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A Comparative of Life Cycle Assessment of Post-Combustion, Pre-Combustion and Oxy-fuel CO_2 capture

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Abstract

This paper presents a life cycle assessment (LCA) of three different carbon dioxide (CO_2) capture technologies, namely post-combustion, pre-combustion and oxy-fuel capture. The Boundary Dam Power Station (BDPS) in Saskatchewan, Canada was chosen as a case study for modeling of operations at the electrical generating station. This study showed that CO_2 capture technologies have the potential of reducing greenhouse gas (GHG) emissions. Where an increase in the impact categories associated with soil and water was observed, the release of pollutants to the atmosphere were reduced and became more manageable in their waste streams.

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Keywords: *LCA; carbon dioxide capture; GHG emissions; TRACI*

1. Introduction

Carbon dioxide capture is increasingly seen as an important component of any broadly-based greenhouse gas reduction program, such as the use of renewable energy sources. Fossil fuel electrical generating stations are typically large emitters of carbon dioxide (CO_2) and other emissions such as sulphur oxides, heavy metals, nitrogen oxides and particulates, although emissions reduction technologies are in place at most electrical generating stations today. When CO_2 capture is employed, these emissions can be further reduced.

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However, the CO_2 capture requires additional energy for its operation thereby lowering the overall efficiency of the electricity generating plant. More fossil fuel per unit of electricity generated must be used to compensate for the lost capacity, resulting in a higher level of emissions and resource consumption. It is necessary to evaluate the environmental performance of CO_2 capture from a full life cycle perspective to comprehensively understand its environmental impacts.

Most recent LCA studies of the CO_2 capture technologies include [1-8]. These studies were based on hypothetical plants.

The Boundary Dam Power Station (BDPS) in Saskatchewan, Canada was chosen as a case study for modelling of operations at the electrical generating station. The unit processes in each system were modelled in Microsoft Excel and AspenPlus® (trademark of Aspenplus, USA) simulation software so that emissions and wastes associated with each unit process are tracked. The modelling results were then fed to GaBi5 (trademark of PE International, Germany) for LCA analysis.

The assessment of environmental impacts from the CO_2 capture systems was conducted using the “cradle-to-gate” approach which included the life cycle stages of open surface lignite coal mining, construction, and operations of an electricity generation station with and without CO_2 capture. The complex system was broken down into elementary flows which were then grouped and categorized based on the effects they have on the environment. The TRACI life cycle impact assessment (LCIA) method was adopted for the analysis. The environmental impacts of the three technologies were assessed based on twelve impact categories.

2. Implementation of LCA methods

2.1. Goal and scope definition

The goal of this study was to evaluate and compare the environmental performance of three different CO_2 capture technologies integrated with lignite coal-fired electricity generation system.

The modelled electricity generation systems were based on the lignite coal-fired Boundary Dam Power Station in Saskatchewan, Canada. The assessment of environmental impacts was conducted using the “cradle-to-gate” approach.

2.2. Functional unit

The functional unit used in this study was 1 MWh of electric energy produced and delivered to the grid (i.e. net electric energy output) by a lignite coal-fired electricity generation system. All energy necessary for CO_2 capture was assumed to come from the electrical generating station and was assumed to reduce the net electricity generation system output. Constant energy output from all three electrical generating stations was assumed in order to evaluate the resource efficiency of the different technologies.

2.3. System boundaries

This was a cradle-to-gate study that included the life cycle activities from resource extraction (e.g., coal and limestone), production (e.g., steel, concrete, solvent) to generation of electrical energy at the electrical generating station combined with the CO_2 capture process. The system boundary in this study is presented in Figure 1.

