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Comparative environmental life cycle assessment of oxyfuel and post-combustion capture with MEA and AMP/PZ - Case studies from the EDDiCCUT project

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Abstract

This work presents the results of a comparative life cycle assessment study for three CCS technologies applied to a coal-fired power plant: post-combustion capture with MEA, post combustion capture with AMP/PZ and cryogenic oxy-fuel. This study has been performed in the context of the EDDiCCUT project, which aims to develop an environmental due diligence framework for assessing novel CCUS technologies. The research shows that there are no significant differences in climate change potential (CCP) for the technologies under study. In the three cases the reduction is about 70% (70% for the plant with MEA, 71% for the plant with AMP-PZ, and 73% for the plant with oxy-fuel technology). With regard to other impacts (e.g., acidification, toxicity, resource depletion) the results show an increase in the impacts as consequence of CCS, mostly driven by the increase amount of feedstock per kWh. Contrary to CCS, there are clear differences among the technologies with results ranging between 20 and 30%. Toxicity impacts related to the operation of the solvent-based carbon capture unit were also considered; however, it was observed that their contribution was only around 2% of the total impact for human toxicity potential. Rather, the largest contributor to human toxicity impacts in the life cycle of coal power plants with and without CCS is coal mining waste disposal.

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1. Introduction

The energy sector accounts for about 32% of global CO_2 emissions, as a consequence of fossil fuel combustion for power generation [1]. The deployment of carbon capture and storage technologies in energy and large industrial CO_2 emitting sources is therefore crucial to meet climate stabilisation targets [2]. CO_2 utilisation as a feedstock to produce fuels, polymers and other valuable chemicals is also gaining attention [3, 4]. The high energy consumption associated with conventional monoethanolamine (MEA) solvent-based capture technologies has led the search for less energy intensive CO_2 capture processes [5]. A large portfolio of CCS technologies is currently under research [6]. Several authors have made efforts to assess the performance of novel solvents for post-combustion capture or novel process configurations [7,8,9]. Studies have also focused on different technologies such as oxy-fuel combustion [10,11], adsorbent-based separations [12,13], membranes [14,15] and other novel separation processes with low technological readiness levels (TRL). Results of these studies are often difficult to compare due to differences in focus, system boundaries, processes, etc.

As considerable investments in CCS are forecasted to take place in the coming years [2], it is necessary to develop a methodological framework that enables a fair comparison of the different technologies in order to select those that will be scaled up and commercially developed. This comparison should not only be based on techno-economic performance indicators, but also consider the life cycle environmental performance of the investigated technologies. However, the analysis of the potential environmental benefits and trade-offs throughout the life cycle of CCS technologies is often based on different techno-economic parameter assumptions and system boundaries, which causes in a large variation within reported results. Analyses also seldom consider the most novel CCS options. As a response to these challenges, the Environmental Due Diligence for Carbon Capture and Utilisation Technologies (EDDiCCUT) project [16, 17] aims to assess the technical, economic and environmental performance of novel carbon capture and utilisation technologies in an integrated, systematic and harmonized way. Special attention is made to identify and understand the knowledge gaps for these novel options.

In this paper, we present the results of applying the EDDiCCUT framework to a comparative life cycle assessment for carbon capture technologies deploy to coal-fired power plants. Three technologies are considered: a conventional MEA post-combustion process; an absorptive post-combustion unit employing a blend of aminomethyl propanol with piperazine as separation agent (AMP/PZ), and a cryogenic oxy-fuel combustion plant. Previous articles devoted to evaluating the environmental performance of CCS technologies have mostly focused on post-combustion MEA processes [18, 19]. Fewer LCA studies for oxy-technologies can be found in literature [20] and to our knowledge, no previous works have analysed environmental impacts for the incorporation of blended solvent-based post-combustion units. It is important to underline that the comparison presented in this paper has been undertaken systematically, i.e., the same system boundaries and the same background databases are used, as well as detailed process and cost estimations [21,22] for the foreground processes within the power and CO_2 capture island.

