Report on an integrated environmental performance assessment of power plants with CCS

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1. Executive Summary

Life cycle inventory, analysis, and valuation of the environmental performance of Carbon Capture and Storage chains are important inputs for development, implementation, and policy evaluation of technologies in order to minimize environmental trade-offs to other industries or countries.

This study assesses the environmental performance of power plants with CCS over their complete life cycle in a transparent way by using the environmental performance tool, developed within WP4.3. The user can build one or multiple chains simultaneously to allow direct comparison. The tool uses a well-accepted methodology (ReCiPe) by default for calculating the environmental impacts. Monetization of the impacts is possible to express the environmental costs across the life cycle. Such analyses may show under what conditions the benefits of CCS outweigh the trade-offs, from different stakeholder perspectives

Findings of the work indicate that the implementation of CCS will lead to trade-offs between climate change and all other themes. The CO_2 emissions will be reduced due to CCS, but all other impacts will increase. The valuation of environmental themes, either via monetization or another method, thus determines whether the net balance between the advantages of CCS and its trade-offs are positive or negative.

Fuel extraction, logistics and the conversion and capture process are the three dominating steps in the power generation chain. Except for the gas fired chain, in which the logistics have negligible impacts as the gas mainly originates from the Netherlands. The implementation of CCS will lead to a further shift in the significance of environmental impacts from the conversion and capture step towards the fuel extraction and logistics step. This shows the importance of having an integrated view on the life cycle of a power generating technology as well as of taking into account multiple environmental themes.

The use of biomass reduces the impacts of power production to climate change due to the CO_2 uptake from the atmosphere by biomass growth. The overall environmental costs increase by an growing amount of biomass. This is mainly caused by the impacts from the use of land for the biomass cultivation. The monetary valuation of this impact has a large uncertainty.

The natural gas chains clearly outperform the coal fired and biomass co-fired chains. This is mainly due to fuel extraction and logistics step of the natural gas chain, which have far less impacts than the corresponding steps in the coal and biomass chains. The overall environmental costs for the PC and IGCC chains are similar.

The results of the Environmental Performance Tool EPT should not be used to place a definite value (in terms of absolute environmental damage costs) to a certain technology or life cycle. It should be used to facilitate the discussion on:

- How to compare climate change with other environmental concerns by different stakeholders?
- Where in the full life cycle are opportunities to further improve the environmental performance and should efforts be devoted to?
- Does the EPT flag issues regarding the environmental performance that require clarification or refinement of the research?

Distribution List

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

Version	Nr of pages	Short description of change	Pages
See header	1 - 96	Final draft V2	96

Table of Content

2. Applicable/Reference documents and Abbreviations

2.1. Applicable Documents

	Title	Doc nr	Version
AD-01d	Toezegging CATO-2b	FES10036GXDU	2010.08.05
AD-01f	Besluit wijziging project CATO2b	FES1003AQ1FU	2010.09.21
AD-02a	Consortium Agreement	CATO-2-CA	2009.09.07
AD-02b	CATO-2 Consortium Agreement	CATO-2-CA	2010.09.09
AD-03h	Program Plan 2014	CATO2-WP0.A-D03	2013.12.29

2.2. Reference Documents

	Title	Doc nr	Version
RD-01			

2.3. Abbreviations

ALOP	Agricultural Land Occupation
a.r.	As received, without accounting for preparative treatments of the fuel (such as drying and grinding).
ASU	Air Separation Unit
CCS	Carbon Capture and Storage
ESP	Electrostatic Precipitator
FDP	Fossil Depletion
FEP	Freshwater Eutrophication
FETPinf	Freshwater Ecotoxicity
FGD	Flue Gas Desulphurization
GWP100	Climate Change
HTPinf	Human Toxicity
HHV	Higher Heating Value
IRP_HE	Ionising Radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating Value
MDP	Metal Depletion
MEP	Marine Eutrophication
METPinf	Marine Ecotoxicity
NLTP	Natural Land Transformation
NO_x	Nitrogen Oxides
ODPinf	Ozone Depletion
PM	Particulate Matter
PMFP	Particulate Matter Formation
POFP	Photochemical Oxidant Formation
SCR	Selective Catalytic Reduction
SEA	Strategic Environmental impact Assessment
SO_x	Sulphur Oxides
TAP100	Terrestrial Acidification
TETPinf	Terrestrial Ecotoxicity
ULOP	Urban Land Occupation
WDP	Water Depletion

3. Introduction

3.1. Background

Life cycle inventory, analysis, and valuation of the environmental performance of Carbon Capture and Storage (CCS) chains are important inputs for implementation, development and policy evaluation of technologies in order to minimized environmental trade-offs to other industries or countries. However, state of the art environmental performance assessments of CCS chains to date are not satisfactory (Corsten et al, 2013). They have been executed for only a few capture technologies and solvents, lack possibly important toxic emissions and waste, and are surrounded by large uncertainties due to a lack of public available measurements.

Furthermore, integration of monetization and weighting factors, based on current data and public acceptance, is needed to execute a strategic environmental performance assessment across the whole chain of CCS in which different environmental aspects for different technologies can be compared.

Work package 4.3 aims to assess the environmental performance of CCS technologies over the complete life cycle, to deepen insights of all CATO2 partners in the other (non-CO_2) environmental aspects of CCS in general and of capture in particular. WP 4.3 does this by enlarging the amount of available and accessible data, and to provide input that would be required to carry out a strategic environmental impact assessment (SEA) for CCS in the Netherlands. Improved insights into the environmental performance of CCS technologies may help both policy makers and the public at large, to better understand the implications of CCS technologies, and therefore support public communication.

3.2. Objective

This deliverable aims to assess the environmental performance of power plants with CCS over its complete life cycle. The impacts of the various steps in the CCS chain, from fuel extraction to CO_2 storage will be assessed in a transparent way by using the environmental performance tool (Koornneef et al., 2012).

3.3. Reading instruction

Chapter 4 - Approach - describes the methodology of the assessment used in this study.
Chapter 5 - Definition of CCS chains - describes the CCS reference chains.
Chapter 6 - Assessment of CCS chains - describe the environmental assessment of the individual CCS chains and compare the results, including the scenarios & sensitivity analysis.
Chapter 7 - Conclusions & recommendations - describes the conclusions and recommendations based on the study.

