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# Life Cycle Thinking in decision-making for sustainability: from public policies to private businesses

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Edited by: Giovanni Mondello, Marina Mistretta, Roberta Salomone
Arianna Dominici Loprieno, Sara Cortesi, Erika Mancuso

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# LCA overview on different post-combustion carbon capture applications

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## *Abstract*

*The aim of this paper is to compare, from a technical environmental point of view, different post-combustion capture technologies applied to a supercritical pulverized coal power plant. All the selected technologies are based on chemical absorption using different solvents. In particular, two of them are amine-based technologies, while the other two are inorganic solvents using aqueous ammonia and aqueous potassium carbonate. This paper presents the results of a comparative LCA among the four different technologies and the reference case without* $CO_2$ *capture. The benefits of the inorganic solvents compared with amines are principally due to avoidance of emissions from amine degradation along with a cleaner footprint during the production and transport process of the solvent maintaining almost the same global warming potential and energetic performances.*

## 1 Introduction

One of the most important sources of global anthropogenic carbon dioxide emissions is the combustion of fossil fuels for power generation. Power plants contribute more than 40% of the worldwide anthropogenic $CO_2$ emissions and more than 24% of total GHG emissions (Stern, 2006). Scenarios about the future global energy requirements forecast an increasing demand for electricity, which in 2040 is predicted to be 40% higher than the current demand (IEA, 2018). In particular, in many countries, coal is a convenient raw material for power generation because it is cheap, and the technologies based on coal are well developed (Zhao and Chen, 2015). As a consequence, the capacity of the coal-fired power plants will increase by approximately 40%, and the carbon dioxide emissions derived from those plants are inevitably expected to rise (H2-IGCC, 2010).

The International Panel on Climate Change (IPCC) have suggested that carbon dioxide ($CO_2$) equivalent levels should be estabilished at 490–535 ppm in an effort to contain human induced global warming to between 2 °C and 4 °C over the next century to prevent catastrophic climate change. In order to meet these aggressive targets, a suite of solutions for reducing $CO_2$ emission is necessary including energy efficiency, renewable, nuclear and carbon capture and storage (CCS). CCS is a recognised part of this solution as it has potential to provide deep cuts in $CO_2$ emissions from large stationary sources such as power generation, which will continue to be dominated by burning fossil fuels (IEA, 2018).

Post-combustion capture has the large benefit of being readily applicable to already existing power plants, both coal or natural gas-fired. The carbon capture can be accomplished by adsorption or chemical absorption. The use of amine aqueous solutions for the chemical absorption is widely used in other industrial sectors, such as the oil&gas or the urea industries.

The most studied post-combustion technology is the chemical absorption. In particular, monoethanolamine (MEA) represents the reference chemical for this purpose (Giuffrida et al., 2013;Wang et al., 2011;Sanchez Fernandez et al., 2014). Other amines have been proposed such as methyl diethanolamine MDEA (Oyenekan and Rochelle, 2003) and piperazine (Sanchez Fernandez et al., 2014;Kvamsdal et al., 2014) in order to decrease the energy impact of the carbon capture plant on the net power produced by the power plant.

As an alternative to the amine, aqueous ammonia solvent (Valenti et al., 2012;Bonalumi and Giuffrida, 2016; Bonalumi et al., 2016) and potassium carbonate solvent (Nejad et al., 2015; Grant et al., 2014) are examples of inorganic solvents with promising energetic performances. The third generation solvents are not far from the theoretical minimum (Kim and Lee, 2017), so in addiction to the energetic efficiency of the capture process other parameters must be considered in order to lead to the application of the best technology.

The aim of this paper is to compare, from a technical environmental point of view, different post-combustion capture technologies applied to a supercritical pulverized coal power plant. All the selected technologies are based on chemical absorption using different solvents. In particular, two of them are amines technologies with MEA and MDEA, while the other two are inorganic solvents using aqueous ammonia and aqueous potassium carbonate.

