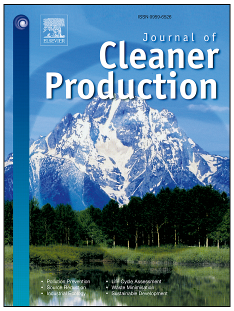

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Life cycle assessment for supercritical pulverized coal power plants with post-combustion carbon capture and storage

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Abstract

Environmental and technical aspects of four supercritical (SC) pulverised-coal processes with post-combustion carbon capture and storage (CCS) are evaluated in the present work. The post-combustion CCS technologies (e.g. MDEA, aqueous ammonia and Calcium Looping (CaL) are compared to the benchmark case represented by the SC pulverized coal without CCS. Some important key performance indicators (e.g. net electrical power, energy conversion efficiency, carbon capture rate, specific CO_2 emissions, SPECCA) are calculated based on process modelling and simulation data. The focus of the present work lies in the environmental evaluation, using the Life Cycle Analysis (LCA) methodology, of the processes considered. The system boundaries include: *i)* power production from coal coupled to energy efficient CCS technologies based on post-combustion capture; *ii)* upstream processes such as extraction and processing of coal, limestone, solvents used post-combustion

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CCS, as well as power plant, coal mine, CO_2 pipelines construction and commissioning and *iii)* downstream processes: CO_2 compression, transport and storage (for the CCS case) as well as power plant, CCS units, coal mine and CO_2 pipelines decommissioning. GaBi6 software was used to perform a "cradle-to-grave" LCA study, to calculate and compare different impact categories, according to CML 2001 impact assessment method. All results are reported to one MWh of net energy produced in the power plant. Discussions about the most significant environmental impact categories are reported leading to the conclusions that the introduction of the CCS technologies decreases the global warming potential (GWP) indicator, but all the other environmental categories increase with respect to the benchmark case. There is also a competition between the aqueous ammonia adsorption and CaL for some impact categories (other than GWP). The implementation of these new CCS technologies is more favorable than the traditional amine-based CO_2 capture.

Keywords: Life Cycle Assessment (LCA); Supercritical coal power plant; Post-combustion CO_2 capture; Aqueous ammonia process; Calcium Looping (CaL).

1. Introduction

Energy is an essential need of the modern society, being used for various purposes (slighting, communications, heating, air conditioning, transportation). Industry, in all its forms, produces goods for our welfare, and it is a significant energy consumer (Ghoniem, 2011). When evaluating various energy production technologies relevant aspects such as: energy and raw-materials consumptions, energy efficiency, environmental issues, have to be considered. In the last period, the environmental impact has become an important factor when evaluating energy conversion technologies (Zhao and Chen, 2015).

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). The utilization of coal is foreseen to rise by 30% in the next two decades. 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 (H_2-IGCC, 2010).

For almost 100 years, pulverised coal firing has been the dominant technology for generating power in utility boilers (Barnes, 2015). According to Buchan and Cao, pulverized coal technologies can be classified as follows: fluidized-bed combustion, advanced combustion and integrated gasification combined cycles (IGCC) (Buchan and Cao, 2004). The main advantages of pulverised coal combustion are: high reliability, full automation, adaptation to a wide range of coal ranks and operating requirements, excellent capacity for increasing unit size, and cost-effective power generation. High energy consumption and high SO_2 and NO_x emissions are some disadvantages of this technology (Toporov, 2014).

Depending on the maxium pressure reached in the boiler, the power plants are distiguished as subcritical plants or supercritical plants. It depends if this pressure is below or above the critical pressure of the water (220.64 bar). A more detailed classification and typical values of maxiumum temperature and pressure of the steam are: *i)* conventional subcritical power plant (steam temperature approximately 820 K, pressure around 16 - 17 MPa, plant fuel to electricity conversion efficiency of ca. 38%; *ii)* supercritical power plant (steam temperature approximately 870 K, pressure around 22 - 24 MPa, efficiency of ca. 45%; and *iii)* ultra-supercritical power plant (steam temperature approximately 975 K, pressure higher than 26 MPa, efficiency around 50% (Zhang, 2013). The focus of this study is put on the supercritical pulverised coal power plant.

Conventional coal-fired plants are significant contributors to air pollution. The pollution is due to the release of the hot flue gas produced from the combustion of coal into the atmosphere. The combustion pollutants include oxides of sulphur, nitrogen, and carbon as well as fine organic and inorganic particulates (fly ash, dust, etc.). Today, there is a continuing and increasing requirement to burn coal worldwide in an environmentally acceptable manner (Barnes, 2015). There are many adverse effects of various emissions from power plants. For instance dust has been linked to cancers, SO_2 and NO_x have a great influence on acid rains or photochemical smog formation. Significant progress was recorded, in the last period, in the field of pollutant control systems and those systems are still under development. The control of emissions of particulates, NO_x and SO_x but also of trace elements, polycyclic aromatic hydrocarbons and, importantly, CO_2 has been implemented or is going to be implemented (Barnes, 2015). The tendency is to develop technologies that are more environmentally friendly, technologies that lower or cut down the pollutant emissions, those technologies being called clean coal technologies (Toporov, 2014).

The reduction of CO_2 emissions from coal can be done in two ways. The first one is by improving the efficiency of the coal-fired power plants. This improvement will lead to lower emissions per unit of energy output. The second way to reduce the CO_2 emissions from coal is by applying CCS technologies. This method will decrease the CO_2 emissions to the atmosphere by 80 - 90% (Toporov, 2014). CCS is viewed as a kind of arrangement between the further use of fossil fuels to satisfy increasing energy demand and CO_2 emissions reduction (Sathre et al., 2012). Carbon capture is not a single technology, but a suite of technologies. Some of these technologies can be applied to existing coal-fired power stations, and other involve new technologies for transforming coal into energy (Falcke et al., 2011).

Different techniques have been developed to capture the CO_2 released by the coal plants and to sequester it in storage sites (Sathre et al., 2012). Three alternative approaches can integrate CO_2 capture technologies with power generation systems: post-combustion, pre-combustion and oxy-fuel combustion. These CCS options differ in terms of economic cost, the level of maturity, energy penalty, material demand and emission intensity (Singh et al., 2011). Choosing one or other CCS technology is strongly dependent on the power plant conditions (Korre et al., 2010).

Post-combustion CO_2 capture was used in the present study. In the post-combustion technology CO_2 is removed after combustion of the fossil fuel (Wang et al., 2011). The main advantage offered by the post-combustion technology is that it can be implemented as a retrofit option for the existing power plants (Davison, 2007). Wang and co-authors classified the technologies that could be employed with post-combustion CCS. Adsorption, physical absorption, chemical absorption, cryogenics separation and membranes are some technologies mentioned by the authors (Wang et al., 2011).

According to Korre and co-authors, chemical absorption for CO_2 capture is conveniently applicable to post-combustion systems. This fact is due to the low CO_2 partial pressure in the flue gas obtained in the coal-fired power plants (Korre et al., 2010). The amine technology suites well and is dedicated for retrofitting of existing power plants. The major challenge, however, is minimizing the operating and investment costs (Pellegrini et al., 2010; Oyenekan and Rochelle, 2007).

In the recent years, the alternative chemical absorption in aqueous ammonia solutions has been proposed. The process is considered a promising technology that still needs further numerical modeling and pilot testing to prove its viability (Valenti et al., 2012). In order to selectively capture the CO_2 from the flue gases, an ammonia-based solution is used. The process takes place at a reduced temperature in an absorption column (Hilton, 2009). The ammonia solution is subsequently regenerated in a desorption column, and the cycle is resumed. According to Versteeg and Rubin the advantages offered by the ammonia-based technology are: high CO_2 carrying capacity, low reboiler regeneration energy, low power for CO_2 compression and low cost for ammonia (Versteeg and Rubin, 2011).

The Ca-looping (CaL) technology is considered a feasible process for post-combustion CO_2 capture (Valverde et al., 2014). This technology is suitable for integration not only in power plants but also in other large CO_2 emission industrial plants, e.g. cement industry, steel plants (Fan, 2010). The process is based on the multi-cyclic carbonation / calcination of CaO at high temperatures. CO_2 from flue gases reacts with the solid sorbent (CaO) at 500 - 650˚C leading to calcium carbonate formation. The carbonate formed is furthermore decomposed into CaO and a CO_2 stream which is sent to the drying and compression section of the plant, being ready for storage. The carbonation process takes place at 800 - 950˚C. The CaO is recycled back in the carbonator in order to absorb more CO_2, and the cycle process is repeated (Cormos, 2014).

From technical point of view some key performance indicators such as: net power produced, net electrical efficiencies, carbon capture rate, specific CO_2 emissions, Specific Primary Energy Consumption for CO_2 avoided (SPECCA) were calculated in the present work. Environmental indicators such as: 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) can be also evaluated.

The aim of this paper is to compare, from a technical and environmental point of view, three SC pulverized coal power plants coupled with different post-combustion carbon capture technologies. The conventional SC pulverized coal power plant without CCS is also evaluated for comparison reasons.

The following case studies were evaluated in detail within this paper:

Case 1. SC pulverized coal power plant without CCS;

Case 2. SC pulverized coal power plant with amine-based (MDEA) post-combustion CCS;

Case 3. SC pulverized coal power plant with aqueus ammonia post-combustion CCS;

Case 4. SC pulverized coal power plant with CaL post-combustion CCS.