4. Approach

4.1. Overall Methodology

Figure 4-1 depict the overall methodology used in this deliverable.. The first step comprehends the definition of reference CCS chains. These CCS chains are described in detail in chapter 5. In the second step, the data is collected for the various steps in the reference CCS chains. This data is provided as input in the environmental performance tool. The inventory of data has been published in deliverable D07 (Horssen et al., 2013). The environmental performance tool, described in the Paragraph 4.2, is used to assess the environmental impacts of the CCS chains. In the scenario analysis, an assessment of the robustness of the results to y to the selection of fuel, extraction location and transport and to conversion and capture technologies is assessed. Finally, outcomes of the implementation plan (produced in WP2.4) are used as to assess the impacts of future CCS scenarios.

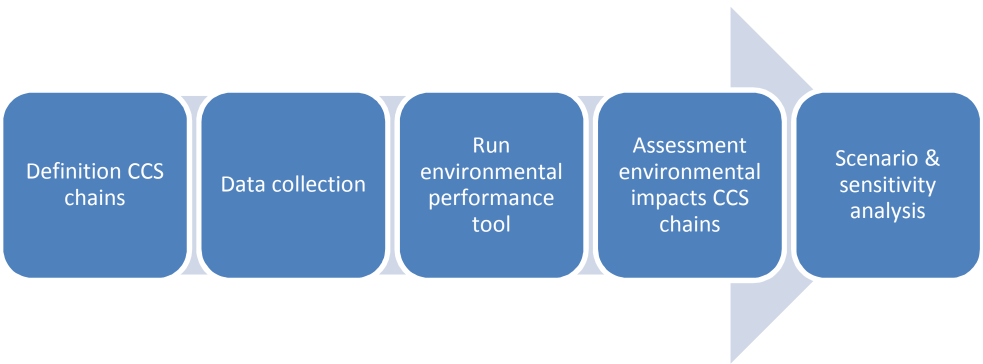


Figure 4-1 Methodology to assess the environmental performance of CCS chains

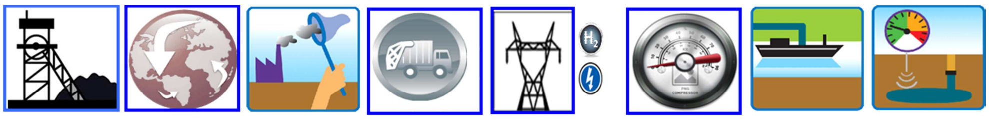
4.2. General description of Environmental Performance Tool

A *Strategic Environmental Performance Tool* has been developed to conduct environmental performance assessments for CCS chains (WP4.3-D06b). The life cycle of a CCS chain comprises nine steps in this tool:

1. Fuel extraction
2. Fuel logistics
3. Conversion and capture of CO_2
4. Waste from energy conversion
5. Waste from capture of CO_2
6. Distribution of the energy carrier
7. CO_2 compression
8. CO_2 transport
9. CO_2 storage

A CCS chain - or *scenario* as it is called in the tool - is constructed by choosing a specific activity per step. An example of building a CCS chain can be seen in Figure 4-2. Information on the environmental performance for each step is defined in the tool (or can be added or modified by the user if needed). The tool calculates the environmental performance of the whole chain and also reports the results per step of the life cycle. Various chains can be built and the results can be compared based on the user's preferences. The basis of comparison - the functional unit – is either GJ_{input} or MWh_{output}.

The results can be shown by environmental theme (e.g. climate change, acidification, fossil depletion etc.) for the whole chain or per step. In addition, it is possible to attach weighting factors to environmental themes and obtain in this way an overall score for the selected CCS chain(s). The tool allows including a number of weighting methodologies, including economic valuation. Alternatively, the user can also define its own weighting set.



Fuel Extraction	Fuel logistics	Conversion and CO2 capture	Waste from Conversion & Capture	Distribution of energy carrier	CO2 Compression	CO2 Transport	CO2 Storage

Lot of combinations possible, for example:

•Coal (Dutch supply mix)	•Ship oceanic + inland	•Pulverized coal + post combustion capture	•Reclaimer waste from post-combustion capture	•General distribution	•Electric (from power plant)	•Pipeline onshore	•Hydro-carbon (onshore)

Figure 4-2 Overview of steps in the life cycle for power generation with and without CCS.

A general overview of how the tool works is graphically presented in Figure 4-3. A tool manual is given in Annex B. Briefly, the user basically has to walk through three steps when using the tool.

1. The user opens the Excel interface of the tool and reviews the environmental performance data on each step in the life cycle of CCS chains that are already defined in the database.
2. The user selects or builds its own scenario (CCS chain from cradle to grave) in the Excel interface of the tool and runs the scenarios with the tool.
3. An export file is generated in MS Excel that allows analysing and comparing the performance of the scenarios. In this step also major assumptions can be changed to allow for sensitivity analysis.

The basic design and features of the tool are explained in the sections below.

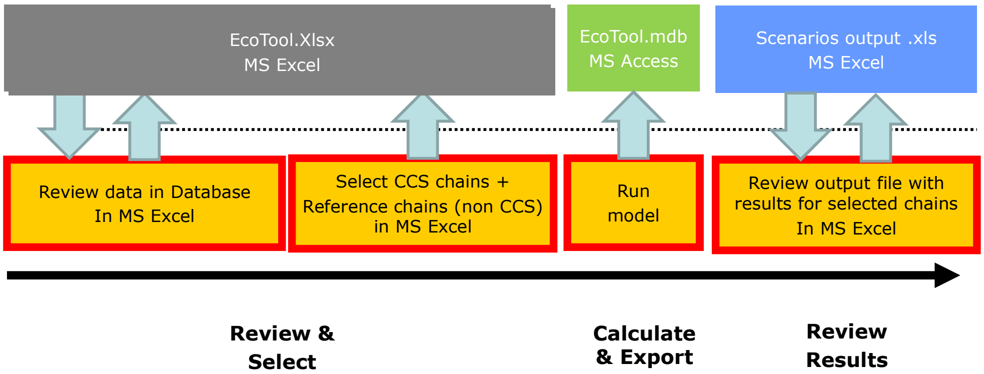


Figure 4-3 Schematic overview of the general workflow to review and change the database and allow general users to assess the environmental performance of CCS and reference chains

