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Comparative impact assessment of CCS portfolio: Life cycle perspective

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Abstract

This study presents life cycle assessments of different capturing technologies with natural gas and hard coal feedstock for fossil fuel power plant. Post-combustion capture with amine-based absorption, pre-combustion capture with selexol absorption and oxyfuel-combustion capture by condensation of flue gas from oxygen fired fuel combustion are considered. The captured CO2 is transported over 500km pipeline and sequestered in secure geological storage.

Results show a substantial decrease in greenhouse gas emissions for all CO2 capture approaches in comparison with power plants without CCS, reducing the net global warming potential (GWP) by 64-78% depending on the technology used. The emissions at the plant and in the chain leads to considerable increase in toxicity and eutrophication impacts. Human toxicity impact increases by 40-75%, terrestrial ecotoxicity by 60-120%, and freshwater eutrophication by 60-200% for different technology. The detailed assessment of the impacts quantifies impact contribution from various processes in the chain and identifies the energy penalty and infrastructure as the major contributing processes to the increase in most of the impacts.

keywords: carbon capture and storage; life cycle assessment; post-combustion; pre-combustion; oxyfuel

1. INTRODUCTION

The technology portfolio assessed of CCS with power generation contains three capture techniques: post-combustion capture, pre-combustion capture and oxyfuel capture. Captured CO_2 can then be transported by pipeline or ship and tankers; and stored in geological storage, depleted oil and gas fields, or used for enhanced oil recovery (EOR) [1]. These CCS options differ in their economic cost, level of maturity, energy penalty, material demand and emission intensity. A trade-off in environmental impacts is expected due to the additional energy, chemicals, infrastructure etc. demand and therefore a systematic process of evaluation of complete life cycles for all available CCS options is needed.

This study evaluates and compares the life cycle impacts of various coal and natural gas electricity generation chains with and without CO_2 capture, transport and storage. The assessment is based on a hybrid model using elaborate

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physical data for all processes and economic data for infrastructure of the power plant and the CO_2 capture facility. The detailed unit process level information obtained from process model data and the Ecoinvent v2 database is incorporated into the input-output model of the background US economy. The characterization factors from ReCiPe 2008 method v1.02 [2] are used to estimate the potential environmental impacts of the emissions incurred. A factor of 0.24 1,4-DCB kg eq/kg [3] for human toxicity potential of monoethanolamine (MEA) is used. The environmental impacts are categorized into different mid-point indicators: global warming potential (GWP), terrestrial acidification potential (TAP), fresh water eutrophication potential (FEP), human toxicity potential (HTP), terrestrial ecotoxicity potential (TETP), fresh water ecotoxicity potential (FETP), and marine ecotoxicity potential (METP)
This analysis discloses the environmental trade-offs and benefits explicit due to CCS with different technologies and the results are used to identify the target sites for technology development in the chain so as to minimize the adverse impacts. Section 2 gives a detailed description of the technologies and inventories of the systems. Section 3 presents results and discussion for the environmental impacts. Section 4 presents the conclusion and outlook for future work.

2. SYSTEM DESCRIPTION

2.1 General framework for all power plants and CCS systems

All power plants are assumed to have 400MW net electricity output and the 'functional unit' for the study is chosen as 1 kWh of net electricity produced. The foreground system consists of fuel combustion in power plant, capture process, transport and storage of CO_2. Specific performance parameters and emission factors are discussed separately for each capture technology. Table 1 presents the performance parameters of the studied power plants. The captured CO_2 is supplied to the transport chain at 110 bar and transported over 500 km to a geological storage site. It mainly requires construction, some energy for CO_2 recompression, maintenance, dismantling and monitoring of the pipeline. Storage requires well drilling, CO_2 injection and monitoring. CO_2 is to be stored above supercritical pressure; therefore additional energy may be required to inject CO_2 into storage formation. Monitoring of the storage site is not included in this study, and leakage of the injected CO_2 is assumed to be negligible.
The LCI data for fuel supply and combustion (for state-of-art technologies), pipeline, and storage well is derived from the Ecoinvent v2 database [4]. Emission factors for prospective technologies are based on literature, and the inventory of the capture operation is based on process modeling data. Infrastructure for power plant and capture unit is accounted as capital investment [1] attributed to various sectors in US I/O 1998 database [5]. Other emissions arising from upstream, e.g., the production of fuel (coal/natural gas), absorbent etc. and the emissions from downstream, e.g., waste treatment and disposal are also included in the assessment.

