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Environmental assessment of Pressure Swing Adsorption carbon capture and storage in an integrated gasification combined cycle power plant

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SUMMARY

The global atmospheric concentrations of CO_2 have nearly doubled since the industrial revolution. The consequence of this is the thread of climate change. A global consensus on the importance to mitigate climate change exists. Over the next decades a transition towards low carbon emitting industries has to be made, meaning that all industries have to lower their CO_2 emissions. In the power section Carbon Capture and Storage (CCS) is expected to play a key role in achieving these CO_2 reductions. CCS allows fossil fueled power generation with low CO_2 emissions. However, at the moment CCS for power plants is still in a research phase. Numerous of different technologies exist that all have to be assed at a technical, economical, and environmental to accommodate the search for the best option.

One of these technologies is Pressure Swing Adsorption (PSA), which is typically suitable for gasification power plants. For this technology no environmental assessment has been published yet. Therefore this report provides the first environmental assessment of PSA pre combustion CCS applied to a power plant. The project consists of three environmental assessments that were compared with each other to get to the conclusions. The three systems that were assessed are: (1) a reference power plant without CCS; (2) a power plant equipped with the more mature CCS technology 'Selexol absorption'; and (3) a power plant with PSA CCS.

To assess to the environmental performance of the systems, three separate Life Cycle Assessments (LCA's) were made. A LCA provides the opportunity to assess the environmental impacts of a system, and provides the option to get insight in what processes the impacts are coming from.

The results of the LCA's are presented in the form of ten environmental indicators, including an analysis of the contributing processes. Comparing the environmental impacts of the different systems led to the following conclusions: (1) the global warming potential of the systems with ccs is significantly lower than the reference system; (2) the Selexol CCS systems slightly outperforms the PSA CCS system on all environmental indicators; (3) the processes contributing to the environmental impacts are the same for all systems; (4) a relation was found between the plant efficiency and the environmental performance; and (5) when the PSA CCS system is optimized in the future, there is a chance that the environmental performance could outperform that of the Selexol CCS system.

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1 INTRODUCTION

1.1 Background

According to the IPCC the atmospheric concentration of carbon dioxide (CO_2) has increased by more than 40% since pre-industrial times (IPCC 2013). This increase, mainly associated with fossil fuel emissions, is considered the main driver of the greenhouse effect and thus climate change. Fossil fuel based power generation contributes to approximately 36% of the global CO_2 emissions (Janssens-Maenhout et al. 2012). While the demand for power is growing exponentially, the emissions associated with the energy sector must decrease by 68% in 2050 to reach the atmospheric CO_2 levels associated with the 2^0C degree target according to OECD/IEA (2015). Carbon capture and storage (CCS) is expected to play a key role in accomplishing this objective; allowing low carbon fossil fuelled power generation that enables approximately 20% of the emission reduction predicted for the energy sector (OECD/IEA 2015). However, the incorporation of CCS processes in power plants leads to an efficiency reduction associated with the energy consumption for the operation of the carbon capture unit. Consequently, research is currently undertaken in the development and optimisation of gas separation technologies to reach CO_2 capture targets with the lowest energy penalty (Jansen et al. 2015; Markewitz et al. 2012).

Three different genres of CCS technologies can be applied to power plants: pre combustion, post combustion and oxyfuel. Pre combustion processes are the preferred option in the case of coal gasification plants (IGCCs). In this type of plants, coal is gasified to produce a H_2 rich fuel called syngas (also containing CO, CO_2, NO CH_4), which can be burned in a gas turbine to produce electricity. Using a water-gas-shift (WGS) reactor, the syngas can be converted to a high-pressure stream containing mainly CO_2 and H_2. The high partial pressure of CO_2 allows the use of physical separation technologies to capture the CO_2 before entering the gasifier. Physically based separations (gas absorption or adsorption) are expected to exhibit lower energy consumption for the operation of the carbon capture unit than chemical post combustion processes (IPCC 2005). However, the energy associated with the water gas shift reactor (WGS) adds an additional energy penalty on pre combustion technologies.

There are already demonstration IGCC plants in which physical solvents like Selexol are employed in the role of pre combustion CCS (Elcogas 2015). However, research is being carried out in order to design novel gas separation technologies (using other solvents or other techniques) that do not require as much power for solvent pumping and refrigeration of the absorptive units (Jansen et al. 2015). Pressure swing adsorption (PSA) seems to be an economical alternative for absorptive Selexol CCS. PSA possibly yields a lower energy penalty than absorptive Selexol CCS, according to simulation based studies that can be found in literature (Luberti et al. 2014; Riboldi and Bolland 2015).

1.2 Research aim and scientific relevance

Besides technical performance, a fair comparison between technologies can only be made with the addition of an economic and environmental analysis. On the latter, different studies analysed the environmental performance of Selexol based absorptive pre combustion carbon capture technologies However, environmental performance studies for pre combustion PSA CCS are lacking. This paper intends to close this gap of information by providing an environmental analysis of Selexol absorption and PSA pre combustion CCS applied to a full scale IGCC power plant

In other words, this *project aims to assess the environmental performance of (1) Selexol absorption and (2) Pressure Swing Adsorption applied as pre combustion carbon capture option in a full scale Integrated Gasification Combined Cycle (IGCC) power plant, compared to a reference IGCC power plant without CCS.*

1.3 Research questions

In order to fulfil the research aim this project sets out to answer the following two research questions:

1. *How does the environmental performance of (1) Pressure Swing Adsorption (PSA) and (2) Selexol absorption, both applied as pre combustion carbon capture technology in an Integrated Gasification Combined Cycle (IGCC) power plant, compare to a reference IGCC power plant without carbon capture?*
2. *What is the contribution of the different steps of the total value chain to the overall environmental performance of the different systems?*

1.4 Scope

The project sets out to assess the environmental performance of three different systems. The first system, serving as a baseline to compare the other two systems to, is a full scale IGCC power plant without CCS. This system will be referred to as the reference system (ref). The second system is an IGCC power plant with an integrated Selexol pre combustion CCS unit, referred to as the absorbent (ABS) system. The third system represents an IGCC power plant with an integrated PSA CSS unit, referred to as the adsorbent (ADS) system. In the Chapter 3 the system boundaries of each assessment are defined.

To make the three environmental assessments comparable, all assumptions made in this project must be as consistent as possible between the different systems. Therefore it is assumed that all the power plants are located in Den Bosch, The Netherlands. And all the power plants use the Dutch coal basket as fuel. Because Riboldi and Bolland (2015) is the only technical study available evaluating a full scale IGCC with PSA pre combustion CCS, for technical data this project relies on Riboldi and Bolland (2015).

1.5 Structure

This report will (1) provide insight in the basic principles of CCS technology and the current state of development, and explain the Life Cycle Assessment methodology in the chapter Theory; (2) describe how the LCA method was applied to the three systems described above in the chapter Methodology; (3) present and compare the environmental impacts and contribution analysis of the three systems in the chapter Results; (4) Further analyze the results using an sensitivity analysis in the chapter Sensitivity analysis; and (3) answer the research questions and draw conclusions in the chapter Conclusions.

2 THEORY

This chapter discusses the theoretical background of the project. First the concept of carbon capture and storage is discussed, including some different type of technologies, and the physical and chemical principles they rely on. Then Life Cycle Assessment methodology will be explained.

2.1 Carbon Capture and Storage

Carbon capture and storage (CCS) refers to three separate processes, that combined are referred to as carbon capture and storage. The first process is carbon capture, the process in which CO_2 is separated from a bulk gas. The second process is carbon transport, the transportation of CO_2 from the place where it is captured to the place where it is stored. And the third process is carbon sequestration, the process in which the carbon is stored for the longer term. For all components of CCS numerous technologies exist, that differ in stage of development, availability and economic development. This paragraph provides an overview of the different technologies used in CCS and explains some of the main principles that they rely on.

2.1.1 Capture

CO_2 capture technologies are typically divided in three different categories: post combustion, pre combustion, oxyfuel, and industrial separation (Figure 2.1). However, the industrial separation capture technologies are not applicable for use in power plants and therefore won't be discussed further. The other categories are discussed separately in the paragraphs below.

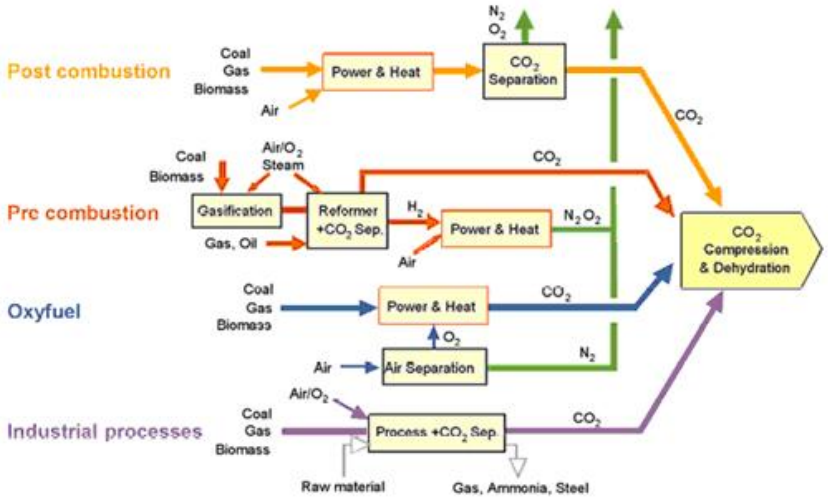

Figure 2.1 Types of CCS (IPCC, 2005)

Post combustion capture

Post combustion capture is an end of pipe technology. This means that the capture unit is added at the end of the production line without interfering with the conventional production line. The CO_2 is captured from the flue gas after producing electricity. A typical post combustion CO_2 scheme for a coal fired power plant is shown in Figure 2.2. Currently, the preferred technique for post combustion capture is absorption using chemical solvents (e.g. Sulfinol, Selexol, MDEA, MEA). Besides the use of post combustion carbon capture in power plants, these technologies can also be applied to other installations that are burning large amounts of fossil fuels (e.g. cement kilns or industrial furnaces).

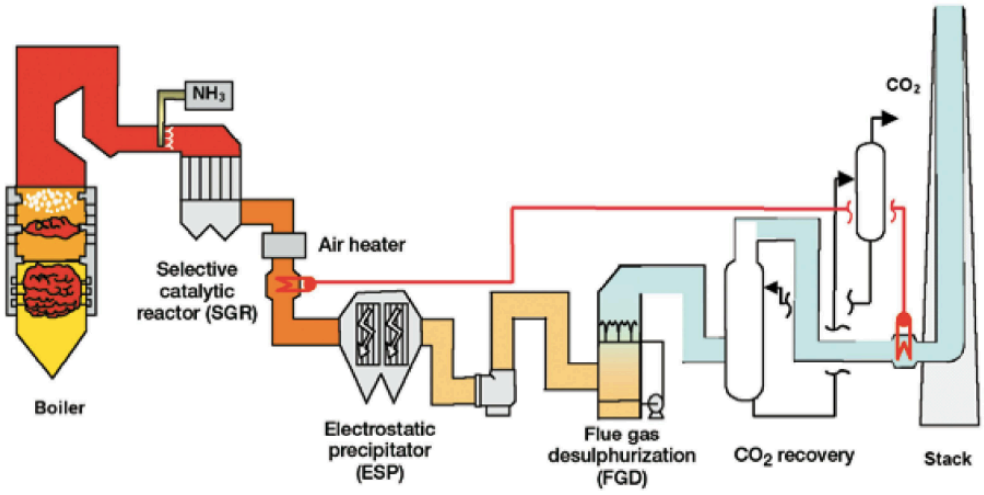

Figure 2.2 Schematic overview of amine based post combustion capture applied to pulverized coal-fired power plant (IPCC 2005).

In a typical post combustion CO_2 capture installation the flue gas of the power plant is cooled down to approximately 50°C before entering the bottom of the absorption column. At the same time and temperature the solvent is injected at the top of the column. The flue gas is brought in contact with the solvent in a counter directional flow due to the difference in densities. During this contact the CO_2 binds to the solvent, resulting in a CO_2 lean flue gas leaving the top of the absorber, and a CO_2 rich solvent leaving the bottom of the absorber. The CO_2 rich solvent is pumped to the top of a stripper column, where it is heated to temperatures above 100°C to regenerate the chemical solvent. The CO_2 that is released in this step leaves the stripper column and is sent to the compressor before is transported to the storage site. The CO_2 lean solvent is cooled down and pumped back to the absorber column.

An important performance parameter of CO_2 capture systems is the energy penalty. The energy penalty is the energy used by the CCS system. The energy penalty lowers the power output, and thus efficiency of the power plant. The energy penalty in post combustion capture is mainly due to the thermal energy used to regenerate the solvent. To a smaller extend the energy penalty is also due to pump, blowers, and the compressor. With the aim to reduce the energy penalty novel solvents are being developed. And also research is carried out to optimize the process design with improved packing types, different concentrations of the solvent, possible catalysts etc. Emerging technologies like Pressure Swing Adsorption, membrane separation and others are being researched at the moment.

Pre combustion capture

Pre combustion CO_2 capture removes the CO_2 before end product (electricity or chemicals) is derived. Other than post combustion the pre combustion capture units are integrated in the production line of the plant. Pre combustion is typically applicable to gasification plants producing a syngas (containing mainly H_2 and CO) of which the carbon can be separated before utilizing the energy rich hydrogen to produce electricity or chemicals. Figure 2.3 shows a general scheme for gasification processes plants with pre combustion CO_2 capture.

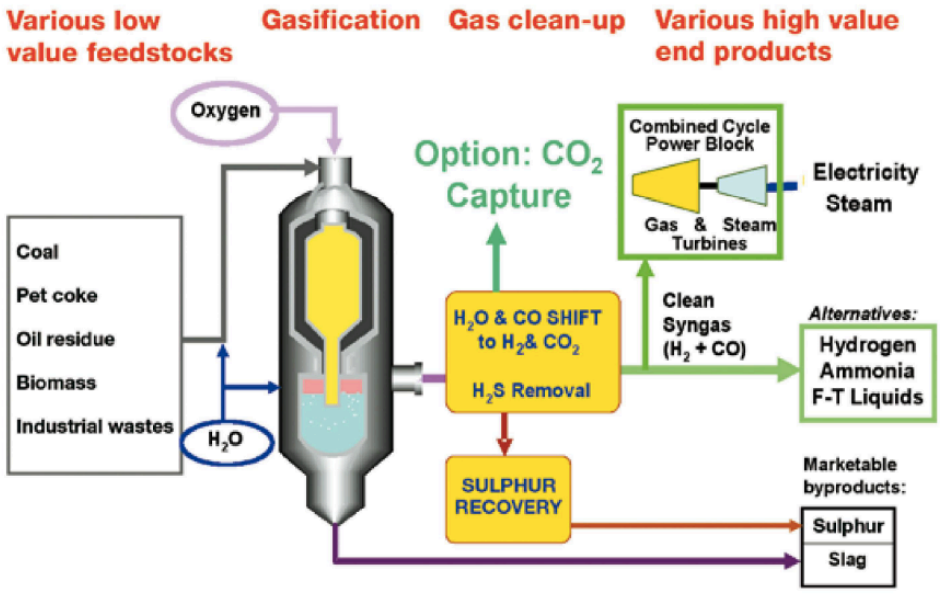

Figure 2.3 Schematic overview of pre combustion carbon capture for a gasification plant producing electricity, hydrogen or other chemicals (IPCC 2005).