4.3. Database – data types

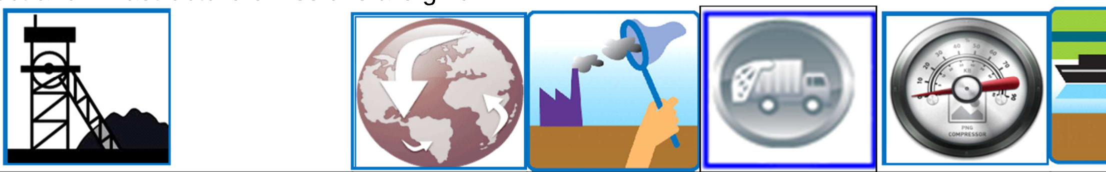
An environmental performance database of energy conversion supply chains including carbon capture and storage has been designed in MS Access. The database has an MS Excel overlay to ease data entry, calculations and review. The database functions as a platform, where the data on the environmental performance of steps in the life cycle of a power plant with or without CCS is gathered, prepared and stored.

The information feeding the database is per chain element gathered from (LCA) literature, existing life cycle inventory databases e.g. (EcoInvent, 2010) and - where possible - results of international emission measurement programmes at CCS pilot/demonstration plants. However, the amount of publicly available data on environmental performance of pilot and demonstration plants is currently limited. Given the uncertainty of current data, the database allows to include uncertainty ranges for data entries. In the tool this feature can be used to run Monte Carlo analyses.

As commonly used in life cycle assessment, the environmental impacts of a certain intervention are split up into the direct, indirect and infrastructure impacts. The definitions used in the environmental performance tool and database are:

- Environmental intervention: exchange between environmental compartments (also between economy and environment) including resource extraction, emissions to the air, water, or soil, and aspects of land use.
- Direct intervention: intervention occurring during the production processes of the product or service (e.g. electricity production).
- Indirect intervention: intervention due to the production and transport of (half) products (or raw materials) and energy carriers required for the steps in the life cycle
- Infrastructure interventions: interventions allocated to processes that provide the infrastructure, or capital goods, for the various processes in the life cycle

Examples of direct, indirect and infrastructure emissions are given in



	Fuel Extraction			Fuel logistics	Conversion and CO_2 capture	Waste from conversion and capture	CO_2 Compression	CO
Direct	Coal -Direct emissions (CO, particulates, coal mine methane etc.) -On site emissions due to fossil fuel conversion	Gas -On site emissions due to fossil fuel conversion -Emissions from production of natural gas: fugitive methane leakage, flaring, etc	Bio direct emissions fossil fuel use for Harvesting/ growing Milling/Bio Pre-treatment (pellet)	Emissions from burning transport fuels (e.g. diesel/bunker fuel) for long distance transport of coal, gas and biomass. Gas: pipelines fugitive emissions and emissions from fossil fuel conversion booster/compression.	Emissions on site (incl deNOx, deSOx, water treatment/intake), including emissions that can be allocated to compression energy use	-emissions from waste treatment of capture and conversion	-CO_2 fugitive leakage - emissions due to fossil fuel conversion if gas fired compressor is used	-CO_2 f -Boost emissi pump -Emiss shippi consu
Indirect	Supply chain emissions of consumptive materials used in process Emission from allocated energy (electricity) use							
			-Emissions due direct and indirect land use change (LUC and ILUC) -Transport of intermediates -Emission resulting from production use of fertilizers	Emission from allocated energy (electricity) use (not fuel combustion emissions for shipping/transport)	Emissions allocated to production of solvents		Emissions that can be allocated to compression energy use are included under direct and indirect emissions of conversion and capture (in the output file the emissions are allocated to compression)	
Infrastructure	Emissions allocated to hardware/infrastructure production/installation only!! (includes port, power plants, pipeline , compressor, trains, trucks, ship etc). Examples: Steel etc for ships and trains and rails, Material use for port and station construction							

Figure 4-4.

	Fuel Extraction			Fuel logistics	Conversion and CO_2 capture	Waste from conversion and capture	CO_2 Compression	CO_2 Transport	CO_2 Storage
Direct	Coal -Direct emissions (CO, particulates, coal mine methane etc.) -On site emissions due to fossil fuel conversion	Gas -On site emissions due to fossil fuel conversion -Emissions from production of natural gas: fugitive methane leakage, flaring, etc	Bio direct emissions fossil fuel use for Harvesting/ growing Milling/Bio Pre-treatment (pellet)	Emissions from burning transport fuels (e.g. diesel/bunker fuel) for long distance transport of coal, gas and biomass. Gas: pipelines fugitive emissions and emissions from fossil fuel conversion booster/compression.	Emissions on site (incl deNOx, deSOx, water treatment/intake), including emissions that can be allocated to compression energy use	-emissions from waste treatment of capture and conversion	-CO_2 fugitive leakage - emissions due to fossil fuel conversion if gas fired compressor is used	-CO_2 fugitive leakage -Booster station emission if gas fired pump -Emissions from shipping fuel consumption	-On site emissions due to fossil fuel conversion -Fugitive emissions (leakage)
Indirect	Supply chain emissions of consumptive materials used in process Emission from allocated energy (electricity) use								
			-Emissions due direct and indirect land use change (LUC and ILUC) -Transport of intermediates -Emission resulting from production use of fertilizers	Emission from allocated energy (electricity) use (not fuel combustion emissions for shipping/transport)	Emissions allocated to production of solvents		Emissions that can be allocated to compression energy use are included under direct and indirect emissions of conversion and capture (in the output file the emissions are allocated to compression)		
Infrastructure	Emissions allocated to hardware/infrastructure production/installation only!! (includes port, power plants, pipeline , compressor, trains, trucks, ship etc). Examples: Steel etc for ships and trains and rails, Material use for port and station construction								

Figure 4-4 Examples of direct, indirect and infrastructure emissions for the different steps in the value chain

4.4. Environmental themes

Life cycle inventory (LCI) data - such as data on emissions, water consumption, raw material use etc., - is used to estimate the scores of a certain CCS chain on a set of environmental impact categories. Several steps are required to make this possible. Characterization factors are used to add different LCI data into one common denominator, such as expressing methane emissions into CO_2 equivalents. The relevant LCI data is now grouped and characterized for multiple impact categories. The combined value of the LCI data into one denominator reflects the potential impact of an activity on a certain environmental category.