There are some LCA studies in the literature regarding the SC pulverized coal power plant and amine based post-combustion for SC pulverized coal power plant, but the comparison between traditional technologies using amine with more advanced technologies (such as aqueous ammonia and CaL) was not performed up to this moment.

Odeh and Cockerill focused their attention on three types of fossil-fuel-based power plants: a supercritical pulverized coal, a natural gas combined cycle (NGCC) and an integrated gasification combined cycle (IGCC), with and without CCS. Their main results show that: *i)* For a 90% CO_2 capture efficiency, life cycle GHG emissions are reduced by 75 - 84% depending on what technology is used and *ii)* GWP is reduced when MEA-based CO_2 capture is employed, the increase in other air pollutants such as NO_x and NH_3 leads to higher eutrophication and acidification potentials (Odeh and Cockerill, 2008).

Koornneef and co-authors made a detailed "cradle-to-grave" LCA study of three pulverized coal power plants with/without post-combustion CCS. Two reference chains were considered in their study: subcritical and ultra supercritical pulverized coal fired electricity generation. They observed a reduction of more than 70% in the global warming potential indicator when CCS is used, but notable environmental trade-offs are the increase in human toxicity, ozone layer depletion and fresh water ecotoxicity potential. The state-of-the-art power plant without CCS also shows a better score for the eutrophication, acidification and photochemical oxidation potential despite the deeper reduction of SO_x and NO_x in the CCS power plant (Koornneef et al., 2008).

An interesting comparison between different fuel technologies (e.g. IGCC, NGCC, oxy-fuel and Pulverised Coal - PC) coupled with CCS was performed by Corsten and co-authors (Corsten et al., 2013). The conclusions drawn back from their study was that *i)* CCS results in a net reduction of the GWP of power plants through their life cycle in the order of 65 - 84% (PC-CCS), 68 - 87% (IGCC-CCS), 47 - 80% (NGCC-CCS), and 76 - 97% (Oxyfuel), *ii)* eploying CCS in PC, IGCC and NGCC results in relative increases in eutrophication and acidification when comparing to power plants without CCS. The authors stress also the highly relative importance of emissions occurring upstream (e.g. coal mining, coal transport, MEA production) and downstream (e.g., CO_2 transport, CO_2 storage) when assessing the environmental performance of power plants with CCS (Corsten et al., 2013).

Post-combustion CO_2 capture combined with CO_2-enhanced oil recovery was investigated in Canada, under a demonstration project in Saskatchewan, by Manuilova and co-authors (Manuilova et al., 2014). The fuel used in their case was lignite coal and the post-combustion CCS is based on monotehanolamine (MEA). The results of the study showed a reduction in global warming and air impact categories. Another important conculsion of the study was that even though increases in some categories associated with soil and water were observed, the broad distribution associated with atmospheric release was significantly reduced. LCA studyes for coal fired power plants were also performed in Brazil (Rostrepo et al, 2015) and in Japan (Tang et al., 2014).

The present paper is organised as follows: Section 1 is represented by the Introduction, Section 2, called Methods, presents the process modelling and simulation assumptions, a brief description of the technical key performance indicators as well as a detailed LCA methodology. Results and discussions are presented in Section 3. Finally, the conclusions are reported in Section 4.

2. Methods

2.1. Process modeling and simulation

Processes description

The coal, transported pneumatically using pre-heat air, is fed to a boiler. Coal combustion occures 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 furthemore 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 was considered that SCR unit will decrease the NO_x limit to below 20 ppm as required for downstream CO_2 capture plant. The SCR chemical reactions are described by R1-R4:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad \text{(R1)}$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \quad \text{(R2)}$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \quad \text{(R3)}$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \quad \text{(R4)}$$

Reactions R1 and R2 are the predominant with one mole of ammonia consumed per each mole of NO_x converted. Reactions R3 and R4 occur in gases in which large fractions of the NO_x is present as NO_2. A catalyst is used, for favouring the reactions to take place at lower temperatures (around 250-450°C) The most typical SCR catalyst is a vanadium pentoxide (V_2O_5) catalyst on a titanium dioxide (TiO_2) carrier (Hatton and Bulionis, 2008). The cooled flue gases are sent to the Flue Gas Desulphurisation (FGD) in order to remove sulphur. Limestone is used as raw-material for desulphurization, and gypsum is formed in the process according to R5:

$$SO_2 + CaCO_3 + 1/2O_2 \rightarrow CaSO_4 + CO_2 \quad \text{(R5)}$$

The process simplified schema for the SC pulvrized coal power plant without CCS is presented in Fig.1.

Fig. 1. *Block diagram for SC pulverized coal power plant without CCS (**Case 1**)*

For SC pulverized coal case studies with carbon capture, the flue gases at the back end of the FGD unit are feed to a capture unit as follows: MDEA absorption process for **Case 2**, aqueous ammonia for **Case 3** and CaL for **Case 4**.

The MDEA carbon dioxide capture process (**Case 2**) is based on absorption – desorption cycle using the following reversible chemical reaction (where R is an alkanol radical R = (HO-CH_2CH_2)$_2$-N-CH_3):

$$R_3N + CO_2 + H_2O \leftrightarrow R_3NH^+ + HCO_3^- \qquad \text{(R6)}$$

The amine regeneration, following carbon dioxide capture and stripping, is thermally performed using heat (steam extracted from the Rankine cycle). The captured carbon dioxide stream is dehydrated using tri-ethylene-glycol (TEG) in a standard absorption – desorption cycle and then compressed to 120 bar. The compression is done in four stages with inter-cooling. The process simplified schema for SC pulverized coal power plant with amine-based (MDEA) post-combustion CCS is presented in Fig 2.

Fig. 2. *Block diagram for SC pulverized coal power plant with amine-based (MDEA) post-combustion CCS (**Case 2**)*

The design for **Case 3** is also based on absorption-desorption cycle, but aqueous ammonia is used in this case. The chemical reactions involved in this process are described by Darde and co-authors (Darde et al. 2012). The main reaction taking place is (R7):

$(NH_4)_2CO_3 + CO_2 + H_2O \leftrightarrow 2NH_4HCO_3$ (R7)

The original process, proposed by Alstom, operates at a temperature of about 5°C in the absorber. This conditons promote the precipitation of salts. This work is based on the scheme that operarates at a temperature of about 25°C in the absorber avoiding the formation of salts. The simplified schema for **Case 3** is presented in Fig.3.

Fig. 3. *Block diagram for SC pulverized coal power plant*

*with aqueous ammonia post-combustion CCS (**Case 3**)*

In **Case 4** the flue gases at the end of FGD are sent to the CaL unit. The CO_2 from the flue gases reacts, in the carbonation reactor, with the oxygen carrier (CaO) according to reaction R8, leading to the formation of calcium carbonate:

$CaO + CO_2 \rightarrow CaCO_3$ (R8)

In the calcination reactor, $CaCO_3$ is decomposed (see R9) regenerating in this way the sorbent.

$CaCO_3 \rightarrow CaO + CO_2$ (R9)

An extra fuel must be burned to provide the requested heat of the endothermic calcination process. To avoid the contamination of the CO_2 stream formed with nitrogen, oxygen is used for combustion rather than air. The gas phase is dried and compressed, and the CO_2 stream is sent to the storage sites. A significant benefit offered by the CaL process is that calcium compounds are inexpensive materials, they are non-toxic, and they are easy to handle being stable at ambient conditions (Cormos and Petrescu, 2014). The block diagram for **Case 4** is depicted in Fig. 4.

Fig. 4. *Block diagram for SC pulverized coal power plant*

*with CaL post-combustion CCS (**Case 4**)*

Process modeling and simulation assumptions

Details regarding the composition and thermal properties of the coal used in all four cases are given in the next part. Coal proximate analysis are (% wt.): moisture 8.10% and volatile matter 28.51%. The values corresponding to the ultimate analysis, expressed as % wt. dry, are: carbon 72.04%, hydrogen 4.08%, nitrogen 1.67%, oxygen 7.36%, sulphur 0.65%, chlorine 0.01% and ash 14.19%. The coal lower heating value is 25.35 MJ/kg. SC pulverized coal power plant with / without post-combustion CO_2 capture were modeled and simulated using ChemCAD, Aspen Plus and GS software packages. The mathematical models involve mass, energy and momentum balances, as well as industrial constraints. The main design assumptions for all cases are reported in **Table 1**. The thermodynamics packages used in the simulations are: Partial Pressures of Aqueous Mixtures (PPAQ) for SC pulverized coal, Ideal Vapour Pressure for MDEA post-combustion unit, Extended UNIQUAC thermodynamic model implemented in Aspen Plus for aqueous ammonia and Soave Redlich Kwong (SRK) for CaL. The main parameters (temperature, pressure, mass flow and weight composition) of the input and output streams, for all cases, are available as supplimentary information.

Technical evaluation

The technical key performance indicators (KPI) are reported in **Table 2**. The definition and calculation of those indicators are described by Petrescu and Cormos (Petrescu and Cormos, 2015).