2.2 Post-combustion capture system

In a typical post-combustion capture process, the treated flue gas is passed through a chemical absorption column where the solvent takes up the CO_2. The CO_2-rich solvent is regenerated by heating in the stripper unit. The CO_2 is then compressed and supplied to the pipeline.
Net efficiency of 43.4% and 58.1% [6] is assumed for the coal and natural gas power plant respectively and the emissions are derived from ecoinvent v2 database. For the system with CO_2 capture, 90% CO_2 is assumed to be captured using monoethanolamine (MEA). The energy requirements for the capture process are for regeneration of solvent, solvent pumps, flue gas blower, cooling water pumps and CO_2 compression, resulting in an energy penalty of 10.2% and 8% respectively for coal and natural gas plant (estimated from IPCC, 2005[1]). A solvent make-up of 1.6 kg MEA/tCO_2 [1] is needed due to its loss via vapors and formation of degradation products. Besides chemical solvent, the capture process also requires caustic soda to reclaim the amine from the heat stable salt and activated carbon to remove degradation products. Air emissions and degradation waste from capture process are quantified based on literature [3][7][8][9]. The capture process also removes SO_2, NO_2 and particulates[9].

2.3 Pre-combustion capture, transport and storage system

In a typical pre-combustion capture process, steam and oxygen is added to the primary fuel producing a mixture of hydrogen and carbon monoxide (syngas). This is followed by the 'shift' reaction to convert CO to CO_2 by the addition of steam. The CO_2 is removed from the CO_2/H_2 gas mixture, and the gas mixture is then supplied to combined cycle generating electricity.
The IGCC power plant consists of a gasification unit, a gas cleaning unit and a gas-fired combined-cycle unit. A net efficiency of 44.1% [6] is assumed for the plant and the emissions are derived from Ratafia-Brown et al., 2002[10].

Table 1. Performance parameters for different power generation systems

Parameters		Coal[a]					Natural gas[a]				
		supercritical BAT	IGCC	supercritical with post-combustion capture	IGCC with pre-combustion capture	oxyfuel capture	NGCC	partial oxidation	NGCC with post-combustion capture	partial oxidation with pre-combustion capture	oxyfuel capture
CO_2 capture		–	–	90 %	90 %	90 %	–	–	90 %	85 %	96 %
Net efficiency		43.4%	44.1%	33.2%	37.6%	34.6%	58.1%	56 %	50.1%	48.1%	46.8%
Energy penalty		–	–	10.2%	6.5%	8.8%	–	–	8 %	7.9%	11.3%
Co-capture		–	–	SO_2, NO_2, particulates	particulates	–	–	–	SO_2, NO_2, particulates	particulates	–
Solvent consumption	kg/tCO_2	–	–	1.6 (MEA)	0.007 (selexol)	–	–	–	1.6 (MEA)	0.007 (selexol)	–
Power plant capital cost[b]	$/kW	1286	1326	2096	1825	1857	568	447	998	978	1034
CO_2 sequestered	Mt/y	–	–	2.2	2.1	2.2	–	–	1	1	1.1
Energy for transport and storage	kW	–	–	735	696	735	–	–	334	327	356
Emissions											
CO_2	g/kWh	763.4	722.8	100.1	85.7	95.5	346.7	359.7	40.5	62.8	17.4
SO_2	mg/kWh	543.2	287.5	26.8	341.0	679.4	3.1	3.2	0.0005	3.7	3.9
NO_x	mg/kWh	514.2	328.6	641.1	389.8	322.1	309.6	321.2	343.9	374.0	194.1
NH_3	mg/kWh	–	1.6	31.4	1.9	–	–	–	12.7	–	–
Particulates	mg/kWh	87.5	86.1	57.3	51.1	109.4	3.1	3.2	1.8	1.9	3.9
solvent	mg/kWh	–	–	56.5	–	–	–	–	22.8	–	–
solid degradation product	kg/tCO_2	–	–	3.2	0.007	–	–	–	3.2	0.007	–