In the environmental performance tool, midpoint impact categories have been selected as the default method. ReCiPe (Goedkoop, 2009), which is the successor of midpoint method CML2000 and end-point method EcoIndicator 99 (Guinée, 2002), ise used. ReCiPe has a scientific basis, is commonly accepted, includes both midpoints and endpoints and has an extended set of scientifically validated valuation and weighing factors available. For the calculation of the environmental impacts, a midpoint approach is used, which is the recommended approach by the SETAC Working Group on Impact Assessment. The method distinguishes a number of baseline impact categories which should be included in a comparative LCA. The midpoint impact categories are given in Table 4-1.

Table 4-1 Description of environmental themes included in the environmental performance tool, based on ReCiPe (Goedkoop, 2009)

Environmental theme	Unit	Description
Climate change	kg CO_2 eq	Uses commonly accepted CO2 equivalency factors published in the IPCC report 2007. Includes greenhouse gases (GHG): CO_2, CH_4, N_2O, CFCs, HCFCs, HALONs, etc.
Ozone depletion	kg CFC-11 eq	The characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting
Photochemical oxidant formation	kg NMVOC	substances Ozone is not directly emitted into the atmosphere, but it is formed as a result of photochemical reactions of NO_x and Non Methane Volatile Organic Compounds (NMVOCs). This formation process is more intense in summer. Ozone is a health hazard to humans because it can inflame airways and damage lungs. Ozone concentrations lead to an increased frequency and severity of humans with respiratory distress, such as asthma and Chronic Obstructive Pulmonary Diseases (COPD). Ozone formation is a non-linear process which depends on meteorological conditions and background concentrations of NO_x and NMVOCs
Particulate matter formation	kg PM_{10} eq	Fine Particulate Matter with a diameter of less than 10 μm (PM_{10}) represents a complex mixture of organic and inorganic substances. PM_{10} causes health problems as it reaches the upper part of the airways and lungs when inhaled. Secondary PM_{10} aerosols are formed in air from emissions of sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NOx) among others. The effects of chronic PM exposure on mortality life expectancy) seem to be attributable to $PM_{2.5}$ rather than to coarser particles. Particles with a diameter of 5–10 μm ($PM_{2.5–10}$), may have more visible impacts on respiratory morbidity PM has both anthropogenic and natural sources
Ionising radiation	kg U^{235} eq	The damage to Human Health related to the routine release of radioactive material to the environment
Terrestrial acidification	kg SO_2 eq	Atmospheric deposition of inorganic substances, such as sulfates, nitrates, and phosphates, cause a change in acidity in the soil. For almost all plant species there is a clearly defined optimum of acidity. A serious deviation from this optimum is harmful for that specific kind of species and is referred to as acidification
Freshwater eutrophication Marine eutrophication	kg P eq kg N eq	Aquatic eutrophication can be defined as nutrient enrichment of the aquatic environment. Eutrophication in inland waters as a result of human activities is one of the major factors that determine its ecological quality. On the European continent it generally ranks higher in severity of water pollution than the emission of toxic substances. The long-range character of nutrient enrichment, either through air or rivers, implies that both inland and marine waters are subject to this form of water pollution, although due to different sources and substances and with varying impacts.

Terrestrial ecotoxicity Freshwater ecotoxicity Marine ecotoxicity Human toxicity	kg 1,4-DB eq	The characterisation factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. Fate and exposure factors can be calculated by means of 'evaluative' multimedia fate and exposure models, while effect factors can be derived from toxicity data on human beings and laboratory animals.
Agricultural land occupation Urban land occupation Natural land transformation	m^2*a m^2	The land use impact category reflects the damage to ecosystems due to the effects of occupation and transformation of land. Although there are many links between the way land is used and the loss of biodiversity, we concentrate on the following mechanisms: 1. occupation of a certain area of land during a certain time; 2. transformation of a certain area of land. Both mechanisms can be combined, often occupation follows a transformation, but often occupation occurs in an area that has already been converted (transformed).
Water depletion	m^3	Water is a scarce resource in many parts of the world and extracting water in a dry area can cause very significant damages to ecosystems and human health. This is a midpoint indicator that simply expresses the total amount of water use.
Metal depletion	kg Fe eq	The unit of this characterization factor is 1/$.yr, The method uses increased marginal costs as a result of mining the deposit and the slope (relation grade-yield) divided by availability as midpoint indicator. Similar to all other midpoint impact categories the midpoints are presented as a substance equivalent, in this case iron equivalents.
Fossil depletion	kg oil eq	The term fossil fuel refers to a group of resources that contain hydrocarbons. The group ranges from volatile materials (like methane), to liquid petrol, to non-volatile materials (like coal). As reference resources is chosen: "Oil, crude, feedstock, 42 MJ per kg, in ground".

A more extended version, covering all impacts used in ReCiPe, is given in Figure 4-5. The figure shows the relationship between the Life Cycle Inventory (LCI) results and the mid-and endpoint indicators.