This article consists of four sections, including this introduction. The method section briefly describes the environmental due diligence (EDD) framework, with particular focus placed on the development of the life cycle inventory. The results section presents the life cycle results for the stressors and impacts under study in this work. The conclusion section highlights the main findings of this study, their relevance and the role of the conducted research in the development of the EDD framework.

2. Methodology

2.1 EDD framework

The EDD framework provides a strategy for the integrated technical, economic and environmental assessment for a given technology. **Figure 1** presents the four main phases of the EDD framework. During the scoping phase, the design basis and the system boundaries are defined based on a comprehensive literature review that includes technical, economic and environmental data collection for the technology under study and the different processes that are part of the value chain. The quality of the knowledge base in the state of the art literature is assessed by using specially developed pedigree matrices [23]. Considering the knowledge available and its quality, the modelling strategy for the different disciplines (technology, costs, environmental) is defined. Furthermore, the performance indicators for each discipline are defined (e.g., energy efficiency, LCOE, CCP).

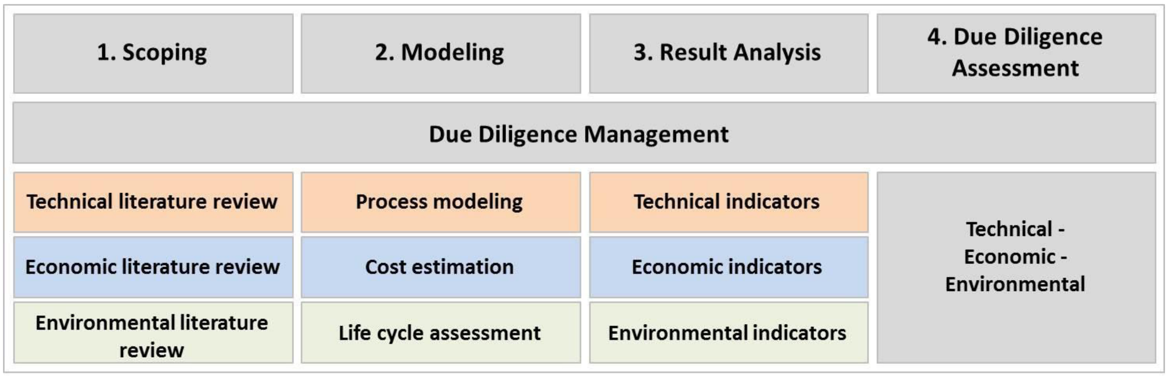

Figure 1: Schematic approach used in the EDDiCCUT framework

During the modelling phase (Phase 2), technical, economic and environmental modelling is carried out. Process simulations and cost estimations cover the power plant and the CO_2 capture unit. The environmental assessment comprises the inventory development and impact quantification for the whole value chain. The inventory makes use of process data and cost data from the technological and economic assessments in a hybrid lifecycle assessment approach. When necessary, data from conventional process-based life cycle inventory databases are used to complement the information from technical and economic disciplines and to model other processes of the value chain. Phase 3 involves the evaluation and analysis of the performance indicators that have been scoped for analysis. Process and stressor influence for the indicators is analyzed and understood. In phase 4, the performance indicators are reviewed and filtered using relevance (which are defined by the team and by other involved parties in the study) and quality criteria. A more detailed description of the employed framework can be found in a previous publication [17].

2.2 Case study description

As mentioned in the introduction, in this study the life cycle impacts associated with MEA, AMP/PZ and oxy-fuel carbon capture processes are anlyzed. **Table 1** displays the main technical and economic performance indicators as well as other relevant information for the plants under consideration.