The formula used for SPECCA indicator calculation is:

$$SPECCA \stackrel{\text{def}}{=} \frac{HR - HR_{REF}}{E_{REF} - E} \equiv \frac{3600\left(\frac{1}{\eta_e} - \frac{1}{\eta_{e,REF}}\right)}{E_{REF} - E}$$

where all parameters refer to the either power plant equipped with the carbon capture or the reference power plant without CCS. HR is the heat rate [MJ_{th}/MWh_e], E the specific CO_2 emission [kg_{CO2}/MWh_e], η_e [nondimensional] the net electrical efficiency and REF stays for reference (Romano et al., 2010).

2.2. Life Cycle Assessment (LCA)

Goal and scope of the study, system boundaries, limitations

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. For this purpose, a detailed assessment of each pathway step, from raw materials extraction to power production, including CO_2 transport and storage, is presented. The present LCA study 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 mean that electricity must also be produced to drive the machinery.

The functions considered in this study (gros electric power output) are: the production of 502.32 MW_e of electricity for **Case 1**, 541.3 MW_e for **Case 2**, 412.03 MW_e for **Case 3** and 649.6 MW_e for **Case 4**. From these quantities 27.45 MW_e of electricity are used to run the machinery for **Case 1**, 65.68 MW_e of electricity are used to run the machinery for **Case 2**, 27.45 MW_e of electricity are used to run the machinery for **Case 3** and 105.38 MW_e of electricity are used to run the machinery for **Case 4**. The functional unit proposed is one MWh of net power produced. The net power produced is obtained, for each case, by subtracting the ancillary 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 desired for the present study. "Cradle-to-grave" starts with the extraction of raw materials used in the analysis and ends with the disposal of the final product. The boundary conditions for the casses under study are depicted in Fig. 5.

Fig. 5. *Boundary conditions for SC pulverized coal power plant (**Case 1-4**)*

The following items are excluded from the system boundaries: *i)* construction of infrastructure (e.g. pipelines, roads, railways) as well as construction of trains and trucks for transportation; *ii)* the transmitting of electricity to the transmission and distribution (T&D) network, and the delivery of the electricity to the customer; *iii)* installation of railcar unloading facilities; *iv)* indirect land use; *v)* human activities as well as labor costs associated with the number of employees at each energy conversion facility; *vi)* low-frequency, high-magnitude, non-predictable environmental events (e.g., non-routine/fugitive/accidental releases). However, more frequent or predictable events, such as material loss during transport or scheduled maintenance shut down, were included when applicable.

LCA main assumptions and Life Cycle Inventory (LCI)

The most significat assumptions used in the LCA, for the upstream and downstream processes are presented in **Table 3**. For the core processes, the assumptions used are those reported in the process modelling and simulation section (see **Table 1**).

The following issues have been considered regarding the construction: construction of the coal mine; construction of the SC pulverized coal power plant; construction of the MDEA absorption unit; construction of the aqueous ammonia unit; construction of the CaL unit and construction of the CO_2 pipelines. The LCI for coal mine and power plant construction, as well as data for commissioning/decommissioning of the previously mentioned plants were found in the literature (NETL, 2010). The emissions related to the construction, commissioning/decommissioning of the MDEA unit, aqueous ammonia plant and CaL unit represents 25% of the emissions correspondent to the the power plant construction, commissioning/decommissioning. The commissioning/decommissioning of the CO_2 pipelines have been also included in the analysis (NETL, 2010).

A summary of the most relevant inputs and outputs data for Life cycle inventory (LCI) phase**,** is summarized in **Table 4**. It should be specified that **Table 4** shows a selection of emissions, waste and used energy. Along the value chain for producing electricity, there are emissions and waste, and energy is used in several other facilities and equipment also.

Impact Assessment

The CML 2001 method assessment implemented in GaBi software version 6 (PE International, 2015) was used for the present LCA. CML 2001 is one of the most broadly applied method on the European context. According to Hernandez and co-aouthors problem-oriented methods such as CML 2001 model problems at an early stage in the cause-effect chain, allowing a more transparent assessment and limiting the uncertainties (Hernandez et al., 2016). The midoint 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).

3. Results and discussions

3.1 Results and discussions regarding the technical evaluation

The results of the technical evaluation are presented in **Table 2**. From **Table 2** it can be noticed that, in terms of fuel consumption, the coal flow rate varies in the range 156 - 217 t/h. The coal flow rate is particularly high in **Case 4**: SC pulverized coal power plant with CaL post-combustion CCS. In this case, supplementary coal is necessary in the CaL to provide the heat for calcium carbonate decomposition.

The ancillary power consumption of various plant sub-systems varies in the range 27.45 - 105.38 MW_e. The highest power consumption is in **Case 4** due to increase coal flow rate and to post-combustion capture configuration (captured CO_2 stream has to be compressed from atmospheric pressure to 120 bar). All plant concepts evaluated generate about 385 - 545 MW_e net power, with a net plant electrical efficiency of about 43.33 % for the case without CCS and about 34 - 36% for CCS cases (**Cases 2-4**). The CCS cases investigated in the present work are designed to capture more than 85% of the feedstock carbon. The highest carbon capture rate is obtained when CaL is used for CO_2 capture (**Case 4**). Specific CO_2 emissions of the evaluated concepts with CCS are in the range of 70 - 140 kg/MWh. For comparison, the case without CCS has specific CO_2 emissions about 800 kg/MWh.

Taking into account the SPECCA indicator, the lowest value was obtained for CaL post-combustion CCS (**Case 4**), this case representing the most attractive configuration.

3.2 Results and discussions regarding the environmental evaluation

The results of the environmental evaluation for **Cases 1 - 4** are reported in **Table 5**. Details regarding each indicator are presented in Fig. 6.

Fig. 6. *Significant environmental indicators for*

SC pulverized coal power plant with / without CCS (***Cases 1-4***)

There are significant differences, in terms of GWP, between the cases with CCS (**Cases 2**, **3** and **4**) and the benchmark process (**Case 1**) which has the highest GWP caused by the uncaptured CO_2 emissions.

The GWP value for **Case 1** is 970.37 kg CO_2-Equiv./MWh. Looking deeper into the details of this impact from the total GWP value (e.g. 970.37 kg CO_2-Equiv./MWh), a quantity of 801 kg CO_2-Equiv./MWh is coming from the SC pulverized coal power plant operation, 154 kg CO_2-Equiv./MWh is coming from coal mine operation, a small impact, e.g. 12 kg CO_2-Equiv./MWh, is provided by ammonia involved in the SCR and the rest of 3.25 kg CO_2-Equiv./MWh is coming from the limestone requested for FGD (see Fig. 6a). For **Case 2** the total GWP value is 495.93 kg CO_2-Equiv./MWh. The SC power plant with MDEA capture represents 91 kg CO_2-Equiv. /MWh of the total value. The GWP correspondent to power plant operation was decreased by 88.66% compared to the benchmark case power plant operation Coal mine operation has a contribution higher that in the benchmark case (e.g. 195 kg CO_2-Equiv./MWh vs. 154 kg CO_2-Equiv./MWh) due to the fact that a higher quantity of coal is 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 transport and storage (71.4 kg CO_2-Equiv./MWh), MDEA production (e.g. 65 kg CO_2-Equiv./MWh) and CO_2 pipelines commissioning (e.g. 52 kg CO_2-Equiv./MWh), steps that are not present in the benchmark study (see Fig. 6a). When CO_2 capture is performed using ammonia solution (**Case 3**) the total GWP value is slightly higher than in the case of MDEA adsorbtion (e.g. 500.33 kg CO_2-Equiv./MWh vs. 495.93 kg CO_2-Equiv./MWh) but lower than the benchmark case (e.g. 500.33 kg CO_2-Equiv./MWh vs. 970.37 kg CO_2-Equiv./MWh). The distribution of the total GWP, for **Case 3**, is as follows: 152 kg CO_2-Equiv./MWh is due to the SC power plant operation, 190 kg CO_2-Equiv./MWh is coming from coal mine operation, 66 kg CO_2-Equiv./MWh is due to the CO_2 transport and storage operation while 52 kg CO_2-Equiv./MWh is due to the CO_2 pipelines commissioning, 15 kg CO_2-Equiv./MWh represents the impact of the SCR process. Comparing **Case 3** and **Case 2** it can be noticed a decerease of greenhouse gases emissions in the CO_2 transport and storage step (66 kg CO_2-Equiv./MWh vs. 71 kg CO_2-Equiv./MWh). This decerease was due to a lower quantity of CO_2 transported from the power plant to the storage site (326.74 t/h vs. 437.99 t/h, see **Table 5**). The values for the CO_2

pipelines commissioning is the same in **Case 3** and **Case 2** (e.g. 52 kg CO_2-Equiv./MWh) (see Fig. 6a). In the case of using a solid sorbent for CO_2 capture (**Case 4**) the total GWP impact is 402.2 kg CO_2-Equiv./MWh . A quantity of 71 kg CO_2-Equiv./MWh is coming from the power plant operation, 186 kg CO_2-Equiv./MWh is due to the coal mine operation, 69 kg CO_2-Equiv./MWh is represented by CO_2 transport and storage, 52 kg CO_2-Equiv./MWh is due to the CO_2 pipelines commissioning, and 15 kg CO_2-Equiv./MWh is due to the SCR process (see Fig. 6a).