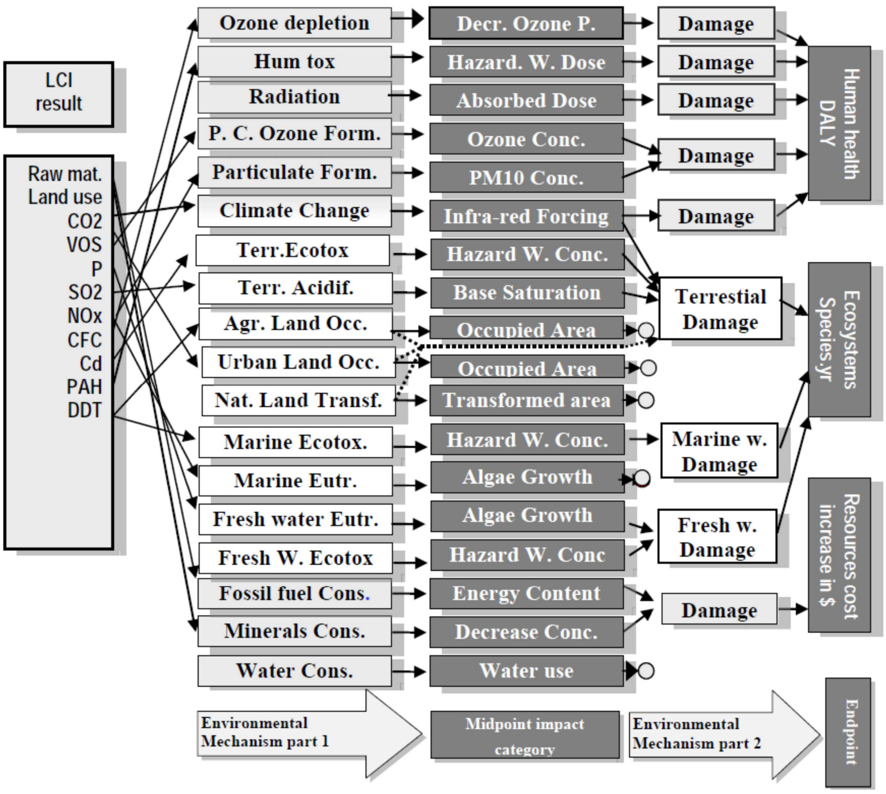


Figure 4-5 Relationship between LCI parameters (left), midpoint indicators (middle) and endpoint indicators (right) in (ReCiPe 2008)

4.5. Weighing

To enable comparison of various cases, the results of all impact categories relevant for life-cycle analysis needs to be converted into a similar unit. To that purpose, valuation of each impact category was desired. It has been decided to apply monetary valuation for the impact categories, referred to as monetization.

The monetary value of environmental impacts may be based on (De Bruyn et al, 2010):

- abatement costs: cost of the most expensive technique required to meet government targets
- damage costs: estimated damage occurring as a result of emissions and other changes in natural capital

As has been described by (Sleeswijk et al, 2010), valuation is a topic of hot debate within the scientific community. For example, according to the International Organization for Standardization (ISO), valuation may not be applied for comparative assertions disclosed to the public, because of its subjective and/or arbitrary character. It may also be argued that the intrinsic value of e.g. human life or nature cannot be expressed in terms of money (Sleeswijk et al, 2010).

Against these arguments, one has to keep in mind that LCA results being used in a decision process, various impact categories have to be weighed, by someone in some way, either implicit or explicit. Therefore, it is argued that valuation factors in that situation needs to be explicit and clear as this would make the decision making process transparent (Sleeswijk et al, 2010).

In this report, weighing set 2 from “Handboek Schaduwprijzen” (De Bruyn et al, 2010), has been used (see Table 4-1). This is basically a set of damage costs based on the NEEDS project. These costs are discounted over time. This set however, does not cover all impact categories, e.g. toxicity is excluded. A limited number of studies provide estimates for the external costs or shadow prices for other impact categories like eco-toxicity and depletion. The major sources used in this study for these categories are (Goedkoop et al, 2013) and two article series by TNO (Van Harmelen et al, 2004 and 2007).

For the metal and fossil depletion indicators, an approach based on (Goedkoop et al, 2013) has been applied. This means that external costs are based on a discounted surplus cost representing a hierarchist LCA. A hierarchist perspective seeks consensus, and the 100 year timeframe is the most frequently used, and in the ISO standards on LCA (14044) it has been referred. It also coincides with the view that impacts can be avoided with proper management, and that the choice on what to include is based on the level of (scientific) consensus. Because a certain level of adaptation is scientifically accepted but the ability of total adaptation is not being proved yet, we assume a mean adaptation.

For iron, as reference for the metal depletion indicator, the practical interpretation is that the consequence of extracting a kilogram of iron will cause a cost to society of 7 US$ cents when a 3% discount rate is used. For oil as the fossil depletion reference, they assume, based on IEA data, that up to 3000 Gbbl, oil production costs rise with 25 US$/bbl and from 3000 till 4500 Gbbl, the cost rise is 40 US$/bbl (Goedkoop et al, 2013). For fossil depletion, it is proposed to use the surplus cost for the up to 3000 Gbbl oil production. Note that the surplus cost method cannot be used to predict oil market prices, it only reflects fundamental increases in production costs, and at best it provides a lower limit of future oil prices.

Land transformation and water depletion are not monetized. However, a lot of attention has recently been given to water footprints (WFN, 2013) and published studies give insights into water consumption quantities related to products. Although impact assessments are reported, these are limited to quantification (water stress and water scarcity), while monetization is not addressed. An EU water framework Directive (WFP, 2013) exists with water sustainability objectives and reporting obligations for member states. Member states are obliged to report amongst other elements on incurred costs of river basin water management systems, but these are not suitable as indicator for water depletion costs. Based on this it was concluded not to monetize water depletion.

For each impact category, the mid-point estimate is given in Table 4-2. When two values are provided in the table, it means that the sources mentioned before provide different estimates. As they have been determined using different methodologies and are inherently uncertain, they can be considered as bandwidths rather than absolute values.

