Carbon capture and storage: Life cycle assessment and external costs of future fossil power generation

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Abstract

The recently finalized project NEEDS of the European Commission continues the ExternE series with the objective of improving and integrating external cost assessment, Life Cycle Assessment (LCA), and energy-economy modeling, using multi-criteria decision analysis for supporting the development of a European energy strategy up to year 2050. This paper presents the LCA of selected advanced hard coal, lignite and natural gas power technologies with and without Carbon Capture and Storage (CCS), modeled for three different scenarios in the reference years 2005, 2025, and 2050. The three technology paths for CO_2 capture – pre-combustion, post-combustion, and oxyfuel combustion – are analyzed. Transport of CO_2 per pipeline and its geological storage in saline aquifers and depleted gas reservoirs are modeled. Entire energy chains from fuel extraction through, when applicable, the ultimate storage of CO_2, are considered, using the ecoinvent database – modified for 2025 and 2050 in order to consider future technology development – for supply of background LCA data. The analysis shows that adding CCS to fossil electricity chains results in a substantial reduction of Greenhouse Gas (GHG) emissions per unit of electricity produced. However, still substantial GHG emissions are generated considering the entire energy chain, especially for post-combustion capture technologies and hard coal as a fuel. The reduction in net power plant efficiencies due to the high energy demand for CO_2 capture and compression leads to higher consumption rates of non-renewable fossil fuels and associated environmental burdens. The overall assessment of the environmental performance of CCS is highly dependent on the weighting of GHG emissions vs. other impacts.

Introduction

Power generation based on fossil fuels, mainly coal and natural gas, will remain essential for covering a significant fraction of the continuously growing electricity demand in industrialized countries as well as the dramatically increasing demand in fast developing countries. Expanding the currently limited generation capacities of renewable sources and nuclear power plants at rates which would allow abstaining from using fossil fuels does not seem to be realistic in the short to medium term on a worldwide scale. Consequently, power generation with Carbon dioxide Capture and Storage (CCS), which can substantially reduce CO_2 emissions from fossil electricity generation chains, represents an important option against the increase of atmospheric GHG concentrations and to mitigate the climate change, while at the same time allowing for the continued use of fossil fuels.

Within the integrated project NEEDS (New Energy Externalities Development for Sustainability) of the European Commission (2004-2009) [1], aiming at improving and integrating external cost assessment, LCA, and energy-economy modeling as well as applying multi-criteria decision analysis for a technology roadmap up to year 2050, LCA of various renewable, fossil and nuclear electricity generation technologies for European supply were performed. This paper presents environmental life cycle inventories and cumulative LCA and Life Cycle Impact Assessment (LCIA) results as well as external costs of electricity production for representative evolutionary hard coal, lignite, and natural gas power technologies including CCS with focus on long term (2025-2050) technology development.

Methodology

The presented LCA of current and future technologies, based on the three reference years 2005, 2025, and 2050, covers complete energy chains from resource extraction and processing, transport of fuels and other materials, operation of power plants and waste disposal through, when applicable, the sequestration of CO_2 in geological formations [2], as shown in Figure 1 for hard coal as an example.

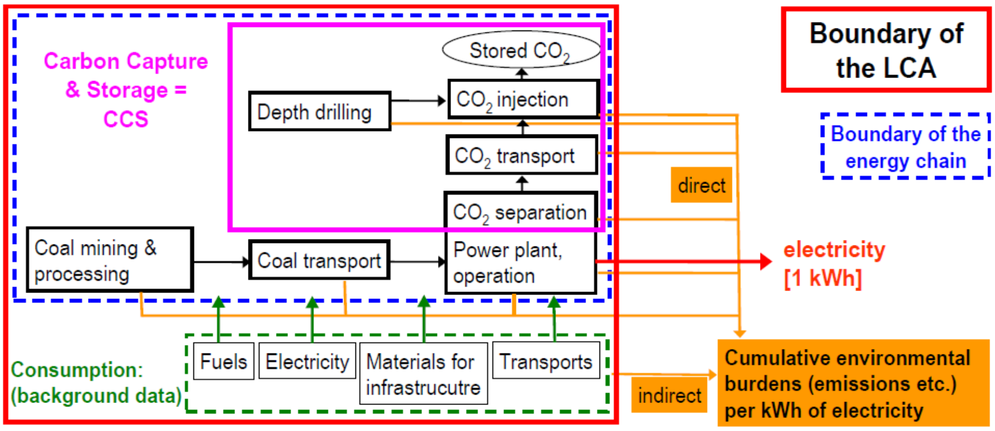


Figure 1: Scheme of the hard coal chain for power generation including Carbon Capture and Storage.