[a]8000 full load hours per year with plant life-time of 25 years

[b]IPCC (2005), Rubin et al. (2007)

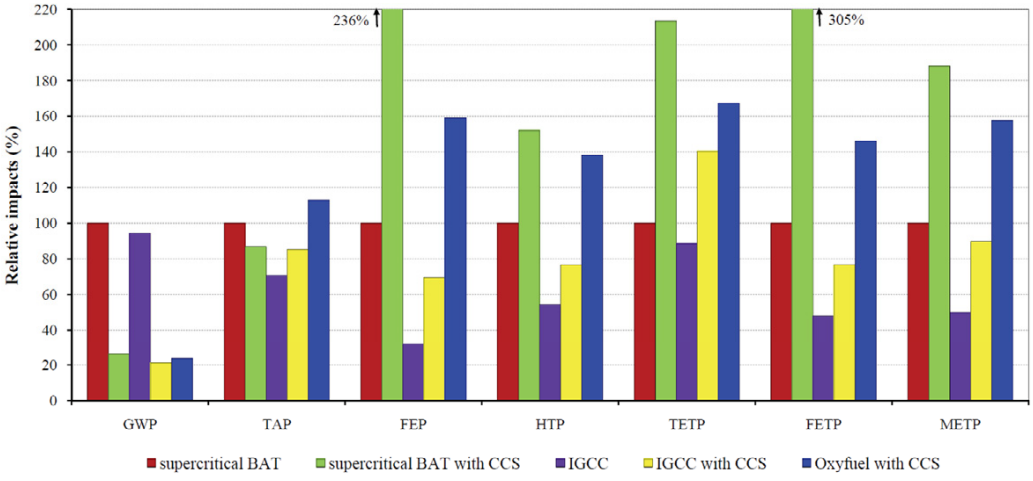
For the IGCC system with CO_2 capture, 90% CO_2 is assumed to be captured using selexol. The efficiency loss due to 'water-gas-shift' reaction and solvent circulation is assumed to be 6.5% (derived from IPCC, 2005[1]). Consumption of 0.005 kg selexol/MWh from IGCC is projected [11], however no literature is found considering solvent loss to atmosphere or emission of solvent degradation products. An additional reduction of particulates by 50% from syngas is assumed [12] by the selexol capture process. Selexol is non-toxic and has a low vapor pressure [13], therefore it is assumed that all spent solvent ends up as solid waste and is incinerated. For natural gas feedstock, primary fuel (natural gas), steam and oxygen is fed to the reformer. In the auto-thermal reformer, partial combustion of methane provides the heat for the endothermic reforming reaction, hence avoiding CO_2 emissions from external firing [14]. A net efficiency of 56% is assumed for the plant as the literature suggests a range of 54.5% to 56.2% [1][15][16]. In the pre-combustion CO_2 capture unit, 85% CO_2 is assumed to be captured using selexol. The efficiency loss of 7.9% is assumed [16].

2.4. Oxyfuel capture, transport and storage system

In a typical oxyfuel combustion process, fuel is combusted in either pure oxygen or O_2/CO_2 mixtures, thus eliminating nitrogen from the flue gas. The flue gas consist mainly of CO_2 and water vapor together with excess oxygen, which after cooling to condense water vapor, contains about 80-98% CO_2 [1].