The processes that are part of the full value chain were combined in ten (10) interconnected system areas containing similar processes (**Figure 2)**. System Area (SA) 1 represents coal mining operations. SA 2 comprises the supply chains of materials required for operation. These materials consist mainly of chemicals such as NH_3 for the deNOx unit, solvent production and other substances. SA 3 includes coal transport from the original production site to the power plant site (in this case Rotterdam, NL). Intermediate storage is also included in this SA. Energy and material requirements for utilities are considered in SA 4. Power plant and flue gas treatment processes (deNOx, deSOx) are included in SA5 and SA6, respectively. CO_2 capture units are considered in SA7 while CO_2 compression, CO_2 transport and CO_2 storage related processes are grouped in SA8, SA9 and SA10 respectively. For the oxy-fuel case, O_2 production via a cryogenic air separation unit replaces the carbon capture unit in SA7. CO_2 purification processes are considered in SA8 in the oxy-fuel case.

Table 1. Case studies under study in this article. The efficiency and CAPEX are the result of the technical and economic modeling in Phase2.

	REF	MEA	AMP/PZ	OXYFUEL
Plant type	Advanced supercritical	Advanced supercritical with MEA post-combustion	Advanced supercritical with AMP/PZ post-combustion	Advanced supercritical with cryogenic oxy-fuel
Location	Northern Europe (Rotterdam)	Northern Europe (Rotterdam)	Northern Europe (Rotterdam)	Northern Europe (Rotterdam)
Temporal	2014	2014	2014	2014
Current technology maturity	TRL 9	TRL 7	TRL 6	TRL 6
Lifetime (years)	40	40	40	40
Capacity (MW)	800	800	800	800
Power plant efficiency (%)[†]	46.1	36.2	37.2	37.9
CAPEX (M€)	1094	1417	1438	1609

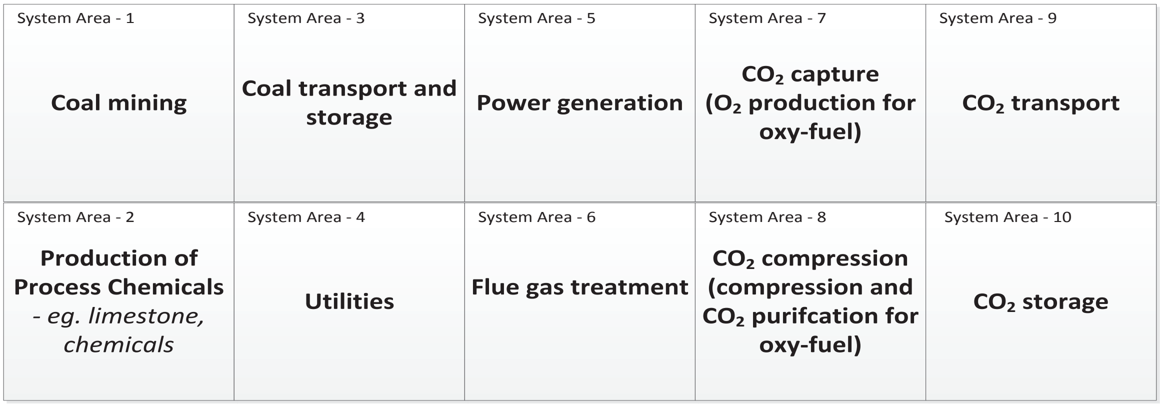

Figure 2: System area layout

2.3 LCA methodology

Inventories for the operation phase of power island and CO_2 capture units (SA5, SA6, SA7 and SA8) are mainly modelled using the outputs of the technical and economical simulation carried out as part of Phase 2 in the framework [21,22]. The technical assessment provided key performance indicators such as efficiency, water use, SPECA, CO_2 avoided, CO_2 per kWh, and several air pollutant emissions such as SO_x and NO_x. Literature data from LCA databases [24] are also used for completing the emission dataset. Solvent degradation emissions for MEA are based on articles that report measurements from the Mongstad Technology Centre [25]. Several sources were used for determining degradation species and rates for the AMP/PZ-based carbon capture units [26, 27, 28]. The other systems areas were modelled by adapting data from the *ecoinvent 2.2* database [24]. The fuel value chain is modelled based on a representative coal mix suggested by the utility companies participating in the EDDiCCUT project. Mining, local and international transport as well as intermediate storage are all modelled in the fuel value chain. The inventory for CO_2 transport was developed by scaling data reported in *Ecoinvent* for natural gas transport network. CO_2 storage was assumed to take place offshore and its inventory was modelled using the data for the construction of natural gas