LCA is an internationally recognised methodology for comparing alternative products and processes taking into account the impacts from cradle to grave and over a range of relevant environmental indicators. This paper presents the results of a comparative LCA among the four different capture technologies cited before and the reference case without $CO_2$ capture.

The LCA analysis will return the results considering the following environmental impact indicators: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Abiotic Depletion Potential (ADP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Human Toxicity Potential (HTP), Photochemical Oxidation Potential (PCOP), Terrestrial Ecotoxicity Potential (TEP), Marine Aquatic Ecotoxicity Potential (MAETP). Indicators such as GWP and ADP are related more on the energetic efficiency of the capture process which influences the specific emissions of greenhouse gasses and the Abiotic depletion potential (which is related to the fossil and chemical consumptions). The other environmental indicators such as the acidification potential or the human toxicity potential are maily influenced by the solvent used for the carbon capture and the related emissions.

## 2 Methods

### a. Process modelling and technical evaluation

The coal, transported pneumatically using pre-heat air, is fed to a boiler. Coal combustion occurs here and hot flue gases are formed in the combustion process. The hot flue gases are used to pre-heat the primary and secondary air streams and to generate steam, which is then expanded in the steam turbine for power generation. The $NO_x$ emission control is done by Selective Catalytic Removal (SCR) using ammonia. In the study (Petrescu et al., 2017) was considered that SCR unit will decrease the $NO_x$ limit to below 20 ppm as required for downstream $CO_2$ capture plant. The cooled flue gases are sent to the Flue Gas Desulphurization (FGD) in order to remove sulphur. Limestone is used as raw material for desulphurization, and gypsum is formed in the process.

The carbon capture processes differ among them by the chemical absorption reactions of the carbon capture section. The different processes have different feedproduct, different bypoduct and different emissions. The description of the MDEA and ammonia technologies are presented in the paper by (Petrescu et al., 2017), while the MEA and potassium carbonate technologies in the work by (Grant et al., 2014). In Figure 1 there is the schematic layout of the coal power plant including the $CO_2$ capture; all the analysed cases are considered with a $CO_2$ capture efficiency higher than the 85% on the total $CO_2$ flow at the stack.

Where considered, the captured carbon dioxide stream is dehydrated using tri-ethylene-glycol (TEG) in a standard absorption and desorption cycle and then compressed to 120 bar. The compression is done in four stages with inter-cooling.