Table 4-2 Proposed monetisation values for the impact categories used in the CATO environmental performance tool

Impact categories		Unit	External costs (euro/unit)
climate change	GWP100	kg CO_2-Eq	0.025[a] or 0.05[bc]
ozone depletion	ODPinf	kg CFC-11-Eq	30.0[bc] or 39.1[a]
terrestrial acidification	TAP100	kg SO_2-Eq	0.638[a] or 4.0[bc]
freshwater eutrophication	FEP	kg P-Eq	1.78[a] or 27.6[bc]
marine eutrophication	MEP	kg N-Eq	12.5[a]
human toxicity	HTPinf	kg 1,4-DCB-Eq	0.0206[a] or 0.084[c]
photochemical oxidant formation	POFP	kg NMVOC	0.585[a] or 2.0[bc]
particulate matter formation	PMFP	kg PM_{10}-Eq	51.5[a]
terrestrial ecotoxicity	TETPinf	kg 1,4-DCB-Eq	1.28[c]
freshwater ecotoxicity	FETPinf	kg 1,4-DCB-Eq	0.03 or 0.04[c]
marine ecotoxicity	METPinf	kg 1,4-DCB-Eq	0.0001[c]
ionising radiation	IRP_HE	kg U_{235}-Eq	0.0425[a]
agricultural land occupation	ALOP	m^2a	0.585 or 0.64[a]
urban land occupation	ULOP	m^2a	0.78[a]
natural land transformation	NLTP	m^2	0[d]
water depletion	WDP	m^3	NA
metal depletion	MDP	kg Fe-Eq	0.0596[d]
fossil depletion	FDP	kg oil-Eq	0.0433[d]

Sources : [a] De Bruyn et al (2010), Handboek Schaduwprijzen, tabel 22 en 43, CE Delft, March 2010
[b] Van Harmelen et al (2004), The price of toxicity, tabel 7, TNO, 2004
[c] Van Harmelen et al (2007), The price of toxicity. Methodology for the assessment of shadow prices for human toxicity, ecotoxicity and abiotic depletion, table 4.5, 2007
[d] Goedkoop et al (2013), ReCiPe 2008, tabel 12.2, VROM, May 2013

Based on this table, the following valuation series are available in the analysis tool Table 4-3. Series A is based on CE Delft and Pré Consultants (De Bruyn et al, 2010; Goedkoop et al, 2013). Series B is based on TNO and Pré Consultants (Van Harmelen et al., 2004, 2007; Goedkoop et al, 2013). Series C is the highest valuation for Climate Change and lowest valuations for other impact categories. Series D the lowest valuation for Climate Change and highest valuations for other impact categories. The user is able to adjust the valuations accordingly. For series C, the user may consider to enter the highest price needed for CCS being attractive. For series D, the user may consider to enter the current ETS price. Series E is a complete set of shadow prices, covering all environmental themes as far as available. It is using the most recent set of shadow prices based on ReCiPe (De Bruyn et al, 2010; Goedkoop et al, 2013) with the ecotoxicity prices developed by TNO (van Harmelen, 2007).

Table 4-3 Proposed monetisation values for the impact categories used in the Environmental performance Tool

Impact categories	Series A (euro/unit)	Series B (euro/unit)	Series C (euro/unit)	Series D (euro/unit)	Series E (euro/unit)
climate change	0.025	0.05	0.05	0.025	0.025
ozone depletion	39.1	30	30	39.1	39.1
terrestrial acidification	0.638	4	0.638	4	0.638
freshwater eutrophication	1.78	27.6	1.78	27.6	1.78
marine eutrophication	12.5	NA	12.5	12.5	12.5
human toxicity	0.0206	0.084	0.0206	0.084	0.0206
photochemical oxidant formation	0.585	2	0.585	2	0.585
particulate matter formation	51.5	NA	51.5	51.5	51.5
terrestrial ecotoxicity	NA	1.28	1.28	1.28	1.28
freshwater ecotoxicity	NA	0.04	0.03	0.04	0.04
marine ecotoxicity	NA	0.0001	0.0001	0.0001	0.0001
ionising radiation	0.0425	NA	0.0425	0.0425	0.0425
agricultural land occupation	0.64	NA	0.585	0.64	0.64
urban land occupation	0.78	NA	0.78	0.78	0.78
natural land transformation	0	0	0	0	0
water depletion	NA	NA	NA	NA	NA
metal depletion	0.0596	0.0596	0.0596	0.0596	0.0596
fossil depletion	0.0433	0.0433	0.0433	0.0433	0.0433

4.6. Power generating life cycles included in the study

The reference life cycles for power generation covered in the environmental performance tool are shown in Table 4-4. They include coal and gas fired power plants as well as the co-firing of 15 and 30 % wood pellets in a coal fired plant. Post and pre combustion carbon capture technologies are used in the study and compared with reference power plants without CCS. Detailed assumptions regarding each life cycle are described in Chapter 5.

Table 4-4 Overview of power generation life cycles in the study

Fuel	Capture Technology		
	No CCS	Post-combustion	Pre-combustion
Coal	X	X	X
Biomass co-firing (15 & 30 %)	X	X	X
Natural gas	X	X	

In this report, the individual chains are first assesses according the given methodology by using the environmental performance tool. Subsequently the results of the individual chains are compared. The comparison is made on the level of the whole chain, as well as on the level of fuel extraction and logistics and power generation and capture .

To assess the robustness of the results, variations in the fuel mix are made. For the gas fired plants the origin of the gas, the Netherlands or Russia, is varied. The composition of the coal import mixtures of different years, based on CBS statistics (Smekens & Plomp, 2013), are used to examine the sensitivity to the inputs.

Monetization of the impacts is used to compare the various chains in the assessment. The different sets of shadow prices, given in the report, are used to see whether and to what extend the choice affects the results.

4.7. Link to deployment scenarios

The environmental performance tool yields insights into the environmental performance and, after monetization, insights into potential environmental costs and benefits of deploying CCS in the power sector. Combining these insights with deployment scenarios for CCS towards 2050 in the Dutch power sector allows to roughly estimate the overall environmental costs and benefits of deploying CCS in the Dutch power sector.

In CATO2 WP 2.4.3 several deployment scenarios have been developed and modelled for the Dutch power sector. Here three illustrative and relatively extreme scenarios from that study have been used to demonstrate clearly the effects. The deployment scenarios modelled include a reference describing a scenario without (stringent) climate mitigation targets. It also includes two scenarios that have mitigation targets and actions in place for the Dutch power sector or that have a CO_2 price in place that stimulates the deployment of CCS (and other low carbon power supply options). Details on modelling set-up and assumptions will be provided in a separate (online) publication (Van den Broek et al., 2014).