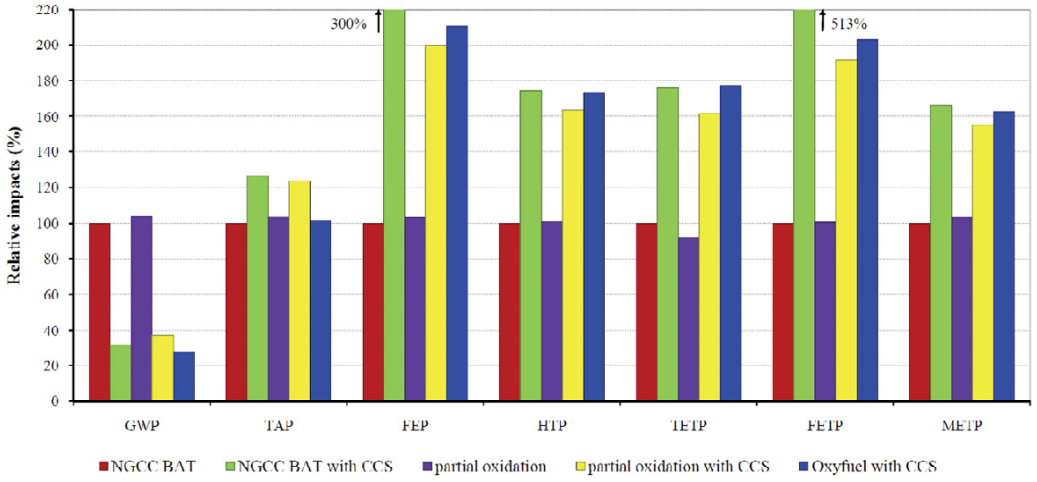
For the coal power plant, a baseline efficiency of 43.4% (same as supercritical power plant), with an overall efficiency loss of 8.8% points is assumed [17], and the emission factors are based on literature [1][17][18][19]. 90% CO_2 is assumed to be captured by condensation separation, which is then compressed, dried and further purified before delivery to pipeline. In the natural gas oxyfuel combustion system, the baseline efficiency is 58.1% (same as NGCC power plant), with an assumption of 11.3% efficiency loss [17] due to energy allowance for ASU, and the emission factors are derived from the literature review [1][17][20]. 96% CO_2 is assumed to be captured.

3. RESULTS AND DISCUSSION



Impact	GWP	TAP	FEP	HTP	TETP	FETP	METP
Unit (kg eq)	CO_2	SO_2	P	1,4-DB	1,4-DB	1,4-DB	1,4-DB
supercritical BAT	$8.4*10^{-1}$	$1.3*10^{-3}$	$3.3*10^{-6}$	$9.6*10^{-3}$	$2.0*10^{-5}$	$1.7*10^{-4}$	$2.1*10^{-4}$
supercritical BAT with CCS	$2.2*10^{-1}$	$1.1*10^{-3}$	$7.7*10^{-6}$	$1.5*10^{-2}$	$4.2*10^{-5}$	$5.1*10^{-4}$	$3.9*10^{-4}$
IGCC	$8.0*10^{-1}$	$9.3*10^{-4}$	$1.0*10^{-6}$	$5.2*10^{-3}$	$1.8*10^{-5}$	$8.0*10^{-5}$	$1.0*10^{-4}$
IGCC with CCS	$1.8*10^{-1}$	$1.1*10^{-3}$	$2.3*10^{-6}$	$7.3*10^{-3}$	$2.8*10^{-5}$	$1.3*10^{-4}$	$1.9*10^{-4}$
oxyfuel with CCS	$2.0*10^{-1}$	$1.5*10^{-3}$	$5.2*10^{-6}$	$1.3*10^{-2}$	$3.3*10^{-5}$	$2.4*10^{-4}$	$3.3*10^{-4}$

Figure 1. Relative impacts of electricity generation from different technologies for coal with and without CCS relative to supercritical BAT and absolute impact scores for all cases after characterization