AP indicator is due to the sulfur dioxide, nitrogen oxides, hydrochloric acid, hydrofluoric acid and ammonia. Taking into account this evironmental indicator, it can be said that the highest value for acidification potential (AP) indicator is obtained in **Case 2** (e.g. 4.57 kg SO_2-Equiv./MWh) (see **Table 5)**. A significant percentage of this value is provided by MDEA production process. Another possible explanation of the high value obtained in this case is a higher quantity of hydrochloric acid emissions compared to the basecase (0.018 t/h in **Case 2** vs. 0.015 t/h in **Case 1**). The values of this environmental indicator are very close in the cases of using ammonia and CaL for CO_2 capture, **Case 3** and **Case 4**, e.g. 1.61 kg SO_2-Equiv./MWh vs. 1.66 kg SO_2-Equiv./MWh. Those values are five times higher than the benchmark case (e.g. 0.49 kg SO_2-Equiv./MWh). The quantity of hydrochloric acid obtained in those case are the same as in the benchmark case (e.g. 0.015 t/h) (see **Table 4**), but there are additional downstream phases of the CCS such as CO_2 transport and storage operation, commissioning / decommissioning of the CO_2 pipelines, which bring contribution on the AP indicator (see Fig. 6b).

EP environmental impact category is related to phosphorous compunds (e.g. phosphate) or nitrogen compounds (e.g. nitrogen oxides, nitrogen, nitrates, ammonia). EP has the highest value in the ammonia process (**Case 3**) 1753.7 kg Phosphate-Equiv./MWh. The entire impact is due to the power plant operation. The impact to eutrophication was increased compeared to the base case (1753.7 kg Phosphate-Equiv./MWh vs. 1285.4 kg Phosphate-Equiv./MWh) due to ammonia and nitrogen emissions. Acoording to mass balance derived from simulation a quantity of 1.94 t/h of ammonia and 1603.98 t/h of nitrogen are released into the atmosphere (see **Table 4**) leading to a increase by 26.7% of EP indicator. A very close value 1739.76 kg Phosphate-Equiv./MWh is obtained in the **Case 2** when MDEA is used for CO_2 capture. From the total 1739.76 kg kg Phosphate-Equiv./MWh a quantity of 1623.89 kg Phosphate-Equiv./MWh is due to the power plant operation while the rest (e.g. 115.75 kg Phosphate-Equiv./MWh) is due to the ethylene oxide emissions from MDEA production and to the high value of nitrogen released into the atmosphere (e.g. 1838.82 t/h – see **Table 4**). The lowest value for this impact indicator corresponds to **Case 4**, 1121.86 kg Phosphate-Equiv./MWh (see Fig. 6c).

ADP_{fossil} has the lowest impact in **Case 1**: 9829.29 MJ/MWh. .Almost all the impact, more exactely 9645.38 MJ/MWh is due to the power plant operation and 156 MJ/MWh is due to the SCR process. (see Fig. 6d). ADP_{fossil} has the highest value in **Case 2** e.g. 15231.63 MJ/MWh (see **Table 5)**. The impact of the power plant in this case is 12188.25 MJ/MWh, the contribution of the SCR process being the same as in the benchmark case. The source of additional ADP_{fossil} impact is: 991 MJ/MWh from MDEA production process, 766 MJ/MWh is coming from the CO_2 transport and storage operation , 991 MJ/MWh and 140 MJ/MWh are represented by other processes. When ammonia is used for CCS, **Case 3**, the distribution of ADP_{fossil} is at follows: 11912 MJ/MWh is coming from power plant operation, 186 MJ/MWh is coming from ammonia production, 192 MJ/MWh from the SCR process, 706 MJ/MWh is coming from the CO_2 transport and storage operation, 991 MJ/MWh from CO_2 pipelines commissionig and 150 MJ/MWh are represented by other processes. In **Case 4**, the value of the ADP_{fossil} is 13752.06 MJ/MWh, which is the lowest from the CCS case studies. From this value 11640.5 MJ/MWh is due to the power plant operation, 137 MJ/MWh from the SCR process, 742 MJ/MWh is coming from the CO_2 transport and storage operation, 991 MJ/MWh from CO_2 pipelines commissionig and 242 MJ/MWh are represented by other processes (see Fig. 6d).

Other impact categories, such as ODP and ADP elements, have low values in all three cases (see **Table 5**).

The best values of the three impact indicators linked to the lethal concentration LC_{50}, FAETP, HTP, MAETP, TE) is obtained also in **Case 1**. The highest values for those impact categories are obtained in **Case 2**, when MDEA is used for CCS (see **Table 5**). If we take into discussion the HTP indicator for the benchmark case the HTP value is 3.67 DCB-Equiv./MWh. Highest value are obtained in the CCS cases (57.11 DCB-Equiv./MWh for **Case 2**, 19.55 for **Case 3** respectively 19.84 DCB-Equiv./MWh for **Case 4).** The biggest contribution on the HTP is represented in **Case 2** by the MDEA production and transportation process (e.g. 35.39 DCB-Equiv./MWh), more exactly to the ethylene oxide emissions from MDEA production process. Other contributions for all CCS cases comes from CO_2 pipelines commissioning (e.g. 10 DCB-Equiv./MWh) and from CO_2 transport and storage (e.g. 5 DCB-Equiv./MWh for **Case 2** and 4 DCB-Equiv./MWh for **Case 3** and **4**). The contribution of the coal mine operation to the total HTP varies in the range of 3-4 DCB-Equiv./MWh for all cases under study (see Fig. 6e). Considering MAETP impact indicator the best value is obtained also in the base case e.g. 6730.54 kg DCB-Equiv./MWh. A percentage of 92.85% of the total value is coming from coal mine operation, 25 kg DCB-Equiv./MWh is coming from power plant operation, 302 kg DCB-Equiv./MWh is due to the SCR process and 155 kg DCB-Equiv./MWh are due to other processes. The highest value for this impact indicator is obtained in **Case 2**. As it can be noticed from Fig. 6f big contribution on this impact category is brought by the MDEA production and transportation process (e.g. 9485.98 kg DCB-Equiv./MWh) and by the CO_2 transport and storage step (e.g. 6767.46 kg DCB-Equiv./MWh)

Smaller contribution is due to the CO_2 pipelines commissioning (e.g. 1096.55 kg DCB-Equiv./MWh), power plant operation (e.g. 33 kg DCB-Equiv./MWh) and the rest of 356 kg DCB-Equiv./MWh is due to other processes. Lower MAETP values are obtained in **Case 3** and **Case 4** due to the fact that the impacts of ammonia and Ca-looping process are not so high compared to the contribution of MDEA production and transportation (see **Figure 6f**). The MAETP impacts of power plants are comparable with **Case 2** (e.g. 7717.74 kg DCB-Equiv./MWh in **Case 3** and 7541.57 kg DCB-Equiv./MWh in **Case 4** vs. 7896.48 kg DCB-Equiv./MWh in **Case 2**). The CO_2 pipelines commissioning has the same value in all CCS cases (e.g. 1097 kg DCB-Equiv./MWh). The contribution of some processes such as coal mine operation, power plant operation and construction are higher in **Case 3** compared to **Case 4**, while CO_2 transport and storage is higher in **Case 4** than in **Case 3** (6559 kg DCB-Equiv./MWh vs. 6421 kg DCB-Equiv./MWh). Limestone extraction process brings also a contribution to the MAETP impact indicator equal to 390 kg DCB-Equiv./MWh.

The lowest value for PCOP impact category is obtained in the benchmark case (**Case 1**). Ammonia case (**Case 3**) and CaL case (**Case 4**) have close value for this impact indicator e.g. 0.25 kg Ethene-Equiv./MWh respectively 0.26 kg Ethene-Equiv./MWh. A particular situation occurs in the MDEA capture case (**Case 2**). Analyzing the PCOP values from **Table 5,** it can be noticed that, the PCOP for **Case 2** is fourteen times higher than in the benchmark process (e.g. 2.71 kg Ethene-Equiv./MWh vs 0.2 kg Ethene-Equiv./MWh). The big impact of this impact category is due to the MDEA production process.

There can be noticed a competition between the aqueous ammonia adsorption and CaL. Some indicators such as AP, EP or those related to lethal concentration (e.g. HTP, FAETP, and MAETP) are better in the case of aqueous ammonia usage for CO_2 capture. Other indicators such as ADP_{fossil}, $ADP_{elements}$, and EP are better in the case of CaL for CO_2 capture.

The results of environmental impacts can be compared to the results published in the literature (Koornneef et al., 2008). Three pulverized coal power plants are presented by Koornneef and co-authors. Compearing the trends of the environmental impact categories obtained in the present study to the supercritical power plant and super critical power plant with CCS (MEA) (**Cases 2** and **3** described by Koornneef) it can be said that the trends of the environemntal results are the same in both studies. GWP impact indicator gives better values when CCS is applied, while the other environmantal impact categories are increasing. The net values of the environemntal impacts obtained in the present study are slightly different compeared to the litterature because in the present study wider boundary conditions for the upstream/downstream processes are considered (e.g. MDEA and NH_3, production and transportation, limestone extraction and transportation for CaL case, CCS construction, commissioning and decomissioning).

4. Conclusions

The paper presents a detailed environmental life cycle analysis for SC pulverized coal for power generation with / without CCS. Three CCS cases are investigated in the present paper *i)* gas-liquid absorption using MDEA as a chemical solvent, *ii)* gas-liquid absorption using aqueous ammonia as a chemical solvent and *iii)* gas-solid absorption using calcium oxide. As benchmark option, a conventional SC pulverised power plant without carbon capture was also considered.

