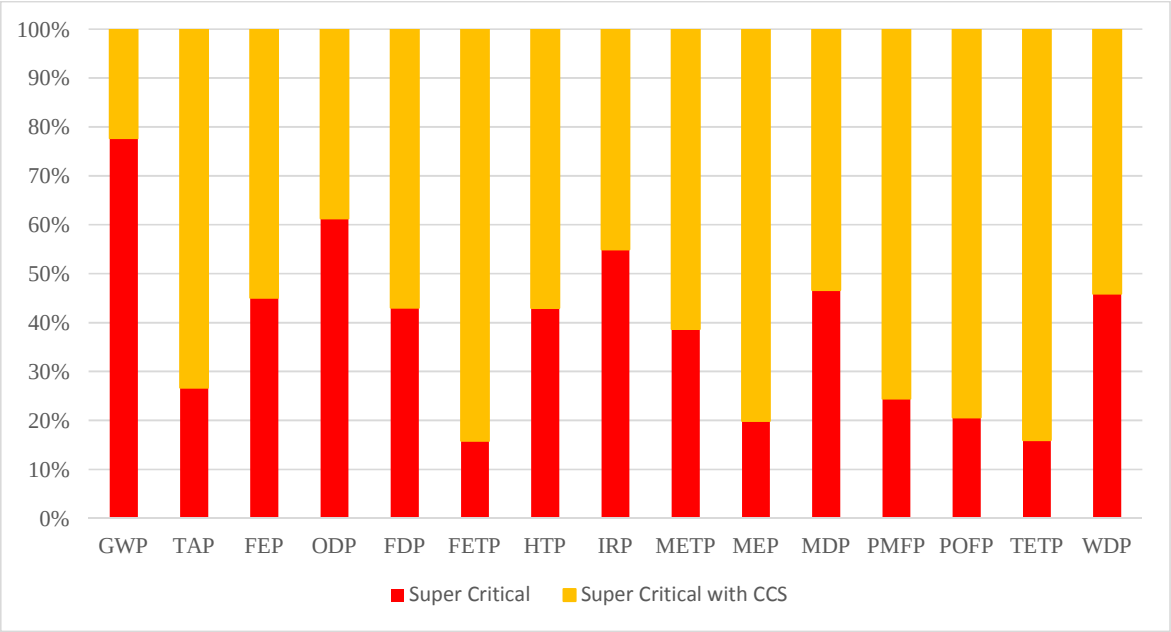

Fig. 3. Graph of environmental impact assessment (GWP is Global warming, TAP is Terrestrial Acidification, FEP is Freshwater Eutrophication, ODP is Ozone Depletion, FDP is Fossil Depletion, FETP is Freshwater Ecotoxicity, HTP is Human Toxicity, IRP is Ionization Radiation, METP is Marine Ecotoxicity, MEP is Marine Eutrophication, MDP is Metal Depletion, PMFP is Particulate Matter Formation, POFP is Photochemical Oxidant Formation, TETP is Terrestrial Ecotoxicity, WDP is Water Depletion)

4. CONCLUSION

The goal of this study was to conduct life cycle assessment to determine the environmental impacts of CCS on supercritical coal power plant in China. Results indicate that CCS can reduce global warming potential by 71 % on supercritical power plant. Moreover, coal supply chain is the main contributing factor of life cycle GHG emission for CCS.

CCS increases other environmental impact categories except for ozone depletion and ionization radiation. These increases are mainly attributed to coal supply chain, energy penalty, direct emissions, waste disposal and infrastructure of capture technology. Supercritical however, experiences high values for ozone depletion and ionization radiation potentials due to emission of radioactive and organic compounds during ammonia production.

This study therefore, pointed out major areas in CCS technology for supercritical power plant that could need further technical development. Therefore, inventories, potential environmental impacts and improvements presented in this study could inform policy makers in decision making regarding the construction of CCS in China.

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