Pre combustion CO_2 capture starts with the production of syngas from a fuel. This 'gasification' step involves two routes known as steam reforming and partial oxidation. In the steam reforming reaction the fuel reacts with high temperature steam:

$$Steam\ reforming: C_xH_y + xH_2O \leftrightarrow xCO + \left(x + \frac{y}{2}\right) H_2 \Delta H_{CH4}$$

And in the partial oxidation reaction the fuel reacts with oxygen produced in an air separation unit (ASU) or present in ambient air:

$$Partialoxidation: C_xH_y + x/2O_2 \leftrightarrow xCO + (x + y/2)H_2 \Delta H_{CH4}$$

The syngas coming from the gasifier undergoes several cleaning processes, including particular removal and sulfur removal in the acid gas removal unit (AGR), which avoids possible damage to the equipment and maintains operability of the catalysts used in downstream processes. Then the

syngas goes to the water gas shift (WGS) reactor where CO is converted to CO_2 by the water gas shift reaction using high temperature steam and a catalyst:

$$Water\ gas\ shift\ reaction: CO + H_2O \leftrightarrow CO_2 + H_2$$

The syngas leaving the WGS reactor contains between 15-60% CO_2 and a pressure of 2-7 MPa. Due to the high pressure a physical based separation process can be applied. Like in post combustion capture, pre combustion uses absorption or adsorption to capture to CO_2. Only the regeneration step in PSA is carried by reducing pressure to levels where the CO_2 releases from the solvent or sorbent.

The advantage of pre combustion carbon capture is the low energy consumption needed for the regeneration step, as only energy is needed for pressurizing. However, the steam needed in the WGS reactor compensates for this, resulting in an energy penalty comparable to post combustion technologies. Emerging technologies like membrane reactors or pressure swing adsorption show potential to reduce the energy penalty.

Oxyfuel combustion capture

In oxyfuel the fuel of a plant is burned in nearly pure oxygen. The result of this is a nitrogen free flue gas containing mainly H_2O and CO_2. By compensating the H_2O an almost pure CO_2 stream is created. A typical scheme of an oxyfuel power plant is shown in Figure 2.4.

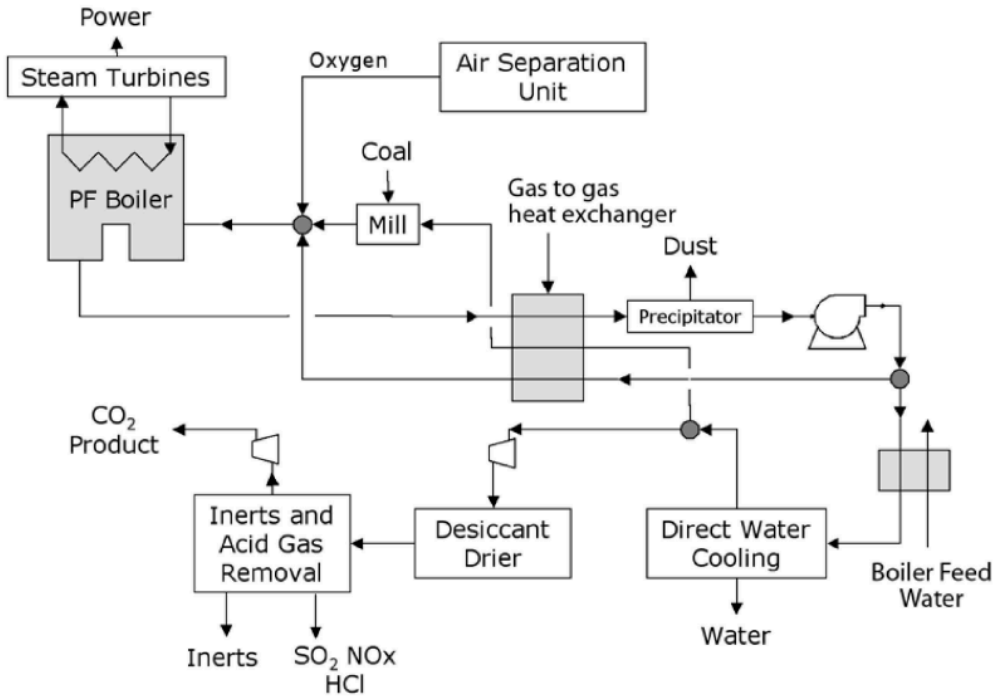

Figure 2.4 Schematic overview of an oxyfuel coal power plant (IPCC 2005).

Burning fuels with pure oxygen can reach temperatures of approximately 3500°C, which is too high for typical materials used in a power plant. Therefore, the temperature is controlled by recycling the flue gas and H_2O produced by the plant back to the combustion chamber. Oxyfuel CO_2 capture can

reach CO_2 purities of around 80-98%. The energy penalty of oxyfuel installations is caused by the high energy demand of the ASU.

2.1.2 Transport

For CO_2 transport three types can be distinguish: pipeline transport, shipping, and road and rail transport. The three different types differ in the conditions that CO_2 is transported in, in economics and in stage of development. This section briefly describes the different types of CO_2 transport.

Pipeline transport is the most common type of CO_2 transport. In this type of transport the CO_2 is compressed to a pressure of above 8 MPa, to ensure a one-phase flow and decrease the density, making it cheaper to transport. Pipelines are usually the most economic option of CO_2 transportation with high investment cost, but low marginal cost.

Shipping of CO_2 is also an option for transport. However this technique is still in a research and development stage. In this type the CO_2 is transported as a liquid in tankers with large insulated tanks at a temperature below ambient temperature and at high pressure. Shipping includes a lot of loading and unloading to temporary storage sites and therefore comes with a lot more coordination then pipelines. The advantage is that ships can go to different storage sites, while pipelines are fixed to one or two storage sites.

The third type of transport is road and rail. This type of transport uses tankers with temperatures around -20°C and a pressure around 2 MPa. Road and rail is the most uneconomical option compared to pipelines and shipping. Therefore road and rail transport is expected only to be used on small scale and unlikely to be used for power plants with CCS.

2.1.3 Storage

Various options exist to store CO_2. This section discusses the storage options: geological storage, ocean storage, and mineral carbonation. Besides these long term storage options CO_2 can also be used for industrial purposes like urea and methanol production. However since the typical lifetime of CO_2 storage is only a few days this is not considered a long term storage option.

Geological storage makes uses of existing geological formation to store CO_2 in. Examples of this are depleted oil and gas wells and deep saline formations. The technologies used are the same as developed for oil and gas winning. The CO_2 is first compressed to a fluid state and then injected to the geological formations at depths below 1 km. There the CO_2 is physically trapped by: clay, shale or rocks known as cap rock.

The second type of storage is called ocean storage and is still in a research phase. In this type of technology the CO_2 is injected into the sea via a fixed pipeline at depths below 3 km. Here the CO_2 is denser than the seawater and will form a ‘lake’, which delays the dissolution of CO_2 into the surrounding environment. Eventually the CO_2 would become part of the carbon cycle again.

The third type of storage is mineral carbonation and is also still in a research phase. This techonology involves converting CO_2 into carbonates using alkaline like magnesium oxide or calcium oxide. A chemical reaction between alkaline and CO_2, produces silica and carbonates. These stable formations can be stored or reused for construction purposes. The disadvantage is the large amount of energy needed for the carbonation process.

2.2 Life cycle assessment

Life cycle assessment is a method used to assess the environmental impacts associated with a certain process, product, or service. A Life cycle assessment takes into account all stages from cradle to grave. This means that all the processes from raw material extraction, manufacturing, distribution, use, and recycling or disposing are taking into account. Life cycle assessments are often used as a decision making tool to choose between different alternatives.

2.2.1 General LCA procedure

The general LCA procedure consist of four phases: (1) Goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation. In Figure 2.5 an illustration of a life cycle model together with the general LCA procedure is shown. The remainder of this paragraph discusses the various phases of the general LCA procedure.

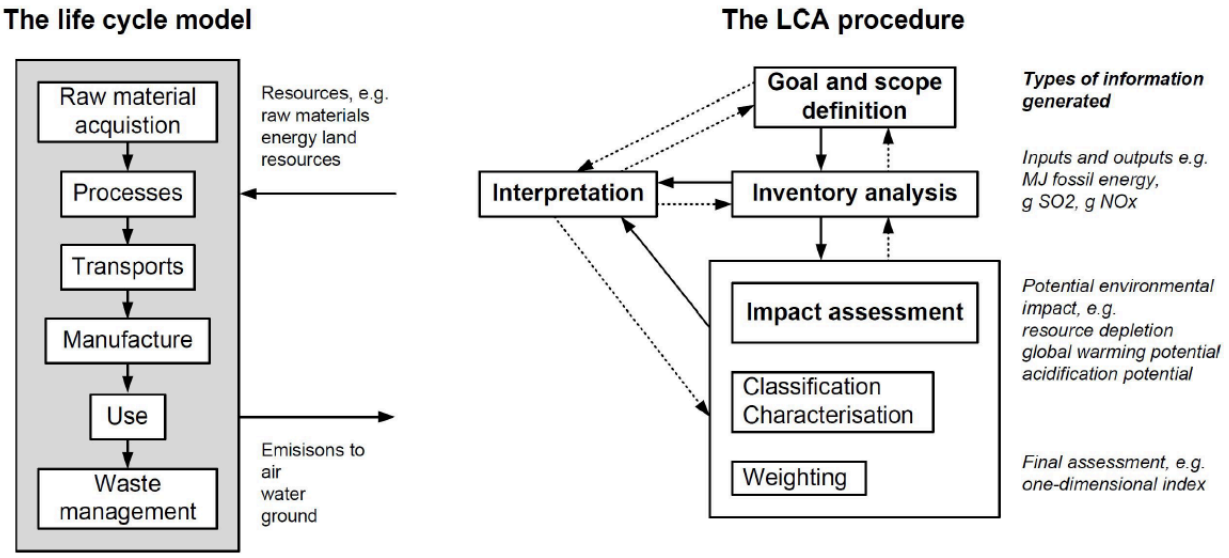

Figure 2.5 Life cycle model and LCA procedure (Baumann, H., Tillman 2004)

Goal and scope definition

The phase goal and scope definition includes the purpose of the LCA. Usually the purpose is expressed in a functional unit, which defines what exactly is being studied and quantifies a reference to which inputs and outputs can be related. The goal and scope can also contain assumptions and limitations. And finally the system boundaries are set. System boundaries include the level of detail, by describing which processes are included.

Inventory analysis

In this phase a flow model according to the level of detail described in the system boundaries is developed. The inventory analysis also includes gathering data on all the in- and outputs (e.g. energy, materials, waste, air/water, emissions), and calculation of the amount of resource use and pollutant emission of the system in relation to the functional unit.

Life cycle impact assessment (LCIA)

In this phase the information that was gathered in the phase inventory analysis is translated into more relevant information on actual environmental impacts (e.g. global warming potential). The first

step that's done in this phase is selecting the impact indicators, and selecting a characterization model. In the second step; the classification, the inventory parameters are sorted and assigned to the impact indicators. In the third step; the characterization, the actual impacts are calculated, using the consumption of resources and the contribution of the emissions. The next step is the normalization step, in which the impacts are expressed in a single unit.

There are many different LCIA methodologies in which the classification and characterization step are typically the same. However, they differ in the normalization methods.

Interpretation

In the interpretation phase of a LCA, the results obtained in the inventory analysis and LCIA re combine and analyzed to get to the research goal, conclusions, and recommendations. An important part of the interpretation is sensitivity and uncertainty analysis.

2.2.2 Basic LCA calculations

LCA calculations are typically performed using matrix calculations. The key block in LCA calculations is the requirement matrix A_{ij} (Strømann 2010):

$$A_{ij} = \begin{bmatrix} A_{ff} & 0 \\ A_{bf} & A_{bb} \end{bmatrix}$$

The requirement matrix consists of four subsections of which three contain a sub matrix. The first matrix that has to be constructed is the foreground matrix A_{ff}, defining the requirement of physical units and relations between foreground processes. Then the input requirement matrix A_{bf} defines the need for background processes. And the background matrix A_{bb} defines the inter-process flow of background processes. The LCIA software usually constructs the background matrix Abb.

Besides the requirement matrix a stressor matrix S_f has to be constructed, which for every foreground process specifies the stressors. The LCA software typically defines the stressors of the background processes. Stressor is basically the word used instead of emission in LCA studies. Finally the LCA software will need a demand vector that defines the systems demand, which should equal the functional unit.

With the requirement matrix, the stressor matrix and the demand vector the stressors associated with the functional unit can be calculated.

2.2.3 Characterization method

The results of LCA assessments are typically presented in midpoint or endpoint indicators. Midpoint indicators are a translation of hazardous emissions and extraction of resources into midpoint level indicators (e.g. global warming potential, acidification). Endpoint indicators extend this cause effect chain, using the midpoint indicators to assess impacts on a greater category like human health or ecosystems. Midpoint indicators are typically expressed as a qualitative comparison, while endpoint indicators consider the environmental relevance already in the indicator. The advantage of midpoint indicators is the level of certainty. And the advantage of endpoint indicators is the understandability for non wide audiences with small understanding of environmental studies (Bare et al. 2000; Haes et al. 2002).

ReCiPe 2008

ReCiPe provides a method which expresses the results of a LCIA in both midpoint and endpoint indicators (Goedkoop et al. 2013). All the midpoint and endpoint indicators are presented in Figure

2.6. This figure also shows why the certainty of midpoint indicators is higher than that of endpoint indicators, as certainty decreases as the path to get to the results gets longer.

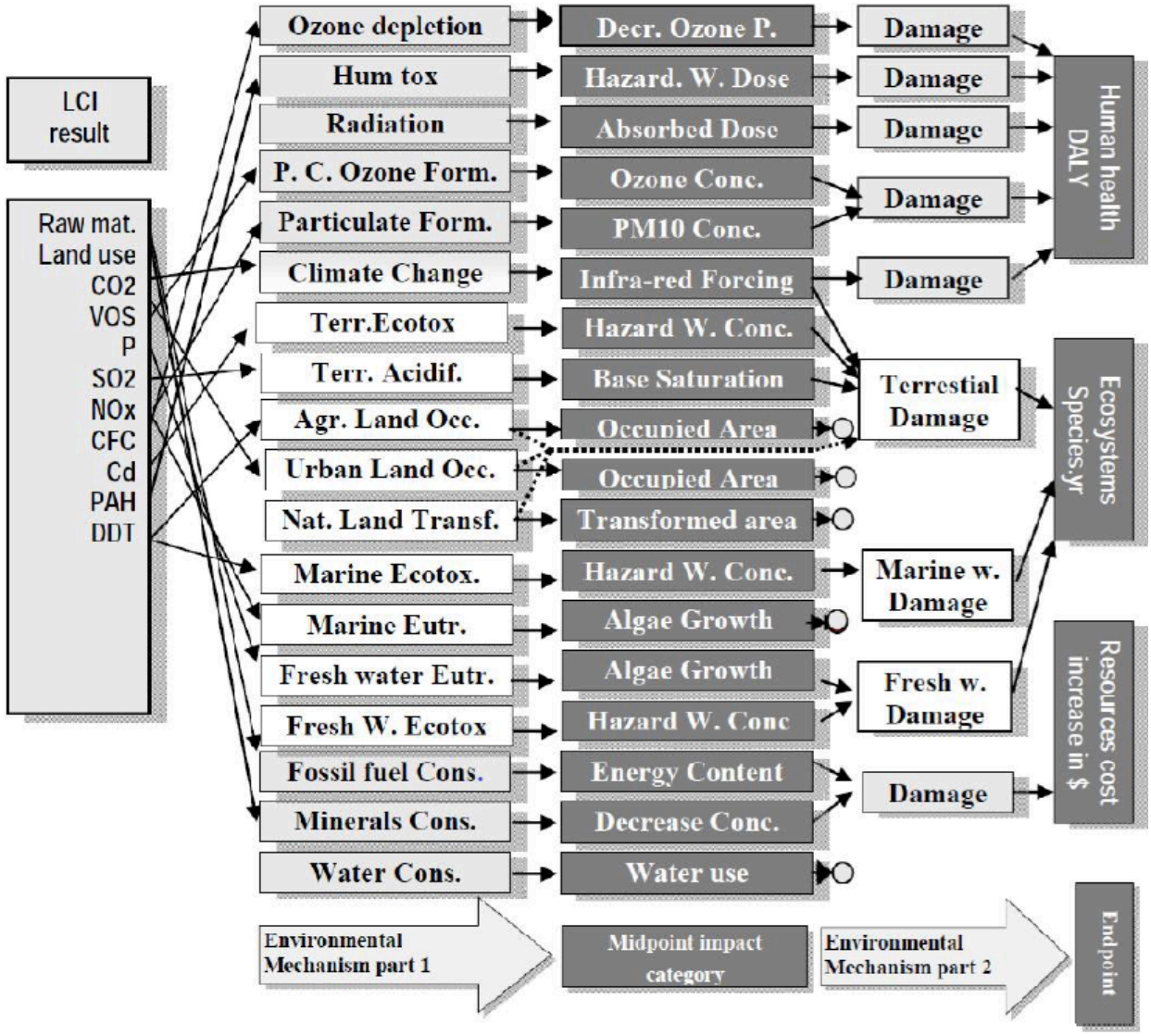

Figure 2.6 Overview of parameters included in midpoint and endpoint indicators (Goedkoop et al. 2013).

