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The role of Life Cycle Assessment in identifying and reducing environmental impacts of CCS

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Abstract

Life Cycle Assessment (LCA) should be used to assist carbon capture and sequestration (CCS) planners to reduce greenhouse gas (GHG) emissions and avoid unintended environmental trade-offs. LCA is an analytical framework for determining environmental impacts resulting from processes, products, and services. All life cycle stages are evaluated including raw material sourcing, processing, operation, maintenance, and component end-of-life, as well as intermediate stages such as transportation. In recent years a growing number of LCA studies have analyzed CCS systems. We reviewed 50+ LCA studies, and selected 11 studies that compared the environmental performance of 23 electric power plants with and without CCS. Here we summarize and interpret the findings of these studies. Regarding overall climate mitigation effectiveness of CCS, we distinguish between the capture percentage of carbon in the fuels, the net carbon dioxide (CO_2) emission reduction, and the net GHG emission reduction. We also identify trade-offs between the climate benefits and the potential increased non-climate impacts of CCS. Emissions of non-CO_2 flue gases such as NO_x may increase due to the greater throughput of fuel, and toxicity issues may arise due to the use of monoethanolamine (MEA) capture solvent, resulting in ecological and human health impacts. We discuss areas where improvements in LCA data or methods are needed. The decision to implement CCS should be based on knowledge of the overall environmental impacts of the technologies, not just their carbon capture effectiveness. LCA will be an important tool in providing that knowledge.

Introduction

The purpose of CCS is to reduce CO_2 emissions and help mitigate climate change. A well-functioning CCS system can achieve this, although the overall climate benefits may be less than expected, and they may come at the cost of other environmental impacts. LCA can assist in evaluating and understanding the overall benefits and impacts of CCS.

LCA is an analytical framework for determining environmental impacts resulting from processes, products, and services. All life cycle stages are evaluated including raw material sourcing, processing, operation, maintenance, and component end-of-life, as well as intermediate stages such as transportation (Figure 1). LCA includes four phases (ISO 2006). *Goal and scope definition* describes the purpose of the study, the system boundaries of the analysis, and the functional unit used for assessment and comparison. *Inventory analysis* quantifies indicators that describe processes occurring within the system boundary. *Impact assessment* characterizes the effects of the indicators considering human and environmental exposure and responses. *Interpretation* of the inventory and impact assessment results assists the practitioner in identifying the significant conclusions, recommendations and implications for decision-making.

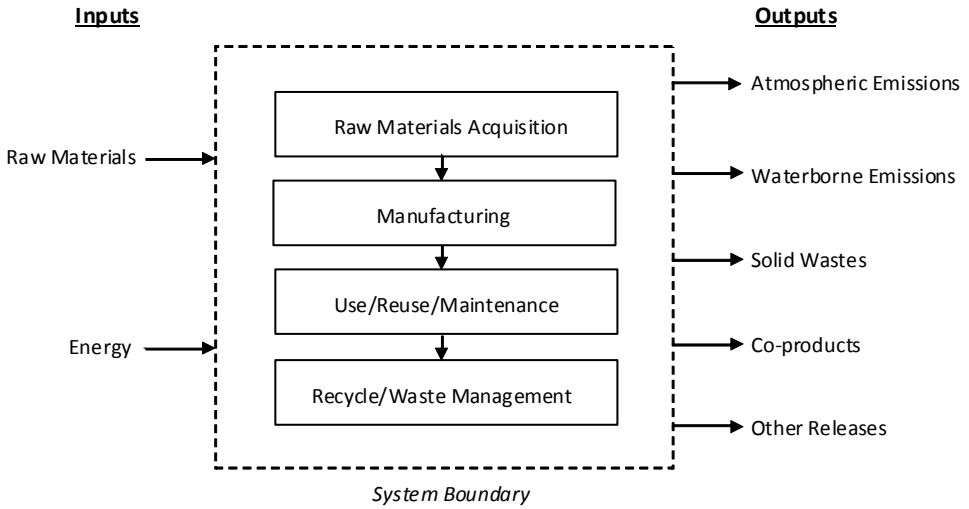

Figure 1. Schematic diagram of life cycle stages, inputs, and outputs.

In recent years a growing number of LCA studies have analyzed CCS systems, with varying degrees of thoroughness and transparency. A sufficient body of literature has been accumulated to allow these studies to be compared and contrasted, to generate additional knowledge. Here we review LCA studies and interpret their findings, seeking to identify general conclusions regarding the overall climate mitigation effectiveness of CCS, as well as potential trade-offs between climate benefits and non-climate impacts of CCS.