All cases have been modeled and simulated using process flow modelling. All CCS evaluated power plant concepts generate about 385 - 545 MW_e net power. The carbon capture rate is higher than 85% for the CCS cases. Specific CO_2 emissions of the evaluated plant concepts with CCS are in the range of 70 - 140 kg/MWh.

The environmental evaluation is performed using the LCA methodology. A "cradle-to-grave" approach was used considering several upstream and downstream processes. Eleven environmental impact categories, according to CML 2001 method assessment were defined, calculated and compared using GaBi software. All data in the assessment were normalised to the functional unit (one MWh). Details regarding each phase of the LCA are presented.

The CCS are expected to be an important part of the future for stabilizing atmospheric CO_2 concentration and for solving the global warming issue. The introduction of CCS technologies decreases the GWP indicator while other environmental impact indicators are increasing. Upstream processes such as MDEA production, aqueous ammonia production, limestone extraction, as well as downstream processes such as CO_2 pipelines commissioning and CO_2 transport and storage are responsible for the increase on the other environmental impact indicators.

Amine technologies give good performance for GWP, but the results are not satisfactory for all the other environmental categories. There can be noticed a competition between the aqueous ammonia adsorption and CaL. Some indicators such as AP, EP or those related to lethal concentration (e.g. HTP, FAETP, MAETP) are better in the case of aqueous ammonia usage for CO_2 capture. Other indicators such as ADP_{fossil}, $ADP_{elements}$, EP are better in the case of CaL.

Trying to answer to the question: "How can the results of the present work be used to advance the concepts of cleaner production with electricity generation and CSS?", the answer could be: from the environmental point of view, taking into account the hole supply chain of the SC pulverized coal power plants, other than the mature amine-based CO_2 capture technology (e.g. aqueous ammonia and CaL) are more favorable. Those new capture methods have the potential to become important carbon capture technologies in the future.

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Nomenclature

AP - Acidification Potential

ADP - Abiotic Depletion Potential

$ADP_{elements}$ - Abiotic Depletion Elements

ADP_{fossil} - Abiotic Depletion Fossil

CaL - Calcium Looping

CCS - Carbon Capture and Storage

EP - Eutrophication Potential

FGD - Flue Gas Desulphurization

FAETP - Freshwater Aquatic Ecotoxicity Potential

GHG – Greenhouse Gas

GWP - Global Warming Potential

HTP - Human Toxicity Potential

IGCC - Integrated Gasification Combined Cycles

ISO - International Standard Organisation

KPI - Key Performance Indicators

LCA - Life Cycle Assessment

LCI - Life Cycle Inventory

MAETP - Marine Aquatic Ecotoxicity Potential

MDEA - monodiethanolamine

MEA – monoethanolamine

NGCC – natural gas combined cycle

ODP - Ozone Depletion Potential

PC – pulverised coal

PCOP - Photochemical Oxidation Potential

PPAQ - Partial Pressures of Aqueous Mixtures

RK - Redlich Kwong

SC - Supercritical

SCR - Selective Catalytic Removal

SPECCA - Specific Primary Energy Consumption for CO_2 avoided

SRK - Soave Redlich Kwong

TEG - tri-ethylene-glycol

T&D - Transmission and Distribution

TEP - Terrestrial Ecotoxicity Potential

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List of Figures and Tables

Table 1. Main design assumption **(Cases 1-4)**

		ASSUMPTIONS
UNIT NAME	**PARAMETER**	**Cases 1 - 4**
SC pulverized coal	coal moisture (%)	8.1
	primary air (% of the total air flow)	30
	secondary air (% of the total air flow)	70
	boiler heat losses (% of the total coal thermal input)	0.75
FGD	SO_x capture (%)	98
	limestone slurry (% wt.)	15
	limestone conversion (%)	98
Rankine (steam) cycle parameters	main steam parameters (bar/˚C)	290 / 582
	MP reheat 1 (bar/˚C)	75 / 580
	MP reheat 2 (bar/˚C)	20 / 580
	BFW pre-heating temperature (^{o}C)	250
	number of steam extraction for the turbine to preheat the BFW	3
	steam pressures from the turbine to preheat the BFW (bar)	76.4 / 30 / 1.1
Heat exchangers	ΔT min. (°C)	10

	Pressure drop (% of inlet pressure)	1 - 3			
		Case 1	**Case 2**	**Case 3**	**Case 4**
MDEA absorption (**Case 2**)	solvent concentration (%)	-	50	-	-
	absorption column temperature (˚ C)	-	50	-	-
	desorption column temperature (˚ C)	-	125	-	-
Aqueous ammonia absorption (**Case 3**)	solvent concentration (%)	-	-	7.5	-
	absorption column temperature (˚ C)	-	-	25	-
	desorption column temperature (˚ C)	-	-	106	-
Ca-based CL (**Case 4**)	steam/coal ratio (kg/kg)	-	-	-	2.2
	carbonation reactor temperature (°C)	-	-	-	625
	calcination reactor temperature (°C)	-	-	-	915
	O_2 pressure to CaL (bar)	-	-	-	2.37
	oxygen-carrier removed (%)	-	-	-	1
CO_2 compression and drying	delivery pressure (bar)	-	120	120	120
	compressor efficiency (%)	-	85	85	85
	solvent for drying	-	TEG	TEG	TEG
	Pressure drop (% of inlet pressure)	1 - 3			

Table 2. Results for key performance indicators (**Cases 1-4**)

MAIN PLANT DATA	**UNITS**	**CASE STUDIES**			
		Case 1	**Case 2**	**Case 3**	**Case 4**
Coal flow-rate	t/h	156.74	198.35	156.74	216.74
Coal LHV (as received)	MJ/kg	25.17	25.17	25.17	25.17
Feedstock thermal energy	MW_{th}	1095.87	1386.79	1096.87	1515.37
Steam turbine output	MW_e	502.32	541.3	449.74	649.6
Total ancillary power consumption	MW_e	27.45	65.68	65.16	105.38
Net electric power output	MW_e	474.87	475.62	384.58	544.22
Gross electrical efficiency	%	45.83	39.03	37.6	42.86
Net electrical efficiency	%	43.33	34.29	35.09	35.91
Carbon capture rate	%	0	90.49	85	92.66
CO_2 specific emissions	kg/MWh	800.58	86.75	139.99	69.94
SPECCA	MJ/kg_{CO2}	-	2.80	2.92	2.74

Table 3. LCA assumptions for SC pulverized coal with / without CCS (**Cases 1-4**)

PARAMETER/ PROCESS	**UNITS**	**Assumption type**	**Literature value**	**Literature source**	**Values used in the study**			
					Case 1	**Case 2**	**Case 3**	**Case 4**
Fuel type	-				coal	coal	coal	coal
CCS type	-				post-combustion			
CCS technology	-				-	MDEA	NH_3	Ca-L
Upstream processes								
Coal[*]								
Coal Extraction								
Extraction type		under ground						
Coal pre-processing operations		cutting, drilling, blasting, loading, hauling						
Electricity	kWh/t	literature based	12-124	Spath et al., 1999	85			
Coal preparation & cleaning	Size reduction, removal of ash-forming material, rocks, fine coal; Jig washing							
Electricity	MJ/t	literature based	0.79	Spath et al., 1999	0.79			
Water	m^3/t	literature based	0.17	Spath et al., 1999	0.17			
Coal Transportation								
Transportation type					rail			
Distance	km	hypothetical			250			
Electricity	kWh/t/km	literature based	0.02	Spath et al., 1999	0.02			

Losses during transportation	%	literature based	0.05-1	Spath et al., 1999	1
Wagon capacity	t	literature based	60-130	Spath et al., 1999	100
Ammonia for SCR & for CCS (Case 3)					
Ammonia production					
Process considered		Haber-Bosch process from natural gas			
Ammonia transportation					
Transportation type					truck
Truck capacity	m^3				100
Distance	km	hypothetical			300
Diesel used for transportation	l / km	hypothetical	30 / 100		30
Catalyst for SCR					
Catalyst quantity	m^3/MW$_e$	literature based	1 / 1		1 / 1
Limestone for FGD & for CCS **					
Limestone extraction					
Diesel	kg/ t	literature based	6.86	Dolley et al., 2006	6.86
Gasoline	kg/ t	literature based	0.76	Dolley et al., 2006	0.76
Electricity	MJ/ t	literature based	146	Dolley et al., 2006	146
Natural gas	kg/ t	literature based	10	Dolley et al., 2006	10
Thermal energy	MJ/ t	literature based	34.2	Dolley et al., 2006	34.2

Groundwater	kg/ t	literature based	11138	Dolley et al., 2006	11138
Surface water	kg/ t	literature based	35687	Dolley et al., 2006	35687
Public supply	kg/ t	literature based	43915	Dolley et al., 2006	43915
Limestone transportation					
Transportation type					truck
Distance	km	hypothetical			150
Transportation fuel					Diesel
Losses during transportation	%	hypothetical			0.01
***MDEA* for Case 2**[***]					
MDEA production					
Ethylene oxide	kg/ kg	calculated			0.37
Methyl amine	kg/ kg	calculated			0.13
Water	kg/ kg	calculated			0.5
MDEA transportation					
Transportation type					rail
Transportation distance	km	hypothetical			100
Tank wagons capacity	kg/ wagons	calculated	200		200
Downstream processes					
CO_2 transportation & storage[4*]					