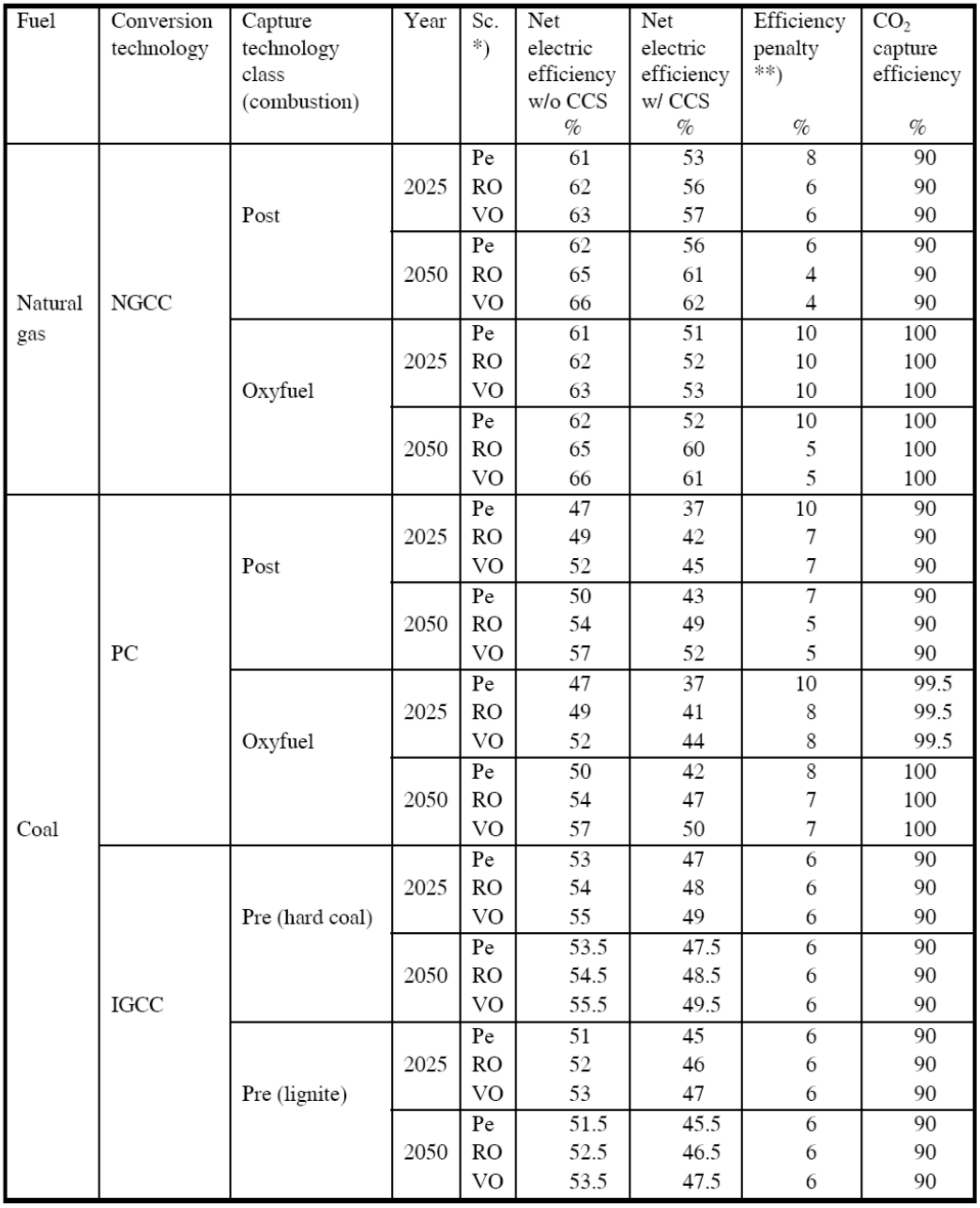
The LCA database ecoinvent, v1.3, is used for supply of background Life Cycle Inventory (LCI) data [3]. Selected sectors of the background database are modified for the future time horizons in order to consistently represent technology advancements throughout the whole economy. These modifications, specifically performed for each of the reference years, include the European electricity mix, which is modeled with LCI data for electricity chains generated within this project and using compositions of the mix based on European energy-economic models. Furthermore, LCI data of selected key sectors of the economy outside the electricity sector are modified. Three different scenarios for technology development, so-called “pessimistic” (PE), “realistic-optimistic” (RO), and “very optimistic” (VO), are included in the modeling of both the LCI data of power generation technologies and the modifications of background data, covering the expected range of possible technical advancement until 2050 [4].