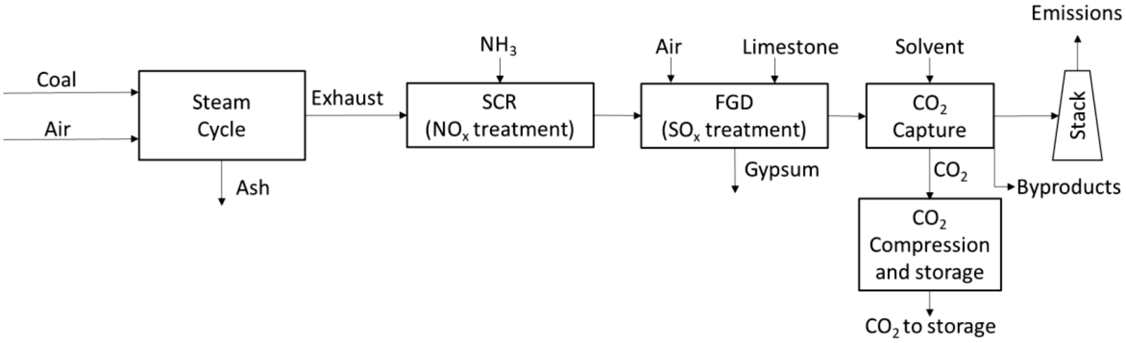

*Figure 1: Generic plant layout of the coal power plant with the $CO_2$ capture*

### b. LCA analysis and assumptions

The primary goal of this study is to quantify and analyze the total environmental aspects of power production using SC pulverized coal power plant with/without post-combustion CCS technologies. To this purpose, the present work analyses the results, taken from the literature, of different technologies, as mentioned above. There are two comparative analyses: (i) the first between aqueous ammonia solvent technology and the MDEA technology with respect to the coal plant without $CO_2$ capture and (ii) the second between the $K_2CO_3$ technology and the MEA technology. Finally, a third paragraph reports a sensitivity analysis focused on MEA capture plant in order to present the parameters that maily impact on the LCA indicators.

In the first comparison ($NH_3$ vs. MDEA) the functional unit proposed is one MWh of net power produced. The net power produced is obtained, for each case, by subtracting the auxiliary power consumption from the gross electric power. The material and energy balance are available from the modeling and simulation phase. A “cradle-to-grave” LCA approach is adopted in the study by (Petrescu et al., 2017).

A detailed assessment of each pathway step, from raw materials extraction to power production, including $CO_2$ transport and storage, is presented. The LCA study by (Petrescu et al., 2017) is based on the energy and material consumption of each unit process. Several assumptions have to be considered in the LCA. A requirement of the study is that the plant is self-sufficient in all its utilities, which means that electricity must also be produced to drive the machinery (Figure 1). The midpoint impact categories considered in CML 2001 method are: GWP, AP, EP, ODP, ADP, FAETP, HTP, PCOP, TEP, MAETP. These indicators are widley described in the literature (Korre et al., 2010).

In the second comparison (Grant et al., 2014), the functional unit proposed is one tonne of $CO_2$ separated by the capture plant. The analysis considers the pathway steps of the plant construction, the raw material exstraction and the emission related to the power production until the carbon separation process. Both the $CO_2$ compression and the $CO_2$ transport and storage are not taken in to account. The same midpoint impact categories are considered because the same method is selected, i.e. CML 2001. LCA boundaries adopted in different papers are illustrated in Figure 2.

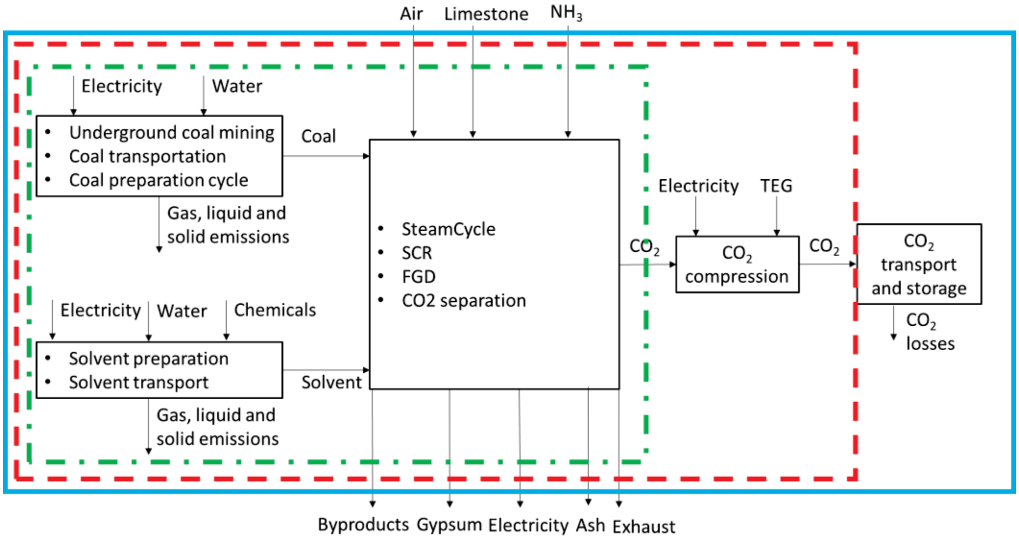

*Figure 2: Boundary conditions for the cited works: (i) in blue solid line the boundary of the work (Petrescu et al., 2017), (ii) in red dashed line the boundary of the work (Schreiber et al., 2009) and (iii) in green dashed-dotted line the boundary of the work (Grant et al., 2014)*

