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Can Carbon Dioxide Capture and Storage from Power Plants Reduce the Environmental Impact of Electricity Generation?

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ABSTRACT: Carbon dioxide capture and storage has been presented as a necessary component of energy plans, because it is presumed to deliver significant environmental benefits. In this study, we systematically evaluate the environmental impact of electricity generated by natural gas and coal power plants with selected CO_2 capture technologies with and without CO_2 storage. To examine uncertainties that could arise from the provided environmental impacts of the applied methodology of life cycle assessment, we perform sensitivity analyses of important parameters over a large range of values. In addition, a sensitivity analysis of the thermodynamic efficiencies allows evaluation of power plants with different thermodynamic performances. We find that, in plants using either natural gas or coal, post-combustion capture results in a higher environmental impact per MWh than that of business-as-usual (i.e., no CO_2 capture). Furthermore, chemical looping combustion only marginally decreases the environmental impact of electricity generation in natural gas plants, while in coal plants it can decrease the impact by up to 17%. In addition, CO_2 transportation and storage result in a net negative environmental impact, making an improvement in comparison to the business-as-usual environmental footprint of a plant more difficult. Overall, the most decisive factor affecting the environmental impact of electricity is the energy penalty associated with CO_2 capture; because of this factor, CO_2 capture and storage does not necessarily result in a reduction of the overall environmental impact.

1. INTRODUCTION

According to the IPCC report on carbon dioxide capture and storage (CCS), measures to reduce anthropogenic CO_2 emissions include reducing energy demand, increasing the efficiency of energy conversion and/or energy utilization, switching to less carbon-intensive fuels, increasing the use of renewable energy sources and nuclear energy, and utilizing CCS.[1] CCS is a three-step process, consisting of (i) CO_2 capture and compression to a high pressure, (ii) CO_2 transport to a selected storage site, and (iii) CO_2 storage. Over the last several years, CCS has been strongly supported as a means to mitigate CO_2 emissions from the combustion of fossil fuels,[1−5] attracting substantial financial resources intended for global energy and climate solutions.[6,7] Transport and, particularly, storage are both areas of concentrated research activity that are still associated with high risk and uncertainty.[2] Furthermore, although several alternative approaches for capturing CO_2 have been proposed in a relatively short period of time,[8−10] few appear promising, with respect to efficiency and cost.[11−16] As discussed in a VGB PowerTech report involving CCS,[5] any emission reduction (up to practically 100%) can be achieved with a sufficiently high level of monetary expenditure. The question is whether a given CCS strategy is a reasonable measure when balancing the benefit to the environment against a greatly increased cost.

Life cycle assessment (LCA) is a methodological tool used to quantitatively analyze the life cycle of activities within the context of environmental impact. Recently published LCA studies on the performance of CCS in the power sector base their results on individual impact categories, such as global warming, human toxicity, and others.[17−20] These types of analyses focus, however, on one-to-one comparisons of specific impact categories, rather than on overall evaluations of plant performance.

2. METHODOLOGY

In our analysis, we use the ability of the life cycle impact assessment (LCIA) method Eco-indicator 99[21]—one of the most widely used life cycle impact assessment methodologies - that aggregates all individually calculated environmental impacts of an activity into a single number using normalization and weighting. In this paper, we present a tool that allows objective evaluation of CCS technologies, which can aid public policy decision-making, concerning its implementation.

The environmental impacts for each aspect of coal and natural gas CCS plants (e.g., CO_2 emissions, construction, etc.) are combined to calculate the environmental impact of the electricity (EIE) of the plants (based on the method of exergoenvironmental analysis (e.g., ref 22). In the present analysis, the EIE is the main parameter used to compare the environmental performance of selected energy conversion systems. In earlier work of the authors, power plants with several CO_2 capture methods have been simulated and their thermodynamic, economic and environmental performance have been studied.[23−25] Two of these CO_2 capture technologies are chosen for the analysis presented here.

The analysis is conducted for three natural gas- and three coal-fired power plants. Each group of plants includes a reference plant, which represents the business as usual scenario, and two power plants with CO_2 capture: one with chemical absorption using monoethanolamine (MEA),[27,28] and one with oxy-fuel chemical looping combustion (CLC).[29−33] These CO_2 capture technologies represent the most technologically

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mature, and the most promising (in terms of efficiency) CO_2 capture alternatives, respectively.[13] The CCS plants are first examined including only CO_2 capture and, subsequently, also including transport and storage (see section 2.3).

The simulation of the plants with CO_2 capture was performed by incorporating the capture methods into the structure of the respective reference power plant.[13] In order to evaluate the plants under comparable conditions, the parameters and operation of the capture plants agree with those of the reference plants whenever possible. In this way, it is possible to directly isolate the effects of the capture technologies.

In the CLC plant, we assume that 98% of the fuel is combusted, while the rest is considered to remain unreacted and is regarded as a pollutant. Chemical absorption captures ∼85% of the produced CO_2, while the CLC plant captures close to 100%. The environmental footprint of the plants is calculated assuming favorable (i.e., best-case) conditions with minimal losses, in the sense that we do not account for the production of chemicals that would normally be disposed of to the environment after their use in the MEA plant[20] and small amounts of NO_X emissions that would be formed during CLC combustion. Also, assuming marginal contribution to the total, the environmental impact of the production of the chemicals used to separate the CO_2/O_2 in the CCS plants has been neglected at this stage of the analysis.

To account for uncertainties of the LCIA method stemming from subjective assumptions of normalization and weighting that can affect the derived conclusions,[26] we conduct sensitivity analyses of the individual specific impact factors applied: the environmental impacts of fuel (natural gas or coal), emissions (CO_2, SO_2, and NO_X) and CO_2 transport and storage. Such an analysis can also be used to understand how the EIE would be affected if alternative technologies were used and to reveal environmentally related tolerance limits of the environmental impacts. Furthermore, although CO_2 capture consumes energy and results in significant efficiency penalties, it is possible that the efficiencies of CO_2 capture technologies or of technologies that facilitate CO_2 capture will improve in the future. To account for technological progress, we vary the thermodynamic efficiency of each plant and observe its influence on the EIE. Starting from the default efficiencies of the MEA and CLC plants, we incrementally raise their values until reaching the efficiency of the respective reference plant (implying no energy-input requirement for carbon capture). Although such a decrease in energy demand for technologies involving CO_2 capture is currently infeasible, significant improvements may become possible in the future through the incorporation of advanced technologies, such as fuel cells.

2.1. Eco-indicator 99. Eco-indicator 99 considers three types of environmental damages (end points): human health, ecosystem quality, and resources depletion, each one of which may include various subcategories. Because the damage categories of the Eco-indicator are calculated in different units, they undergo appropriate conversion that allows their combination. This conversion is performed through normalization and weighting. The value obtained from adding the normalized or normalized and weighted environmental impacts of Eco-indicator 99, are reported as dimensionless figures or in Eco-indicator millipoints (mPts). One Pt is the equivalent of 1000th of the yearly environmental load of the average European inhabitant.

Normalization and weighting depend on the relative importance of different environmental effects. In an effort to include different perspectives, Eco-indicator 99 includes three "archetypes" adopted from the Cultural Theory framework:[21] the perspectives of the egalitarians, the individualists, and the hierarchists. The hierarchist perspective represents a balance between short- and long-term effects and is commonly combined with average weighting ("H,A") that considers (a) human health and ecosystem quality of equal importance, and (b) the depletion of resources half as important. The differences in the specific environmental impacts according to the different perspectives using three weighting methods (average, A; weighting of individualists, I; and weighting of egalitarians, E) are shown later in Tables 2−4. The default and more-balanced option of Eco-indicator 99 (hierarchists, average "H,A") is used to produce the main results of the paper. Respective results using the other two, most relevant, perspectives of the assessment method (E,E and I,I) are shown and discussed in the Appendix.

According to Eco-indicator 99, the environmental impact of the extraction of a fuel is based on its relative abundance in the Earth, in the sense that its extraction and use decreases the amount of easily extractable resources. This means that future extractions will utilize fuels of relatively lower quality. Fuels of lower energy density and/or involving energy intensive extraction processes are linked to a higher environmental footprint that increases fuel use by an estimated "energy surplus", which will have to be "paid for" by future generations. The total environmental impact of a fossil fuel is the sum of the environmental impact caused by its conventional (present) extraction and that caused by its estimated energy surplus.