† Electrical efficiency and CAPEX for the different plants are reported in [21 and 22] where a detailed modeling description can be found.

production wells from *Ecoinvent*. Inventories for the required on-site infrastructure were developed using an hybrid approach. Hybrid life cycle combines economic and process data to develop inventories with good detail and completeness and can improve LCA modelling as conventional LCA comprises a high resolution in foreground processes but suffer from incomplete system boundaries. For a more detailed description of hybrid LCA see [29].

Life cycle impacts were estimated using the ReCiPe 1.08 characterisation method [30]. Given the concern regarding toxicity impacts from solvent degradation emissions and the lack of human and eco-toxicity characterisation factors for these species in ReCiPe, these characterisation factors were modelled using the USEtox software [31] and data reported in literature [32].

3. Results

Figure 3 shows life cycle stressors and indicators per kWhe. It displays the relative contribution of system areas for the different technologies. In terms of stressors, results are shown for CO_2, NO_x, SO_x and PM emissions. Life cycle impacts include the following categories, climate change potential (CCP); terrestrial acidification potential (TAP); particulate matter formation (PMFP); fresh water (FEP) and marine eutrophication potential (MEP), and human toxicity potential (HTP).

In this study, the coal power plant without CCS (reference) has a CCP of about 850 g CO_2-eq/kWh$_e$. Deployment of CCS results in reduction in CCS of about 70% for the three technologies (70% for the plant with the MEA-based carbon capture process, 71% for the plant with AMP/PZ and by 73% for the plant with oxy-fuel technology). CCP is largely determined by CO_2 emissions, which comprise 96% of the total life cycle impact throughout the whole value chain. Life cycle reductions are lower the CO_2 capture targeted in the capture technology (90%) due to the increased emissions upstream which are driven by the decrease in efficiency in the power plant. Furthermore, the CCS plants require extra infrastructure and the separation agent value chains, which are additional sources of CO_2 not present in the reference plant.

Besides CO2, implementing carbon capture units also enables a reduction in (on-site) SO_x (99% for MEA, 74% for AMP/PZ and 99% for oxy-fuel) and PM emissions (-64% for MEA, -62% for AMP/PZ and -99% for oxy-fuel) in the power plant. This is due to additional cleaning process (direct contact coolers) and co-capture effects in the case of solvent-based units. It must be noted, however, that both solvents have different levels of co-capture, particularly for SO_x. Despite the reductions in power plant direct emissions, life cycle increases of NO_x (+29% for MEA and +25% for AMP/PZ), SO_x (+4% for MEA and 6% for AMP/PZ) and PM (+24% for MEA and 20% for AMP/PZ) emissions are observed for the plants with solvent-based carbon capture units. These increases are a consequence of the higher coal demand required to maintain the same power output. Coal transport (liquid fuel combustion for transoceanic freight) accounts for 70% and 60% of life cycle SO_x and PM emissions, respectively. Higher direct and life cycle NO_x emissions are observed for these plants due to the fact that higher combustion and upstream process emissions can not be offset by the co-capture reduction. Lower on-site emissions are reported for these three stressors for the plant with installed oxy-fuel technology (-85% for NO_x, -99% for both SO_x and PM) due to their removal in the CO_2 purification processes. As the oxy-fuel plant has higher efficiency than power plants with solvent-based capture, the reductions in direct NO_x and SO_x emissions also result in lower life cycle emissions.