3 METHODOLOGY

This section describes the methods used to assess the environmental impact of the three investigated systems. For each system the main method used is the process based Life Cycle Assessment (LCA). Therefore this chapter is structured according to the main components of a process based LCA, which are explained in detail in Chapter 2. First, the goal and scope definition of the LCA's are discussed. Second, the methodologies used to complete the Life cycle inventories (LCI's) are explained. And third, the models to actually assess the environment impacts are explained.

3.1 LCA goal and scope definition

To compare the environmental performance of the three systems, a separate LCA for each system was made. The primary goal of each LCA was to determine the environmental impacts of the total system over the whole life cycle from cradle-to-grave. The secondary goal was to provide a contribution analysis showing the processes contributing to the total environmental impact.

The scope of the research was set to include the three systems described in the introduction, being: the reference system (ref), the absorbent system (ABS), and the adsorbent system (ADS). For each system the system boundaries are explained under heading 3.1.2.

3.1.1 Functional unit

To make the LCA results of the three systems comparable a single functional unit was defined. The functional unit selected for the LCA's was 1 kWh of net electricity produced at the power plant facility. The reason that this functional unit was chosen is to be consistent with the ones used in previous LCA studies (Koornneef et al. 2008; Schakel et al. 2014; Singh, Strømman, and Hertwich 2011). Consistency in functional units provides the possibility to compare environmental impacts of different systems defined by different studies.

3.1.2 System boundaries

The system boundaries of the LCA's are set to include the life cycle from cradle-to-grave (Figure 3.1-3). In the figures the black outlined box represents the power plant, of which the most important processes are presented in the boxes. For the ABS and ADS system, CCS processes are partly integrated in the power plant. The up- and downstream processes taken into account are located

outside the power plant but within the system boundaries, represented by the dotted line in the figures.

To structure the contribution analysis, the processes are grouped into the following five system areas: coal supply, power plant operations, waste treatment, infrastructure, and CCS. In Figure 3.1-3 the system areas are indicated by the different background color. Only the system area infrastructure is not presented here because this is not associated with operational processes. The system area infrastructure includes the construction and demolition of the power plant itself, as well as the extra infrastructure needed for the CCS units, including the infrastructure needed for transport and storage.

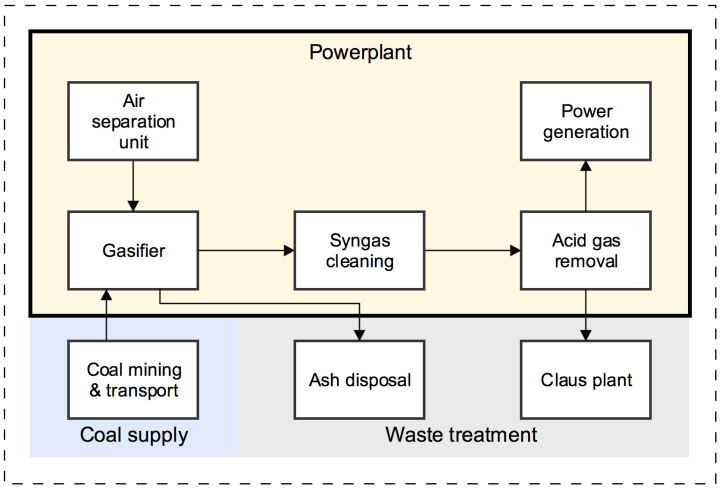

Figure 3.1 System boundaries for the reference system

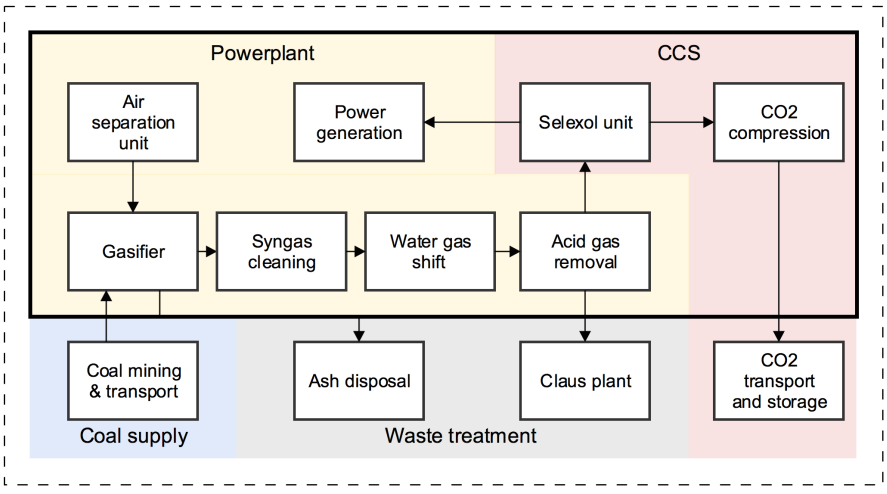

Figure 3.2 System boundaries for the ABS system

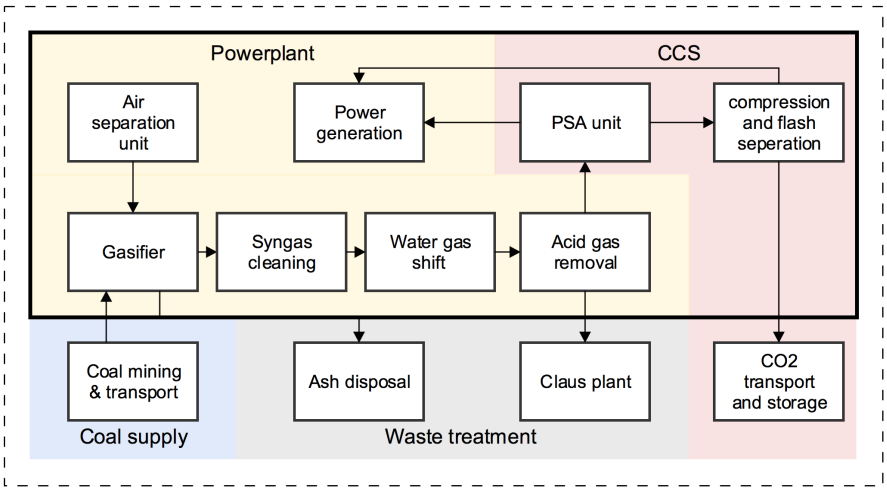

Figure 3.3 System boundaries for the ADS system

3.2 Life Cycle Inventories

The LCI's that were used are described per system area. For some processes the inventories are the same for all systems, regardless whether or not CCS is applied. However, for the processes where the inventories change when CCS is applied this is clearly indicated in the description below.

3.2.1 Coal supply

Coal supply is an upstream process taking into account the whole coal supply chain, which includes coal mining, coal processing, and transportation of coal. As the plant is assumed to be located in the Netherlands, the Dutch coal supply mix: 'hard coal supply mix/ NL/ kg' from the EcoInvent database version 2.2 was selected to represent the coal supply chain.

However, the transportation of coal in the process 'hard coal supply mix/ NL/ kg' only takes into account the transportation until the regional storage silo. To include the transportation from the regional storage silo to the power plant an extra process was added. The assumed type of transportation for this short distance is freight by train. Therefore the transportation process 'transport, freight, rail/ RER/ tkm' was selected to include the coal transport from the silo to the Netherlands. Hereby a distance of 100 km was used being the distance between the port of Rotterdam and Den Bosch where the power plant is located.

3.2.2 Power plant operations

The LCI of the power plant operations consists of the consumption of energy and materials, and the emissions of stressors. The material consumption was divided in energy consumption, chemicals consumption, and water consumption. Each category is discussed separately in the paragraphs below.

Energy consumption

The energy demand of the plant operation processes are assumed to be fulfilled by the power plant itself. These energy streams are modeled in the foreground matrix, and therefore are explained under heading 3.3.1.

Chemicals consumption

The chemicals consumed in the power plant operations are presented in Table 3.1. For the reference and ABS system the chemical consumptions are taken from Schakel et al. (2014). While for the ADS system the consumption of the Selexol in the acid gas removal unit is assumed to be equal to the ABS system. The consumptions of chemicals are expressed as kg/kWh net output. The additional chemicals consumed in the CCS processes are presented under the system area CCS.

Chemical	Consuming process	Ref	ABS	ADS	Source
COS hydrolysis catalyst (kg/kWh)[a]	Syngas cleaning	1,14E-5	-	-	(Schakel et al. 2014)
Selexol (kg/kWh)[b]	Acid gas removal	1,2E-5	1,4E-5	1,4E-5	(Schakel et al. 2014)

Table 3.1 Material consumption of power plant operation

[a] COS hydrolysis catalyst is made of TiO_2 (Schakel et al. 2014)
[b] The Selexol composition is taken from (Schakel et al. 2014), consisting of mainly ethylene oxide and methanol.

Water consumption

The water consumption was taken from the water balances presented in the report 'cost and performance baseline for fossil energy plants' (DOE/NETL 2015). In this report the water consumption is expressed in kg/s, which then was scaled based on net power output to get to the water consumption representative for the systems modeled. The water consumption of the non-CCS processes in the foreground was assumed to be equal for all three systems (WGS is not considered here but under heading 3.2.4). However, since the environmental impact of water consumption is negligible compared to the other consumables, the effect on the final impacts will be negligible too. This doesn't apply to the indicator 'water depletion potential', though since this indicator isn't considered in this study this isn't be a problem. To express the water consumption per unit of output of the associated process, the water consumption has to be divided by the mass flow of corresponding process output. The water consumption taken into account is presented in Table 3.2.

Process	Consumption (L/s)	Source
Gasifier	23	(DOE/NETL 2015)
Syngas cleaning[a]	61	(DOE/NETL 2015)
Gas turbine	8,5	(DOE/NETL 2015)
Cooling tower[b]	167	(DOE/NETL 2010)

Table 3.2 Water consumption (kg/s)

[a] Assigned to acid gas removal process
[b] Assigned to total power production

Stressors emitted

All stressors, for which there was data available are taken into account in the stressor inventory. In reality more stressors may be emitted. Previous LCA studies however successfully assed the environmental impact of IGCC power plants using the same amount of stressors, or less stressors than the ones used in this study (DOE/NETL, 2015). The data used to complete the stressor matrix was taken from DOE/NETL (2015) & DOE/NETL (2010). The stressors are expressed in g per kg of coal input and assigned to the coal input process in the model. For the two CCS systems the stressors of Table 3.3 are assumed to be equal per kg coal. The reason for this is that there is no

specific data for the ADS system available. This assumption can be justified by the fact that the ABS and ADS system only differ in the CCS process.

	Reference	CCS	Source
SO_2	4,8E-02	2,6E-02	(DOE/NETL 2015)
NO_x	6,9E-01	5,7E-01	(DOE/NETL 2015)
PM	8,2E-02	8,3E-02	(DOE/NETL 2015)
Hg	5,1E-06	4,3E-06	(DOE/NETL 2015)
NH_3	7,0E-07	5,9E-07	(DOE/NETL 2010)
Pb	3,8E-05	3,9E-05	(DOE/NETL 2010)
CO	1,4E-03	1,3E-03	(DOE/NETL 2010)

Table 3.3 Emission factors (g/kg coal)

A different approach was used to complete the stressor inventory of CO_2 emissions, because for this stressor more detailed information was available. For the reference system, the emission factor of CO_2 was calculated by multiplying the CO_2 emission factor (g/kWh LHV_{coal}) and the LHV_{coal} (MJ/kg) taken from DECARBit (2011). The results of CO_2 formed was 2,4 kg/kg coal. This CO_2 emission factor is also used for the CCS systems. However, the CCS units will capture a portion of the CO2 formed. The real amount of CO_2 emitted is thus different for all three systems.

3.2.3 Waste treatment

The processes included in the system area waste treatment are ash disposal and sulfur recovery in the Claus plant. For the ash disposal the process 'disposal, hard coal ash, 0% water, to residual material landfill/ NL/ kg' was selected from the EcoInvent database. The Claus plant consumes a catalyst of which the consumption is presented in Table 3.4. The Claus catalyst consumption is expressed in kg/kWh.

Parameter	Reference	CCS	Source
Claus catalyst (kg/kWh)[a]	2,6E-6	3,5E-6	(Schakel et al. 2014)

Table 3.4 Chemical consumption Claus plan

[a] Claus catalyst is assumed to be 100% Al_2O_3

3.2.4 CCS

The CCS system area is only applicable to the ABS and ADS system. The LCI of the CCS processes consist of energy and material consumption, and CO_2 captured. The additional infrastructure needed for the CCS systems is presented in the system area infrastructure. The energy consumption was modeled as a foreground process and therefore discussed in the section foreground matrix.

The material consumption consists of chemicals and water and is presented in Table 3.5 and Table 3.6. The activated carbon is expressed in a different unit then the other chemicals, namely in kg/kg CO_2. The reason for this is that the calculations were based on the amount of CO_2 captured. Since in the model it also had to be expressed per kg CO_2 (captured), an extra conversion is not necessary. The water consumption was only available for the ABS system and therefore assumed to be equal for the ADS system. This assumption can be justified because most water in the CCS system is used in the water-gas shift reactors, and not in the capture unit themselves.

Chemical	Consuming process	Reference	ABS	ADS	Source
WGS catalyst (kg/kWh)[a]	Water gas shift	-	8,1E-6	8,1E-6	(Schakel et al. 2014)
Selexol (kg/kWh)	Selexol unit	-	1,4E-5	-	(Schakel et al. 2014)
Activated carbon (kg/kg CO2)[b]	PSA unit	-	-	1,7E-5	(Own calculation)

Table 3.5 Chemicals consumed by CCS processes

[a] WGS catalyst compositions is assumed to be: 3,5%w CoO, 14%w MoO_3, 82,5% Al_2O_3 (Schakel et al. 2014)
[b] Activated carbon composition is assumed to be black carbon activated with 0,1 kg steam for each kg of activated carbon. The consumption carbon is based on the column properties provided by Riboldi & Bolland (2015), assuming a lifetime of 5 years for the carbon beds.