The fossil fuel based power units, namely Pulverized Combustion (PC) and Integrated Gasification Combined Cycle (IGCC) plants for hard coal and lignite as well as natural gas Combined Cycle (NGCC) plants are modeled with (2025, 2050) and without (2005, 2025, 2050) CCS. Pre-combustion, post-combustion, and oxyfuel combustion CO_2 capture are modeled for hard coal and lignite, post-combustion capture for natural gas. An evolutionary approach for technology development until 2050 is applied on the basis of the inventories of best available technologies around year 2000. The level of detail in the LCA modeling of future technologies is limited by the speculative nature of the assessment of medium- to long-term technology development. However, these approximate models are strictly required for the assessment of future scenarios in the energy sector, since long-term energy policy strategies must not be based on characteristics of current technologies, neglecting technology specific potentials for future advancements, especially in case of technologies like CCS, which are currently in the demonstration phase and only existing as pilot plants or at test sites.

The hard coal plant in Rostock, Germany, with a net capacity of 509 MW_{el} and 43% net efficiency is used as hard coal PC reference for 2005. Reference for the year 2005 lignite PC technology is the power plant “Niederaussem K” (Bergheim, Germany) with a net capacity of 950 MW_{el} and a net efficiency of 43.2%. The reference IGCC power plant considered for year 2005 conditions is an “enhanced Puertollano (Spain) IGCC power plant”, modified to higher net power and efficiency (450 MW_{el} and 45%, respectively). LCI data for future PC and IGCC units are approximated using the above reference cases as basis for technology development. Although the LCA for this study is for power plants to be built up to 2050, today’s conditions in coal mining, processing and transport as modeled in [5] are not modified in first approximation. Selected technology characteristics of natural gas supply like leakage rates are improved for 2050 compared to current conditions as modeled in [6].

CO_2 capture and compression at the power plant requires electricity, supplied by the power plant itself and modeled with a reduced net efficiency. Tab. 1 shows the efficiencies assumed for gas and coal power plants with and without (w/o) CO_2 capture for the scenarios in 2025 and 2050 [2, after 7-9 for power plants w/o CCS and after 10, 11 for units with CCS].

Table 1: Net efficiencies assumed for natural gas and coal power plants with and without CCS for the range of scenarios in year 2025 and 2050 [2, after 7-11].



Fuel	Conversion technology	Capture technology class (combustion)	Year	Sc. *)	Net electric efficiency w/o CCS %	Net electric efficiency w/ CCS %	Efficiency penalty **) %	CO_2 capture efficiency %
Natural gas	NGCC	Post	2025	Pe	61	53	8	90
				RO	62	56	6	90
				VO	63	57	6	90
			2050	Pe	62	56	6	90
				RO	65	61	4	90
				VO	66	62	4	90
		Oxyfuel	2025	Pe	61	51	10	100
				RO	62	52	10	100
				VO	63	53	10	100
			2050	Pe	62	52	10	100
				RO	65	60	5	100
				VO	66	61	5	100
Coal	PC	Post	2025	Pe	47	37	10	90
				RO	49	42	7	90
				VO	52	45	7	90
			2050	Pe	50	43	7	90
				RO	54	49	5	90
				VO	57	52	5	90
		Oxyfuel	2025	Pe	47	37	10	99.5
				RO	49	41	8	99.5
				VO	52	44	8	99.5
			2050	Pe	50	42	8	100
				RO	54	47	7	100
				VO	57	50	7	100
	IGCC	Pre (hard coal)	2025	Pe	53	47	6	90
				RO	54	48	6	90
				VO	55	49	6	90
			2050	Pe	53.5	47.5	6	90
				RO	54.5	48.5	6	90
				VO	55.5	49.5	6	90
		Pre (lignite)	2025	Pe	51	45	6	90
				RO	52	46	6	90
				VO	53	47	6	90
			2050	Pe	51.5	45.5	6	90
				RO	52.5	46.5	6	90
				VO	53.5	47.5	6	90