Table 4-5 Overview of deployment scenarios

Scenario name	Summary
Reference	No CO_2 policy
CO_2 policy and price	Baseline scenario: based on the CO_2 price of IEA's World Energy Outlook (2012) 450 ppm scenario, but then with 5-year delay.
CO_2 bound	CO_2 cap instead of CO_2-price. As alternative a scenario is run with an upper CO_2 bound (-80% compared to 1990 in 2050)

This modelling exercise yields the amount of annual electricity production up to 2050, with a time resolution of five years. The scenarios show divergence in CCS deployment; most important differences are the timing, total amount and technologies deployed. These deployment scenarios are combined with the results of the Environmental Performance tool to estimate the overall environmental costs and benefits of deploying CCS in the Dutch power sector. This is schematically shown in Figure 4-6.

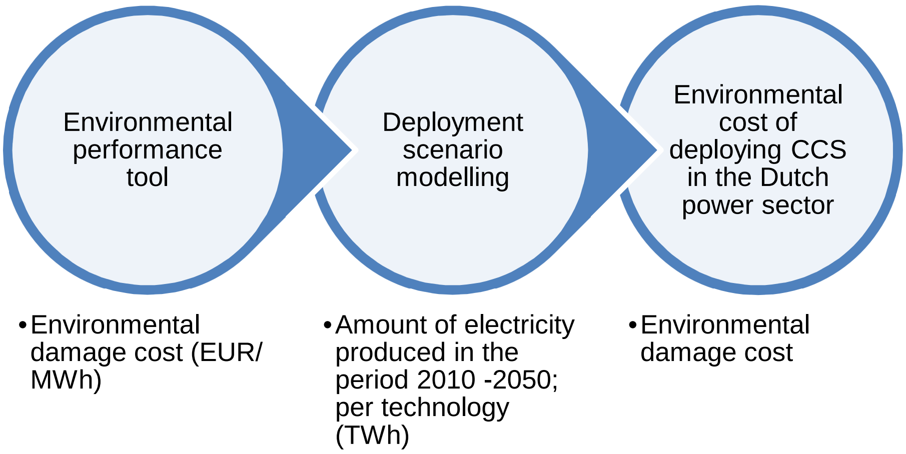


Figure 4-6 Schematic representation of combining the results of the Environmental Performance tool with results from Scenario modelling

It should be noted that the scenario modelling is employed in a modelling environment that works on the basis of cost-optimisation (i.e. Markal). This means that the model tries to find the least cost pathway to meet energy demand, CO_2 mitigation targets (or prices) and other boundary conditions. The environmental costs are not taken into account in this modelling environment.

In the scenario modelling different technologies are distinguished, see Table 4-6. These do not match directly with the technologies included in the environmental performance tool. The calculation of environmental costs is therefore simplified and technologies in the scenarios modelling are matched with technologies assessed in the environmental performance tool, see Table 4-6.

The environmental damage cost of nuclear and renewable power generation are not included and this should be carefully taken into account when reviewing the results in section 6.7. Other coarse assumptions that should be taken into account are:

- Static technology performance is assumed: technology developments are likely to decrease environmental impacts over time, but this trend is not included in the environmental performance tool.
- No distinction has been made between newly built power plants with CCS and retrofit of existing power plants in the environmental performance tool.

Table 4-6 Technologies included in scenario modelling matched with those included in the Environmental Performance Tool (EPT)

Technology in scenario modelling	Technology as included in the EPT
IGCC	IGCC (100% coal) no CCS
IGCC with CCS	IGCC (100% coal) + CCS
IGCC retrofitted with CCS	IGCC (100% coal) + CCS
PC	PC (100% coal) no CCS
PC with CCS	PC (100% coal) + CCS
PC retrofitted with CCS	PC (100% coal) + CCS
CHP plant	NGCC without CCS
NGCC	NGCC without CCS
NGCC with CCS	NGCC with CCS
NGCC retrofitted with CCS	NGCC with CCS
Nuclear	no environmental damage costs assessed
Wind	no environmental damage costs assessed
PV	no environmental damage costs assessed
Other	no environmental damage costs assessed

5. Definition of CCS chains

In the following paragraphs the main characteristics and references of the CCS chains are described. All data on the environmental impacts (as described in the previous chapter) are included in the environmental performance tool, located at the WP4.3 sharepoint site (see CATO2-WP4.3-D03-v2010.09.02-Information-Exchange-Platform): https://ecity.tno.nl/sites/CATO2/WP4.3/default.aspx.

5.1. Up and downstream processes

The up and downstream processes for all chains are defined in the same way. They are described in the following paragraphs.

5.1.1. Upstream coal

The extraction and logistics of coal and co-firing wood pellets is considered in this section. The properties of the coal are assumed to match the properties of Illinois#6 coal, assuring a conservative estimation regarding the sulphur content of the coal, which is relatively high in this coal type (see Table 5-1). The coal production chain is assumed to be represented by the average Dutch coal import statistics (Smekens & Plomp, 2013), which indicate that the majority of the coal (73%) is imported from Colombia (see Appendix C). All country depending coal production and transportation data are extracted from the Ecoinvent database (EcoInvent, 2010).

Wood pellets are assumed to be produced from agricultural residues from Canada (Ecoinvent, 2010) and the fuel properties are derived from the Phyllis Database (ECN, 2013). Key characteristics of the coal and wood pellets are presented in Table 5-1.

Table 5-1 Fuel characteristics (ECN, 2013; NETL, 2012a).

Fuel	Coal	Wood pellets
Mass proportion (%, a.r.[1])		
Moisture content	11.12	3.50
Ash content	9.70	1.60
C	63.75	46.98
H	5.74	5.99
O	16.76	44.98
N	1.25	0.40
S	2.51	0.04
Cl	0.29	0.01
Hg	1.35 E-07	0.00
F	0.00	0.01
Se	1.5 E-06	9.8 E-07
Energy content (a.r.[1])		
HHV (MJ/kg)	27.14	18.91
LHV (MJ/kg)	25.88	17.60

1) As received (a.r.), without accounting for preparative treatments of the fuel (such as drying and grinding).