According to the default "H,A" perspective of the Eco-indicator, ∼94% of the total environmental impact of natural gas is associated with its energy surplus and only 6% with its conventional extraction. This substantial energy surplus was estimated assuming that future extractions of natural gas will involve crude oil, which has a relatively high environmental impact. The conventional extraction of coal is associated with a specific environmental impact of extraction higher than that of natural gas, but its larger availability in the Earth results in a lower energy surplus. Its total environmental impact, thus, is calculated to be relatively small, when compared to other fuels. When using the perspective E,E (normalization and weighting performed based on the egalitarian perspective), the environmental impact of coal is assigned a higher value of energy surplus; this results in a higher normalized value than the perspective H,A. On the other hand, the perspective I,I (normalization and weighting performed based on the individualist perspective) does not consider fossil fuel depletion a problem and assumes zero surplus energy and present extraction of fuels. Thus, the obtained results depend significantly on the archetype assumed (see the Appendix).

Storage options for captured CO_2 depend on the location of a facility. Distance and depth of a storage site increase the associated environmental impact. CO_2 capture with storage in deep geological formations is currently the most advanced and most likely storage option to be deployed on a large scale in the future. If storage has a beneficial use (use, e.g., enhanced-oil recovery (EOR) or enhanced coal bed methane (ECBM) recovery), the impact related to the extraction of fossil fuels can be, indirectly, reduced. This happens because, by additionally extracting more fossil fuels, we avoid extractions that could burden future energy applications.

The environmental impact of transport and storage assumed in this work is based on the work of Khoo and Tan.[34,35] The calculations are based on three cases: (i) mineral storage, (ii) geological storage with EOR, and (iii) geological storage with

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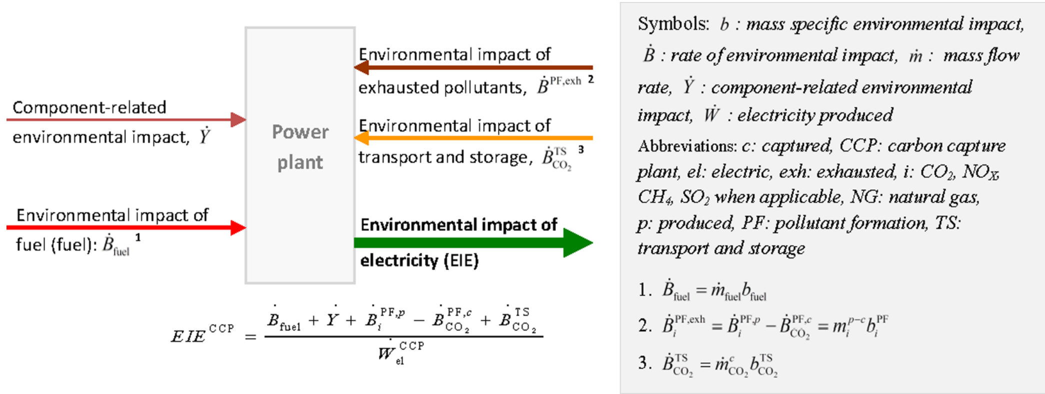

Figure 1. Power plant environmental impact flows. Arrows entering the plant represent operations that increase the overall environmental footprint of the system, the sum of which constitutes the environmental impact of the produced electricity (arrow exiting the plant).

ECBM. Khoo and Tan[35] evaluated five power plants, incorporating different methods for mineral storage and assuming permanent sequestration without post-treatment requirements. The mean environmental impact of the five storage alternatives is found to be 7.60 mPts/kg of CO_2 stored. When excluding the two mineral methods that present relatively high energy requirements, the environmental impact is reduced to 4.39 mPts/kg of CO_2 stored. When compared to mineral storage, geological storage with EOR is found to have a lower environmental footprint by 1.85 mPts/kg of CO_2, while geological storage with ECBM results in a lower impact by 3.07 mPts/kg of CO_2.[34] Thus, depending on the technology used, the environmental impact of transport and storage can vary between 1.32 and 4.39 (or 7.60) mPts/kg of captured CO_2. Because 7.60 mPts/kg of captured CO_2 imply a high environmental impact of the specific mineral storage technologies reported, we chose to neglect these energy intensive technologies and we set the highest limit of the impact factor to 5.0 mPts/kg of CO_2.

Based on the calculations of Khoo and Tan, we chose to evaluate the plant systems assuming the two extreme cases of zero environmental impact of transport and storage (Case 1) and 5.0 mPts/kg (Case 2). Storage scenarios with a lower environmental impact than 5.0 mPts/kg would lie between the curves produced for Cases 1 and 2. In all cases, we consider that all captured CO_2 is also transported and stored with the assigned specific environmental impact.

2.2. Environmental Criterion. The environmental impacts of operation and construction of a power plant are all charged to its product, i.e., the electricity. In this way, the environmental impact of electricity generated in the plants equals the sum of the environmental impacts of the fuel extraction and preparation, the construction and the emissions, as well as the transport and storage of the captured CO_2. Thus, the overall environmental balance of a CCS plant can be written as

$$\mathrm{EIE}^{\mathrm{CPP}}\dot{W}_{\mathrm{el}}^{\mathrm{CCP}} = \dot{B}_{\mathrm{fuel}} + \dot{Y} + \dot{B}^{\mathrm{PF,exh}} + \dot{B}_{\mathrm{CO_2}}^{\mathrm{TS}} \tag{1}$$

with EIE being the environmental impact of electricity, $\dot{B}$ the rate of environmental impact associated with material and energy streams during plant operation, $\dot{Y}$ the component-related environmental impact that includes the environmental impact of all the materials required to construct each plant component,[13] and $\dot{W}$ the (net electric) power. In eq 1, "CCP" stands for carbon capture plant, "el" stands for electricity, "exh" represents exhaust, "fuel" stands for natural gas or coal, PF represents pollutant formation, and TS denotes transport and storage. Solving for the environmental impact of electricity, we obtain eq 2, also shown in Figure 1:

$$\mathrm{EIE}^{\mathrm{CCP}} = \frac{\dot{B}_{\mathrm{fuel}} + \dot{Y} + \dot{B}^{\mathrm{PF,exh}} + \dot{B}_{\mathrm{CO_2}}^{\mathrm{TS}}}{\dot{W}_{\mathrm{el}}^{\mathrm{CCP}}} \tag{2}$$

The component-related environmental impact of the overall plant $\dot{Y}$ consists of the sum of the environmental impacts associated with construction (including manufacturing, transport, and installation), operation and maintenance, and disposal of all the individual plant components. The values of $\dot{Y}$ are relatively low,[13] showing that the environmental impact of a plant is determined mainly by its fuel and pollutants and much less by the components constituting it. Because of the low significance of $\dot{Y}$, no discounting options have been considered.

The environmental impact related to pollutant formation, $\dot{B}^{\mathrm{PF}}$, represents the potential environmental impact caused by emitting the pollutants formed during plant operation to the environment. $\dot{B}^{\mathrm{PF}}$ is defined only when a chemical reaction takes place and pollutants are formed. In any other case, it is zero. Here, it is calculated at the system level and its generalized impact equation is

$$\dot{B}^{\mathrm{PF,exh}} = \sum_i b_i^{\mathrm{PF}} \dot{m}_i^{\mathrm{exh}} \tag{3}$$

where $\dot{m}_i^{\mathrm{exh}}$ is the mass flow rate and b_i the specific environmental impact of pollutant i exiting the system. The pollutants taken into account for the power plants examined here include CO_2, CH_4, SO_2, and NO_X. Hence, the environmental impact of pollutant formation is defined as

$$\dot{B}^{\mathrm{PF,exh}} = \dot{m}_{\mathrm{CO_2}}^{\mathrm{exh}} b_{\mathrm{CO_2}}^{\mathrm{PF}} + \dot{m}_{\mathrm{NO_X}}^{\mathrm{exh}} b_{\mathrm{NO_X}}^{\mathrm{PF}} + \dot{m}_{\mathrm{CH_4}}^{\mathrm{exh}} b_{\mathrm{CH_4}}^{\mathrm{PF}} + \dot{m}_{\mathrm{SO_2}}^{\mathrm{exh}} b_{\mathrm{SO_2}}^{\mathrm{PF}} \tag{4}$$

where $\dot{m}_{\mathrm{CO_2}}^{\mathrm{exh}} = \dot{m}_{\mathrm{CO_2}}^{p} - \dot{m}_{\mathrm{CO_2}}^{c}$ (c: captured, p: produced), while $b_{\mathrm{CO_2}}^{\mathrm{PF}}$, $b_{\mathrm{NO_X}}^{\mathrm{PF}}$, $b_{\mathrm{CH_4}}^{\mathrm{PF}}$ and $b_{\mathrm{SO_2}}^{\mathrm{PF}}$ are the specific environmental impacts of the annotated elements, when they are exhausted to the atmosphere.