Methods

We conducted a comprehensive review of 50+ full- or partial-LCA studies of CCS systems. The studies differed in terms of their focus (types of CO_2 sources and capture technologies), their transparency (description of analytical methods and assumptions; availability of source data), and their completeness (life cycle phases considered; analysis of multiple options or uncertainties). We selected 11 studies that directly compared environmental impacts of electric power plants with and without CCS, and were conducted and reported in sufficient detail to allow the quantitative comparison of their results. The 11 studies are Viebahn et al. (2007), Koornneef et al. (2008), Odeh and Cockerill (2008), Pehnt and Henkel (2009), Korre et al. (2010), NETL (2010a, b, c, d), Schreiber et al. (2010), and Singh et al. (2011).

The 11 studies contain comparisons of 23 different types of power plants and capture systems. Among the 23 plants, 13 used hard coal fuel, 6 used lignite fuel, and 4 used natural gas. The generating technology of 15 of the plants was the Rankine cycle, while 8 used combined cycle technology. Amine-based solvent capture technology (primarily MEA) was used in 18 plants, while 5 plants used other capture technologies (primarily physical solvents such as Rectisol and Selexol).

From each study, we collated data on thermal efficiency, CO_2 captured, CO_2 emitted, non-CO_2 GHGs emitted, and non-GHG emissions. Three studies (Koornneef et al. 2008; Odeh and Cockerill 2008; Pehnt and Henkel 2009) reported thermal efficiency based on Lower Heating Value (LHV) of the fuels, while four studies (NETL 2010a, b, c, d) reported it based on Higher Heating Value (HHV). Three studies (Viebahn et al. 2007; Schreiber et al. 2010; Singh et al. 2011) did not specify the basis, so we assumed these European studies use LHV. One study (Korre et al. 2010) did not report thermal efficiency, but we calculated it based on data reported in the study and in personal correspondence with the authors. We harmonized thermal efficiency data so that all data are now based on LHV of the fuels, to allow direct comparison.

The energy penalty associated with CCS applied to an electricity plant may be expressed in two ways, either as the increase in fuel input per unit of delivered electricity, or as the decrease in electricity output per unit of fuel input. For each of the 23 plants we calculated the energy penalty both ways, using the following equations (IPCC 2005):

$$\Delta E = \left[\left(\frac{\eta_{ref}}{\eta_{ccs}}\right) - 1\right] \times 100 \qquad \Delta E^* = \left[1 - \left(\frac{\eta_{ccs}}{\eta_{ref}}\right)\right] \times 100$$

where ΔE is the percent increase in fuel input per unit of delivered electricity, ΔE^* is the percent decrease in electricity output per unit of fuel input, η_{ref} is the thermal efficiency of the plant without CCS, and η_{ccs} is the thermal efficiency of the plant with CCS.

The studies reported non-climate impacts in two different ways. Five of the studies reported non-GHG emissions in absolute quantities, e.g. grams (g) per kWh. Five other studies reported non-GHG emissions aggregated into impact categories, e.g. Acidification Potential, Eutrophication Potential, and Human Toxicity Potential. One study reported a mixture of both methods. We did not attempt to disaggregate or harmonize these two methods; instead, we reported each separately.

Results

Table 1 shows the average thermal efficiency (LHV basis) of the plants with and without CCS, and the energy penalty of the CCS system. The average plant efficiency without CCS is higher than efficiencies found at existing conventional power plants, reflecting the advanced current or expected future plant performance modeled in the studies. The particularly high-efficiency lignite plants are based on German design. The energy penalty is highest for the lignite-fired plants, while the natural gas-fired plants have the lowest energy penalty. This is largely due to higher carbon intensity (carbon emission per unit of heat) of lignite, requiring a greater absolute quantity of CO_2 capture per unit of energy content and electricity production to achieve the desired percent decrease in CO_2 emissions.

Table 1. Average plant thermal efficiency (LHV basis) and energy penalty, by fuel type.