Impact	GWP	TAP	FEP	HTP	TETP	FETP	METP
Unit (kg eq)	CO_2	SO_2	P	1,4-DB	1,4-DB	1,4-DB	1,4-DB
NGCC BAT	$4.2*10^{-1}$	$4.0*10^{-4}$	$8.8*10^{-7}$	$1.8*10^{-3}$	$1.3*10^{-5}$	$3.1*10^{-5}$	$1.3*10^{-4}$
NGCC BAT with CCS	$1.4*10^{1}$	$5.1*10^{1}$	$2.6*10^{6}$	$3.2*10^{3}$	$2.3*10^{5}$	$1.6*10^{4}$	$2.1*10^{4}$
partial oxidation	$4.4*10^{-1}$	$4.2*10^{-4}$	$9.0*10^{-7}$	$1.8*10^{-3}$	$1.2*10^{-5}$	$3.1*10^{-5}$	$1.3*10^{-4}$
partial oxidation with CCS	$1.6*10^{-1}$	$5.0*10^{-4}$	$1.8*10^{-6}$	$3.0*10^{-3}$	$2.1*10^{-5}$	$6.0*10^{-5}$	$2.0*10^{-4}$
oxyfuel with CCS	$1.2*10^{-1}$	$4.1*10^{-4}$	$1.8*10^{-6}$	$3.2*10^{-3}$	$2.3*10^{-5}$	$6.3*10^{-5}$	$2.1*10^{-4}$

Figure 2. Relative impacts of electricity generation from different technologies for natural gas with and without CCS relative to NGCC BAT and absolute impact scores for all cases after characterization

The main objective of CCS systems is to control CO_2 emissions, having some co-benefits for SO_2, NO_x and particulates removal with certain technologies. However, there are various other direct and indirect emissions throughout the value chain, from raw material extraction for fuel and infrastructure, to the waste treatment and disposal. Figure 1 and Figure 2 present impacts relative to supercritical best available CCS system for coal and impacts relative to NGCC best available CCS system for natural gas. These figures also give the absolute impact score for different systems. These impacts are unevenly distributed over various processes, e.g., fuel extraction, transport, combustion at the power plant, CO_2 capture, infrastructure, solvent production , as well as locations, e.g., mining sites, offshore natural gas production facility, chemical manufacturing sites, power plant facility, dispersed transportation, iron & steel industry, etc. Figure 3 presents the relative contribution of processes towards the total impact for the three CCS approaches with coal and natural gas feedstock.

The results of the study reveal that the CCS system achieves a significant reduction of greenhouse gas emissions but has multiple environmental trade-offs depending on the technology. The implementation of CCS reduces the greenhouse gas emissions by 74-78% from coal systems and 64-73% from natural gas power systems. There is net increase in all other environmental impact categories (except some reduction in acidification for post-combustion coal CCS system). Human toxicity impact increases by 40-75%, terrestrial ecotoxicity by 60-120%, and freshwater eutrophication by 60-200% for the different technologies.

Post-combustion capture, transport and storage system

The designed 90% CO_2 capture efficiency for post-combustion coal and natural gas CCS systems resulted in a net reduction of 74% and 68% GWP, respectively. The coal CCS system also shows co-reduction of 13% in acidification potential (TAP) due to co-capture of SO_2 and NO_x. The post-combustion CCS systems show significant increase in freshwater eutrophication and various toxicity potentials. Results show an increase of 136% for the coal CCS system and 200% for the natural gas CCS system in FEP scores which is caused by emission of phosphorus and phosphate to water arising mainly from the disposal of furnace waste from steel manufacturing (for infrastructure), coal ash disposal (for cases of coal feed stock only), and reclaimer waste disposal. Various toxicity impacts show increases of 51% to 205% for the coal CCS system and 66% to 413% in the natural gas system. The