Finally, a concise sensitivity analysis taken by (Schreiber et al., 2009;Grant et al., 2014) for a MEA capture case is presented to show in brief the main parameters that influence the LCA. The parameters considered in the (Schreiber et al., 2009) are only six (Primary energy PE demand, GWP, HTP, AP, POCP, and EP). The system boundaries are from the raw material extraction processes to the $CO_2$ compression and liquefaction, while the $CO_2$ transport and storage are not considered.

## 3 Results and discussion

In this paragraph the three analyses taken from the literature are presented. The results cannot be directly compared because the system boundary, the life cycle inventory and the functional unit are different. Anyway, qualitatively the results return common conclusions that help in the comprehension of the LCA applied to coal plant with carbon capture.

### a. MDEA capture plant vs. aqueous ammonia technology

All plant concepts evaluated generate about 385-545 MWe net power, with a net plant electrical efficiency of about 43.33% for the case without CCS and about 34-36% for CCS cases (Petrescu et al., 2017). The CCS cases investigated are the aqueous ammonia capture plant and the MDEA plant, both compared with the standards SC coal plant without CCS.

Figure 3 *Figure 3* reports the LCA indicators for the three cases, while Figure 4 reports four of the main indicators, where are highlighted all the contributions of the different processes.

The GWP value for SC coal plant is 970.37 $kg_{CO2eq.}$/MWh. Looking deeper into the details (Figure 4) the total GWP is mainly due to two processes: (i) 801 $kg_{CO2eq.}$/MWh is coming from the SC pulverized coal power plant operation, (ii) 154 $kg_{CO2eq.}$/MWh is coming from coal mine operation. For MDEA case the total GWP value is 495.93 $kg_{CO2eq.}$/MWh. The SC power plant with MDEA capture represents 91 $kg_{CO2eq.}$/MWh of the total value which is 88.66% lower than the benchmark case without capture. On the other hand, coal mine operation has a contribution higher that in the benchmark case (e.g.195 $kg_{CO2eq.}$/MWh vs. 154 $kg_{CO2eq.}$/MWh) due to the fact that a lower electric efficiency is correlated to a higher quantity of coal extracted and transported in this case. Significant contribution to the total GWP value is also brought, in the present case, by other steps, e.g. $CO_2$ losses in transport and storage (71.4 $kg_{CO2eq.}$/MWh), MDEA production (e.g. 65 $kg_{CO2eq.}$/MWh) and $CO_2$ pipelines commissioning (e.g. 52 $kg_{CO2eq.}$/MWh), steps that are not present in the benchmark study. The considerations for the MDEA case are valid also for the ammonia case. Indeed, the small differences are due to a lower carbon capture ratio (85% vs. 90.2%), which leads to a higher emission of $CO_2$ from the power plant, but less in the $CO_2$ capture, transport and storage section and less emissions for the solvent production. Anyway, the GWP of this two technologies are very similar (500.33 $kg_{CO2eq.}$/MWh vs 495.93 $kg_{CO2eq.}$/MWh).

As a final result, it is important to highlight that, despite a carbon capture ratio higher than 85% in both the cases, the overall carbon footprint decreases less than 50%.

Considering the other indicators, as Figure 3 shows, the MDEA case has the highest value for almost all the indicators. In particular, MDEA case differs from the ammonia case for the indicatiors like AP, FAETP, HTP, PCOP, TEP, MAETP.