The specific environmental impact of fuel provided to the system (b_{fuel}) is related to its extraction and preparation. Here, all the specific environmental impacts (b) refer to environmental impacts per unit of mass. Thus, the environmental impact rates associated with the fuel ($\dot{B}_{\mathrm{fuel}}$) and with transport and sequestration ($\dot{B}_{\mathrm{CO_2}}^{\mathrm{TS}}$) of the captured CO_2 are given by the following equations:

$$\dot{B}_{\mathrm{fuel}} = \dot{m}_{\mathrm{fuel}} b_{\mathrm{fuel}} \tag{5}$$

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Table 1. Inventory Data and Main Results Obtained from Power Plant Simulations: Subsystem 1

	Natural Gas Power Plants			Coal Power Plants		
	reference plant	CLC plant	MEA plant	reference plant	CLC plant	MEA plant
fuel input, kg/s	14.0	14.0	14.0	42.4	42.4	42.4
CO_2 emitted, kg/s	38.4	0.4	5.5	94.0	0.9	13.5
CO_2 produced, kg/s	38.4	38.1[a]	38.4	94.0	93.2[a]	94.0
CO_2 captured, kg/s (%)		37.7 (99.0)	32.9 (85.0)		92.3	80.5
SO_2 emitted, kg/s				0.19	0.19	0.19
SO_2 produced, kg/s				3.59	3.59	3.59
SO_2 captured, kg/s				3.40	3.40	3.40
NO_X emitted, kg/s	0.05		0.05	0.10		0.10
CH_4 emitted, kg/s		0.28				
net power output, MW	413	376	354	413	280	302
COE, €/MWh[b]	76.3	91.4	97.1	NC[d]	NC[d]	NC[d]
COA-CO_2, €/t[c]		45.3	74.8	NC[d]	NC[d]	NC[d]
EIE w/out TS, mPts/kWh	26.3	25.9	28.9	17.6	14.7	20.5
EIE with TS, mPts/kWh	26.3	27.7	30.6	17.6	20.2	25.6
thermodynamic (exergetic) efficiency, ε (%)	56.5	51.5	48.4	37.3	27.3	25.3

[a]The CLC plant produces less CO_2, because 2% of the fuel is not combusted. [b]COE = cost of electricity. [c]COA-CO_2 = cost of avoided CO_2. [d]NC = not calculated.

Table 2. Damage due to Pollutants Generated (b_{CO_2}, b_{NO_X}, b_{CH_4}, b_{SO_2}) per kg of Substance (Perspectives "H,A"/ "E,E"/ "I,I")

element	damage to human health by climate change (DALYs)	damage to humans due to respiratory effects (PDF m^2 yr)	damage to the quality of the eco-system by acidification and eutrophication (PDF m^2 yr)
CO_2	$2.10 \times 10^{-7}/2.10 \times 10^{-7}/2.00 \times 10^{-7}$		
NO_X		$8.87 \times 10^{-5}/8.91 \times 10^{-5}/1.19 \times 10^{-6}$	$5.71 \times 10^{0}/5.71 \times 10^{0}/5.71 \times 10^{0}$
CH_4	$4.40 \times 10^{-6}/4.40 \times 10^{-6}/4.40 \times 10^{-6}$	$1.28 \times 10^{-8}/1.28 \times 10^{-8}/1.19 \times 10^{-8}$	
SO_2		$5.46 \times 10^{-5}/5.46 \times 10^{-5}/3.90 \times 10^{-5}$	$1.04 \times 10^{0}/1.04 \times 10^{0}/1.04 \times 10^{0}$

$$\dot{B}_{CO_2}^{TS} = \dot{m}_{CO_2}^{c} b_{CO_2}^{TS} \quad (6)$$

The exergy rate of the product of the plant with CO_2 capture is calculated through its exergetic efficiency (ε) and the exergy of the product of the reference plant (denoted by RP), since the fuel is kept constant ($\dot{E}_F = \dot{E}_F^{CCP} = \dot{E}_F^{RP}$):

$$\left.\begin{aligned} \varepsilon^{CCP} &= \frac{\dot{W}_{el}^{CCP}}{\dot{E}_F^{CCP}} \\ \varepsilon^{RP} &= \frac{\dot{W}_{el}^{RP}}{\dot{E}_F^{RP}} \end{aligned}\right\} \xrightarrow{\varepsilon^{CCP}/\varepsilon^{RP}} \frac{\dot{W}_{el}^{CCP}}{\dot{W}_{el}^{RP}} \Rightarrow \dot{W}_{el}^{CCP} = \frac{\varepsilon^{CCP}}{\varepsilon^{RP}} \dot{W}_{el}^{RP} \quad (7)$$

Combining the environmental impact balance with the ratio between the EIE of the CCS and that of the reference plant, we obtain eq 8. This equation determines the EIE of the CCS plants, which constitutes the comparative criterion of the study.

$$\mathrm{EIE}^{CCP} = \Big[(\dot{m}_{fuel} b_{fuel} + \dot{m}_{CO_2}^{exh} b_{CO_2}^{PF} + \dot{m}_{NO_X}^{exh} b_{NO_X}^{PF} + \dot{m}_{CH_4}^{exh} b_{CH_4}^{PF} + \dot{m}_{SO_2}^{exh} b_{SO_2}^{PF} + \dot{m}_{CO_2}^{c} b_{CO_2}^{TS} + \dot{Y})\varepsilon^{RP}\Big] / (\varepsilon^{CCP} \dot{W}_{el}^{RP}) \quad (8)$$

The contribution of each term of eq 8 to EIE depends on the mass flows (Table 1) and the prescribed environmental impacts per unit of mass of the considered quantities. The Eco-indicator values used to calculate the environmental impact of electricity of the power plants can be found in Tables 2–4.[21] The term $\dot{m}_{CO_2}^{exh} b_{CO_2}^{PF}$ of eq 8 tends to zero when the mass flow of CO_2 exhausted to the atmosphere is near zero (e.g., in the CLC plant). However, in such a case, substantial quantities of captured CO_2 increase the mass flow and, thereby, the environmental impact of transported and stored CO_2 ($\dot{m}_{CO_2}^{c} b_{CO_2}^{TS}$). Thus, the environmental benefit of any given CCS option depends fundamentally on the difference between the specific environmental impacts of CO_2 emitted ($b_{CO_2}^{PF}$) and CO_2 captured (transported and stored, $b_{CO_2}^{TS}$). To obtain any environmental benefit through CO_2 capture and storage, the environmental impact of the stored CO_2 must be lower than that of the emitted CO_2.

Table 3. Damage due to Fuel Use (b_{fuel})

	Damage to Resources					
	Surplus Energy for Fossil Fuel Extraction (MJ)			Present Energy for Fossil Fuel Extraction (MJ)		
element / perspective	H,A	E,E	I,I	H,A	E,E	I,I
natural gas	1.50×10^{-1}	8.90×10^{-2}	0.0	1.00×10^{-2}		0.0
coal	6.25×10^{-3}	6.73×10^{-2}	0.0	3.80×10^{-2}		0.0

2.3. System Definition.

To perform the life cycle assessment of the plants, we define their boundaries and collect the corresponding life-cycle inventories (LCI). The boundaries of the reference power plants start with the extraction of the fossil fuel and end with the produced electricity and the exhaust of the flue gases (Figure 2A). The LCA boundaries of the plants with emission control have the same beginning, but their end depends on the case considered. Because the energy requirement associated with CO_2 capture (separation and compression) is covered internally by the plant, CO_2 capture is considered part of Subsystem 1 and not a

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Table 4. Normalized and Weighted Damage due to Fuel Use (b_{fuel}) and Pollutants Generated (b_{CO_2}, b_{NO_X}, b_{CH_4}, b_{SO_2}) Based on Perspectives H,A, E,E, and I,I

	Total Normalized and Weighted Damage (Pts/kg)		
element / perspective	H,A	E,E	I,I
NG (LHV: 50.0 MJ/kg)	1.90×10^{-1}	1.67×10^{-1}	0.0
coal (LHV: 27.0 MJ/kg)	2.22×10^{-2}	8.18×10^{-2}	0.0
CO_2	5.45×10^{-3}	4.06×10^{-3}	1.33×10^{-2}
NO_X	2.75×10^{0}	2.28×10^{0}	3.96×10^{-1}
CH_4	1.14×10^{-1}	8.54×10^{-2}	2.94×10^{-1}
SO_2	1.50×10^{0}	1.16×10^{0}	2.66×10^{0}

separate LCA subsystem. On the other hand, transport and storage of the captured CO_2 is examined as a separate stage that begins with the amount of the CO_2 captured and ends with the amount of CO_2 sequestered (Subsystem 2). Thus, Case 1 (Subsystem 1, power plant with CO_2 capture) ends with the capture of the CO_2, the exhaust of the "clean" flue gas and the generated electricity, while Case 2 (Subsystems 1 and 2) ends with the sequestration of the CO_2, the exhaust of the "clean" flue gas, and the generated electricity (Figure 2B).