Fuel	Plant thermal efficiency		Energy penalty	
	without CCS	with CCS	ΔE	ΔE*
All plants	46%	35%	33%	24%
Lignite	46%	32%	44%	30%
Hard coal	44%	33%	32%	24%
Natural gas	55%	47%	17%	15%

Figure 2 shows the energy and GHG flows associated with producing 1 MWh of electricity, with and without CCS, averaged over the 23 power plants. To produce a unit of electricity, on average 33% more fuel is required with the CCS system. In the power plants without CCS, all of the carbon in the fuel is emitted (763 $kgCO_2$). In the plants with CCS, 90% of the carbon in the fuel is captured and sequestered (916 $kgCO_2$), and 10% is emitted to the atmosphere (98 $kgCO_2$). Because the fuel throughput of the CCS-equipped plants (10.6 GJ/MWh) is greater than in the plants without CCS (7.9 GJ/MWh), the net reduction in CO_2 emission is less than 90%. Furthermore, additional CO_2 is emitted from indirect emissions that arise from processes such as producing the CCS infrastructure and from mining and transporting the additional fuel required. In total, the net CO_2 emission is reduced by 82%. In addition to CO_2 emissions, there are emissions of non-CO_2 GHGs, primarily methane, from coal mining and natural gas leakage and other indirect sources. Total indirect GHG emissions per MWh of electricity are an average of 101 $kgCO_2e$ greater for the plants with CCS compared to the plants without CCS. The overall GHG emission of the CCS-equipped power plant is 74% less than the power plant without CCS.

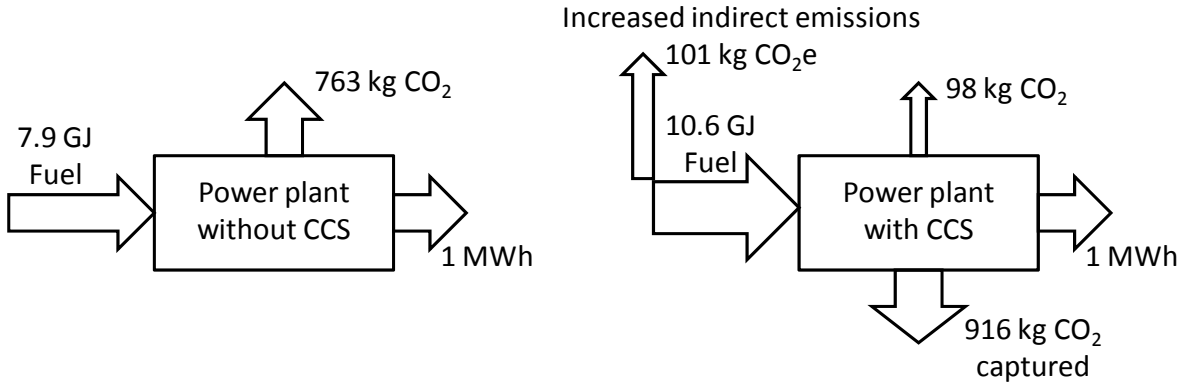

Figure 2. Energy and GHG flows associated with producing 1 MWh of electricity, with and without CCS. Data are averages of 23 case-study power plants.

While Figure 2 shows average emissions for all 23 plants, Table 2 reports emission reduction for plants disaggregated by fuel type. The capture percentage and net CO_2 emission reduction are similar for the hard coal- and lignite-fired plants, but the net GHG emission reduction is greater for the lignite-fired plants. This is largely due to the decreased methane emission from surface-mined lignite, relative to hard coal mining. For natural gas-fired plants, the net emission reduction of both CO_2 and total GHG are lower than for coal- and lignite-fired plants. This is due to the higher proportion of extraction and transport emissions, relative to carbon in the fuel, for natural gas compared to the other fuels.

Table 2. Percent fuel carbon capture, CO_2 emission reduction, and GHG reduction, by fuel type.

	All plants	Lignite	Hard coal	Natural gas
Fuel carbon captured	90%	90%	91%	90%
Net CO_2 emission reduction	82%	84%	83%	74%
Net GHG emission reduction	74%	81%	74%	65%

Figure 3 shows the energy penalty (expressed as the increase in fuel input per unit of electricity) as a function of net GHG reduction for the 23 power plants. The lignite-fired plants show a large range in energy penalty, but maintain consistently high rates of GHG emission reduction. Natural gas-fired plants have smaller energy penalties, but manage lower rates of GHG emission reduction. This pattern is a result of the differences between fuels noted in Table 2. The net GHG emission reduction varies from a low of 59% to a high of 83%.