Transportation type					pipelines
Injection pressure	bar	literature based		(Cormos and Petrescu, 2014).	120
Pressure drop	bar	literature based		(Cormos and Petrescu, 2014).	48
Pipeline distance	km	hypothetical			800
No. of compressor stations	-	hypothetical			8
Storage type					conventional geological storage in off-shore reservoirs
Storage depth	km	hypothetical			2
Compression stations distance	km	hypothetical			100
Time	h/year				7500
Emissions pipelines	t/ year	literature based	2.32	Koornneef et al., 2008	
Emissions compressors	t/MW/year	literature based	23.2	Koornneef et al., 2008	23.2
Compression energy	kWh/ t	literature based	111	Koornneef et al., 2008	111
Fugitive emissions injection	%	literature based	0.1	Koornneef et al., 2008	0.1
Compression energy	kWh/ t	literature based	7	Koornneef et al., 2008	7

Note: * Values for coal are expressed in units/ t of coal; ** Values for limestone extraction are expressed in units/ t of limestone; *** Values for MDEA are expressed in kg/ kg MDEA produced;

^{4*} t from CO_2 transportation & storage represents t of CO_2

Table 4. Most relevant LCI inputs and outputs for **Cases 1-4**

INPUTS	UNITS	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**OUTPUTS**	UNITS	**Case 1**	**Case 2**	**Case 3**	**Case 4**
1. Coal						**Coal**					
Coal extracted	t/h	158.32	200.35	158.32	218.9	Coal to SC power plant	t/h	156.76	198.37	156.76	216.74
Electricity (extraction & preparation)	MJ	48570	61465	48570	67156	Coal losses	t/h	1.56	1.98	1.56	2.16
Water	t/h	26.9	34.06	26.9	37.21						
2. Limestone for FGD & for CCS						**Limestone for FGD & for CCS**					
Electricity for extraction	MJ	371.35	469.44	371.12	5692.5	Limestone	t/h	2.55	3.23	2.55	39.13
Water for extraction	t/h	231.39	293	231.39	3553.38	Waste water	t/h	231.39	293.09	231.39	3550.85
Diesel for extraction	t/h	0.017	0.022	0.017	0.268						
Gasoline for extraction	t/h	0.0019	0.0025	0.0019	0.03						
Natural gas for extraction	t/h	0.026	0.033	0.026	0.39						
Thermal energy from propane	MJ	87.37	110.34	87.3	1338.78						
3. Ammonia for SCR & for CCS						**Ammonia for SCR& for CCS**					
Natural gas (SCR)	MJ	70263	70263	-	70263	Ammonia for SCR	t/h	2.11	2.11	-	2.11
Natural gas (CCS)	MJ	-	-	68265	-	Ammonia for CCS	t/h	-	-	2.05	-

4. MDEA						**MDEA**					
Ethylene Oxide	t/h	-	7.32	-	-	MDEA to be transported	t/h	-	19.83	-	-
Mono Methyl Amine	t/h	-	2.59	-	-						
Water (MDEA 50% wt.)	t/h	-	9.92	-	-						
5. Power Plant						**Power Plant**					
Air to SC power plant	t/h	1933.52	2446.45	1933.52	1933.52	Electricity	MWe	474.87	475.62	384.58	544.22
Ammonia for SCR	t/h	2.11	2.11	2.11	2.11	Ash	t/h	22.15	28.04	22.15	22.15
Water for ammonia solution for SCR	t/h	6.32	6.32	6.32	6.32	Gypsum	t/h	3.44	4.35	3.44	3.44
Catalyst SCR	t/h	0.42	0.42	0.42	0.42	Boiler feed water	t/h	925	1198	925	925
Coal to power plant	t/h	156.74	198.35	156.74	216.74	Water	t/h	44000	31000	44000	64000
Limestone for FGD & for CCS	t/h	2.55	3.23	2.55	39.13	Emissions to air					
Boiler feed water	t/h	925	119.8	925	925	CO_2	t/h	380.17	41.27	55.51	38.09
Water	t/h	44000	31000	44000	64000	CO	t/h	2.47	3.13	-	0.18
Water for limestone slurry	t/h	14.45	18.28	14.45	14.45	H_2	t/h	0.02	0.02	-	0.18
Sulfuric acid	t/h	-	-	0.39	-	Ar	t/h	24.74	31.29	24.74	24.74
Water for aq. ammonia	t/h	-	-	21.89	-	HCl	t/h	0.015	0.018	0.015	0.015

Steam (lp)	t/h	-	-	112.39	468.88	N_2	t/h	1453.33	1838.82	1603.98	1453.33
Water for ammonia plant	t/h	-	-	3.56	-	O_2	t/h	128.75	162.84	4.07	128.75
Ammonia for cooled ammonia plant	t/h	-	-	2.052	-	H_2O	t/h	92.13	57.19	114.73	94.01
O_2 cu Ca-L	t/h	-	-	-	121	NH_3	t/h	-	-	1.94	-
						Ammonium sulphate	t/h	-	-	0.5	-
						Condensate from ammonia process	t/h	-	-	112.39	-
						CO_2 to transport & storage	t/h	-	437.99	326.74	485.78
						MDEA recycled	t/h	-	19.88	-	-
CO_2 transport & storage						**CO_2 transport & storage**					
CO_2 from plant	t/h	-	437.99	326.74	485.78	CO_2 stored	kg/h	-	423.65	316.05	469.87
Electricity for compression	MJ/h	-	169.67	126.57	188.18	CO_2 losses pipeline	t/h	-	13.79	10.28	15.29
Electricity for injection	MJ/h	-	10.68	7.97	11.85	CO_2 losses compressors	t/h	-	0.14	0.11	0.16
						CO_2 losses injection	t/h	-	0.42	0.31	0.46

Table 5. LCA results (**Cases 1-4**) according to CML 2001

KPI	**Units**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
GWP	kg CO_2-Equiv./MWh	970.37	495.93	500.83	402.2
AP	kg SO_2-Equiv./MWh	0.49	4.57	1.61	1.66
EP	kg Phosphate-Equiv./MWh	1285.44	1739.76	1753.7	1121.86
$ODP*10^8$	kg R11-Equiv./MWh	0.59	4.07	3.02	2.63
$ADP_{elements} *10^4$	kg Sb-Equiv./MWh	4.23	4.8	5.42	3.93
ADP_{fossil}	MJ/MWh	9829.28	15231.63	14137.47	13752.06
FAETP	kg DCB-Equiv./MWh	0.27	1.66	1.1	1.1
HTP	kg DCB-Equiv./MWh	3.41	55.27	19.55	19.84
PCOP	kg Ethene-Equiv./MWh	0.20	2.71	0.25	0.26
TEP	kg DCB-Equiv./MWh	0.05	0.28	0.15	0.18
MAETP	kg DCB-Equiv./MWh	6730.54	26011.85	16314.55	16494.81