Process	Consumption	Source
CCS (L/kg coal)	0,97	(DOE/NETL 2010)

Table 3.6 Water consumption CCS unit

The CO_2 captured by the CCS units was defined in kg CO_2 captured/kg coal input. The value was quantified based on the CO_2 recovery rate (R_{CO2}) and the carbon capture efficiency (η_{CO2}). The CO_2 recovery rate expresses the amount of carbon captured by the CO_2 unit, and was calculated using the equation below, with data from DECARBit (2011) and Riboldi & Bolland (2015).

$$\mathrm{R_{CO_2}} = \frac{\dot{m}_{CO_2} \text{ in } \mathrm{CO_2} \text{ stream leaving the carbon capture unit}}{\dot{m}_{CO_2} \text{ in syngas stream entering the carbon capture unit}}$$

The CO_2 capture efficiency expresses to what extent the CO_2 is captured by the CCS system, relatively to the reference system. This parameter was calculated using the equation below, with data from Riboldi & Bolland (2015). This is the actual parameter used to quantify the CO_2 captured.

$$\eta_{\mathrm{CO_2}} = 1 - \frac{\eta_{net,ref}}{\eta_{net}} * \frac{P_{out}}{\mathrm{P}_{out,ref}} * (1 - R_{CO_2})$$

3.2.5 Infrastructure

The infrastructure of the systems consists of the infrastructure for the IGCC power plant and the additional infrastructure needed for the CCS systems. For all infrastructure, the material production and transport, power plant construction and demolition, and material disposal processes were taken into account.

IGCC power plant without CCS

Since there was no detailed information available on the IGCC power plant infrastructure, the LCI data for constructing and dismantling the IGCC power plant was assumed to be equal to that of a pulverized coal plant. Therefore the process 'hard coal power plant/ RER/ unit' was selected from the EcoInvent database to represent the infrastructure of an IGCC power plant without CCS.

CO2 capture unit

The infrastructural LCI of the Selexol carbon capture unit was determined based on the inventory taken from Koornneef et al. (2008). The inventory was scaled based on the amount of steel needed for the absorption column. The amount of stainless steel needed was calculated based on the mass

flow, column diameter and height, and cylinder thickness (Decarbit, 2011; Padurean et al., 2011). The thickness was calculated using the Chemcalc tool, and the process operating temperature and pressure (Decarbit, 2011; Chemcalc, 2015).

The infrastructural LCI of the PSA carbon capture unit was determined by an approach similar to the one for the Selexol carbon capture unit. The amount of steel needed was calculated in the same way, using data from Riboldi (2015). The extra steel for piping and small equipment was assumed to be equal to the Selexol carbon capture unit. The infrastructure of pumps was neglected for both capture systems.

CO2 compression infrastructure

The infrastructure for the carbon product compression was taken from Koornneef et al. (2008) and scaled based on the compressor capacity of 18,7 MW and 41,3 MW for respectively the ABS and ADS system (Riboldi and Bolland 2015).

CO2 transport and injection infrastructure

The infrastructure for carbon product transportation and injection was taken from Koornneef et al. (2008) and scaled based on the pipeline diameter. The optimum economic pipeline diameter was calculated as a function of mass flow and critical temperature, pressure, density and viscosity (Serpa, 2011).

3.3 Impact assessment

To apply the process based LCA to the three investigated systems the software Arda was used. Arda is an in-house developed program at the Industrial Ecology department of NTNU, written by Guillaume Majeau-Bettez. The Arda program requires the user to create a foreground matrix, demand vector, and a stressor matrix, and to specify the upstream inputs of background processes to the foreground system. Once these inventories are completed, the program performs the matrix calculations using the LCI database Ecoinvent V2.2 for the background processes. Arda presents results according to the ReCiPe framework, which translates the stressors into 18 midpoint level environmental impact indicators. Background information on a process based LCA, the Ecoinvent database, and the ReCiPe framework can be found in Chapter 2. Of the 18 indicators the following 10 were selected to present the results of: global warming potential (GWP), terrestrial acidification potential (TAP), fresh water eutrophication potential (FEP), marine eutrophication potential (MEP), photochemical oxidant formation potential (POFP), particular matter formation potential (PMFP), human toxicity potential (HTP), terrestrial ecotoxicity potential (TETP), fresh water ecotoxicity potential (FETP), marine ecotoxicity potential (METP). The selected indicators are considered the most relevant for power plant systems and is based on previous LCA studies of power plants (Singh, Strømman, and Hertwich 2011). The remainder of this chapter focuses on how the process based LCA is applied to the three systems studied.

3.3.1 Foreground matrix A_{ff}

The foreground matrix A_{ff} consist of all the processes included in the flowcharts of Figure 3.1-3. In addition, a process labeled as infrastructure was added, to which all the background processes regarding infrastructure were assigned per kWh net output. This process directly sets the requirement of infrastructure in the A_{ff} matrix to be 1 unit per kWh net power output. Also an extra process labeled ‘coal input’ was added between the gasifier, the coal mining and transport process. This process was used to include the direct emissions, and was set to 1 kg coal per kg coal from the coal mining and transport process.

For the reference system the A_{ff} matrix was constructed using the stream data of the IGCC test case without CCS taken from DECARBit (2011). The additional CCS related processes for the ABS and ADS system were modeled as 'add-on' processes, using the reference model as starting point. This means that interference of the CCS related stream flows and processes with the stream flows modeled in the reference system is prevented. In other words, the copied A_{ff} matrix of the reference system remains unchanged in the ABS and ADS model. Processes and corresponding flow streams were only added to complete the A_{ff} matrices for the ABS and ADS systems. The added processes are presented in Table 3.7.

ABS system	ADS system
- Water gas shift reaction	- Water gas shift reaction
- Absorbent carbon capture unit	- Adsorbent carbon capture unit
- CO_2 compression	- CO_2 compression
- CO_2 transport and injection	- CO_2 transport and injection
- Additional infrastructure	- Additional infrastructure

Table 3.7 Processes added to the foreground matrix of the reference system

Although attempts were made to construct three fully integrated models, the 'add-on' approach was preferred. This less detailed approach is justified by the lack of technical assessment studies for IGCCs with CCS, in which the functional unit (either fuel consumption or power output) is kept constant. The reason for this is the change of mass- and LHV-flow of the syngas entering the gas turbine, which is due to the processes added in a pre-combustion CCS system. The 'add-on' approach allows the use of the same data-source (Riboldi and Bolland 2015) for the ABS and ADS system with a constant functional unit. However the approach ignores the possible technical problems of the gas turbine operating with different flows of syngas. The effect of the simplification however was expected to be insignificant and considered acceptable.

The demand for the (add-on) carbon capture unit was defined in kg carbon captured per kg coal input. The WGS reaction, CO_2 compression, and CO_2 transport and injection were linked to the carbon capture unit, all expressed per kg CO_2. The additional infrastructure was linked to the process infrastructure expressed as kg CO_2 per kWh, since the background processes are expressed in unit/kg CO_2 stream. The plant efficiencies and stream data were taken from Riboldi & Bolland (2015) and DECARBit (2011).

In addition to the processes added to the A_{ff} matrix, the energy penalty associated with the carbon capture unit was also added to the matrix. The energy penalty, taken from (Riboldi and Bolland 2015), was assigned to the responsible processes expressed in kWh/kg CO_2 captured. Note that the energy penalty caused by the steam consumption of the WGS reactor is not allocated to the WGS reactor. This energy penalty is already taken into account in the reduced plant efficiency. This explains that no energy penalty due to the WGS reactor will be visible in the results, although literature shows the WGS reactor is mainly responsible for the CCS energy penalty.

3.3.2 Demand vector y

The demand vector y was set to 1 kWh of net electricity produced. This equals the functional unit of this assessment as defined in the introduction.

3.3.3 Stressor matrix S_f

The stressor matrix represents the direct emissions of the system. The stressors were expressed as emission factors in g emitted per kg/coal gasified and assigned to the coal input process.

3.3.4 Inputs required for upstream processes A_{bf}

To let Arda construct the background matrix A_{bb}, the user must provide input for the A_{bf} matrix in which the background processes are linked to the foreground processes. The links were expressed as unit of selected background process per output unit of associated foreground process. The inputs required for upstream processes were gathered in the LCI's of the processes, which will be discussed in the next section.

4 RESULTS

The results section is divided in two parts. The first part consists of technical results of the systems that were used as input parameters for the LCA. And the second part contains the results of the actual Life cycle assessment. These results are presented as a whole in tables and graphs under heading 4.2. Then the results are individually analyzed and discussed under heading 4.3.

4.1 Technical performance parameters

The most important technical parameters of the systems that had to be calculated to construct the model are presented in Table 4.1. The plant efficiency was not calculated but taken from Riboldi and Bolland (2015). Strictly taken this is not a result, however since it contributes to the understanding of the system it is included in the table.

	Reference	**ABS**	**ADS**
Plant efficiency (%)	47,3	37,1	36,2
CO_2 recovery (%)	-	94,6	89,9
CO_2 capture efficiency (%)	-	88,1	81,8

Table 4.1 Technical parameters

The result of the calculations of CO_2 formed was 2,4 kg/kg coal. And CO_2 captured specific for the ABS and ADS systems are presented in Table 4.2.

	Reference	**ABS**	**ADS**
CO_2 captured (kg/kg coal)	-	2,1	2,0

Table 4.2 CO_2 captured per CCS system

4.2 Total results

Table 4.3 and Figure 4.1 present the impact characterization results for the three power plant configurations. As expected, a significant drop in GWP was found for the CCS systems compared to the reference system. All other impact scores for the CCS systems are higher than the reference system. When comparing the scores of the ABS and ADS system, for all the impact indicators the ADS system scores higher than the ABS system. However, the difference is sometimes so small that it is not always visible in the scores presented in Table 4.3. This is due to the significance of the presented results.

Impact	**GWP**	**TAP**	**FEP**	**MEP**	**POFP**	**PMFP**	**HTP**	**TETP**	**FETP**	**METP**
Unit (kg eq)	*CO_2*	*SO_2*	*P*	*N*	*NMVOC*	*PM_{10}*	*1,4-DB*	*1,4-DB*	*1,4-DB*	*1,4-DB*
BGP	8,2E-01	1,2E-03	4,9E-04	1,4E-04	1,1E-03	4,2E-04	3,2E-01	6,6E-06	8,1E-03	7,8E-03
ABS	1,9E-01	1,3E-03	5,4E-04	1,6E-04	1,2E-03	4,4E-04	3,4E-01	7,3E-06	8,8E-03	8,5E-03
ADS	2,4E-01	1,3E-03	5,4E-04	1,6E-04	1,2E-03	4,5E-04	3,5E-01	7,5E-06	8,9E-03	8,6E-03

Table 4.3 Total scores of environmental performance indicators per kWh net output

To make the results more comparable, Figure 4.1 presents the impact potentials of all systems relative to the reference system. In addition all indicators will be discussed separately through the remainder of this chapter. Hereby for each indicator a breakdown of the contributing system areas will be included.

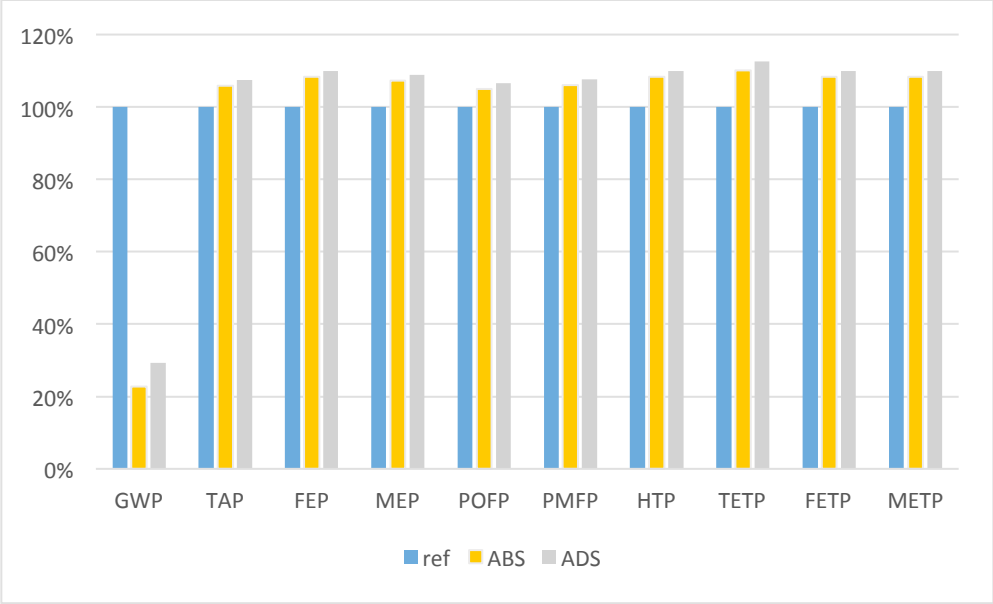

Figure 4.1 Environmental performance for selected midpoint indicators relative to reference system (BGP)

To get insight in the stressors contributing the impact potential, Table 4.4 shows the results of a selection of stressors emissions by the three systems. And in addition Figure 4.2 presents the stressors emitted by the systems relative to the reference system.

Since all indicators are a function of the stressors emitted by the systems, relationships between the stressors and impact indicators can be found. As expected a direct relation between the CO_2 emitted and the GWP is visible. For the other impacts the relation are not always as obvious. Therefore the contributing stressors will be discussed per indicator in section 4.3.

Unit (kg eq)	**CO_2**	**N_2O**	**NO_x**	**PM**	**SO_2**	**CO**
BGP	8,2E-01	4,4E-06	1,0E-03	1,1E-03	5,9E-04	1,9E-04
ABS	1,9E-01	4,8E-06	1,1E-03	1,2E-03	6,3E-04	2,1E-04
ADS	2,5E-01	4,8E-06	1,1E-03	1,2E-03	6,4E-04	2,1E-04

Table 4.4 Stressors (kg/kWh)

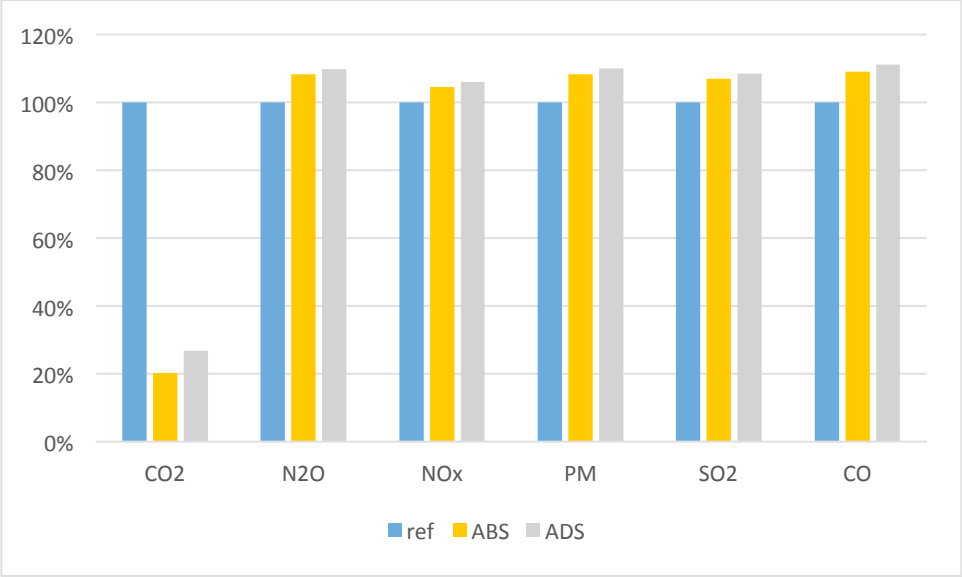

Figure 4.2 Stressors output relative to reference system

4.3 Results per environmental performance indicator

In the figures below the results of individual environmental performance indicators are presented. For each indicator a breakdown showing the contribution of the different system areas is given. Each indicator is discussed briefly, whereby first an explanation of the reference system is given, then the differences with the other two systems are pointed out and explained. Also the main drivers and stressors contributing to the total potentials are named and explained.