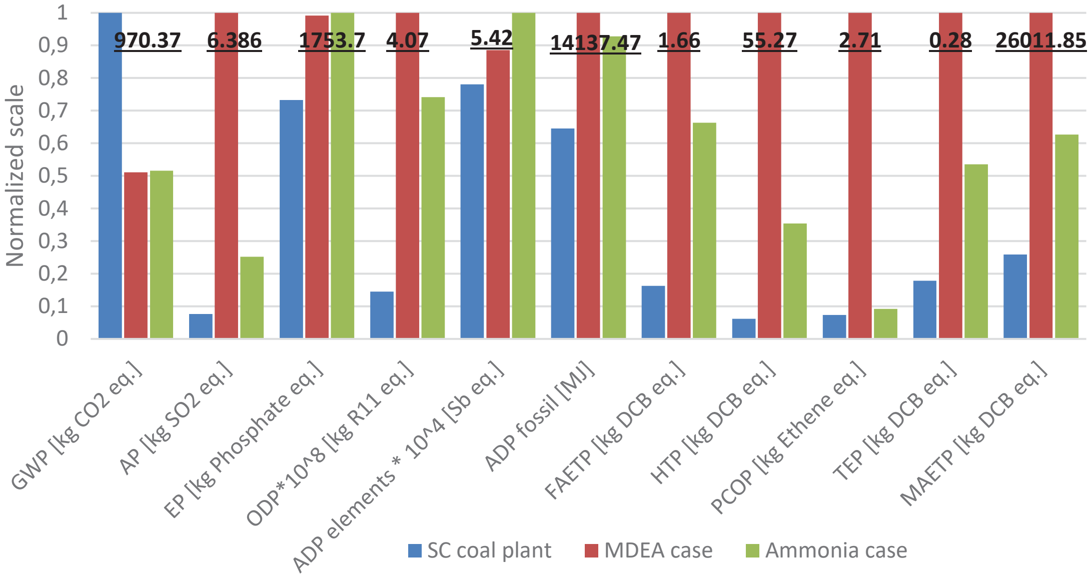

*Figure 3: LCA indicators values for the three cases analysed by (Petrescu et al., 2017) specifics on the MWh of electric power produced. The results are normalized on the higher value of each indicator, which value is reported with the number on the top of the columns*

Analysing deeply the contributions of the different processes for some indicators in Figure 4, the results state that the main reason of the higher toxicity and pollution of the MDEA case is related to the MDEA production and transport process. Hence, since there are not important benefits in terms of $CO_2$ capture and energy efficiency, MDEA technology has a higher environmental impact with respect to aqueous ammonia technology. The reason is mainly due to the production, transport losses and degradation of the solvent.