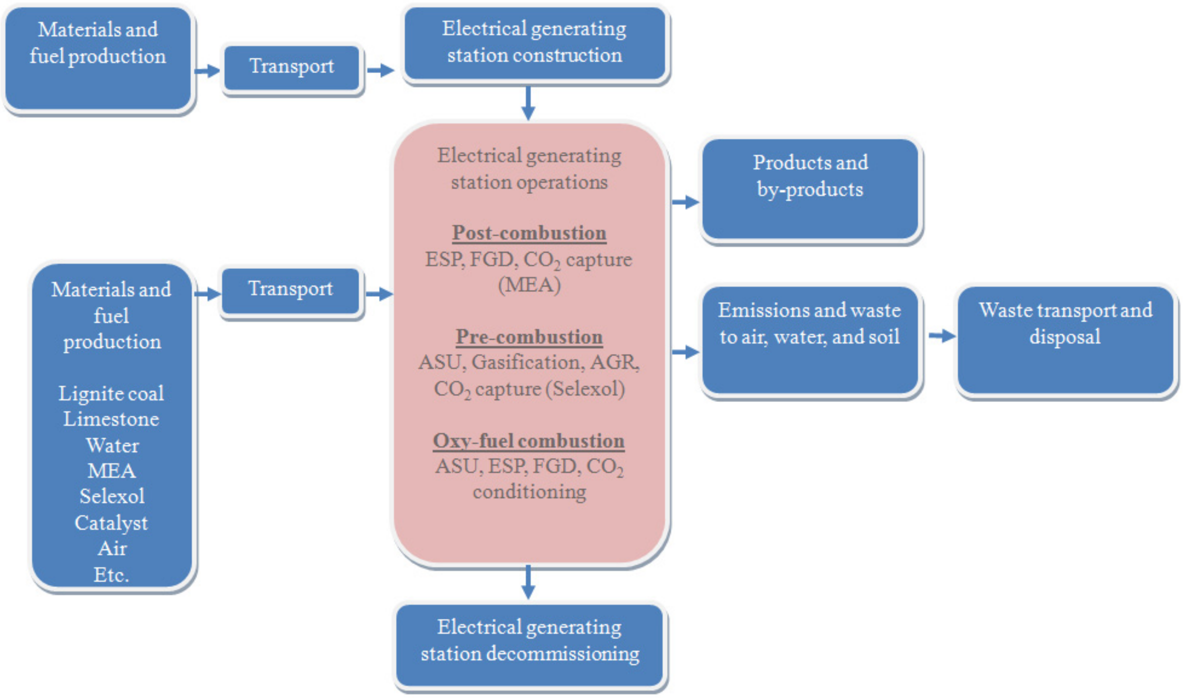

Fig. 1. System boundaries for lignite-fired electrical generating station with post-, pre-, and oxy-fuel combustion CO_2 capture.

2.4. Temporal and geographical boundaries

It was assumed for the purpose of this study that the plant would be operational for 30 years. Most of the processes included in the system boundaries occurred in Western Canada. However, some unit processes occurred in other Canadian provinces, the US and worldwide.

2.5. Technological boundaries

This study evaluated modern CO_2 capture technologies and well established configurations for generation of electrical energy. Four systems were analyzed:

- Conventional pulverized coal (PC) electricity generation system (baseline): Boundary Dam Power Station (BDPS) Unit 3 (150 MW) including boiler and electrostatic precipitator (ESP);
- Pulverized coal electricity generation system with amine post-combustion CO_2 capture: boiler, ESP, flue gas desulphurization (FGD) and post-combustion CO_2 capture using MEA;
- IGCC electricity generation system with Selexol pre-combustion CO_2 capture: air separation unit (ASU), gasification, acid gas removal (AGS), CO_2 capture unit and
- Oxy-fuel electricity generation system: ASU, Boiler, ESP, FGD and CO_2 compression and purification units.

2.6. LCIA method

The TRACI life cycle impact assessment methodology was applied in this study. The TRACI methodology produced assessment results on the midpoint impact categories: ozone depletion, global warming, smog formation, acidification, eutrophication, human toxicity, human health criteria air-point source, and eco-toxicity. In TRACI methodology, the category of human toxicity is divided into six subcategories: (1) human health non-cancer air, (2) human health cancer air, (3) human health non-cancer water, (4) human health cancer water, (5) human health non-cancer ground surface soil and (6) human health cancer ground surface soil. The category of eco-toxicity is divided into the three categories: (1) eco-toxicity of air, (2) water, and (3) ground surface soil.

3. Results

The three CO_2 capture systems were compared based on these environmental impact categories and the results were analyzed. The conventional power generation system with and without the integrated CO_2 capture technology were referred to as the "no capture" and "capture" scenarios, respectively.

The impact to each environmental category of three CO_2-capture scenarios was presented in terms of percentage change compared to baseline scenario in Table 1. Percentages were used rather than absolute quantities in this study and, as a result, the impact categories, particularly under human toxicity related to soil and water, appeared to see significant increases. This was a result of using percentages as the absolute changes were quite small. Global warming was the most significant and this impact category had major health benefits as well as environmental benefits. The analysis of the results of LCA study is presented below.