Increases of 20 and 13% for terrestrial acidification potential (TAP) are reported for the plants with installed MEA and AMP/PZ respectively, while a slight decrease is observed for the plant with oxy-fuel. TAP is mainly determined by SOx (53%), NOx (40%) and NH3 (6%) emissions; the higher life cycle values for this indicator are therefore related to the increased emissions of these stressors in the value chain of the plants with solvent carbon capture processes.

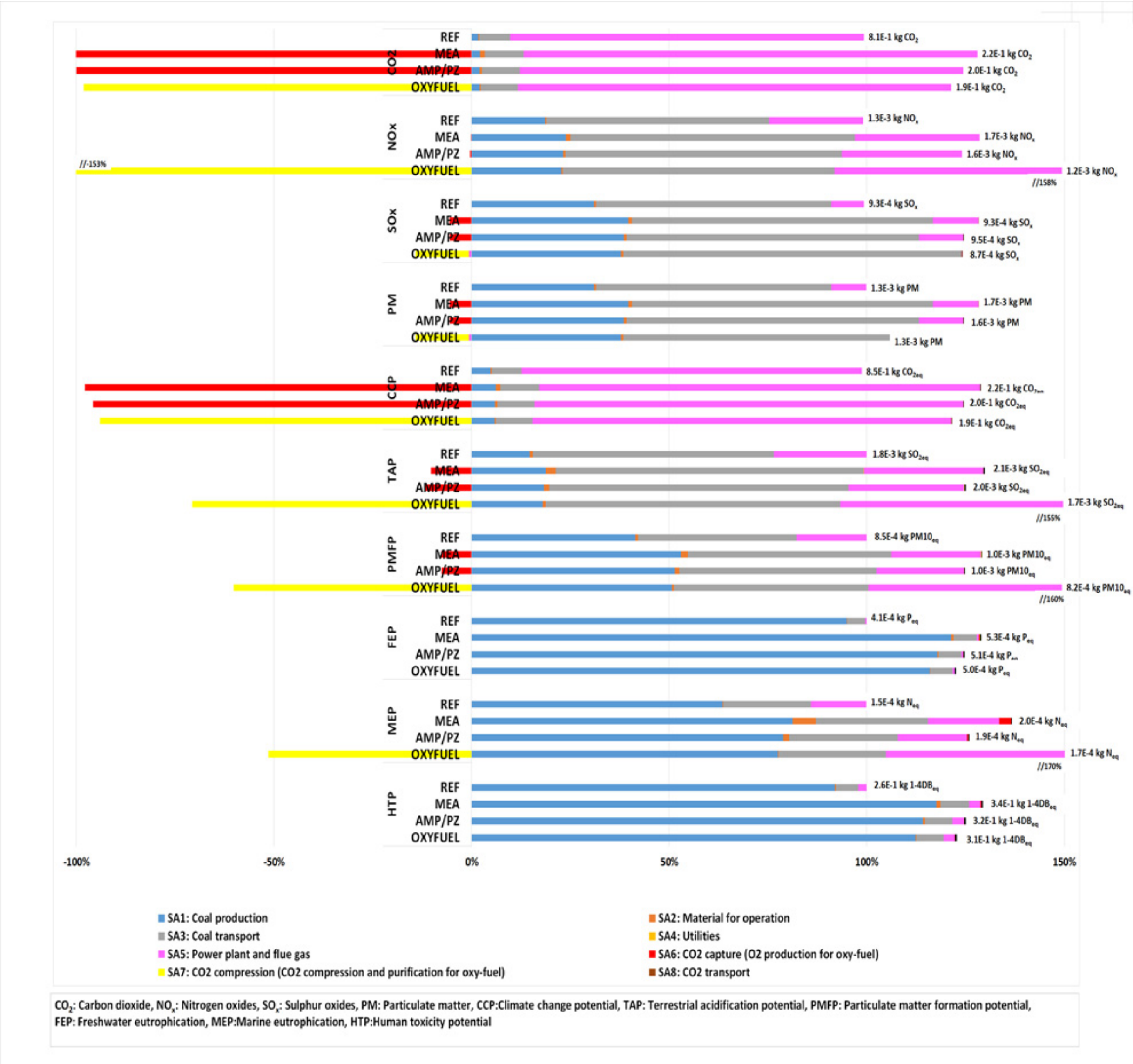

Figure 3: Life cycle stressors and indicators per kWh_e for the technologies under study