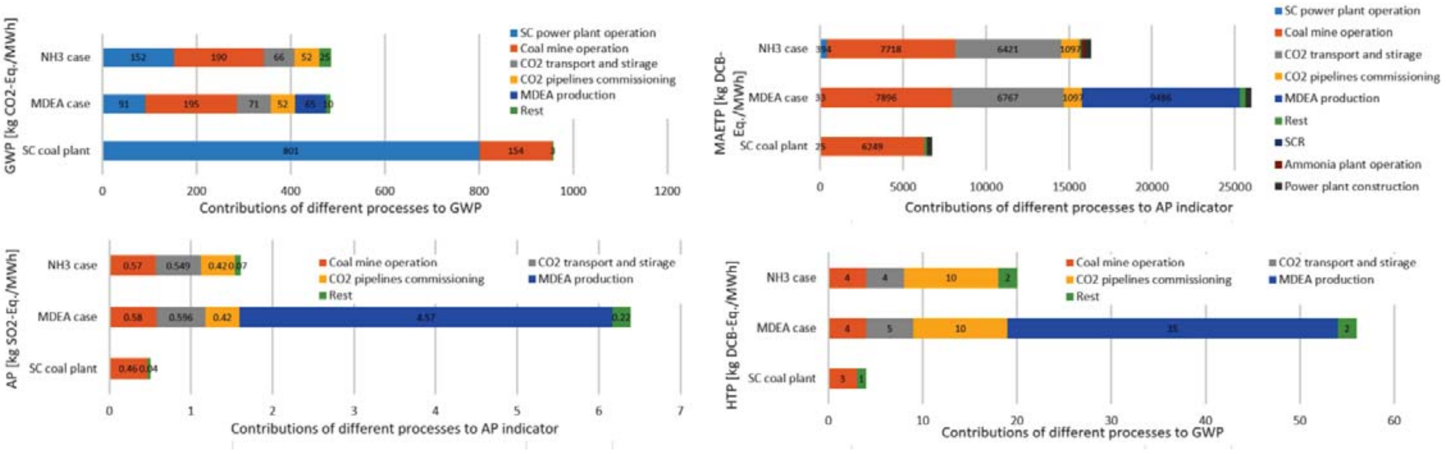

*Figure 4: Significant environmental indicators for SC pulverized coal power plant with/without CCS with the explicit contributions of the different processes by (Petrescu et al., 2017)*

### b. MEA capture plant vs. Potassium carbonate technology

The comparison here presented is taken from (Grant et al., 2014). The functional unit assumed in this study is 1 tonne of $CO_2$ captured. Results for MEA and the potassium carbonate technology UNO MK3 are presented in Figure 5.

The global worming potential and the embodied energy are lower for the $K_2CO_3$ technology mainly due to its higher energy efficiency and the lower energy intensive solvent production process. For example, UNO MK3 uses 36% less electricity and heat than MEA and it has also higher consumptions in the solvent production. This results in lower greenhouse emission specifics on the tonne of $CO_2$ captured (142 $kg_{CO2eq.}$ vs. 223 $kg_{CO2eq.}$)

The toxicity, acidification and eutrophication indicators are higher for the MEA case supposing a recovery of the 95% of degradation products back in to the solvent and not emitted into waterways. Indeed, MEA degrades upon contact with flue gasses impurities such as SOx and NOx forming toxic compounds such as nitrosamines and formaldehyde, which may be emitted within the decarbonized gasses. UNO MK3, on the other hand, is based on an inorganic solvent which is not degradated by the impurities and does not emit degradation products with a lower environmenta impact and toxicity.

The higher value of photochemical ozone creation potential (PCOP) in the MEA case is led by the production of the ethylene and other organic compounds, which are precursors of the MEA production.

Considering both the results of this comparison and the comparison presented in the previous paragraph, the amine production, transport and degradation during carbon capture have a very strong impact on the environmental indicators with respect to other inorganic solvents like $NH_3$ or $K_2CO_3$.