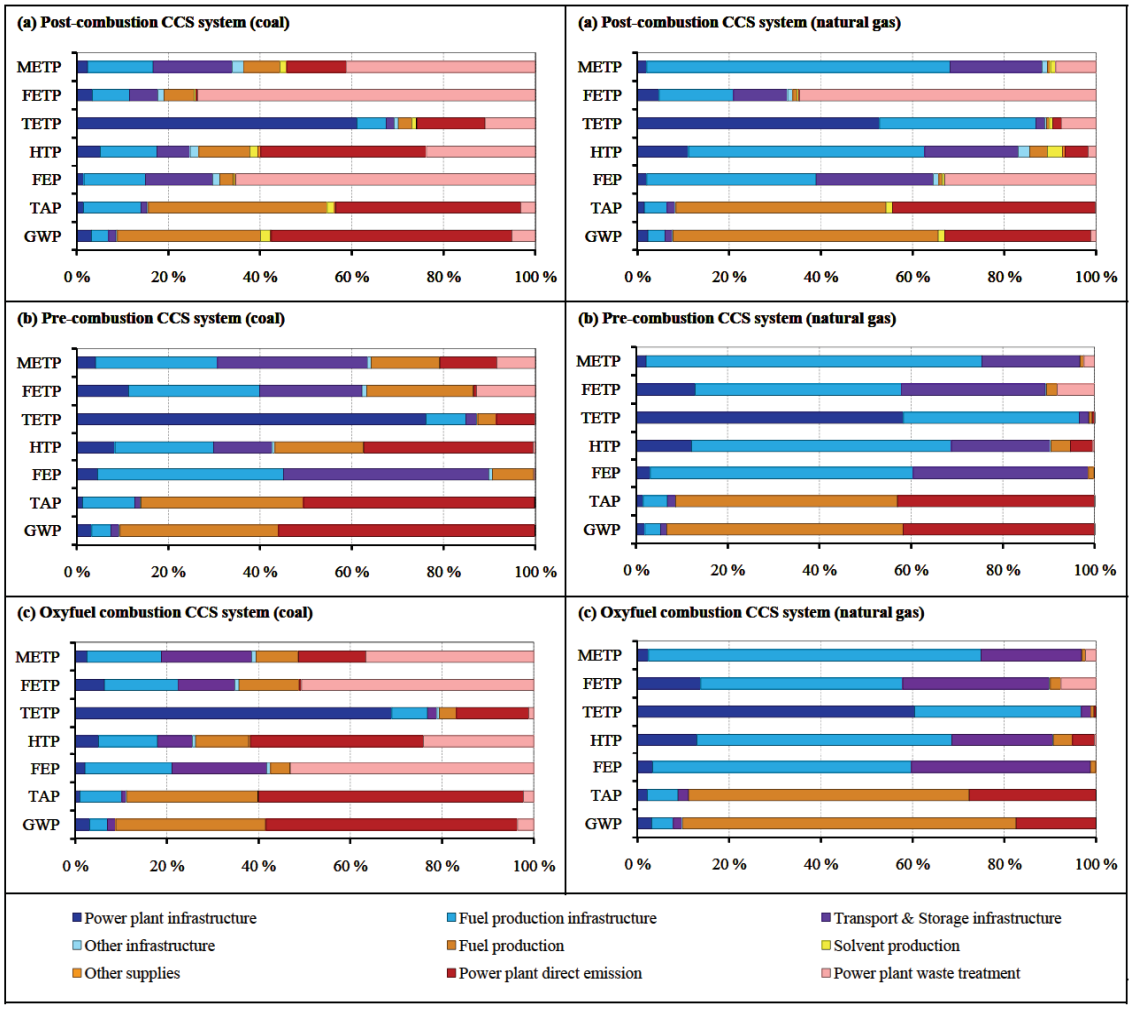


Figure 3. Contribution analysis for various environmental impacts from different electricity generation systems with CCS

main contribution to toxicity is generally associated with the infrastructure requirements and heavy metal emissions associated with the material production. Results show that the infrastructure demand for natural gas CCS systems contributes over 85% to human toxicity (HTP), terrestrial ecotoxicity (TETP), and marine ecotoxicity (METP) and 34% to freshwater ecotoxicity impact (FETP), while for the coal CCS systems, infrastructure development makes about 27% of HTP, 70% of TETP, 19% of FETP and 36% of METP. The post-combustion CCS has the highest FETP impact (compared to all studied systems), with a 2-fold increase for coal and a 4-fold increase for the natural gas system. In these systems the highest contribution (74% for the coal system and 65% for the natural gas system) is from the power plant, where the disposal of reclaimer solid wastes alone is responsible for 48% of the FETP score in the coal system and 62% of the FETP score in the natural gas system caused by leaching from the landfill of incinerator ash from the reclaimer waste to surface- and groundwater.