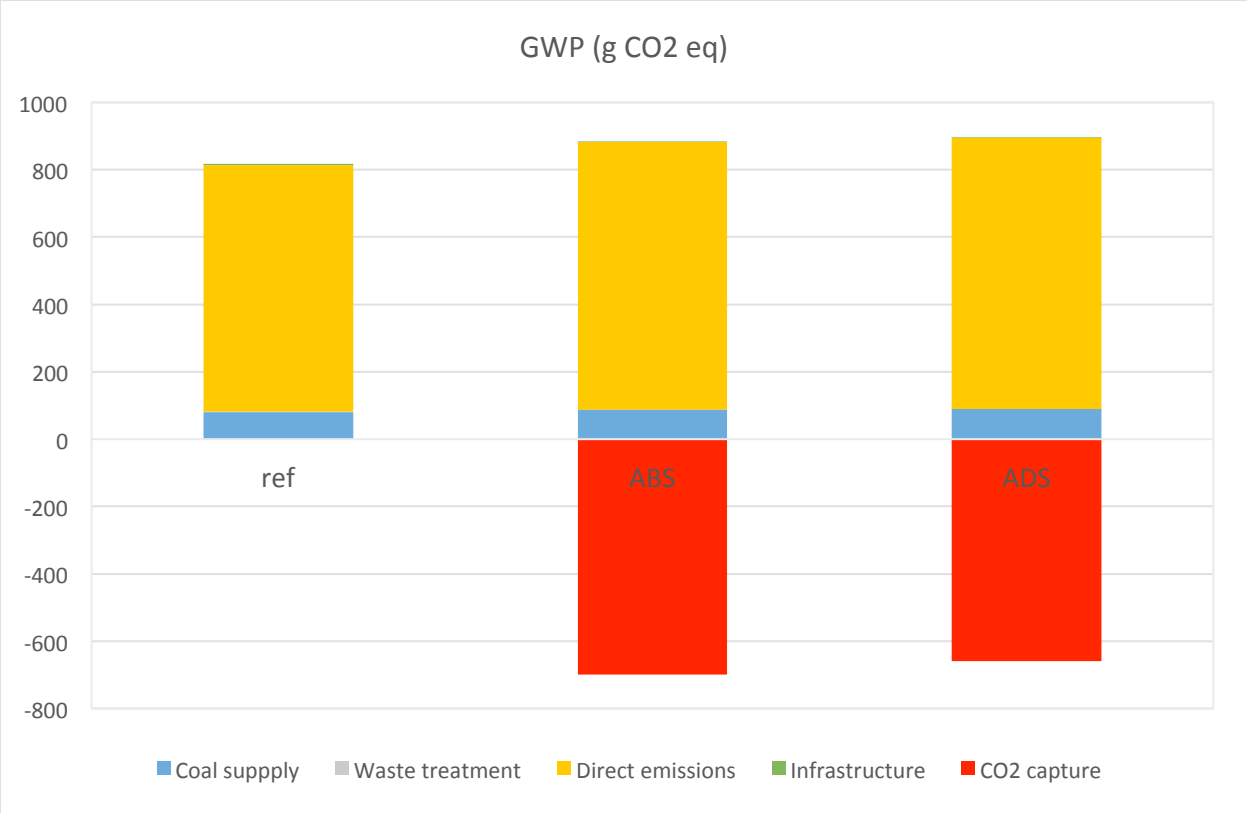

Figure 4.3 System area breakdown for environmental performance indicator: GWP

Figure 4.3 shows the contribution of the different system areas to the GWP. For the reference system the total GWP is 817 g CO_2 equivalents. The direct emissions account for approximately 90% of the total GWP. Within the direct emissions the stressor CO_2 is the only stressor contributing to the GWP. The CO_2 of the direct emissions is formed in the gas turbine when the syngas is burned, and emitted in the flue gas of the power plant. The coal supply contributes for approximately 10% to the GWP. The main process in the coal supply chain accounting for approximately 30% of the total GWP is the transoceanic transport of the coal. The second largest contributing process in the coal supply chain is the direct emission at the coal mining. The GHGs contributing to GWP in the coal supply chain are for 68% CO_2, for 31% CH_4, and for 1% N_2O.

The carbon capture unit reduces the GWP of the ABS system with 79% to 186 g CO_2 equivalents. In the figure the reduction in GWP caused by the carbon capture unit is presented as negative emissions. For the rest the processes contributing to GWP are similar as the ones in the reference system. However, the absolute values of contribution to GWP for these processes are found to be higher for the CCS systems. This increase is explained by the energy penalty that comes with the carbon capture unit. Because the energy penalty requires the CCS systems to have a higher coal input and the coal input is directly related to the GHGs emitted in the coal supply chain. For the ADS system the GWP is reduced with 71% to 239 g CO_2 equivalents. The drivers contributing in the ADS system are the same as in the ABS system, although the increases are a bit larger. This effect is due to the higher energy penalty of the ADS carbon capture unit.

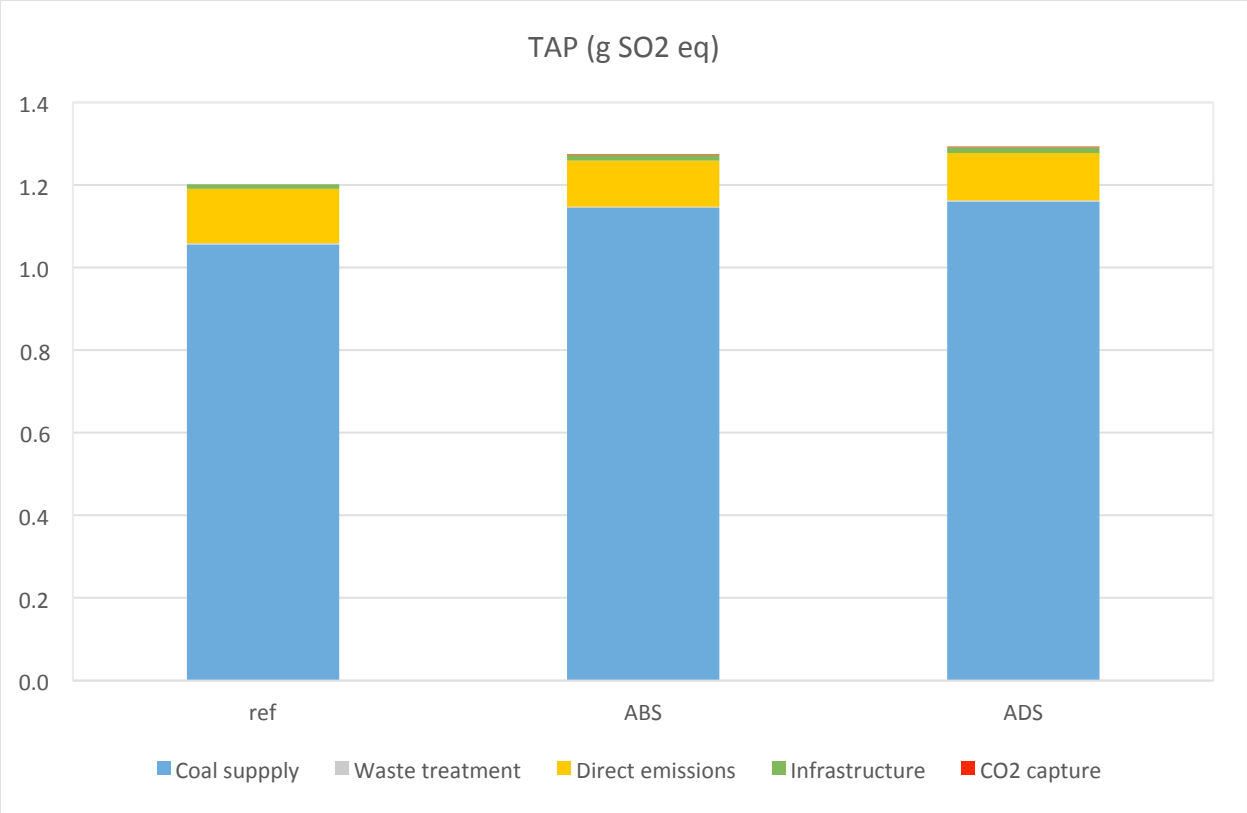

Figure 4.4 System area breakdown for environmental performance indicator: TAP

The terrestrial acidification potential (TAP) for the systems is presented in Figure 4.4. For the reference system the total TAP is 1,2 g SO_2 equivalents. With 88% the coal supply is contributing the most to the TAP. Within the coal supply chain the main contributing process is transoceanic freight accounting for 66% to the total. The second largest contributing process is the blasting in the mining process, accounting for 26% to the TAP. Other contributing processes consist of fuel burning for electricity and machinery used in the coal supply chain. Within coal supply the stressors causing the TAP are for approximately 50% SO_2, for 41% NO_x and 9% NH_3, while within the system area direct emissions the TAP is for 93% caused by NO_x, and for 7% by SO_2 emitted in the flue gas of the power plant.

In the CCS systems an increase of 6-8% to 1,3 g SO_2 can be observed. The main system areas and processes contributing to the total TAP are the same as in the reference system. However a small shift in the values was found. The coal supply increases from 88% to 90% of the total TAP. This increase is caused by the energy penalty, causing an increase in fuel input. Meanwhile the contribution of the direct emission decreases from 11% to 9%.

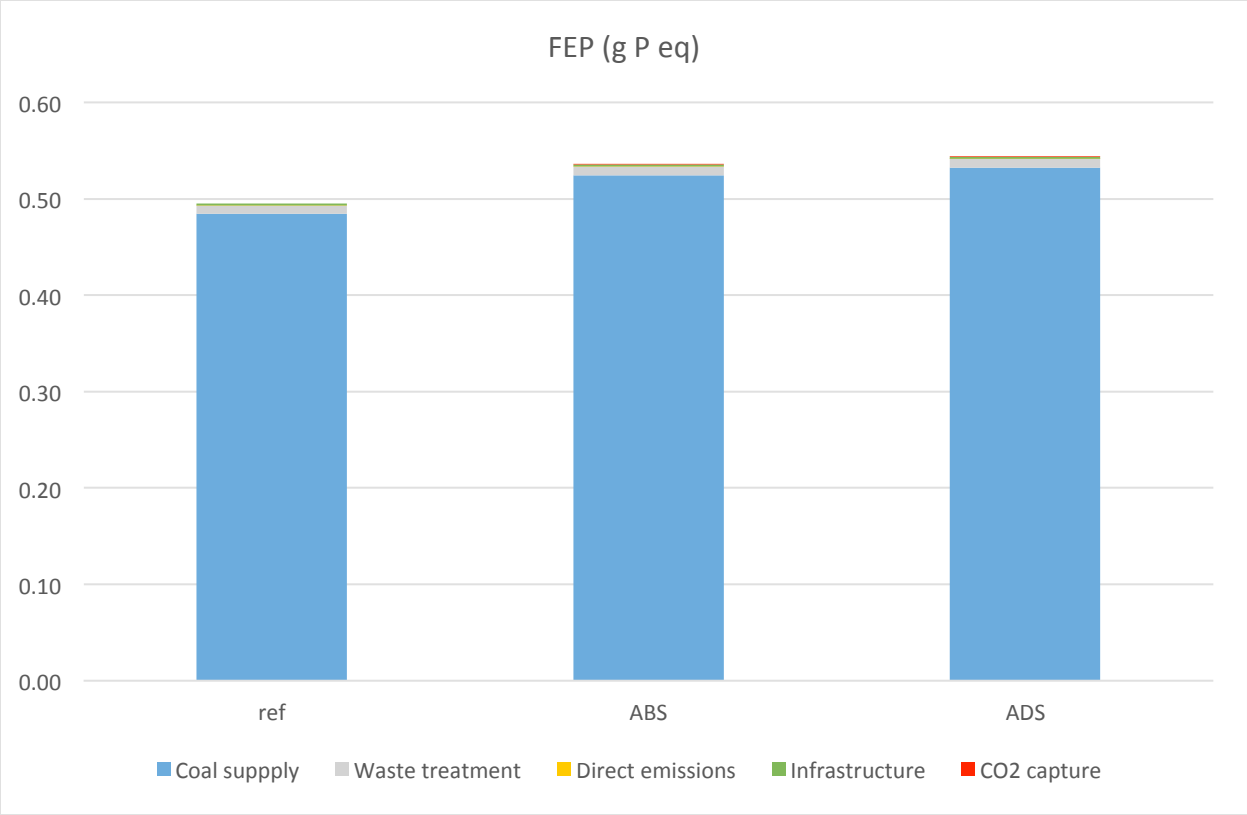

Figure 4.5 System area breakdown for environmental performance indicator: FEP

Figure 4.5 presents the breakdown of Freshwater eutrophication potential (FEP) for all systems. For the reference system the total FEP is 0,49 g P eq. The coal supply accounts for 98% of the total FEP. The main processes causing the FEP is 'the disposal of spoil from coal and lignite mining in surface landfill'. Besides this the waste treatment contributes for almost 2%, due to the disposal of hard coal ash into residual material landfill. The stressor causing the FEP is for 100% Phosphate.

For the CCS systems the total FEP is a little higher. An 8% and 10% increase to 0,54 g/kWh for respectively the ABS and ADS system was found. For both cases the CO_2 capture unit also contributes to the FEP, however this contribution of less than 1% is overshadowed by the contribution of the coal supply and therefore considered to be insignificant. The emissions are coming from upstream processes like chemical production. The system areas and processes contributing to FEP are for the CCS systems the same as for the reference system. The increase in absolute values is explained by the energy penalty associated with the carbon capture unit, similar to the previous environmental indicators.