* Sc. = Technology scenario: Pe = pessimistic; RO = realistic-optimistic; VO = very optimistic.

** Reduction in power plant net efficiency due to electricity demand for CO_2 capture and compression.

The inventory of the post-combustion CO_2 separation and capture process, using an amine-based solvent and few further chemicals, is based on data in [10, 12] without modifications for specific scenarios and reference years. For the oxyfuel combustion process, only the energy requirements for O_2 separation are modeled without taking into account further – however, of minor importance in terms of impact on the overall LCA results – material consumption.

NO_x and SO_x emissions from PC plants with CO_2 separation are reduced along [9], adjusting SO_2 emission to 0.1 g/kWh_{el} thus assuming scrubber efficiency of about 99%, and using bound N content in the hard coal for oxyfuel combustion exhaust (giving <0.2 g/kWh_{el}).

The modeling of the CO_2 transport and storage in supercritical state is based on an engineering bottom-up modeling approach [13, 14]. The transport is assumed to occur by pipeline with a mass flow of 250 kg/s, which would correspond to roughly three of the modeled hard coal power plants with CSS of the 500 MW_{el} class. Two transport distances are considered, 200 km and 400 km, the first without intermediate recompression, the second with one recompression (approximately 30 bar) after 200 km. Two cases of deep geological storage are modeled for coal chains: a saline aquifer at 800 m depth and a depleted gas field at 2500 m depth, each with two injection wells. Only the depleted gas field is used as option for CO_2 storage in natural gas chains. The overpressure assumed additional to the hydrostatic pressure of the reservoir is about 30 bar for both cases (which may be high for aquifers). These characteristics represent generic values used as estimates for applicable cases in Europe, where no land based geological storage site for CO_2 is currently in operation. A key parameter is the electricity demand for compression of supercritical CO_2, calculated as function of the supercritical CO_2 mass flow [15]. Long-term leakage rate of the reservoirs is assumed to be zero.

Results and Discussion

Due to the limitation in the extent of this abstract, only selected aspects of the overall LCA results can be presented and discussed. Nevertheless, these results provide a good overview concerning the environmental performance of CCS technologies to be expected until 2050.