In order to achieve comparable operational conditions for all plants, the inventory data (Table 1) for Subsystem 1 are based on detailed simulations of natural gas[13] and explicit assumptions of coal power plants from previous work.[36,37] Using these data, we calculate the environmental impacts of emissions and construction using the Eco-indicator 99 methodology, allowing, finally, the calculation of the total environmental impact of the CCS plants. When Subsystem 2 is included in the analysis, we assign a predefined environmental impact that includes all related pollutants of the process.

The functional unit of published studies on the LCA of energy conversion systems is commonly a constant amount of energy (1 kWh or 1 MWh). However, our analysis is based on a study examining plants working under similar conditions. If we were to assume a constant amount of net generated energy, when the internal power consumption of the plants increases due to CO_2 capture, we would have to input larger amounts of fuel that would require differently designed plant equipment. In an attempt to keep the plant structure, equipment sizes and operating conditions as similar (and comparable) to those of the reference plant as possible, we maintain a constant fuel input for all plants. The coal and natural gas reference power plants are assumed to generate approximately the same power output, in order to be comparable. Thus as the comparison basis of our analysis, we chose the fuel input that produces a net power output of 410 MW in the reference plants. This assumes equal power output per unit of time in our reference systems. The EIE of the power plants are reported in values per MWh and can be used to compare plants of similar size.

To ensure the same power output in the reference coal plant as in the reference natural gas plant, larger mass flow rates of coal must be used, because coal has a lower heating value than natural gas. Coal combustion generates higher amounts of CO_2 requiring relatively larger amounts of energy for CCS, while it also generates

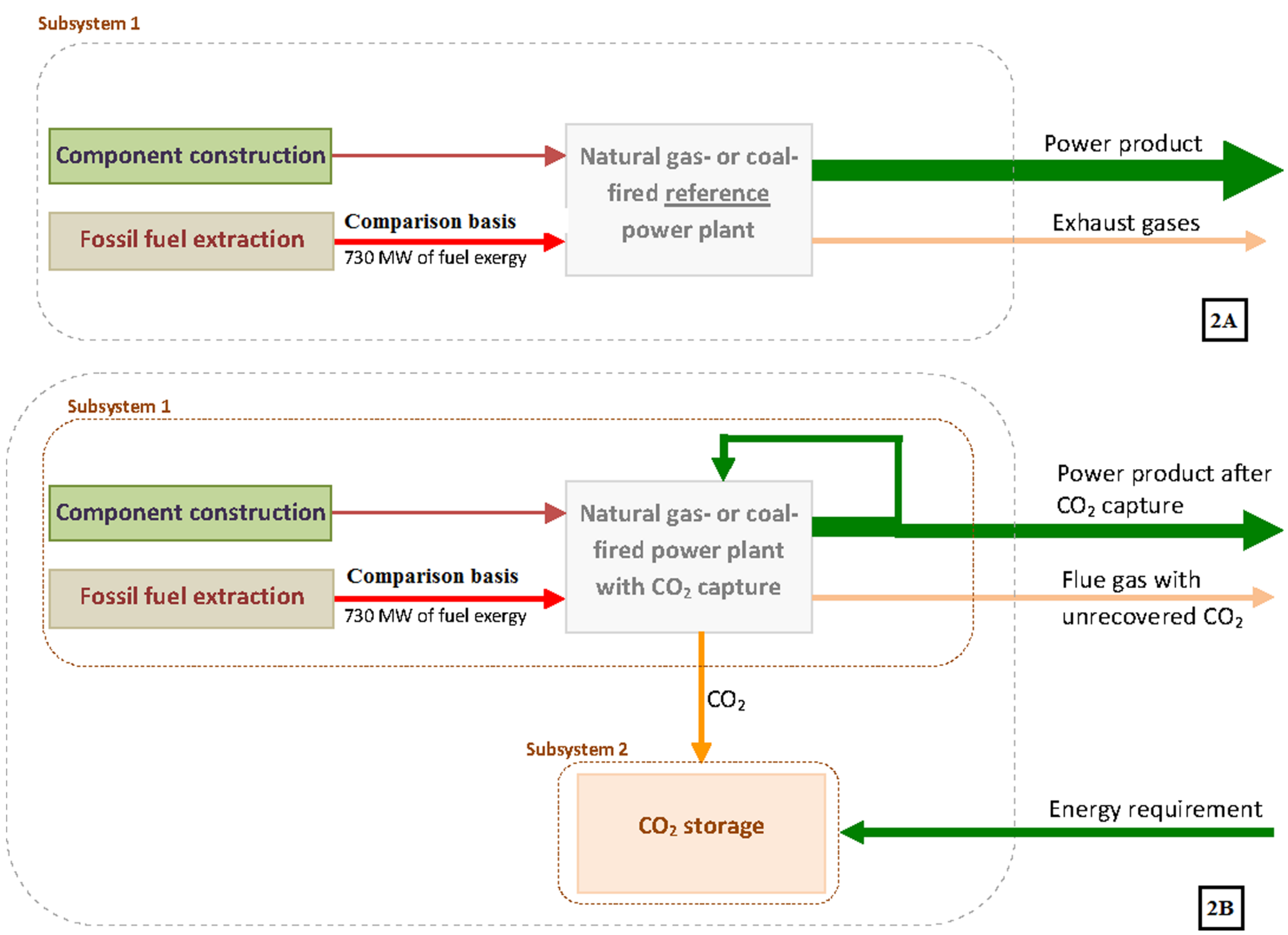


Figure 2. LCA boundaries of (A) reference power plants and (B) power plants with CCS.

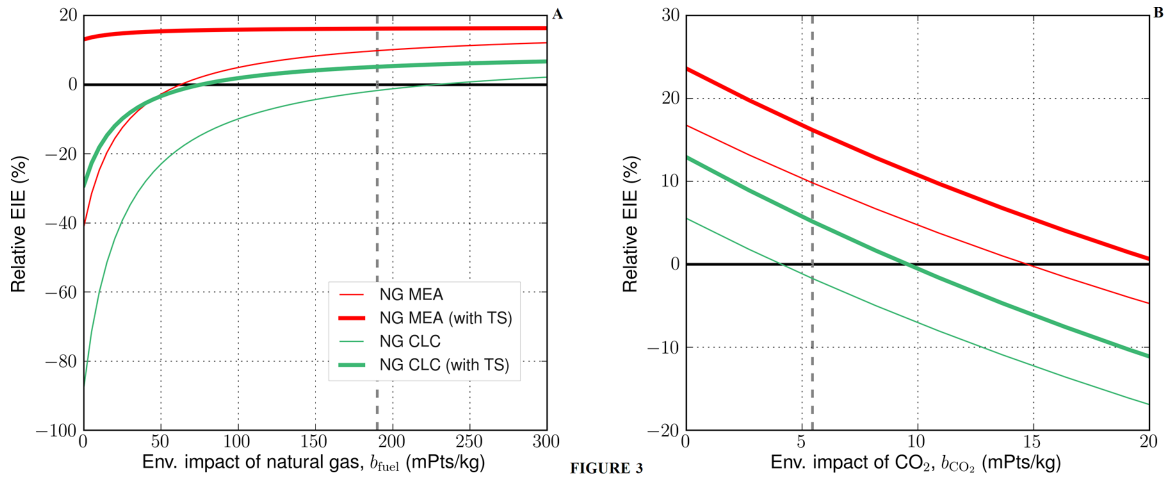


Figure 3. Effect of the environmental impact of (A) natural gas and (B) CO_2 on the EIE of the plants, relative to the reference plant (for an environmental impact of transport and storage of 0.0 – "NG MEA/CLC" – and 5.0 mPts/kg – "NG MEA/CLC (with TS)"). Negative values of the relative EIE imply environmental benefit.