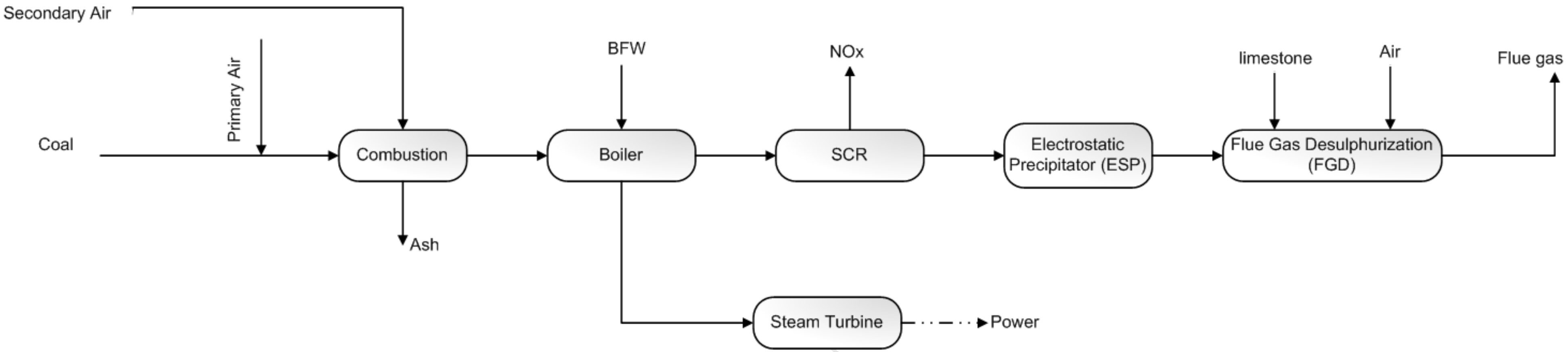


Fig. 1. *Block diagram for SC pulverised coal without CCS* ***(Case 1****)*

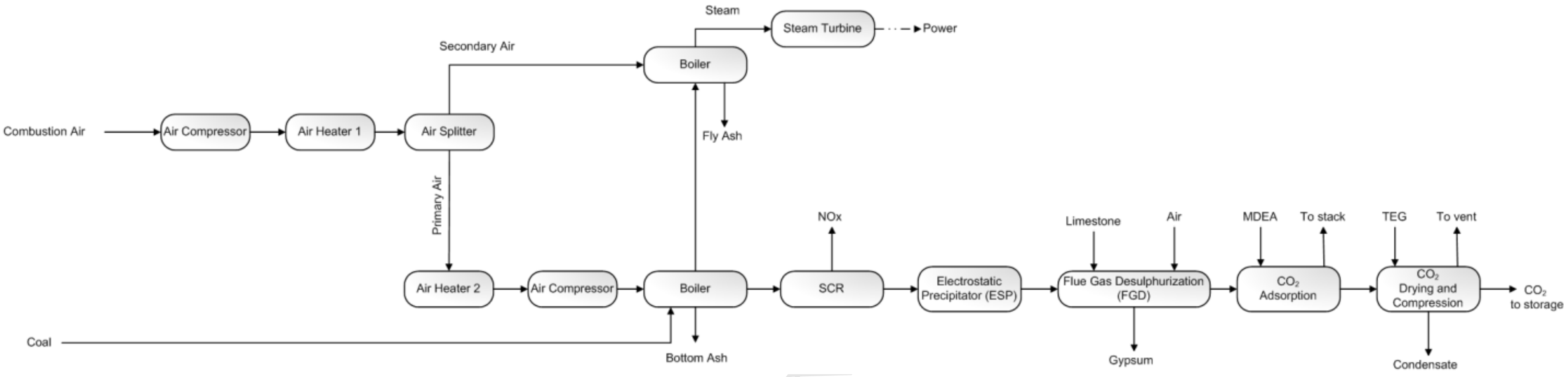


Fig. 2. *Block diagram for SC pulverised coal with MDEA post-combustion CCS (**Case 2**)*

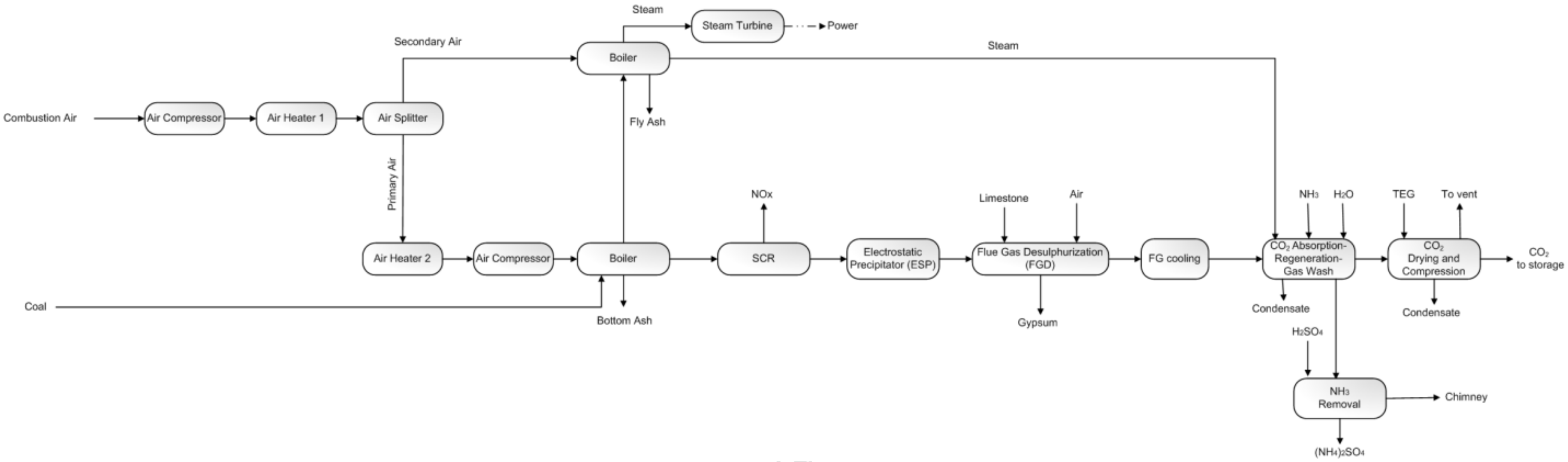


Fig. 3. *Block diagram for SC pulverized coal*

with aqueous ammonia post-combustion CCS ***(Case 3****)*

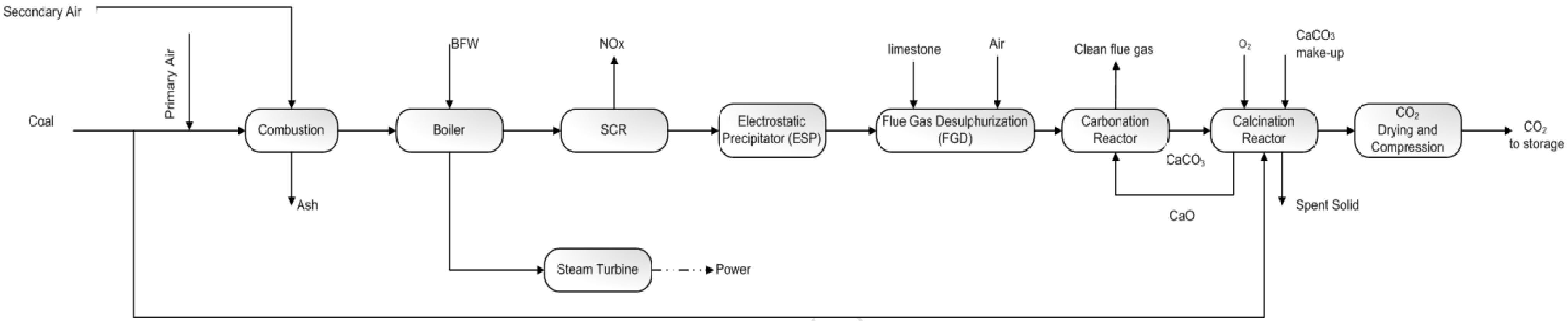


Fig. 4. *Block diagram for SC pulverised coal with CaL post-combustion CCS (**Case 4**)*

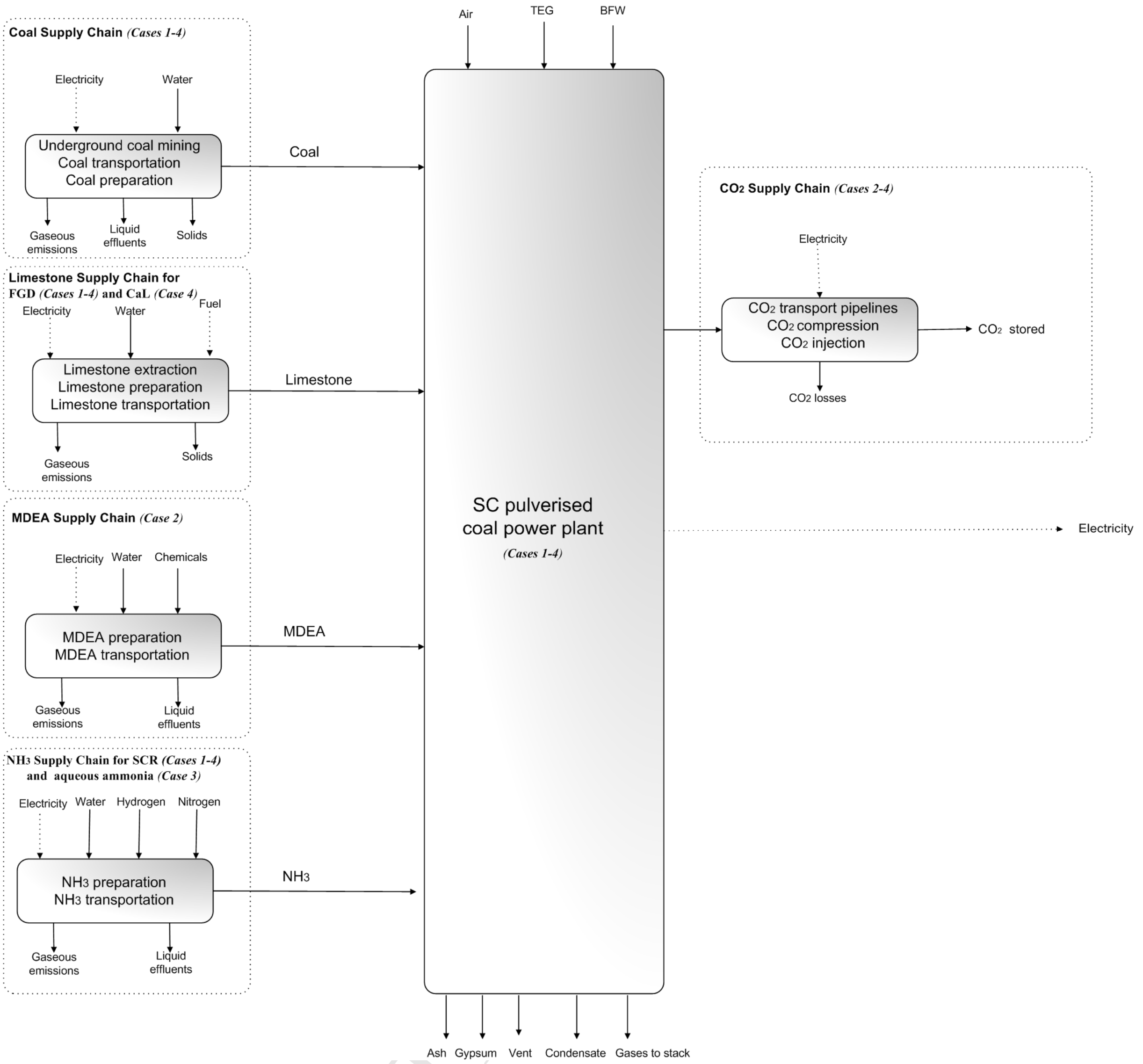
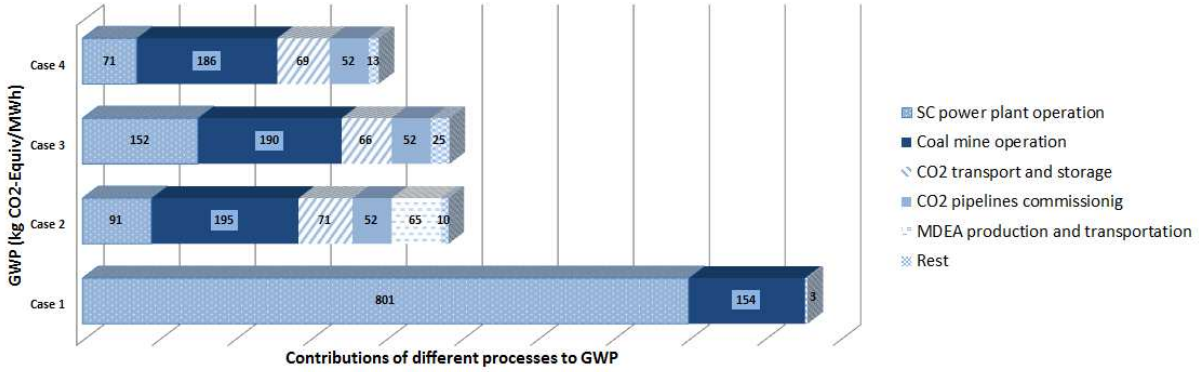
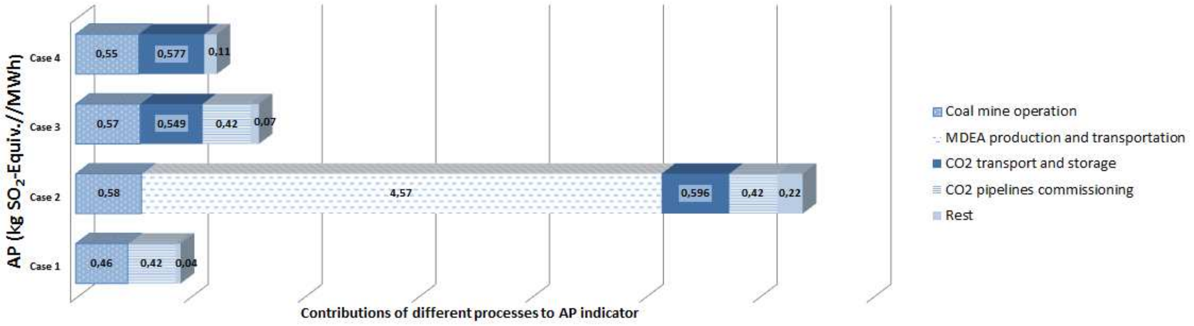