Increases of 29, 25, and 23% are reported for life cycle fresh water eutrophication (FEP) values in the plants with MEA, AMP/PZ and oxy-fuel, respectively. Coal production is the largest contributor to this indicator and it largely results from the impacts associated with phosphate-rich spoils from coal mining.

Higher marine eutrophication (MEP) impacts are also reported in the three cases under study relative to the reference plant (+ 37 % for MEA, +26% for AMP/PZ and 13% for oxy-fuel). Coal production accounts for a large share of the life cycle impact for MEP. This is a consequence of the surface landfill disposal of nitrate-rich spoil from coal mining. Coal transport contributes to 22% of the total MEP impacts due to NO_x and SO_x emissions from fuel combustion from international freight. Direct NO_x emissions are responsible for this impact in the power plant. The incorporation of solvent-based carbon capture units slightly reduces NO_x emissions but leads to higher nitrogen-containing effluents resulting from the disposal of the reclaimer, solvent degradation emissions (mainly NH_3) and infrastructure-related impacts. Lower increases are observed for the oxy fuel case due to lower NO_x and SO_x direct emissions and higher plant efficiency (less fuel to be used) in comparison with plants with solvent based carbon capture units

The three technologies show an increase in human toxicity potential (+29% for MEA,+25% for AMP/PZ and 23% for oxy-fuel) relative to the reference plant. HTP is mainly determined by the coal value chain in particular the disposal of coal mining waste. Plants with installed solvent based carbon capture units exhibit a lager increase than the plant with oxy-fuel technology due to differences in efficiency, to the impacts from the operation of the carbon capture unit and to the human toxicity potential associated with the solvent value chain (approximately 3% of the life cycle value for this indicator for both solvent types). Direct emissions to air associated with solvent degradation emissions account for approximately 0.6% of life cycle HTP for the plant with installed MEA and AMP/PZ carbon capture units.

Conclusion

In this paper, results from a comparative life cycle assessment for three different carbon capture technologies are presented. This study was conducted as a part of the EDDiCCUT project, which aims to develop a methodological framework for the performance of environmental due diligence of carbon capture and utilization technologies. By using this framework, the technological, economic and environmental assessments are conducted systematically, employing the same system boundaries and accounting for uncertainty. This framework therefore makes it possible to consistently analyze and compare different carbon capture and utilization technologies. In this study only results of the LCA are discussed.

The EDDiCCUT methodology framework was applied to conduct a comparative assessment of three carbon capture technologies. Results of the environmental life cycle study show that the introduction of carbon capture technologies enables a drastic decrease of CCP (-70% for MEA,-71% for AMP/PZ and -73% for oxy-fuel) for the plants under consideration, allowing as well reductions in on-site direct NO_x, SO_x and PM direct emissions. However, as a result of the higher coal demand required to maintain the same power outputs, increases were observed for most of the life cycle impacts considered in this study. The plant with oxy-fuel technology presents the lowest impact results for the analyzed mid-point indicators, which is mostly due to its higher efficiency. Toxicity impacts related to the operation of the solvent-based carbon capture unit were also considered; however, it was observed that their contribution was only around 2% of the total impact for human toxicity potential. Rather, the largest contributor to human toxicity impacts in the life cycle of coal power plants with and without CCS is coal mining waste disposal.

This comparison has improved the assessment methodology framework under development, which is planned to be used as a decision-making tool for further deployment of technologies currently under research.

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