3.1. Global Warming

The impact to the category of global warming was decreased by 80% in the post-combustion CO_2 capture system, and by about 86% in the pre-combustion and oxy-fuel systems. Most of the reduction was derived from operation of the electricity generation systems as direct CO_2 emissions from the electricity generation systems were captured. Compared to the electricity generation systems without CO_2 capture, the contribution of coal mining was increased from 3.3% to 25.5%, 39.0%, and 10.7% to the total GHG emissions in the post-combustion, oxy-fuel, and pre-combustion systems, respectively. The increase of greenhouse gases emissions in coal mining was due to increase in coal consumption in three capture scenarios. The construction of electrical generating station had a lowest environmental impact compared to other life cycle stages.

3.2. Eutrophication

The results showed that the impacts to eutrophication varied significantly in the three CO_2 capture systems. In the post-combustion CO_2 capture system, the impact to eutrophication was increased by 66.5% due to ammonia (NH_3) and MEA emissions from capture unit and ethylene emissions from production of MEA.

The eutrophication potential of the oxy-fuel scenario was decreased by 86.0% compared to the conventional power generation system without CO_2 capture. As the oxygen instead of air was used for combustion, the NO, NO_x, and NO_2 were significantly reduced and they were further removed in the ESP, FGD, and CO_2 compression and purification units in the oxy-fuel system.

The eutrophication potential of the IGCC power system showed a significant increase of 63.03% compared to the conventional power generation system. The operation of the IGCC system was the primary contributor and accounts for 99% of the eutrophication impact.

3.3. Acidification

The results showed that three CO_2 capture systems all greatly reduced the impacts to acidification, while the oxy-fuel system had the best performance and the post-combustion system had the highest impact to acidification. The impact to the acidification of the post-combustion scenario was reduced by 50% compared to the baseline scenario. Although SO_2 emissions were significantly reduced by MEA scrubbing process (99% removal rate), the acidification still increased due to the emissions from MEA production and degradation. In the oxy-fuel system, the impact to acidification was reduced by 93.4% compared to the baseline scenario. Only small amount of NO_x was produced due to the oxygen-based combustion, and NO_x and SO_x were removed in the gas cleaning process.

Therefore, operation of electricity generation system accounted for only 28% of acidification. Compared to the baseline scenario, the impact to the acidification of the IGCC system with pre-combustion was reduced by 88.5% due to the gas cleaning process that removed most of the pollutants.

3.4. Ozone Depletion

Compared to the conventional electricity generation system without CO_2 capture, the results showed the impact to ozone depletion was increased by 48.2%, 60.6%, and 45.9% for post-combustion, oxy-fuel, and IGCC with pre-combustion systems. Nearly 100 % of the ozone depletion originated from coal mining in all the four scenarios. The increased impact of ozone depletion was mainly due to the additional coal and fossil fuels needed for operation of the CO_2 capture system and the associated processes.

3.5. Ecotoxicity

The results showed that the impact to the air-ecotoxicity is respectively reduced by about 82.8%, 87.8%, and 89.3% for the post-combustion, oxy-fuel, and IGCC with pre-combustion capture systems compared to the baseline scenario. The heavy metals were captured by the gas cleaning processes in the CO_2 capture system (ESP, FGD, CO_2 compression and purification) instead of being emitted to the air, which led to lower impacts to the air-ecotoxicity.

The results showed that the impact to the soil-ecotoxicity was respectively increased by 111%, 32.8%, and 79.0% for the post-combustion, oxy-fuel, and IGCC with pre-combustion capture systems compared to the baseline scenario. Operation of the electricity generation station was the primary source for terrestrial ecotoxicity in all three CO_2 capture scenarios. The trace elements from bottom ash will eventually leak to the soil when land-filled, which caused an increase in impact of terrestrial ecotoxicity.

The results showed that the impact to the water-ecotoxicity was respectively increased by 187%, 176%, and 47.2% for the post-combustion, oxy-fuel, and IGCC with pre-combustion capture systems compared to the baseline scenario. The increased impact was also derived from the trace elements collected from the electricity generation system and CO_2 capture unit, which were landfilled as bottom ash eventually leaked to groundwater.

3.6. Human Toxicity

The human toxicity was derived from the emissions to three different media of air, water, and soil. In the three CO_2 capture systems, the heavy metals, VOCs, and different inorganic emissions were retained in the gas cleaning processes (ESP, FGD, CO_2 compression and purification) instead of being emitted to atmosphere, the impact category of air toxicity was thereby greatly reduced. These wastes were deposited in landfill with bottom ash, which led to the increased impact to the soil. They may eventually leak to the groundwater leading to increased impact to the aquatic human toxicity.