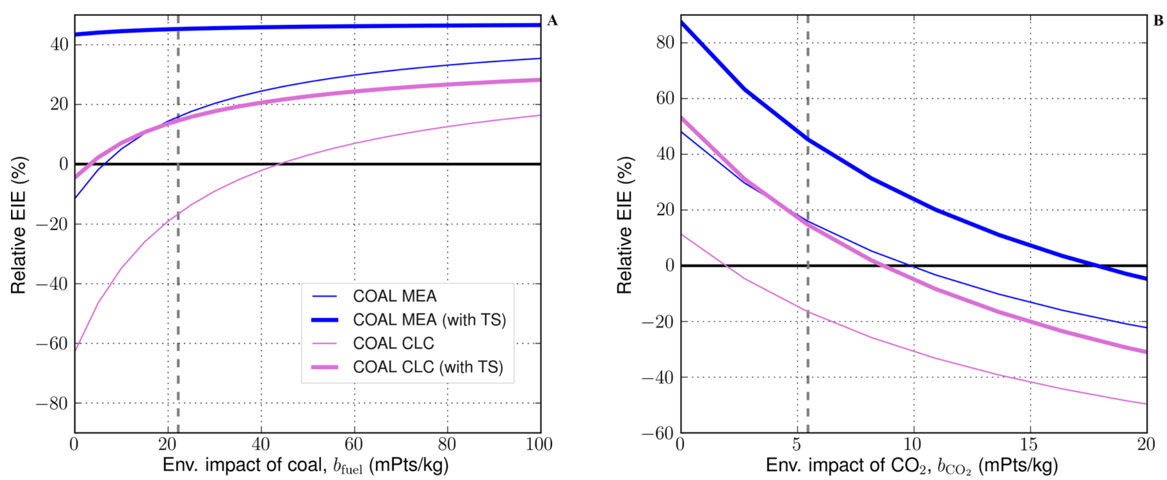


Figure 4. Effect of the environmental impact of (A) coal and (B) CO_2 on the EIE of the plants, relative to the reference plant (for an environmental impact of transport and storage of 0.0 – "COAL MEA/CLC"– and 5.0 mPts/kg – "COAL MEA/CLC (with TS)"). Negative values of the relative EIE imply environmental benefit.

relatively substantial SO_2 emissions, the magnitude of which depends on the sulfur content of the coal. Worldwide regulations of emissions limit the allowed SO_2 exhausts of power plants whereas existing technologies already allow high removal efficiencies.[38] Here, to maintain the emissions at a low level, we conservatively assume that 95% of the generated SO_2 is captured in desulfurization units and 5% of it is exhausted to the atmosphere. The desulfurization unit is assumed to have an energy penalty of 2.15 MW/kg of captured SO_2,[36] which translates into an energy penalty of 1 percentage point in the reference coal power plant (resulting operating exergetic efficiency: 37.3%).

3. RESULTS

Figures 3–5 present the results from varying parameters of eq 1: The default environmental impacts of fuel and $CO_2/SO_2/NO_X$ emissions (H,A), as well as the efficiency for each of the CCS plants relative to the reference plant operating with the same fuel. When comparing with the other two perspectives (E,E and I,I), CCS is favored more when using the perspective H,A (see the Appendix). This stems mainly from the difference between the normalization values of the perspectives.

Performing sensitivity analyses of specific values of environmental impacts, and looking at results relative to a reference plant, eliminates several uncertainties that could arise from using different life-cycle impact assessment methods. Negative values of the relative EIE indicate a reduction in the environmental footprint when CCS is applied, while positive values indicate that using CCS results in a higher environmental impact than exhausting the generated emissions to the environment (business as usual).

3.1. Natural Gas Power Plants. The exergetic efficiency of the reference natural gas plant is 56.5%, and its EIE using the default values of Tables 2–4 is found to be 26.3 mPts/kWh.[13] As shown in Figure 6a, when the perspective H,A is used, 88.2% of the environmental impact of electricity of the reference plant is associated with the extraction of the fuel used, 7.0% with the emissions of CO_2, 4.7% with the NO_X emissions, and only 0.2% with the plant construction.

The calculated exergetic efficiencies of the MEA and CLC plants are 48.4% and 51.5%, respectively. The IEA report related to energy technology perspectives on scenarios and strategies to the year 2050[4] reports that the current energy penalty for CO_2 capture in gas plants with chemical absorption is ~8 percentage points, which is a value that also agrees with

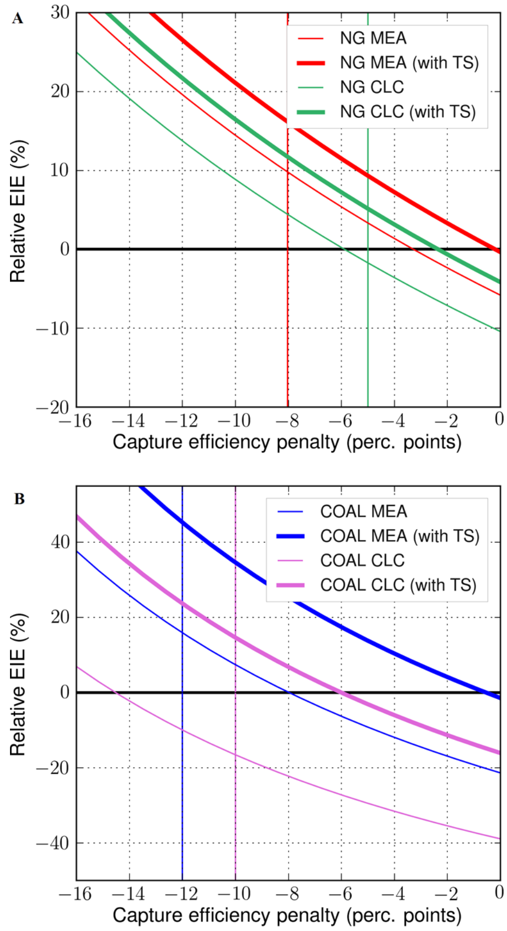


FIGURE 5

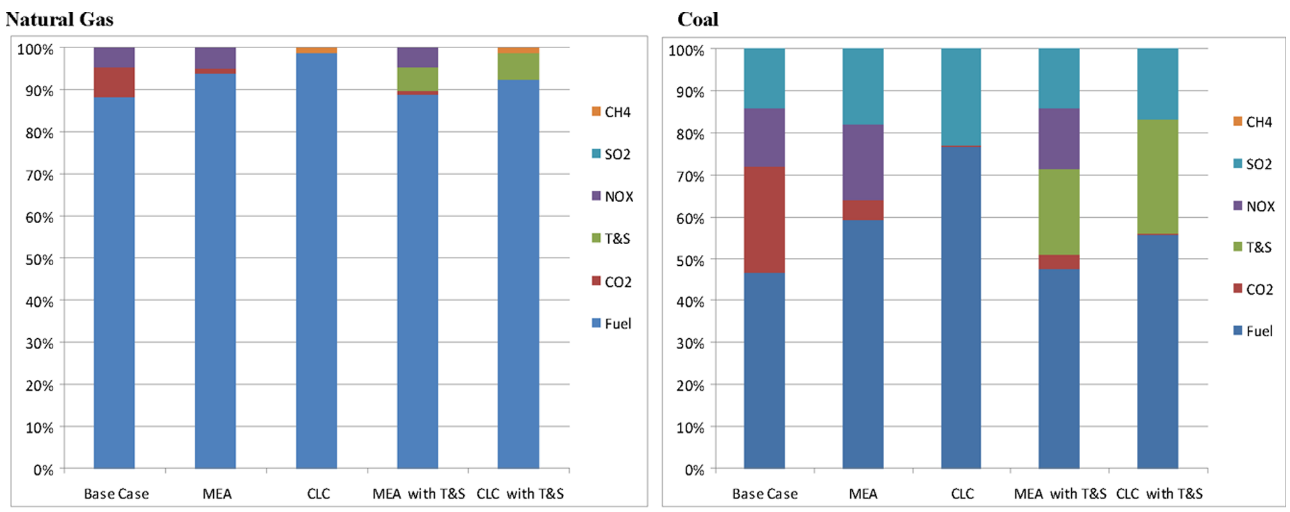
Figure 5. Effect of the overall thermodynamic efficiencies on the EIE of the plants, relative to the reference plant (for an environmental impact of transport and storage of 0.0 – "COAL/NG MEA/CLC" – and 5.0 mPts/kg – "COAL/NG MEA/CLC (with TS)"). Negative values of the relative EIE imply environmental benefit.

our calculations. Detailed data on the performance of these plants can be found in ref 13. Using the default impact assessment values, the EIE of the MEA and CLC plants is 28.9 and 25.9 mPts/kWh, respectively. Small differences between the EIE reported here and in previous work[39] stem from the progress in the methodological process of the analysis and, specifically, from the fact that the environmental impact of conventional extraction of the fuel was previously neglected.