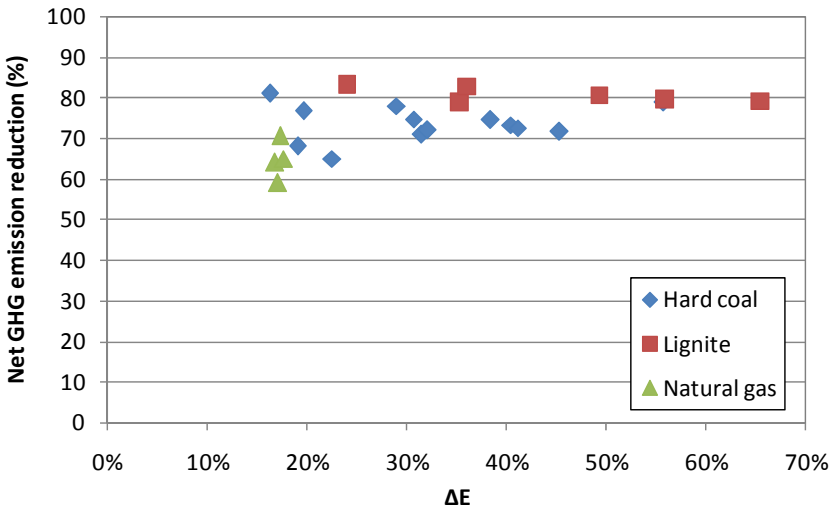

Figure 3. CCS energy penalty (increase in fuel input per unit of electricity) vs. net GHG reduction (percent) for the 23 case-study power plants.

Figure 4 shows the energy penalty (expressed as the increase in fuel input per unit of electricity) as a function of net GHG emission for the 23 power plants. The GHG emission, in units of $kgCO_2e$ per MWh of electricity, is similar for the lignite- and natural gas-fired plants, ranging between 130 and 200 $kgCO_2e$/MWh. Although the lignite fuel has significantly greater carbon intensity than natural gas, the extraction of lignite produces fewer indirect GHG emissions than natural gas. Thus when 90% of the carbon in both fuels is captured, the total GHG emission per unit of electricity is similar for lignite and natural gas. GHG emission is higher for the hard coal-fired plants, at about 180 to 300 $kgCO_2e$/MWh.

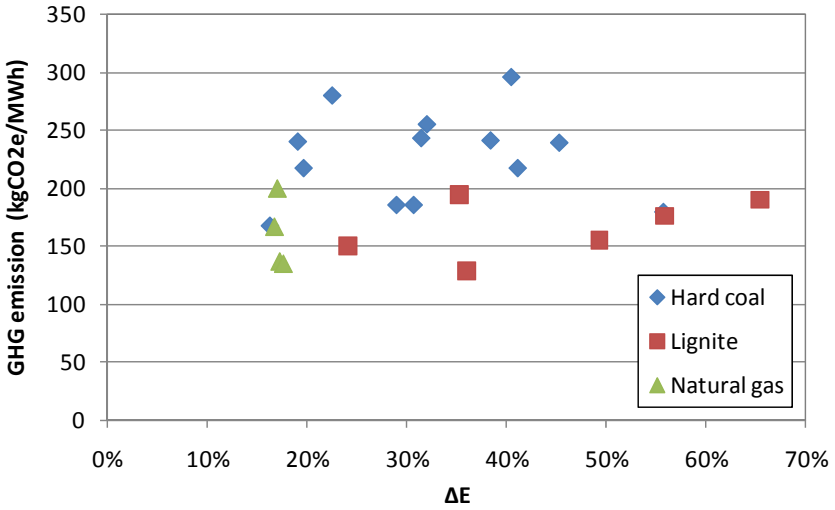

Figure 4. CCS energy penalty (increase in fuel input per unit of electricity) vs. GHG emission ($kgCO_2e$/MWh) for the 23 case-study power plants.

Table 3 shows the percent changes in selected non-climate related emissions due to implementation of CCS in power plants. Six studies reported quantities of non-GHG emissions. In general, NO_X emissions increase when CCS is used, primarily due to increased fuel throughput and indirect emissions. Emissions of SO_X and particulate matter decrease, either removed by the carbon capture solvent or by additional scrubbers placed before the carbon capture unit to reduce solvent degradation. However, there

is large variability in emission levels between the studies and cases. Much of the variability involves the magnitude of the change, but there is also variation in the sign (positive or negative) of some changes. Some of this variation is due to different capture technologies in the plants, while other variability is due to different system boundaries and assumptions in the studies. Some studies (Odeh and Cockerill 2008; NETLa, c, d) also show an apparent increase in NH_3, CO, VOC, Pb, and Hg emissions. In general, the limited number of studies and the large variation prevent definitive conclusions regarding non-GHG emission quantities.