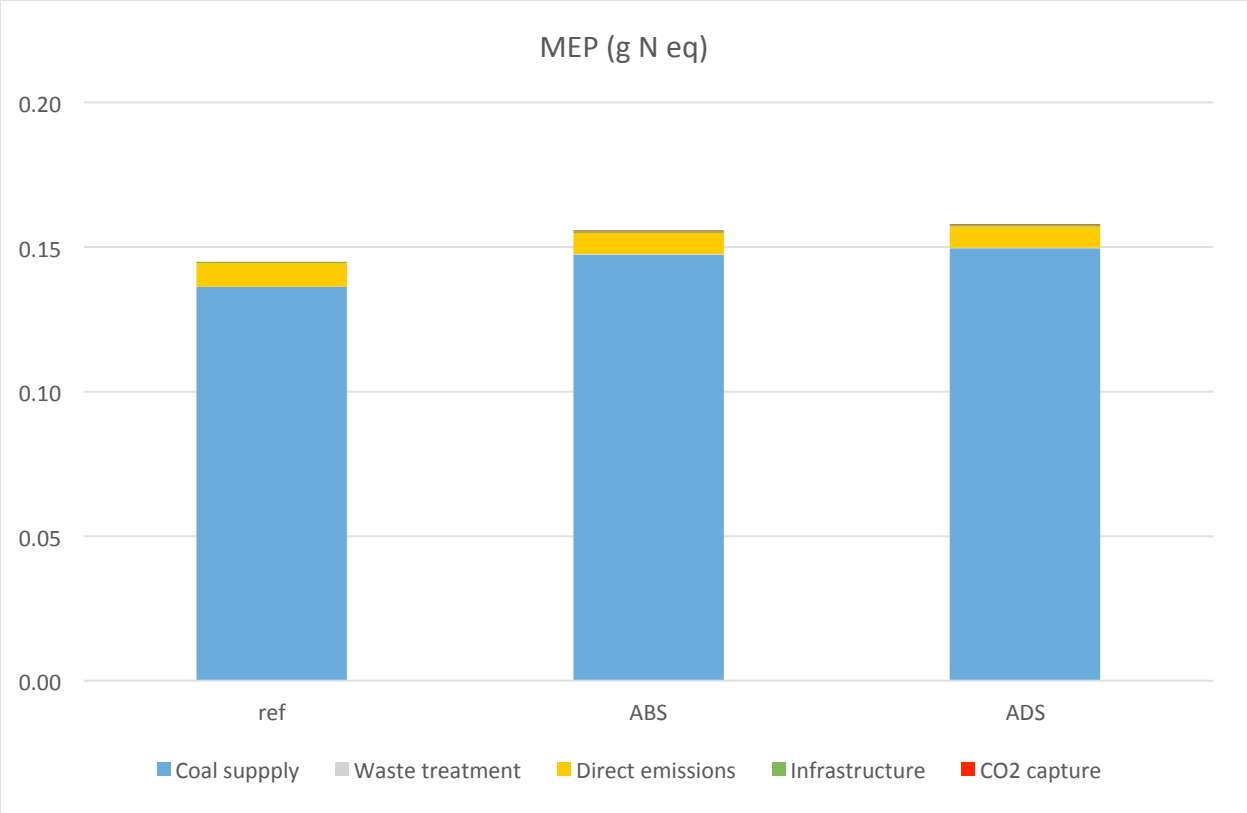

Figure 4.6 System area breakdown for environmental performance indicator: MEP

The marine eutrophication potential (MEP) for all systems is presented in Figure 4.6. For the reference system the total MEP is 0,14 g N eq. Taking up 94% of the bar, the MEP is dominated by the coal supply. For 68% the MEP caused by coal supply is due to the disposal of spoil from coal mining in surface landfill, and for 13% due to transoceanic freight. Main stressors from coal supply causing the MEP are nitrogen (>70%)) and O_x (>25%). The direct emissions complete the Marine Eutrofication, accounting for almost 6% of the total. The direct emissions causing MEP are for almost 100% NO_x. The small amount of NH_3 in the direct emissions is considered negligible, since it contributes for less than 0,001% to the total MEP.

For the CCS systems the MEP is 7% and 9% higher for the ABS and ADS systems respectively. The system areas and processes contributing to MEP are the same as for the reference system. However, in terms of contribution the share of coal supply increases from 94% to 95%, while the share of direct emissions decreases from 6% to 5%.

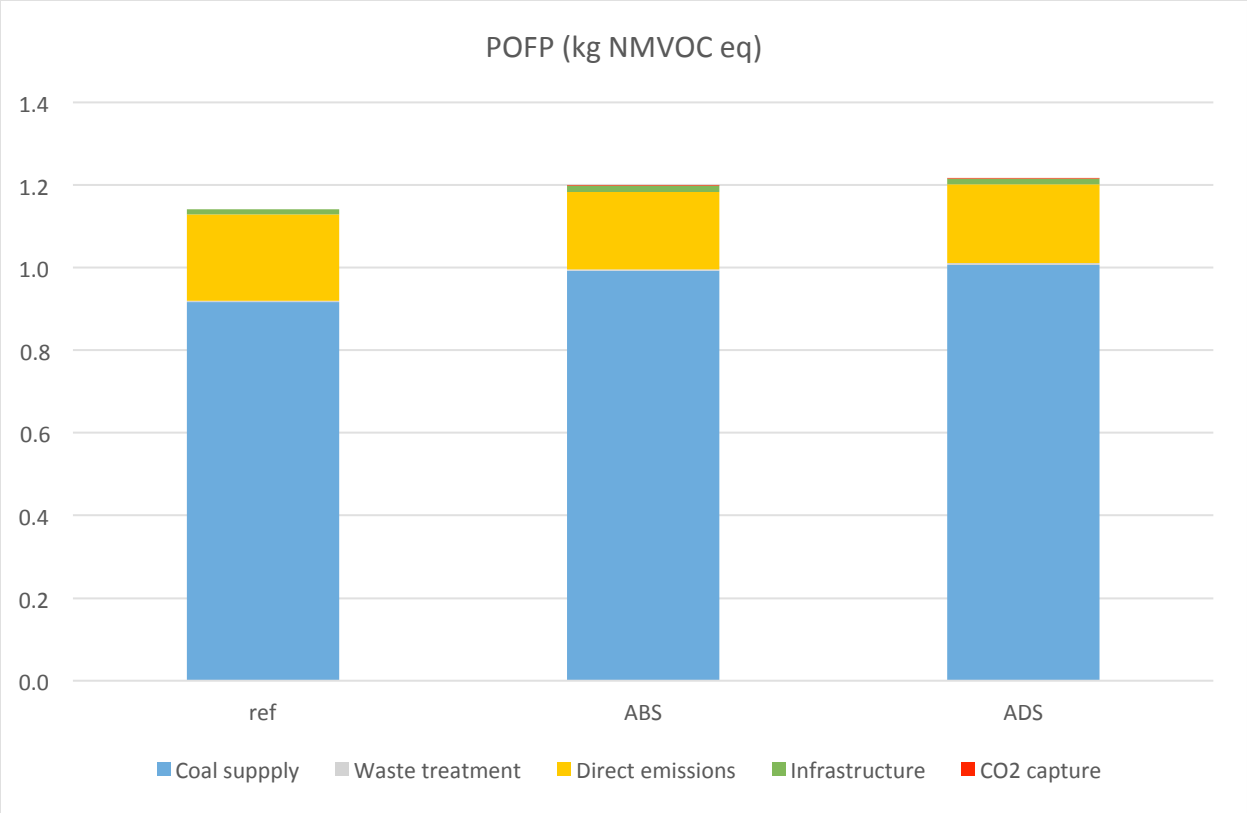

Figure 4.7 System area breakdown for environmental performance indicator: POFP

The Photochemical Oxidant Formation Potential (POFP) of all systems is presented in Figure 4.7. The POFP of the reference system is 1,14 g NMVOC eq. For 80% the POFP is caused by processes associated with the coal supply chain. With a contribution of 59% the processes transoceanic freight is contributing the most to POFP. With 25% the process blasting in the coal supply is the second contributor. The contributing stressors emitted in these processes are NO_x (84%), NMVOC (9%), and the remainder SO_2 and CH_4. For 18% the POFP is caused by the direct emissions, of which 99% is due to NO_x emissions.

For the ABS system a 5% increase to 1,20 g NMVOC can be observed. The system areas and processes contributing are the same as fore the reference system. However, again, a small increase from 80 to 83% is found for the system area coal supply. Compensated by the small decrease in direct emissions from 18 to 16%. The shift in breakdown is caused by the lower emissions of NO_x per kg coal. For the ADS system the same effect occurs, only the total increase of 7% resulting in 1,22 g NMVOC is a bit higher than in the ABS system.

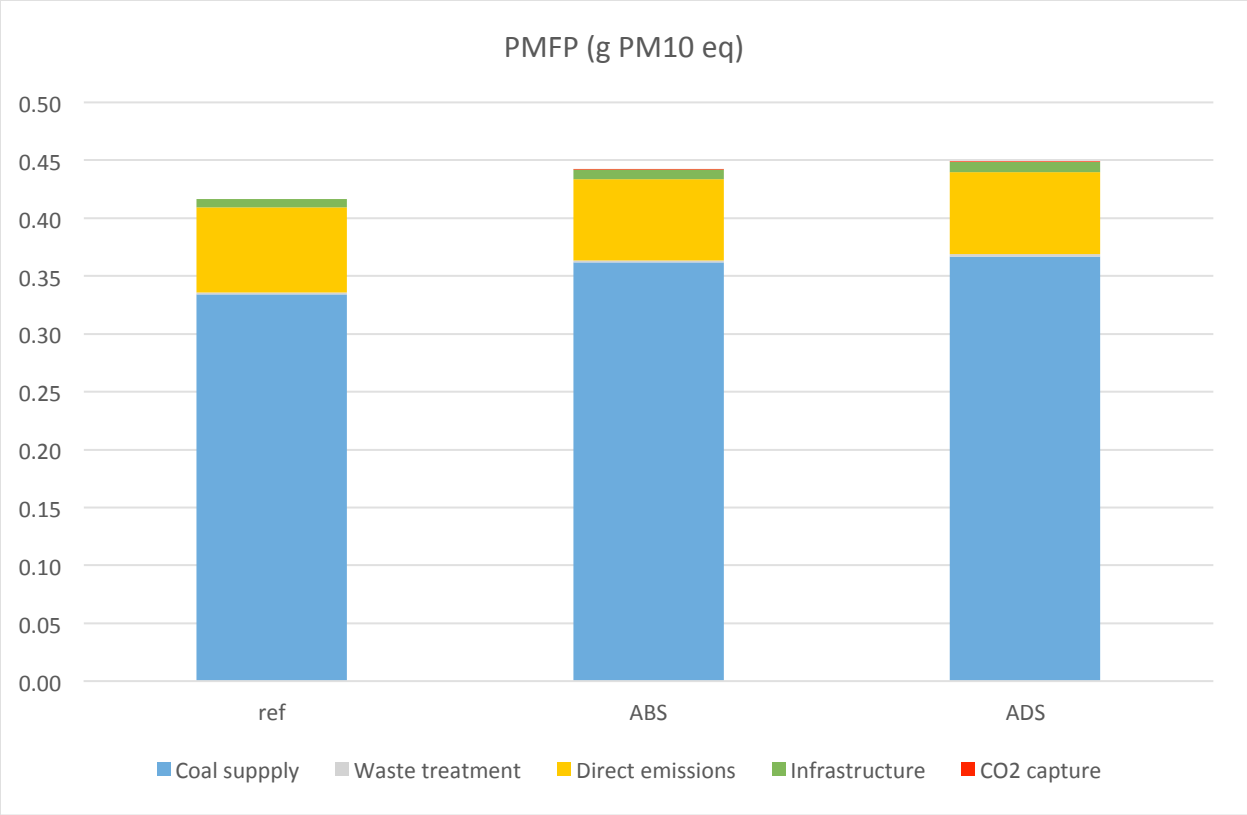

Figure 4.8 System area breakdown for environmental performance indicator: PMFP

The particular matter formation potential (FMFP) is presented in Figure 4.8. For the reference system the PMFP is for 80% caused by processes related to coal supply. The main contributing process in the coal supply is the transoceanic freight, accounting for 65% of the FMFP caused by the coal supply. The second biggest contributing process is the blasting at the mine, accounting for 18% of the FMFP caused by the coal supply. For 18% the PMFP is caused by the direct emissions. The direct emissions contributing to FMFP are for 62% NO_x, for 34% PM_{10}, and for 4% SO_2. For 2% the FMFP is caused by infrastructure due to the iron mining process and fuels burned in machinery.

For the CCS systems the total PMFP is 6 and 8 % higher for respectively the ABS and ADS system. Due to the decrease in NO_x formation per kg coal, for the CCS systems, the share of direct emissions decreases from 18 to 16%. On the other hand, the share of coal supply increases from 80 to 82%. The overall PMFP of the CCS systems increases, due to higher coal input for these systems. The PMFP for the ABS and ADS system increases with 6 and 8% to respectively 4,4 an 4,5 g PM_{10} eq.

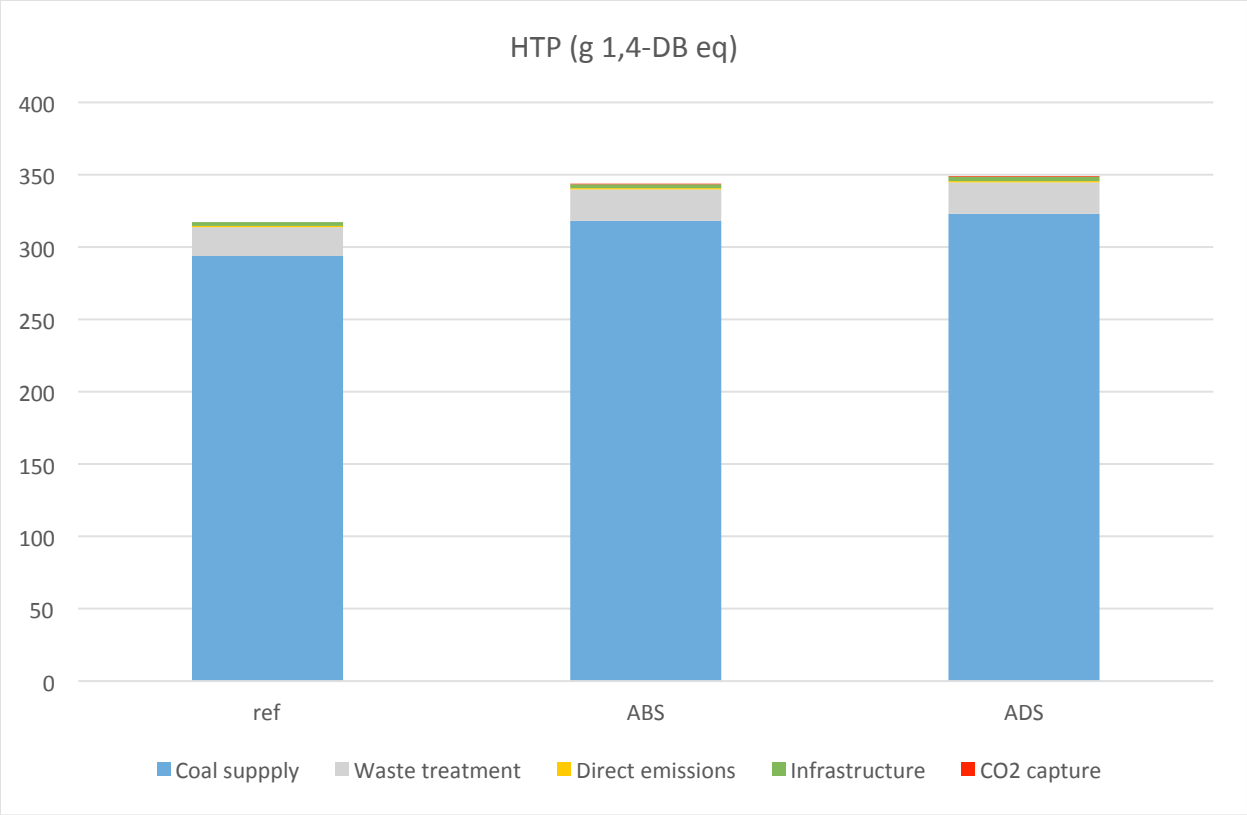

Figure 4.9 System area breakdown for environmental performance indicator: HTP

The Human Toxicity Potential (HTP) of all systems is presented in Figure 4.9. For the reference case the human toxicity potential is for 320 g 1,4-DB eq. Of this amount, 93% is due to processes related to coal supply. Within the system area coal supply, with 92%, the disposal of spoil from coal in surface landfill is the main contributing process. The other contributing processes associated with coal supply are also related to waste disposal. The main stressor from the coal supply is Manganese (Mn), accounting for 80% of the HTP caused by the coal supply. The other system area contributing to the HTP is the waste treatment, accounting for 6%. The HTP caused by the waste treatment are coming for 100% from the process ash disposal to landfill. The stressors emitted in this process are mainly metals including arsenic, accounting for 68%, and selenium, accounting for 15%.