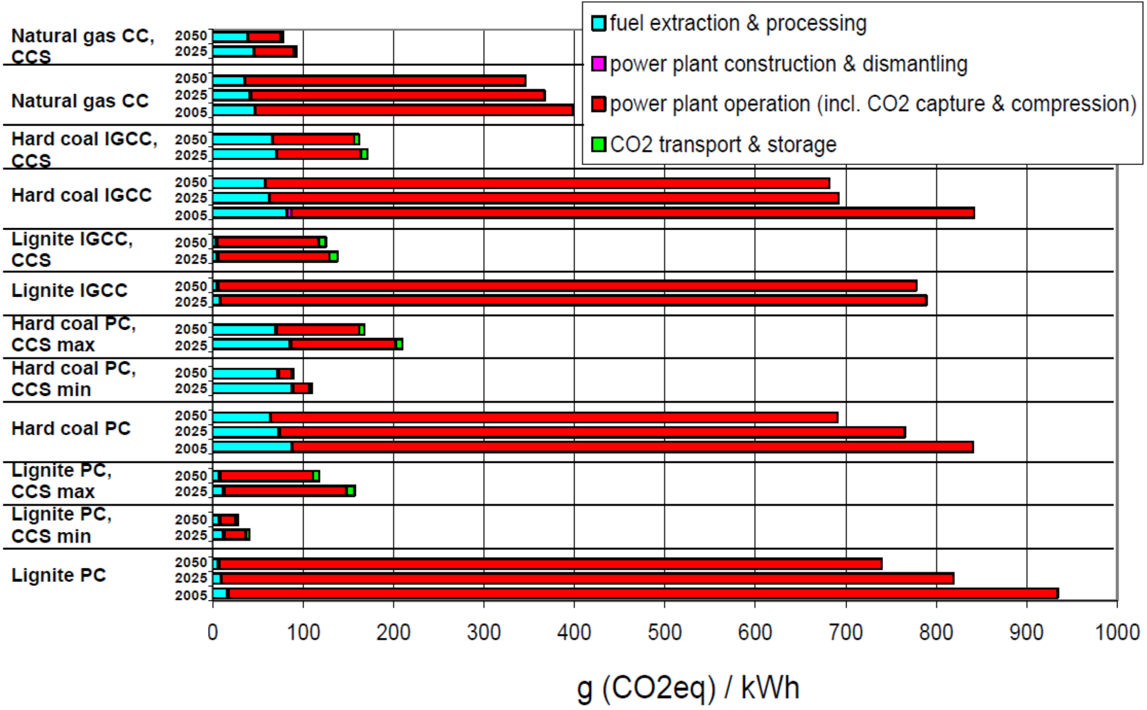


Figure 2: GHG emissions of fossil power generation, realistic-optimistic scenario for technology development. “CCS min”: oxyfuel combustion CO_2 capture, 200 km CO_2 transport, saline aquifer CO_2 storage; “CCS max”: post combustion CO_2 capture, 400 km CO_2 transport, depleted gas field CO_2 storage.

Figure 2 presents cumulative GHG emissions of selected electricity chains per kWh for the “realistic-optimistic” scenario with a breakdown of contributions from “fuel extraction & processing”, “power plant construction & dismantling”, “power plant operation”, and “CO_2 transport & storage”. The option with minimum and maximum GHG emissions for hard coal and lignite and each type of power plant is shown. Minimum emissions result from oxyfuel combustion with transport of CO_2 over 200 km and saline aquifer storage at 800 m depth; maximum emissions result from post-combustion with transport of CO_2 over 400 km and storage in a depleted gas field at 2500 m depth. Total GHG emissions are calculated for a time horizon of 100 years as implemented in the ecoinvent database [16] after [17].

Advanced power plants, with higher efficiencies due to new Nickel-based alloys which can withstand combustion temperatures up to 750℃, will allow GHG emissions of hard coal chains to be reduced from about 840 g(CO_2-eq.)/kWh today to around 650 g(CO_2-eq.)/kWh in 2050, in the best case (very optimistic scenario), but still exceeding the emission levels of natural gas chains by almost 100%.

Greenhouse gas emissions of lignite chains are estimated to be reduced from today's level of around 930 g(CO_2-eq.)/kWh to a minimum of about 700 g(CO_2-eq.)/kWh (scenario VO). Application of CCS leads to a much more substantial reduction, with about 80-250 g(CO_2-eq.)/kWh of cumulative emissions for hard coal, 30-180 g(CO_2-eq.)/kWh for lignite, and 70-100 g(CO_2-eq.)/kWh for natural gas with post-combustion capture in 2050.

The breakdown of contributions from single sectors of the energy chains shows the importance of including the complete fuel chain in the analysis: While hard-coal supply alone is responsible for about 100 g(CO_2-eq.)/kWh, lignite with CCS, due to minor emissions from mining and transport, and natural gas chains with CCS (oxyfuel CO_2 capture), could reach GHG levels of 30-40 g(CO_2-eq.)/kWh, close to nuclear chains and renewable technologies with low GHG intensities. The rate of CO_2 capture (see Table 1), energy demand for CO_2 injection depending on the depth of the reservoir, and contributions from fuel supply are the factors dominating the GHG performance of fossil energy chains with CCS.