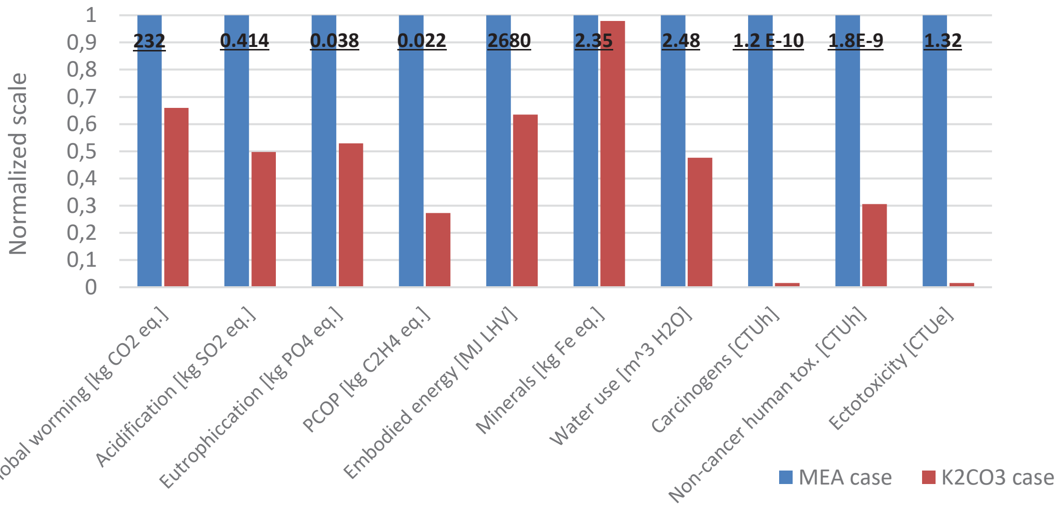

*Figure 5: LCA indicators values for the three cases analysed by (Grant et al., 2014) specifics on the tonne of $CO_2$ separated. The results are normalized on the higher value of each indicator, which value is reported with the number on the top of the columns*

### c. Sensitivity and scenario considerations on CCS technologies

This paragraph aims to cite some sensitity analysis from the literature in order to identify and brefly discuss which parameters have more impact in the LCA indicators results.
Sensitivity analyses are undertaken by (Schreiber et al., 2009) for a MEA capture case to determine the effect on the total life cycle impacts. The parameter considered with the higher impact is the coal origin. As coal origin, in the reference case, the German hard coal mix is assumed. For variations, Western Europe, Australia, South Africa, and Russia are chosen. In our calculation, the origins do not affect the coal quality for combustion, which is assumed to be Pittsburgh No. 8 for all the analyses, but it affects the supply of raw coal, which depends on the upstream processes “mining” and “coal transport”. The influence of the origin of imported coals on the life cycle impact results.

For the selected origins, inventories for extraction and for transports are very different. If the coal exclusively originates from Australia (AUS) or South Africa (ZA) all impact potentials increase except greenhouse gas potential, due to the energy consumption of the long-distance transports (diesel fuel for ships). The slight decrease for greenhouse gas potential is caused by much lower methane emissions during the extraction of coal in Australia and South Africa. If Western European or Russian coal is used, only marginal alteration is observed. Therefore, if a chosen technology needs higher coal inputs, the coal origin with its necessary transports is gaining increasing importance.

In the sensitivity analysis conduced by (Grant et al., 2014) the results highlight that another important parameter is the recovery rate of MEA in the waste water stream is an important parameter as it has a large effect on the ecotoxicity results. A reduction of 5% in recovery from the default of 95% to a 90% recovery rate almost doubles the impact on ecotoxicity. However, if the recovery rate can be increased from the default of 95% up to 99% it would be reduced by a factor of 4. All the same, even at 99% recovery, the ecotoxicity indicator is still ten times higher than the results with $K_2CO_3$ technology. The sensitivity analysis to the fraction of MEA that breaks down into nitrosomorpholine results in a 3% rise of the carcinogens indicator for the case where the nitrosamine emissions increase by a factor of 350. This relatively small rise is because the indicator is still dominated by formaldehyde and ethylene oxide in the baseline scenario. This problem does not happen with inorganic solvents like $NH_3$ or $K_2CO_3$ because they do not degrade in other toxic or carcinogenic substances and their production processes do not include chemical with high toxicity.

## 4 Conclusions

The environmental impacts of different technologies for separating $CO_2$ from the flue gas stream of a coal-fired power station have been compared. In particular, two comparisons between amine based solvents and inorganic based solvents are presented.

The benefits of the inorganic solvents (such as $NH_3$ and $K_2CO_3$) compared with amines (such as MEA and MDEA) are principally due to avoidance of emissions from amine degradation along with a cleaner footprint during the production and transport process of the solvent.

For what concerns the energy saving and the specific $CO_2$ emission, the benefits of the inorganic solvents are less evident. Indeed, the $NH_3$ case has a different $CO_2$ capture efficiency, so the carbon footprint cannot be directly compared with the MDEA case. The $K_2CO_3$ technology, compared at the same capture ratio with MEA case, return better results also in terms of energy afficiency and carbon footprint.

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