For the CCS systems an increase of 8 and 10% was found for respectively the ABS and ADS system. In contrast with most of the indicators discussed before no shift in the contribution of system areas and processes was found. The reason for this the direct emissions only contribute for less than 0,5%, while in the other indicators the shift is caused by the direct emissions.

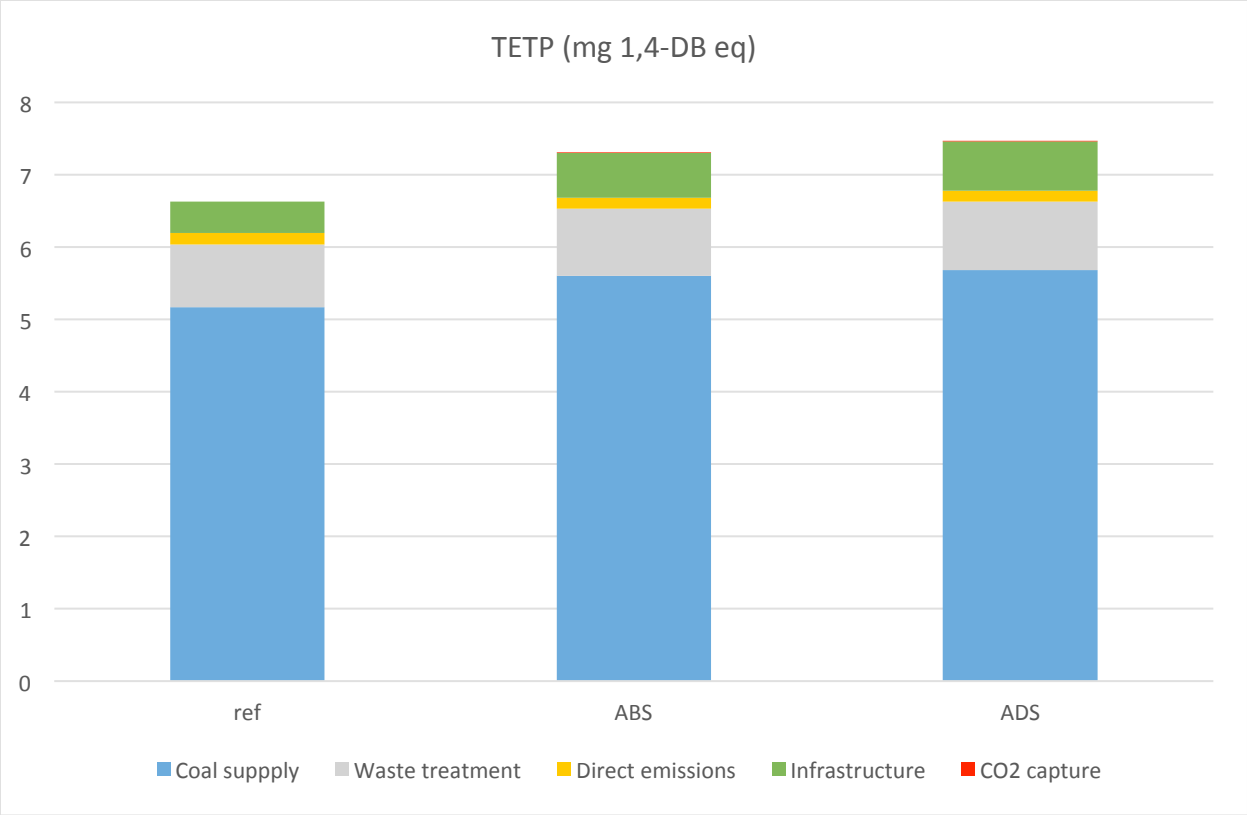

Figure 4.10 System area breakdown for environmental performance indicator: TETP

The Terrestrial Eco-Toxicity Potential (TETP) is presented in Figure 4.10. The total TETP of the reference system is 6,6 mg. The main part of the bar is taken up by the coal supply, accounting for 78% of the total TETP. Within the coal supply chain the disposal of drilling waste to land farming, accounts for 38% to the TETP contribution by the coal supply chain. Accounting for 14% the disposal of wood ash mixture to land farming is the second largest contributing process. With 13% the second contributing system area is waste treatment. The 13% contribution is all coming from the process ash disposal to landfill. Then 6% of the bar is a consequence of processes related to infrastructure. The processes contributing to TETP within infrastructure are mainly related to the steel production. Also a small contribution of 2,4% for the direct emissions is visible, which is due to the mercury and lead emissions.

For the CCS systems a 10 and 13% increase in TETP is observed for respectively the ABS and ADS system. Opposite to the shift in previous indicators, the contribution of the coal supply decreases for both CCS systems. At the same time an increase in the share of infrastructure is from 6% for to reference system to respectively 8 and 9% for the ABS and ADS system. This shift can be explained by the extra infrastructure needed for the CCS systems.

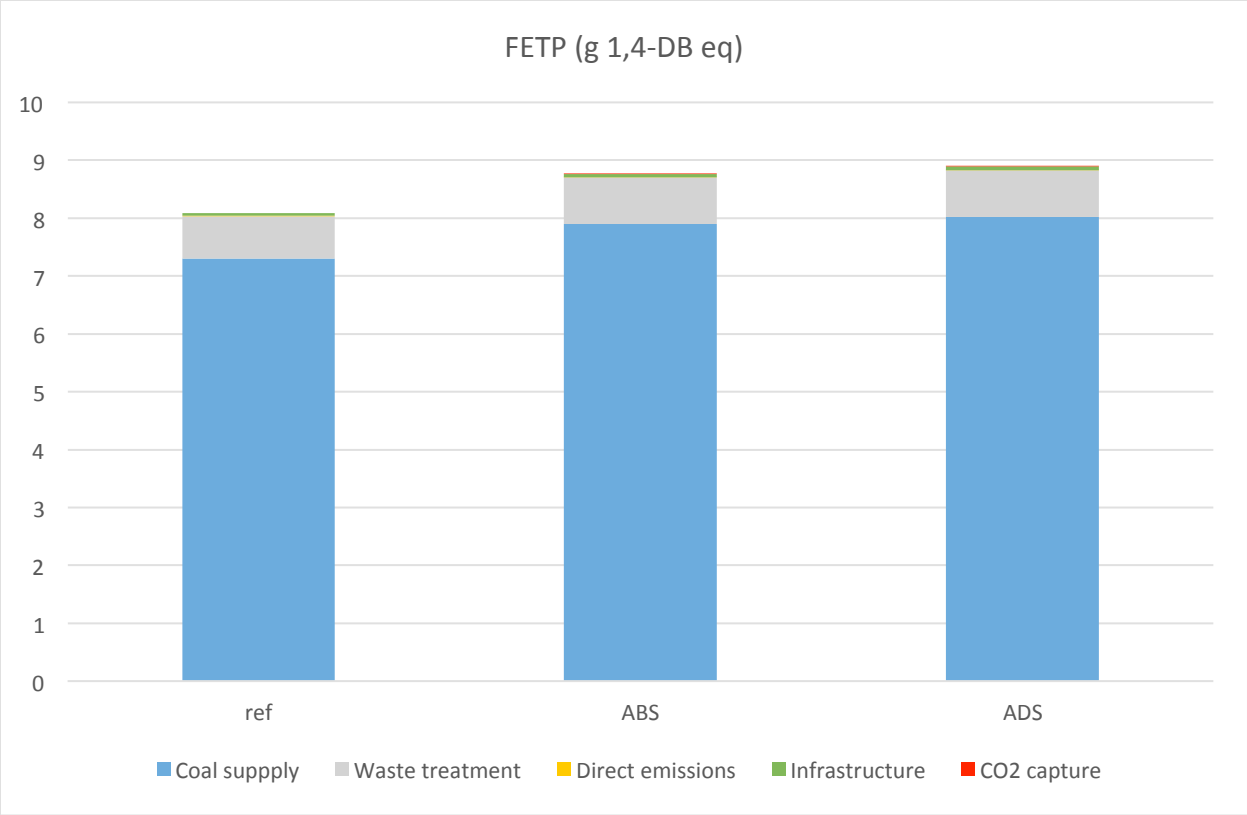

Figure 4.11 System area breakdown for environmental performance indicator: FETP

The Freshwater Eco-toxicity Potential (FETP) for the three systems is presented in Figure 4.11. The total FETP of the reference system is 8,1 g 1,4-DB equivalents. The FETP of the reference system is for 90% coming from processes related to coal supply. Of which 91% is due to the disposal of spoil from coal in surface landfill. The stressor emitted in this process are a collection of heavy metals. The FETP of the reference system is for 9% coming from waste treatment, which for 99% is coming from the process ash disposal. The stressors emitted with the ash disposal responsible for the FETP consist of a variety of heavy metals.'

Due to the energy penalty related to the CCS units, an increase in FETP for the CCS systems is visible. The increase of 8 and 10% results in 8,8 and 8,9 g 1,4-DB equivalents for respectively the ABS and ADS system.

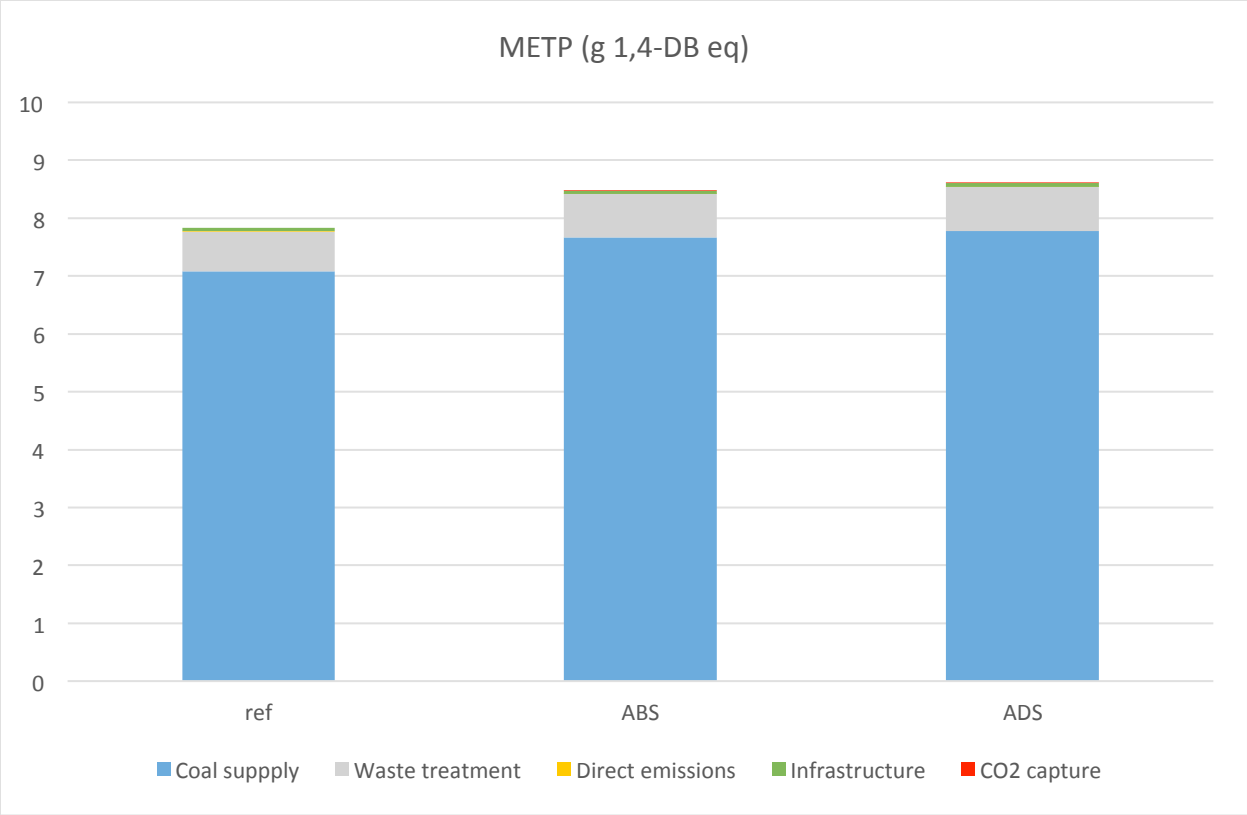

Figure 4.12 System area breakdown for environmental performance indicator: METP

A breakdown for the Marine Eco-Toxicity Potential (METP) of all system is presented in Figure 4.12. The total METP of the reference system is 7,8 g 1,4-DB eq. Of this 90% is on the account of coal supply. The process within the coal supply contributing the most is the disposal of spoil from coal mining to surface landfill, accounting for 90% of the METP caused by coal supply. The stressors associated with this contribution are a variety of heavy metals and carbon monoxide. For 9% the METP is caused by waste treatment, which is for 99% caused by the ash disposal process. Which, like the spoil disposal process stresses a variety of heavy metals and a little carbon monoxide.

For the CCS systems the same trend as for the FETP can be observed. An 8 and 10% increase to 8,5 and 8,6 g 1,4-DB eq for respectively the ABS and ADS system. The explanation for this trend is also the same as for the FETP. Namely, the energy penalty associated with the CCS units, which requires a higher coal input for the CCS systems.

5 SENSITIVITY ANALYSIS

5.1 Energy penalty ADS
5.2 Carbon capture rate

A sensitivity analysis on the two most uncertain parameters was performed. These are two technical parameters of the ADS system. Only the parameters of the ADS were selected because these are expected to improve in the future. The ABS system is a more mature technology, and assumed to be optimized to a higher degree already then the ADS configuration. For these ADS system there is reason to believe that the integration will be optimized, probably resulting a lower energy penalty and higher carbon recovery rate (Riboldi and Bolland 2015). The first parameter on which a sensitivity analysis is performed is the energy penalty, and the second is the CO_2 capture rate. For both analyses the results are presented in two graphs. The first graph shows the sensitivity on GWP, while the second shows the sensitivity on all other impact indicators.

5.1 Energy penalty ADS

For the energy penalty a variation of ±30% was chosen. The reason to choose for this is that the range is large enough to see what happens when the energy penalty of the ADS system would be lower than the energy penalty of the ABS system. The effect of varying the energy penalty is presented in Figure 5.1 for the GWP, and in Figure 5.2 for the other environmental indicators. In both graphs the result is compared with the performance ABS system. For the GWP a slight increase was found when the energy penalty increases. And the opposite effect was found when the energy penalty decreases. However, even when the energy penalty becomes lower than the one of the ABS system, the GWP will still be higher. The explanation for this unexpected result is that there is another factor influencing the GWP more than the energy penalty. This factor is the carbon capture rate. The influence of the carbon capture rate will be explained and discussed in the next paragraph.