For the default impact assessment values and without transport and storage (Case 1), the EIE of the CLC plant is only marginally lower than that of the reference plant, while CO_2 capture through chemical absorption is found to be environmentally worse than business as usual. We find that when lower values are assigned to the environmental impact of natural gas (Figure 3A), the EIE of the plants decreases rapidly. This happens because the impact of the natural gas on the EIE declines, increasing the relative effect of CO_2 emissions. Conversely, if the impact of natural gas is increased, it begins to dominate the overall environmental impact calculation and the differences among the CCS plants decrease. The MEA plant can be considered as environmentally neutral or better than the reference plant only if the specific environmental impact of natural gas is set to a value of less than 62.6 mPts/kg (Figure 3A), which is approximately one-third of its default value (190.0 mPts/kg). In contrast, the EIE of the CLC plant with zero impact of transport and storage remains lower than that of the reference plant for values of the environmental impact of the fuel as high as 228.0 mPts/kg.

The variation of the default environmental impact of CO_2 emissions is shown in Figure 3B. The EIE of the reference plant is significantly affected by the CO_2 emissions, since, in this case, all produced CO_2 is emitted to the atmosphere. This is, of course, where the benefit of CO_2 capture applies. Nonetheless, even without transport and storage, post-combustion technology will not decrease the impact of power production, unless an environmental impact approximately three times higher than the default estimate is assigned to the CO_2 emissions.[21] It should be noted that the NO_X emissions contribute to the absolute EIE of the reference and MEA plants, but varying their specific environmental impact has a negligible effect on the overall results. On the other hand, an increase in the environmental impact of the NO_X emissions would somewhat favor the CLC plant, since this process has approximately zero NO_X emissions.

The operating efficiency of the plants strongly affects their environmental impact. This implies that a net reduction of CO_2



A B

Figure 6. Contribution of different activities (e.g., construction, operation, etc.) to the EIE of the (A) natural gas and (B) coal power plants.

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emissions does not necessarily result in an environmental improvement. The MEA plant has an efficiency of ∼8 percentage points lower than the reference plant, requiring greater fuel usage to generate the same amount of electricity. Thus, while the plant reduces the environmental damage due to CO_2 capture, the impact of the fuel used increases significantly. The same is true for the CLC plant, which has an energy penalty of ∼5 percentage points, although the tradeoff here is more balanced. To account for potential efficiency improvements, we tested a range of efficiencies of the MEA and CLC plants, from their original values (48.4% and 51.5%, respectively) up to the efficiency of the reference plant (56.5%, i.e., no energy penalty for carbon capture) (Figure 5A). In Case 1, post-combustion and oxy-fuel CO_2 capture would decrease the environmental impact of the reference plant only if operating with efficiencies higher than 53.2% and 50.6% (efficiency penalties of 3.3 and 5.9 percentage points), respectively. The seven percentage-point energy penalty targeted in 2020−2030 by the IEA for a post-combustion plant[4] would result in an exergetic efficiency of 49.8% and would, thus, still not produce any net environmental improvement (it results in an EIE 1.8 mPts/kWh higher than that of the reference plant).

Furthermore, the addition of Subsystem 2 (Case 2) can burden the overall impact of the CCS plants significantly. Applying a specific environmental impact of 5.0 mPts/kg for transport and storage results in the CLC plant performing environmentally worse than the reference plant by 1.4 mPts/kWh. In this case, the oxy-fuel plant could potentially be better than the reference plant only if a low value is assigned to the environmental impact of natural gas and/or a high value is assigned to the environmental impact of CO_2 emissions (Figure 3B). On the other hand, the MEA plant has an EIE 4.3 mPts/kWh higher than the reference plant when transport and storage is considered, and it is unable to perform environmentally better for any environmental impact values. In general, higher capture efficiencies are required to sufficiently offset the additional environmental burden of transport and storage. In this case, the environmental performance of the MEA plant could tolerate a minimum energy penalty of 0.2 percentage points, while the CLC plant could suffer an energy penalty of up to 2.4 percentage points (Figure 5A).

3.2. Coal Power Plants. The reference coal power plant has an exergetic efficiency of 37.3% and results in an EIE of 17.6 mPts/kWh. The contributions of the individual specific environmental impacts to the EIE are shown in Figure 6B. Assuming that the efficiency ratio between the coal CLC and MEA plants is the same as for the natural gas plants, the coal MEA plant results in an energy penalty of 12 percentage points,[4] and the coal CLC plant in a penalty of 10 percentage points. In Case 1, the EIE of the MEA plant using the default impact values is ∼16% higher than that of the reference plant, while the EIE of the CLC plant is ∼17% lower.

In general, a variation of the environmental impact of the fuel affects the EIE more in the coal plants than in the natural gas plants and we find that the MEA coal power plant does not show any environmental improvement, unless the specific environmental impact of coal is decreased to approximately one-fourth of its default value (from 22.2 mPts/kg to 6.2 mPts/kg). Conversely, the CLC plant shows a lower environmental impact than the reference plant, even when the specific environmental impact of coal is doubled (see Figure 4A).

Because of the large amount of generated CO_2 emissions in coal plants, the assigned value for the environmental impact of CO_2 influences the EIE of the coal plants more than in the natural gas plants (Figure 4B). In Case 1, the CLC plant can impact the environment up to ∼15% less than the reference plant. Meanwhile, the MEA plant would perform better environmentally than the reference plant only if the specific environmental impact of CO_2 were double its default value.

Although we use a coal with a high content of sulfur (bituminous coal Illinois 6.0 with a mass composition of 60.42% carbon, 4.45% S, 3.89% hydrogen, 1.07% nitrogen, 0.05% Cl, 14.25% ash, and 7.97% moisture) and the SO_2 that is generated is substantial, the absolute mass of SO_2 emissions remains considerably smaller than the CO_2 emissions. However, SO_2, which causes significant damage to the eco-system by acidification and eutrophication (Table 2), results in a much higher specific environmental impact when compared to CO_2 and it, thus, greatly affects the EIE of the plants. Nevertheless, because changes in the environmental impact of SO_2 also affect the reference plant, the relative difference between the plants is not affected by the sulfur content of the coal significantly.

As in the case of the natural gas plants, we also assessed the environmental impact of the coal CCS plants assuming higher efficiencies (Figure 5B). The CLC plant represents a net environmental improvement for a wide range of efficiencies, while the MEA plant requires much higher efficiencies to have a positive effect. The MEA plant without consideration of transport and storage eventually becomes environmentally equivalent to the reference plant for a relative energy penalty of ∼8 percentage points, while the CLC plant can tolerate an energy penalty of up to ∼15 percentage points before showing higher impacts.

When, however, we include Subsystem 2 to our analysis (Case 2), the CLC plant loses its advantage relative to the reference plant, performing worse by ∼2.6 mPts/kWh, while the MEA plant shows a higher environmental impact by 8.0 mPts/kWh. Nonetheless, the CLC plant shows a net reduction in environmental impact (for an energy penalty of ∼6 percentage points), which is sustained for a relatively wide range of efficiencies. In contrast, the MEA plant presents a lower EIE than the reference plant only with an energy penalty very close to zero, because of its relatively low CO_2 capture percentage (85%). Variations in the environmental impact of coal do not affect the results significantly when transport and storage are included. The MEA plant never allows an improvement environmentally, while the CLC plant can reduce the EIE only when the environmental impact of coal is assumed to be ∼60% of its default value. Alternatively, the CLC plant with CCS could reduce the EIE if the specific impact of CO_2 were increased to more than 60% of its default value (8.7 mPts/kg instead of 5.5 mPts/kg). The MEA plant with CCS would require an ∼3-fold higher environmental impact of CO_2 to become environmentally attractive.

4. DISCUSSION

Overall, it has been found that, in both coal and natural gas plants, the efficiency reduction associated with the capture technology is the most important parameter when estimating and comparing the environmental impacts associated with electricity generation using fossil fuels. Also, there are some parameters that contribute significantly to the absolute EIE value, but their influence is very small in relative terms, when comparisons between business-as-usual and CCS are conducted. For example, SO_2 and NO_X emissions determine the magnitude of the environmental impact of the plants, but because they influence the CCS and the reference plants in a similar way, their importance in relative terms becomes very small.

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In natural gas power plants, the EIE is greatly influenced by the specific environmental impact of natural gas, while CO_2 emissions do not affect the environmental performance of the plants significantly. If the impact of natural gas were lower than the default value, capturing emissions would become more important and the absolute values of the EIE would drop significantly.

In coal power plants, the absolute value of the EIE depends strongly on the SO_2 emissions, due to their high specific environmental impact.[21] The assumed 95% capture of the generated SO_2 decreases the overall effect of these emissions on the EIE of the plants considerably. Nevertheless, because the decrease of the CO_2 emissions affects the results of the CCS plants with but not those of the reference plant, it affects the relative EIE of the coal plants more than the SO_2 emissions. Lastly, CO_2 reduction affects coal plants more than natural gas plants, because of the higher CO_2 mass flows of the former.