__Fig. 5.__ Boundary conditions for SC pulverised coal (__Case 1- 4__)



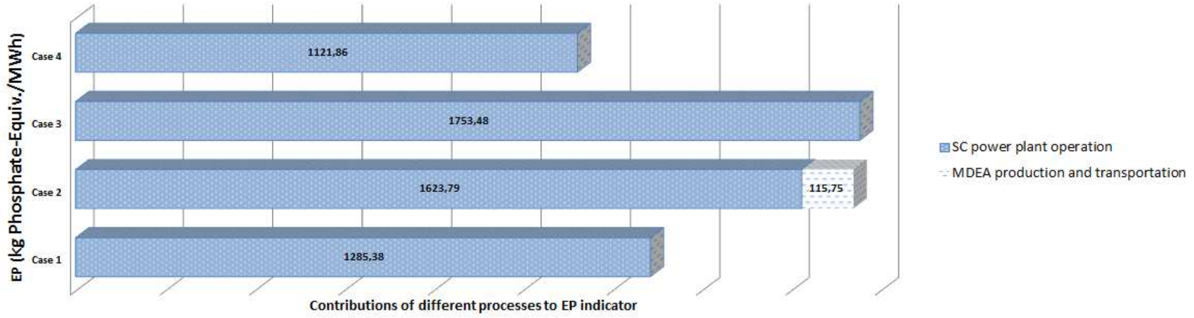
a

Contributions of different processes to GWP



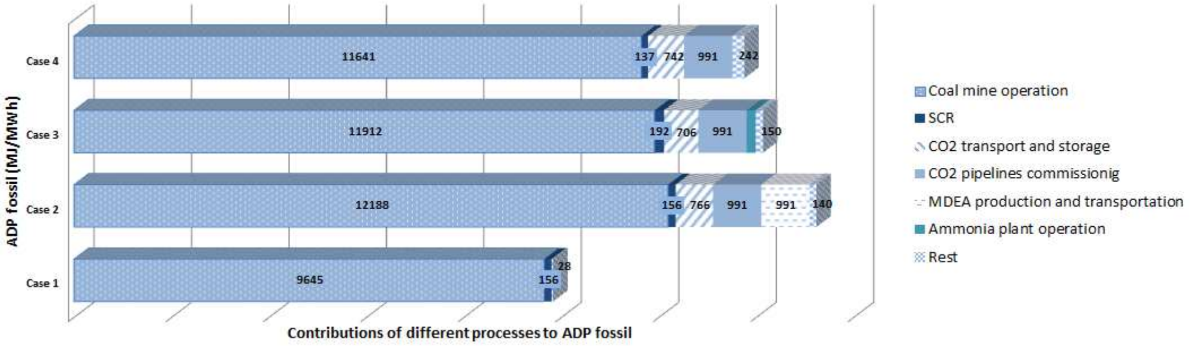
b

Contributions of different processes to AP

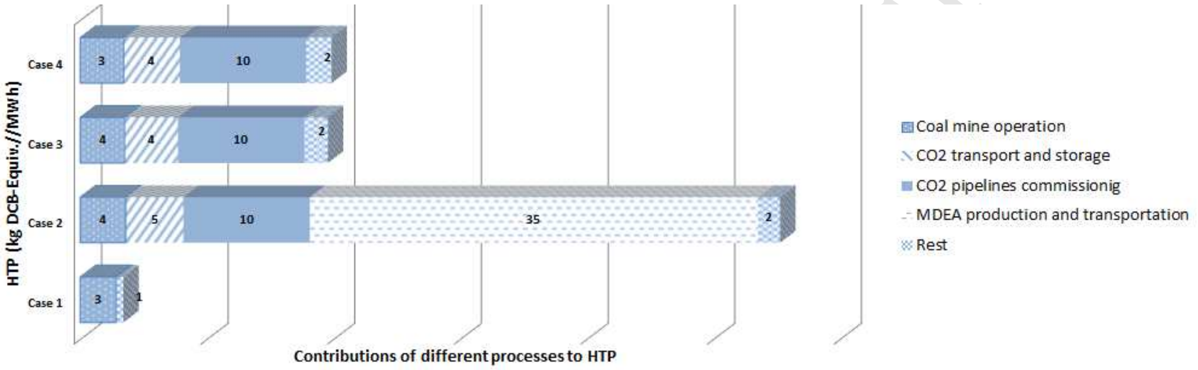


c

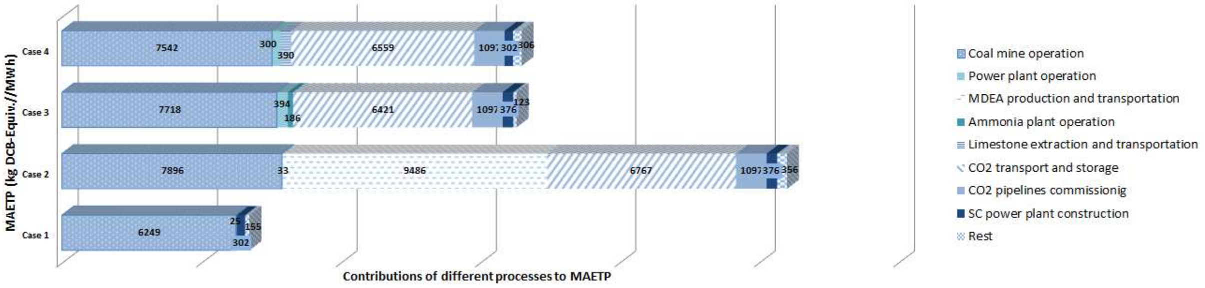
Contributions of different processes to EP



d *Contributions of different processes to ADP_{fossil}*



e *Contributions of different processes to HTP*



f *Contributions of different processes to MAETP*

Fig. 6. *Significant environmental indicators for*

*SC pulverized coal power plant with / without CCS (**Cases 1-4**)*

Research highlights

- Post-combustion CO_2 capture using amine, aqueous ammonia and calcium looping technologies of supercritical pulverised coal power plants.
- Environmental evaluation of supercritical pulverised coal power plants with & without CCS using Life Cycle Analysis (LCA);
- Technical evaluations of supercritical pulverised coal power plants with & without CCS;