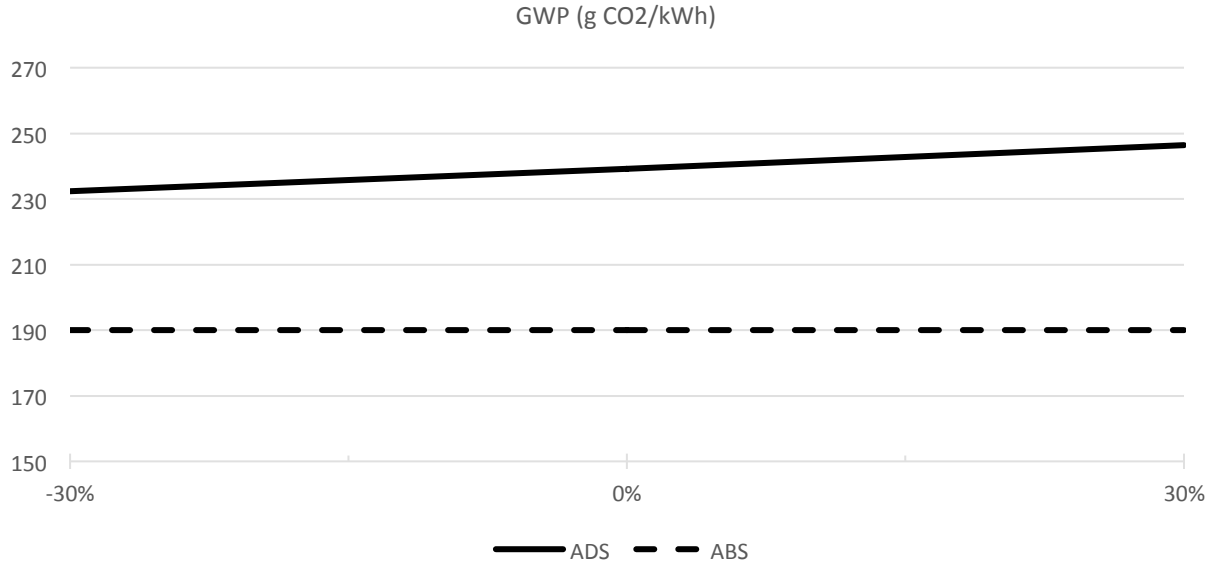

Figure 5.1 Sensitivity of energy penalty ADS on GWP compared to ABS

For the other environmental impact indicators, presented in Figure 5.2, a different result was found. The graph shows all the impact indicators relative to the original energy penalty of 0,15 kWh/kg CO_2.

When the energy penalty decreases with approximately 17%, and thereby becomes lower than the energy penalty of the ABS system, all the environmental impacts become lower than the ones from the ABS system. Notable is that all nine environmental indicators follow the same trend, and are therefore only visible as one line in the graph. The nine impact indicators of the ABS system are also nearly aligned as one line.

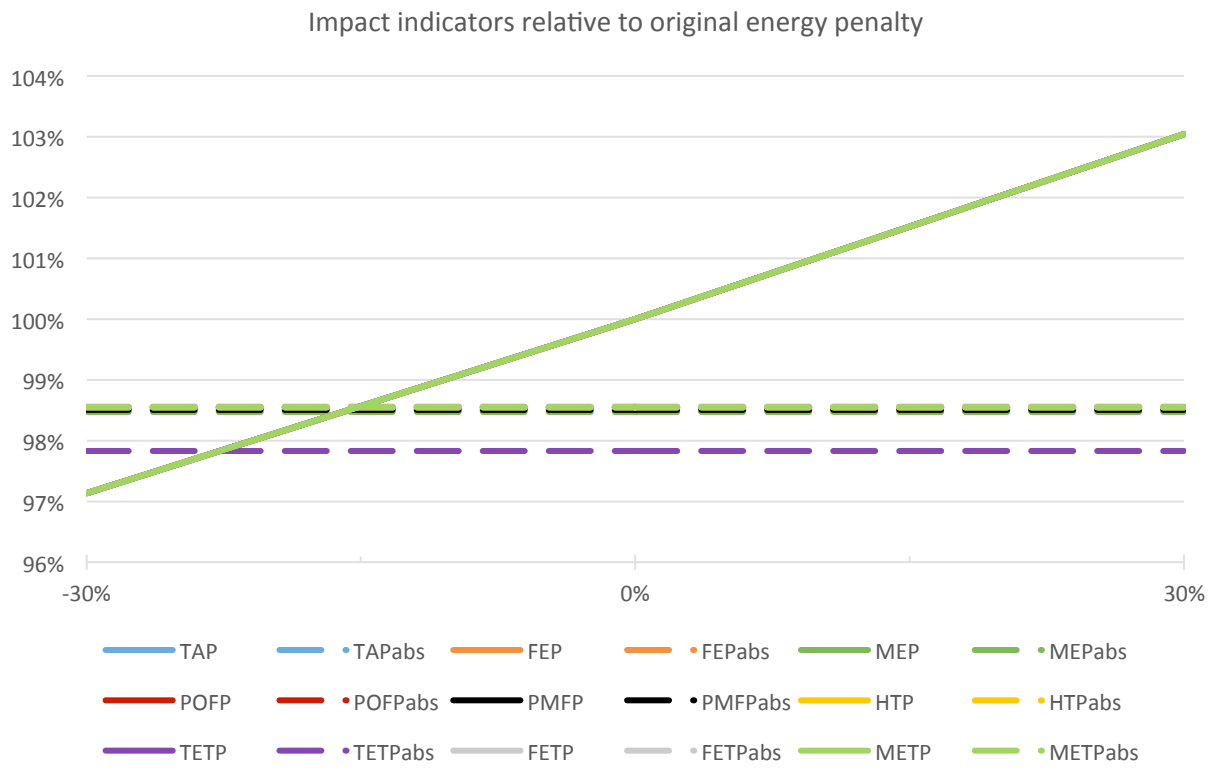

Figure 5.2 Sensitivity of energy penalty ADS on environmental impact indicators compared to ABS

5.2 Carbon capture rate

For the sensitivity analysis on the carbon capture rate a variation of ±15%, allowing the carbon capture rate of the ADS system to become higher than the one of the ABS system without passing the 100% carbon capture. The results of the sensitivity analyses on the GWP are presented in Figure 5.3 and on the other impact indicators in Figure 5.4.

A trend in which the GWP decreases, when the carbon capture rate increases was found. At the point where the carbon capture rate of the ADS system exceeds the one from the ABS system, the GWP of the ADS system becomes lower than that of the ABS system. This turning point is reached at an increase of approximately 8% in carbon capture rate. In other words, when the carbon capture rate increases with 8% the ADS system would perform better than the ABS system in terms of GWP.

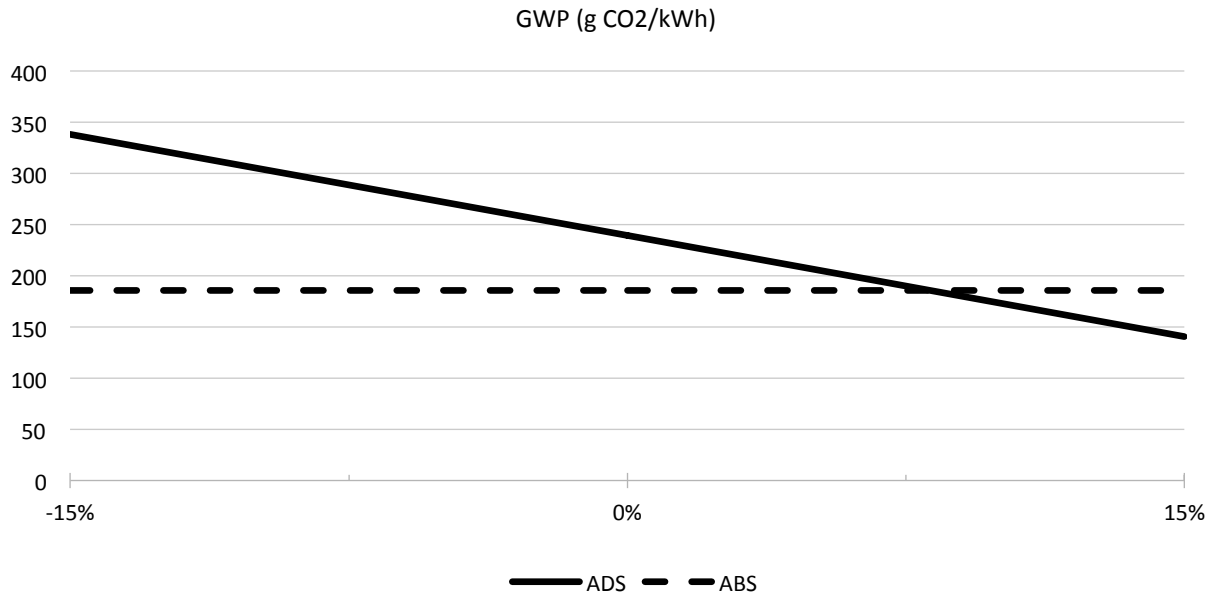

Figure 5.3 Sensitivity of carbon capture rate ADS on GWP compared to ABS

The sensitivity analysis of the carbon capture rate on the other impact indicators shows that there is no influence of carbon capture rate on the other impact indicators. Like the sensitivity analysis on energy penalty the results are presented relative to the impacts related to the original carbon capture rate. And again all the impact indicators show the same relation to the parameter varied. Which in this case is a correlation of 0.

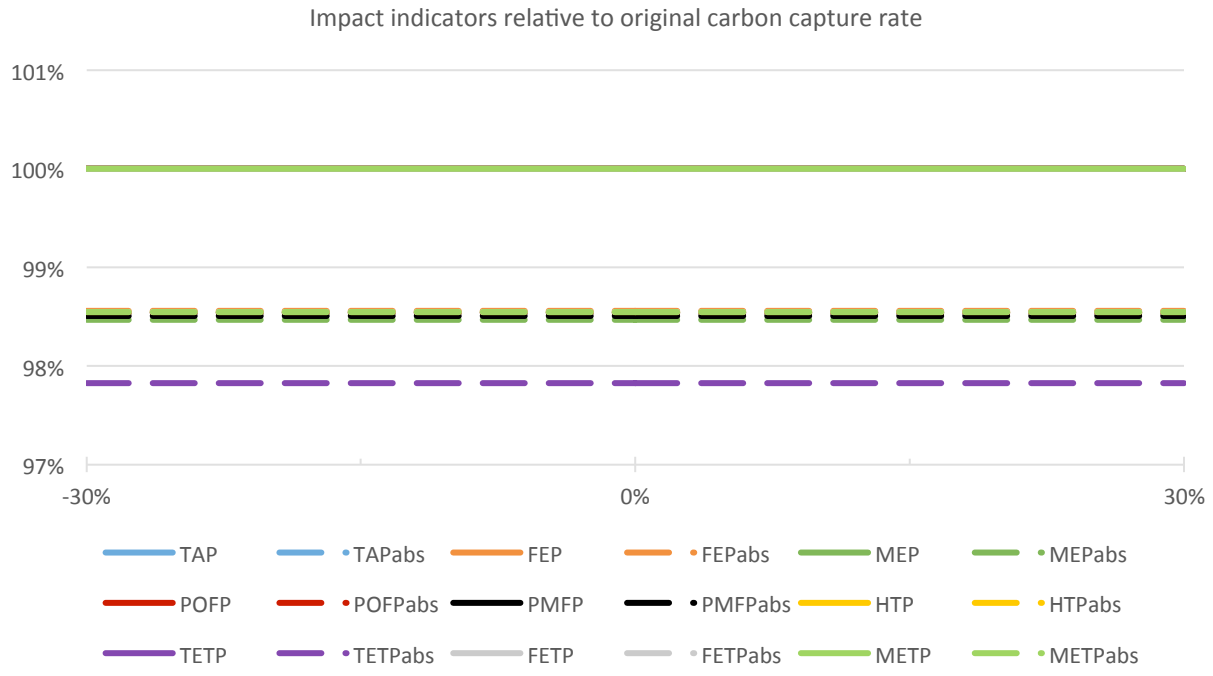

Figure 5.4 Sensitivity of Carbon capture rate ADS on environmental impact indicators compared to ABS

6 CONCLUSIONS

The environmental performances of the three systems were assed based on the environmental performance indicators. The scores on the ten environmental performance indicators of the systems were presented and compared in Chapter 4, which led to the following five conclusions:

(1) The global warming potential of the ABS and ADS system is significantly lower (73% and 80% respectively) than that of the reference system. The decrease of GWP is due to the CCS incorporated in these systems. For the other nine environmental indicators the opposite effect was observed. For these indicators the reference system slightly outperforms the ABS and ADS system. The main reason for this is the energy penalty associated with the CCS systems.

(2) Due to a difference the technical parameters: energy penalty, and carbon recovery rate, the ABS systems slightly outperforms the ADS system for all environmental indicators. Therefore the conclusion could be drawn that the ABS system has a slightly better environmental performance than the ADS system, based on the technical parameters used in this study.

To analyse the contribution of different steps of the total value chain to the overall environmental performance of the different system, a contribution analysis of each environmental performance was made and presented in Chapter 4. Based on these results the following to conclusions can be drawn:

(3) The contribution analysis showed large similarities between the three systems for all environmental indicators except GWP. In the GWP a difference was found between the reference systems and the CCS system due to the carbon capture, which resulted in large negative CO_2 emissions.

(4) Besides the similarities in value chain contribution between systems, a similarity between environmental indicators was found too. For all indicators except GWP the largest contributor was always ‘coal supply’ (78-98%). Since the amount of coal input is determined by the plant efficiency, the conclusion can be drawn that there is a relation between the plant efficiency and environmental performance of the system.

Since there is reason to believe that the technical parameters of the ADS system will improve a sensitivity analysis on the energy penalty and the carbon capture rate of the ADS system was performed (Chapter 4). The sensitivity analysis showed how much the previously mentioned parameters have to improve to affect the conclusions. This lead to the final conclusion:

(5) When the energy penalty of the ADS system decreases with 17%, all the environmental performance indicators except GWP of the ADS system will outperform the ABS system. To outperform the GWP the carbon capture rate of the ADS system has to increase with more than 8%.

7 DISCUSSION

This chapter addresses the robustness of this study. First a reflection on the methods is given, including the limitations of the study. Followed by a reflection on the results, and closing with the contribution to the scientific society and suggestions for further research.

7.1 Reflection on methods and results

The LCA method provides the opportunity to get a very detailed overview of the environmental impacts of a system, including the option to specify what processes the impacts are coming from. However to get these results the method requires very detailed information on the mechanisms of the system. When mechanism or not well understood or simplified, this could lead to model uncertainty (Guldbrandsson and Bergmark 2012). In this study a simplified system was used, in which minor processes were left out, and most of the included processes were simplified. The reason for this was to reduce the level of complexity and to save time. Consequences of this are model uncertainty, which was recognized and accepted. However, attempts to quantify this uncertainty failed. This could be considered a limitation of the study.

Another form of uncertainty that was identified relates to the uncertainty in the data, which is called parameter uncertainty (Guldbrandsson and Bergmark 2012). All data includes a measure of uncertainty, which could be quantified analytically or by simulation. This study did not attempt to quantify this parameter uncertainty because of a lack of time. However the uncertainty and effect that it could have on the outcomes is recognized. This could be considered a second limitation of the study. For the technical parameters energy penalty and carbon capture rate of the ADS system a sensitivity analysis was performed. Although, this analysis doesn't show the uncertainty of the parameters, it provides insight in how much the parameters must change to change the conclusions of the study.

A remarkable result is the large contribution of coal accounting for 78-98% for all the environmental indicators except GWP. The result of this large contribution is that the actual difference caused by the different CCS system become negligible (except for the energy penalty). The value chain of coal basically 'overshadows' the environmental performance of the actual CCS systems. For the systems studied this might not be relevant, though for the comparison of the CCS technologies it is. This could also be considered a limitation of the study.

7.2 Scientific contribution and future research

This study provided the first environmental assessment of a PSA pre combustion CCS system integrated in a full scale IGCC power plant. This assessment could be used when comparing different CCS technologies on an environmental level.

For future research the systems could be compared better by doing the same environmental assessment, only with a different fuel (e.g. biomass). This could eliminate the 'overshadowing' effect of the coal value chain that was discussed in the text above. Future studies could also attempt to quantify the uncertainties that were identified for this research. Or future studies could focus on an environmental assessment of PSA pre combustion CCS in an IGCC based on a different technical paper and compare those results with this study.

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