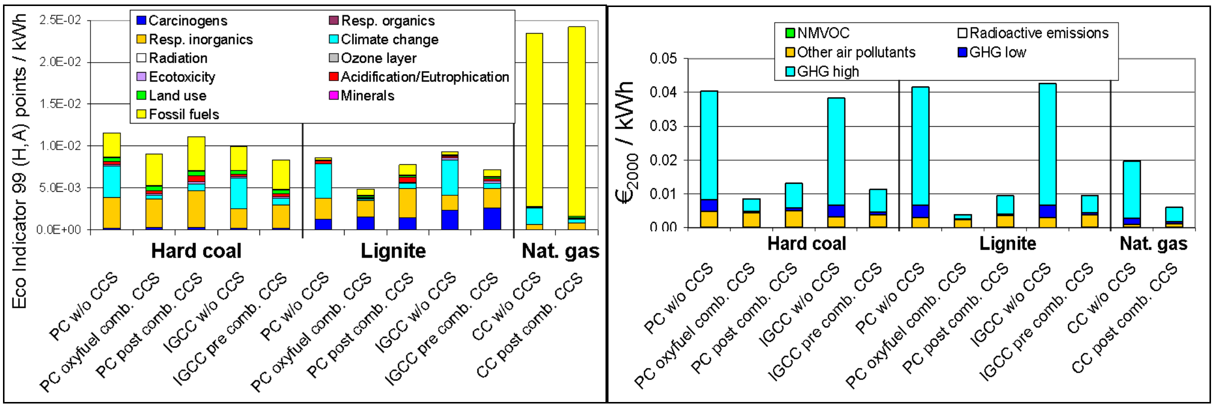


Figure 3: LCIA results (left) and external costs (right) of selected fossil electricity technologies (year 2050), both realistic-optimistic scenario in year 2050; "GHG low": 5 €/t(CO_2-eq), "high": 52 €/t(CO_2-eq).

Figure 3 shows Life Cycle Impact Assessment (LCIA) results (left graph), represented by the commonly used method Eco-indicator 99(H,A) [18], and external costs (right graph) [19] for selected analyzed power generation chains in year 2050 for the realistic-optimistic scenario. Based on this LCIA method, lignite in general shows the lowest score, i.e. the best performance in terms of overall environmental impacts, which is mainly due to the low weighting of lignite consumption compared to hard coal and especially compared to natural gas. This specific weighting of fossil fuel consumption implicitly represents estimates of available remaining energy resources and the associated environmental burdens of future mining activities. Natural gas chains show the lowest scores without considering the damage category "fossil fuels", i.e. the lowest environmental impacts due to emissions of pollutants and land use. The LCIA results show that while CCS allows a substantial reduction of GHG emissions, it increases the fuel demand and associated environmental burdens from fuel production, processing, and transport (the so-called "upstream emissions"), which leads to a distinct reduction of advantages of CCS compared to the assessment only based on GHG emissions.

The external costs of electricity, mainly due to human health damages as a result of air pollution and potential effects of climate change – not including the monetization of resource consumption – are lower for electricity chains with CCS than without. However, the relative advantage of CCS highly depends on the monetized damage factors of GHG emissions, which is associated with high uncertainties. The estimation of these damage factors depends on numerous assumptions as discount rates and weighting issues and can therefore vary within a broad spectrum [20]. In general, natural gas chains show the lowest external costs, in line with the LCIA results excluding fossil fuel consumption as an impact category.

Conclusions

The analysis of the LCA results obtained applying three methods (GHG emissions, Eco-indicator 99(H,A), external costs) shows that application of CCS technologies allows a substantial reduction of GHG emissions from fossil fuel based electricity generation. However, it introduces additional GHG emissions due to material and energy uses and increases the upstream burdens per unit of electricity. Depending on the assessment method, the introduction of CCS may generally not improve the overall environmental efficiency of the systems. External costs of electricity are lower for energy chains with CCS and are very sensitive concerning the damage costs per unit of GHG emission, which are associated with high uncertainties.

Sensitivity analyses should be performed on the various key parameters, in particular: energy uses in CO_2 transport and storage; consumption of operational materials for CO_2 and O_2 (for oxyfuel-combustion) separation; long-term leakage rates of CO_2 reservoirs; technology improvement in future coal and natural gas supply. Additional LCIA methods should be used for comparative assessment.

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