Pre-combustion capture, transport and storage system

Pre-combustion CCS reduces 78% GWP from the coal and 64% from the natural gas system. However, these systems result in substantially higher freshwater eutrophication impact and all toxicity impacts as compared to the systems without CCS. The IGCC coal system significantly reduces the SO_2 and NO_x content in the flue gas from syngas combustion; there is no such advantage with partial oxidation for the natural gas system. Fresh water

eutrophication results show significant increases of 120% for the coal and 94% for the natural gas CCS systems. Development of infrastructure for the fuel production chain and transport and storage systems are the main contributing processes (causing 91% for the coal and 99% for the natural gas systems) to FEP, mainly due to disposal of solid waste from steel manufacturing process. Infrastructure development chain also makes a major contribution to all toxicity potentials, causing 43% of HTP, 87% of TETP, 63% of FETP, and 64% of the METP score from the coal CCS system. For the natural gas CCS system, infrastructure development contributes over 95% to all four toxicity impacts, mainly from infrastructure for natural gas production, except for terrestrial ecotoxicity impact where power plant infrastructure causes 58% of the overall TETP. Analysis shows that emissions and disposal of solid wastes from steel manufacturing, well drilling, and copper production are the important processes contributing to various toxicity potentials. For the coal CCS system, power plant waste treatment contributes about 8% to METP and 13% to FETP score, mainly due to the disposal of residue from the cooling tower.

Oxyfuel capture, transport and storage system

The oxyfuel coal CCS system reduces global warming impact by 76%, and the high capture efficiency of 96% with the natural gas oxyfuel CCS system results in a 73% reduction of GWP. Similar to post-combustion and pre-combustion CCS systems, the oxyfuel CCS also shows a considerable increase in freshwater eutrophication and toxicity potentials. FEP scores show increases of about 60% for the coal system and 110% for the natural gas system. Fuel production and transport and storage infrastructure development, cause 99% and 43% of FEP for the natural gas and coal systems, respectively. Further, the toxicity potentials show increases of 38% to 67% for the coal system and of 63% to 103% for the natural gas system. While the infrastructure development is largely responsible for all toxicity impacts from the natural gas oxyfuel system, for the coal systems, these processes comprise 26% of HTP, 79% of TETP, 36% of FETP, and 39% of METP impact. Direct emissions from the coal plant contributes mainly to the HTP score, and the power plant waste treatment processes (FGD, coal ash disposal, etc.) contributes significantly to the METP and FETP scores.

Overall, it is found that the reduction of the GWP by CCS technologies has considerable tradeoffs. The significant increases in eutrophication and toxicity potentials renders the performance of CCS systems even lower than the world average technologies for these impact categories. The infrastructure development of the facilities contributes mainly to various toxicity potentials. Fuel production, direct emission from power plant, and waste treatment are major contributors to the other impacts. The MEA production chain also makes a substantial contribution to almost all impacts from post-combustion CCS systems. The capture process in itself provides a co-advantage of reducing eutrophication and particulate formation depending on the technology, but increases various toxicity potentials (for post-combustion only). Further, the CCS energy requirements increase emissions throughout the value chain.

Although the technologies assessed are at different levels of maturity, this comparative study underlines the concern for the type and magnitude of possible impacts. This study also identifies the key areas to reduce trade-offs, and it is also found that technical developments to reduce energy penalty, degradation products, and solid waste management from disposal processes are required to reduce the negative environmental impacts.

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