Currently, the most mature and commercially available CO_2 capture technology is chemical absorption with MEA, which still reduces the plant efficiency by ~8 percentage points in natural gas plants and ~12 percentage points in coal plants. We find that, for this specific capture technology to provide even marginal environmental improvement, an energy penalty of <3 percentage points in natural gas plants is required (<8 percentage points in coal plants).

CO_2 capture with chemical absorption, transport, and storage could potentially be considered to perform environmentally better than business as usual, only if the values of the environmental impacts of fuel and CO_2 deviate substantially from their default estimates and the environmental footprint of transport and storage is kept at low levels. In contrast, CO_2 capture with CLC remains environmentally beneficial with an energy penalty of up to 2.4 percentage points in natural gas plants and 6 percentage points in coal plants. Under favorable assumptions, this technology shows a penalty of 5 percentage points when incorporated into natural gas plants and a penalty of 10 percentage points when incorporated into coal plants. It should be mentioned, however, that since this technology is not currently available, its realization is also associated with much higher uncertainties.

Counterintuitively, our results show that coal plants produce electricity with lower environmental impact than natural gas plants. Two factors play a significant role in obtaining this result: the desulfurization process in the coal plants and the fuel energy surplus. If we had ignored the desulfurization unit, the EIE of the reference coal plant would approximately triple, resulting in a much higher environmental impact than that of the reference natural gas plant. Similar results would also have been obtained if the fuel surplus had not been accounted for in the fuels' impacts (i.e., if only present-day extraction impacts were accounted for), because the depletion of natural gas resources is assumed to have a higher future impact than coal.[21] In such a case, because the conventional extraction of natural gas is associated with a lower specific environmental impact than coal, the natural gas reference plant would have a substantially lower EIE than a similar coal reference plant.

Lastly, given that CCS is considered an economically viable option for reducing CO_2 emissions, its evaluation would be facilitated by setting a limit to the acceptable EIE (or relative EIE). Such a limit would allow a more straightforward and transparent evaluation of whether a CCS plant can balance the additional costs with the environmental benefit of CO_2 capture.

5. CONCLUSIONS

With present environmental data and reported efficiency penalties, carbon capture using post-combustion technologies, although implementation-ready, appears to be a rather controversial choice for CO_2 emission reduction in power plants, since it imposes a high investment cost with a questionable benefit or even increased impact on the environment. Chemical looping combustion is a more promising method that could more likely result in an environmentally advantageous performance, assuming that technical implementation challenges are resolved.

The main disadvantage of CCS is that the large energy requirements associated with capture technologies reduce plant efficiency significantly. The most effective way to reduce the environmental impact of a power plant when compared to business-as-usual is to decrease fuel usage, which can directly reduce the amount of CO_2 generated. Thus, investment into improving the efficiency of electricity generation and use (where possible) or into alternative energy sources could, most probably, address the issue of anthropogenic CO_2 emissions more directly and spare the excessive energy penalties, economic burden, as well as high-risk that accompany the application of CCS technologies.

■ APPENDIX: PRESENTATION OF THE RESULTS USING THE PERSPECTIVES E,E AND I,I OF ECO-INDICATOR 99

In the following section, the figures presented in the paper and generated using the default perspective "H,A" are reproduced using the perspectives "E,E" and "I,I" (See Figure A1).

The effects of the environmental impacts of fuel on EIE for the natural gas power plants are similar for both the "E,E" and "H,A" perspectives. On the other hand, coal is assumed to have higher surplus energy and weight in the "E,E". This results in approximately double the contribution of coal to the EIE for the coal-fired power plants, when compared to the perspective "H,A".

In the perspective "I,I", fossil fuel depletion is not taken into account. Thus, in this case, the emissions determine the

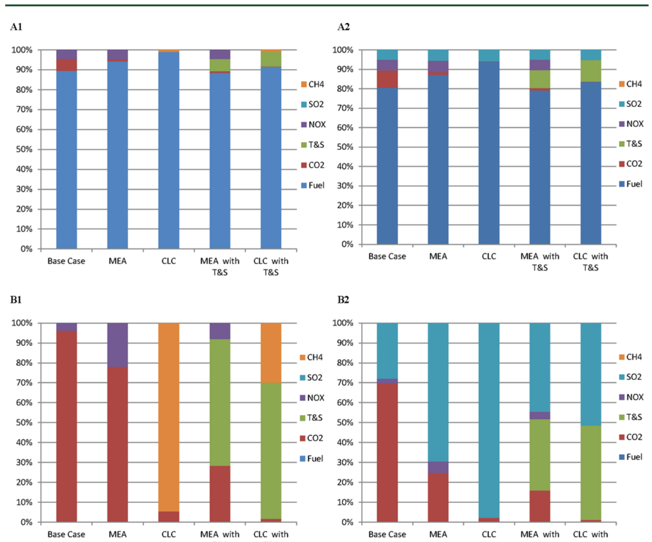

Figure A1. Contribution of different activities (e.g., construction, operation, etc.), based on plant type and perspective. Each panel is labeled XY, where X represents the perspective (A = E,E perspective, B = I,I perspective) and Y denotes the plant type (1 = coal, 2 = natural gas).

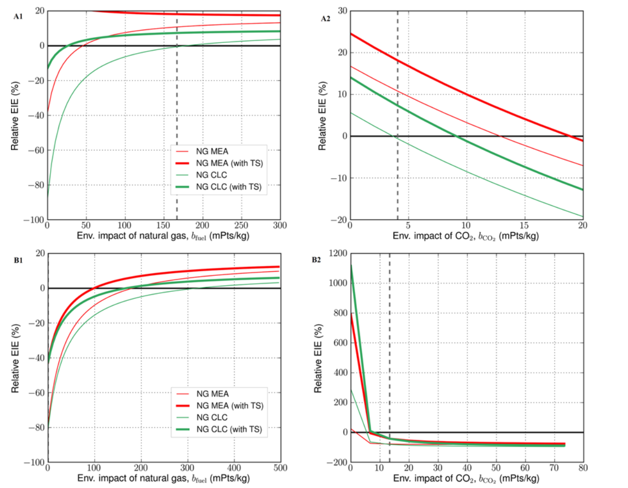

Figure A2. Effect of the environmental impact of natural gas and CO_2 on the EIE of the natural gas power plants, relative to the reference plant, using different perspectives (for an environmental impact of transport and storage of 0.0 and 5.0 mPts/kg). Each panel is labeled XY, where X represents the perspective (A = E,E perspective, B = I,I perspective) and Y denotes the type of gas (1 = natural gas, 2 = CO_2). Negative values of the relative EIE imply environmental benefit.

magnitude of the EIE of the plants. In the reference plants, the main contributor is CO_2, while in the plants with CCS, it is the remaining emissions that largely influence the EIE. When transport and storage are included in the natural gas plants, their environmental impact becomes the main contributor to the EIE, while, for coal plants, the effect of SO_2 emissions remains, at all times, higher than that of transport and storage. (See Figure A2.)

Using the perspective "E,E", we find that the EIE is affected by this only when very low values are assigned to the specific environmental impact of natural gas. As expected, the environmental impact of coal affects the CLC plant more without transport and storage. Changes in the environmental impact of CO_2 show a slightly higher environmental impact, when compared to the default perspective "H,A". When using the perspective "I,I", changes in the environmental impact of CO_2 in the natural gas plants affect the results only when this obtains relatively low values. Only when the environmental impact for natural gas is assigned values higher than 100 mPts/kg do we obtain a higher environmental impact for the least favorable scenario of CCS, compared to the reference plant. (See Figure A3.)