3.7. Human Health-Air Point Source

Compared to the conventional electricity generation system, the impacts to the human health air-point source category were reduced by 78.9%, 89.3%, and 79.2% for the post-combustion, oxy-fuel, and IGCC with pre-combustion scenarios. The decreased impact was attributed to the gas scrubbing processes (ESP, FGD, and CO_2 compression and purification units), which reduced the emissions of particulate matters (total suspended particulates or PM10 and PM2.5) and secondary particulate sulfate (generated from SO_x) to the environment.

3.8. Smog air

In the post-combustion scenario, the impact to smog air was increased 48.6% mainly due to emissions of NO_2 and NO_x from coal mining. The impact was decreased by 0.9% in the oxy-fuel and 93.1% of the impact was derived from the coal mining process. Although more coal was consumed for auxiliary power, less NO_x was produced and emitted due to combustion of oxygen and flue gas scrubbing operations. The IGCC with pre-combustion system had 54.5% higher impact on this category due to higher NO_x concentration in the flue gas from syngas combustion.

Table 1. Comparison of impacts of three systems based on baseline scenario.

		Post-combustion	Oxy-fuel combustion	Pre-combustion
Global warming		-80.0%	–85.5%	–85.5%
Eutrophication		+66.5%	–86.0%	+63.0%
Acidification		–50.0%	–93.4%	–88.5%
Ozone depletion		+48.2%	+60.0%	+45.9%
Ecotoxicity	Air	–82.8%	–87.8%	–89.3%
	Soil	+111%	+32.8%	+79.0%
	Water	+187%	+176%	+47.2%
Human Toxicity	Air	–81.6%	–90.5%	–91.7%
(carcinogenic)	Soil	+98.1%	+25.2%	+31.9%
	Water	+109%	+157%	+45.0%
Human Toxicity	Air	–79.8%	–86.0%	–87.5%
(non-carcinogenic)	Soil	+96.09%	+96.2%	+87.04%
	Water	+75.5%	+84.9%	+49.7%
Air-point source		–78.9%	–89.3%	–79.2%
Smog air		+48.6%	–0.9%	+54.5%

4. Conclusions

The life cycle assessment was conducted on the three technologies of post-combustion, pre-combustion, and oxy-fuel CO_2 capture integrated with pulverized coal-fired power generation system to compare the environmental impacts of the three technologies throughout all the stages in the electricity generation life cycle. The three projects had the same system boundaries and included the upstream and downstream processes of the power generation such as coal mining, construction, operation and decommissioning of the electricity generation plant, as well as CO_2 capture and compression.

The comparison showed that pre-combustion and oxy-fuel technologies performed better than post-combustion in several environmental impact categories. Pre-combustion and oxy-fuel power plants required less coal to produce the same electrical output compared to a power plant with post-combustion capture. The former two technologies resulted in reduced emissions and wastes generated.

The pre-combustion technology has shown the least impact in the acidification category because most of the SOx and NOx emissions have been removed in the gas cleaning process after coal gasification. In the eutrophication potential impact category, the oxy-fuel technology had shown the least impact, because only a small amount of NOx and NH_3 was produced in the oxygen-based combustion, and these compounds were further removed in the ESP, FGD, and CO_2 compression and purification units. A similar result was observed in the smog air impact category. The pre-combustion and oxy-fuel combustion also performed better in the ozone depletion category compared to the post-combustion CO_2 capture technology.

All three technologies can achieve the goal of CO_2 emissions reduction and they demonstrated substantially reduced impacts in the categories of global warming and emissions to air. This in turn resulted in lower impacts in the eco-toxicity (air), human cancer and non-cancer (air), and air-point source impact categories. The pre-combustion technology has shown the best performance in the categories of eco-toxicity (air), human cancer and non-cancer (air) because it can almost completely remove heavy metals and benzene in the gas cleaning process. The oxy-fuel combustion technology has shown the least impact in the category of air-point source, because most of the particulate matter was removed in the ESP, FGD, and CO_2 compression and purification units.

In all three technologies, the pollutants were transferred from the air to the soil and water environmental compartments. When solid wastes were deposited in landfills, there was a chance of pollutants leakage to soil and water. Thus, the three technologies showed a slightly increased impact in the categories of eco-toxicity (water and soil), human cancer and non-cancer (water and soil). With the increase in coal use and the nature of the process being used to reduce atmospheric emissions, the release of pollutants to the atmosphere was reduced and became more manageable in waste streams to water and soil. While there was an increase in certain categories, the broad distribution associated with atmospheric release was significantly reduced.

By using the percentage change as the scale of the impacts, the increase in some impact categories was significant. This was because a small absolute increase can lead to a significant percentage change.

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