Table 3. Changes in quantities of non-GHG emissions due to implementation of CCS in case-study power plants.

	NO_X	SO_X	Particulate matter
Mean change	+17%	-61%	-19%
Standard deviation	36%	48%	49%
Number of plants	12	12	6

Table 4 shows the percent changes in non-climate impact category scores due to implementation of CCS in power plants. Six studies reported aggregated environmental impacts from non-GHG emissions. The Acidification Potential is found to increase, in spite of the decreased level of SO_X emissions shown in Table 3. This is likely due to increased emission of other acidifying agents such as NO_X and NH_3. Eutrophication and Human Toxicity Potential are also found to increase. The manufacture, use, and disposal of MEA capture solvent are apparently responsible for a large share of toxicity impacts (Koornneef et al. 2008; Schreiber et al. 2010; Singh et al. 2011). These impacts are reportedly due to emissions from the solvent production process, from solvent degradation during use, and from the incineration or landfilling of reclaimer wastes. In addition to the indicators listed in Table 4, some studies also showed apparent increases in Abiotic Resource Depletion, Ozone Layer Depletion, Fresh Water Aquatic Ecotoxicity, Marine Aquatic Ecotoxicity, Terrestrial Ecotoxicity, and/or Photochemical Oxidation (Viebahn et al. 2007; Koornneef et al. 2008; Pehnt and Henkel 2009; Korre et al. 2010; Schreiber et al. 2010; Singh et al. 2011). As above, however, the limited number of studies and the large variation prevent definitive conclusions regarding non-climate impacts.

Table 4. Changes in non-climate impact category scores due to implementation of CCS in case-study power plants.

	Acidification Potential	Eutrophication Potential	Human Toxicity Potential
Mean change	+28%	+80%	+215%
Standard deviation	25%	56%	273%
Number of plants	14	14	13

Uncertainties and limitations

The studies reported here begin to illuminate general trends in system-wide performance of CCS. However, these studies are subject to significant uncertainty and limitations. The results described above are based on analyses at the level of the individual power plant, and the impacts are reported "per kWh of electricity." Although instructive at that level, this type of analysis does not consider the aggregate demand for electricity, and the potential impacts from power generated to make up for the energy penalty of CCS. To overcome this limitation, LCA studies should be conducted on a grid scale considering total demand for electricity. Two of the studies did consider scenarios of large-scale implementation of CCS throughout Germany (Viebahn et al. 2007; Schreiber et al. 2010). One of the studies also considered a scenario with "make-up power" based on average grid characteristics to compensate for the energy

penalty of CCS (NETL 2010a). These scenarios have not been included here, to facilitate direct comparison with the other studies.

A further limitation of current LCA methodology is its poor suitability for extended time horizons or for low probability, high impact events, which may be needed for robust analysis of CCS systems. Viebahn et al. (2007) included a sensitivity analysis of CO_2 leakage, but did not consider the temporal dynamics of the radiative forcing implications of the prolonged CO_2 emissions (Levasseur et al. 2010). None of the studies considered potential for groundwater contamination or induced seismicity (Wilson et al. 2007).

Other uncertainties are imposed by the limited data availability on the characterization of some chemicals. One of the most significant non-climate related impact found by many of the studies reviewed here is the life cycle toxicity impacts of MEA. Large uncertainty surrounds the environmental characterization of this chemical, although recent scholarship may reduce this limitation (Veltman et al. 2010). A further uncertainty regards future-oriented analysis of the environmental impacts of large-scale CCS systems, because the scale-up from pilot to global scale may result in process efficiency improvements, with corresponding changes in environmental impacts.

Conclusions

The number of LCA studies of CCS systems is increasing. Here we have selected and compared 11 studies reporting LCA analyses of 23 electric power plants with various types of generating and capture technologies. We find that the net GHG emission reduction varies from 59% to 83%, depending not only on the percentage of carbon in the fuel that is captured, but on the characteristics of the full system. We also find that non-climate impacts, e.g. toxicity and acidification, may increase with CCS. Weighing the climate benefits versus other environmental impacts requires a subjective evaluation because of the varying nature of the effects that occur at different time and spatial scales. The trade-offs could be minimized by reducing the energy penalty and developing more environmentally benign capture media. In any case, the decision to implement CCS should be based on knowledge of the overall environmental impacts and benefits of the technologies, not just their carbon capture effectiveness. LCA will be an important tool in providing that knowledge.

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