Using the default values of the perspective "E,E" we find that all coal power plants are associated with much higher

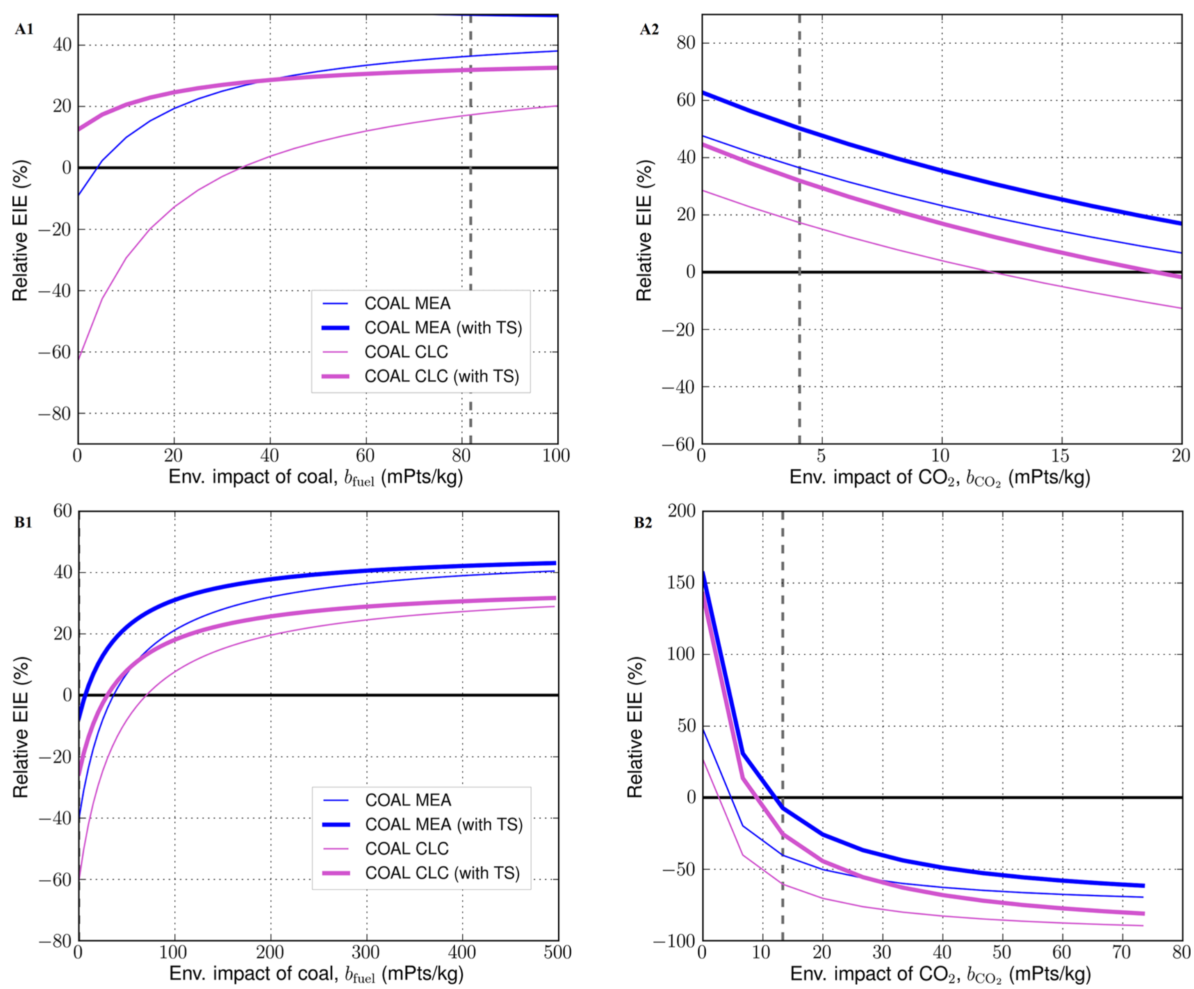

Figure A3. Effect of the environmental impact of coal and CO_2 on the EIE of the coal power plants, relative to the reference plant, using different perspectives (for an environmental impact of transport and storage of 0.0 and 5.0 mPts/kg). Each panel is labeled XY, where X represents the perspective (A = E,E perspective, B = I,I perspective) and Y denotes the material (1 = coal, 2 = CO_2). Negative values of the relative EIE imply environmental benefit.

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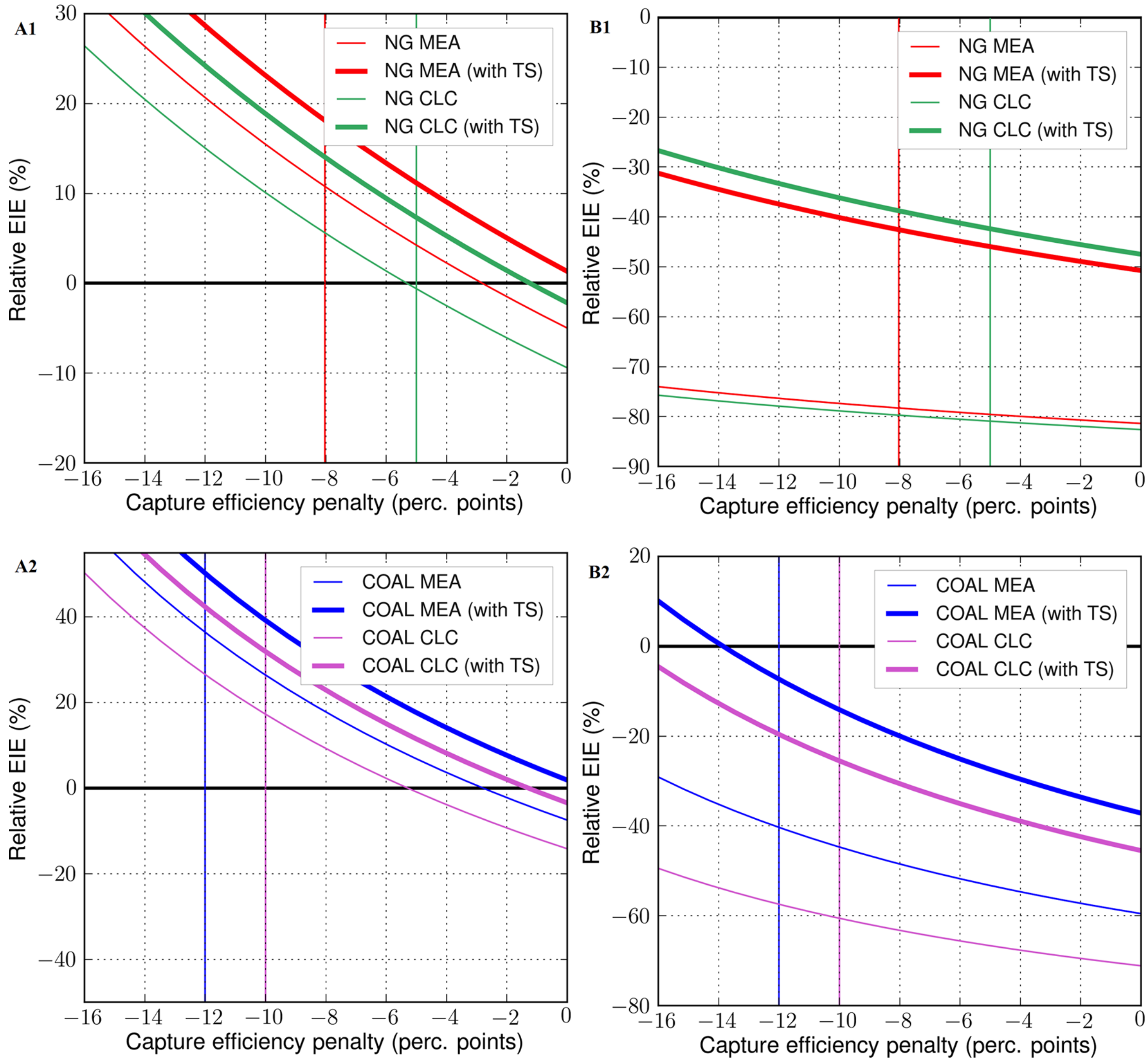

Figure A4. Effect of the overall thermodynamic efficiencies on the EIE, relative to the reference plant, using different perspectives (for an environmental impact of transport and storage of 0.0 and 5.0 mPts/kg). Each panel is labeled XY, where X represents the perspective (A = E,E perspective, B = I,I perspective) and Y denotes the type of plant (1 = natural gas, 2 = coal). Negative values of the relative EIE imply environmental benefit.

environmental impacts than the respective reference plant. Changes in the default environmental impacts of fuel and CO_2 of the perspective show worse results than those obtained using the default perspective "H,A". On the other hand, all coal power plants appear to have better environmental performance when compared to the reference plant, when the perspective "I,I" is considered. Similar to the natural gas plants, a decrease in the environmental impact of CO_2 leads to a higher environmental impact of CCS power plants, when compared to the reference plant. In addition, the assignment of a relatively small environmental impact to coal would quickly result in a higher environmental impact, relative to the reference plant. (See Figure A4.)

The results obtained for natural gas plants using the perspective "E,E" are similar to those obtained when using the perspective "H,A". According to the "E,E", the efficiency penalty of the coal plants must be much smaller, in order for the plants including CCS to present a relative environmental benefit. With the perspective "I,I", the plants can suffer very high energy penalties, compared to the reference plant and still be environmentally beneficial. This, however, is a direct result of the absence of any environmental impact for fossil fuel depletion that strongly influences the results of the other studied perspectives.

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Notes

The authors declare no competing financial interest.

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