5.1.2. Upstream natural gas

The natural gas supply mix in the Netherlands is estimated based on domestic production and import statistics for the year 2011 from (CBS, 2013), (Eurostat, 2013) and (EL&I, 2012). In Table 5-2 the shares of natural gas from different origins, as well as the assumed transport distances, are shown based on (Wikipedia, 2013). All country depending natural gas extraction and transportation data are extracted from the (Ecoinvent, 2010) database. In these datasets methane leakage is assumed to be 0.23% per 1000 km for Russia and about 0.026% per 1000 km for the other countries (Dones et al., 2007). Because of the large differences in environmental impacts from natural gas transport in Russia compared to Western Europe, the dataset for natural transport in Germany is used for the transport of Russian natural gas outside of Russia.

Table 5-2 Natural gas extraction and transport assumptions

Origin	Share in supply mix (2011)	Transport distance (km)
Netherlands (onshore)	58%	200
Netherlands (offshore)	19%	350
Norway	14%	1000
United Kingdom	6%	800
Russia	2%	4000+1000

5.1.3. Downstream

The captured CO_2 stream is dehydrated and compressed to 15.3 MPa using an integrally geared compressor (NETL, 2012a; NETL, 2012b), resulting in a supercritical CO_2 stream containing over 99% CO_2 (NETL, 2012a; NETL, 2012b). The required energy for this compression is generated by the power plant itself and is already accounted for in the presented efficiency drop of the cases including CCS.

Total CO_2 captured varies among the different cases between 4.0-4.5 Mt/year. Required CO_2 transport pipeline infrastructure of 200 km (100 km transport to two different aquifers) is assumed, with an inlet pressure in the range of 11 to 15 MPa and capacity factor of 85% (Koornneef 2008, NETL, 2012a; NETL, 2012b). For this configuration, no booster stations are required and a pipeline made from typical carbon steel with a diameter of 0.41 m is sufficient (Knoope et al, 2013).Transporting CO_2 trough pipelines is very similar to transporting natural gas. The LCI data for offshore pipelines (Ecoinvent, 2010) are multiplied by scaling factors of 0.17 for CO_2 from a supercritical pulverised coal plant and 0.15 for CO_2 from an IGCC (Hertwich et al, 2013). CO_2 leakage of 3.5 kt (Koornneef et al, 2008) over the total lifetime of the pipeline of 30 years is assumed.

For the offshore storage of CO_2 (4.0-4.5 Mt/year), five wells (assuming a capacity of 1Mt CO2 /year per well (van den Broek et al, 2010)) with a depth of 3000 meter are considered (Koornneef et al., 2008). LCI data for offshore well exploration and production have been obtained from the Ecoinvent database (EcoInvent, 2010). Possible leakage of CO_2 from the reservoir has not been taken into account.

5.2. Coal post combustion

Table 5-3 and Figure 5-1 show the main characteristics of post combustion carbon capture technology using MEA, applied on a pulverised coal fired power plant.

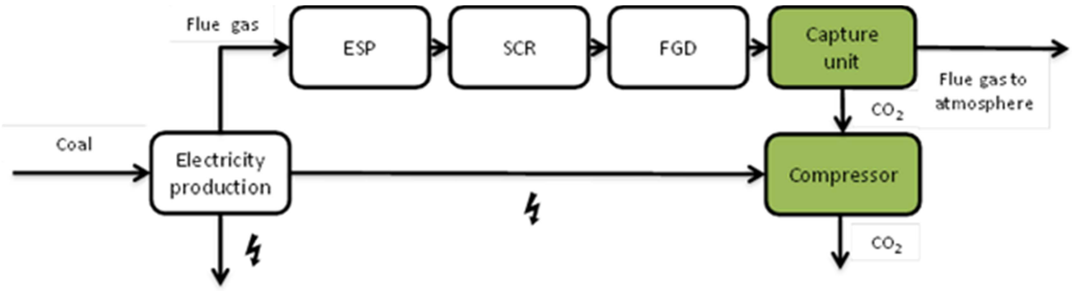


Figure 5-1 Schematic overview of PC process as assessed in this study. The green coloured box points out the new unit that is included when CCS is deployed

Table 5-3 Main assumptions on the performance of two scenarios based on coal fired power plants, with and without post combustion capture

Parameter	No CCS	CCS	Reference(s)
Fuel & Transport			
Fuel type	Hard coal		Koornneef (2008)
Origin	Dutch imported coal mix		Smekens & Plomp (2013)
Transport type	Ship, transoceanic freighter		Smekens & Plomp (2013)
Plant			
Power plant type	Pulverised coal power plant - State of the Art		Koornneef et al. (2008)
Capacity (MW_e)	600	455	Koornneef et al. (2008)
Capacity Factor (%)	90%	90%	Koornneef et al. (2008)
Efficiency (%) LHV	46%	35%	Koornneef et al. (2008)
Flue gas cleaning equipment	ESP, SCR and FGD	ESP, SCR and FGD	NETL (2012b)
Capture technology	-	Post combustion MEA	NETL (2012b)
Flue gas			
SO_2 removal (%) (FGD)	98	98	Koornneef et al. (2008)
NO_x removal (%)	85	85	Koornneef et al. (2008)
PM removal (%) (ESP +FGD)	99.98	99.98	Koornneef et al. (2008)
HCl removal (%)	98	98	Koornneef et al. (2008)
HF removal (%)	98	98	Koornneef et al. (2008)
Hg removal (%)	90	90	Koornneef et al. (2008)
DeNOx unit			Koornneef et al. (2008)
Ammonia consumption (kg/kg NOx removed)	0.35	0.35	Koornneef et al. (2008)
Ammonia emissions (kg/kg NOx removed)	0.004	0.004	Koornneef et al. (2008)

Parameter	No CCS	CCS	Reference(s)
Flue gas desulphurization unit			
Limestone consumption (kg/kg SO_2 removed)	1	1	Koornneef et al. (2008)
Gypsum production (kg/kg limestone)	1.85	1.85	Koornneef et al. (2008)
Carbon capture			
CO_2 removal (%)	-	90	Koornneef et al. (2008)
SO_2 removal (%)		90	Koornneef et al. (2008)
NO_x removal (%)		1.25	Koornneef et al. (2008)
HCl removal (%)		95	Koornneef et al. (2008)
HF removal (%)		90	Koornneef et al. (2008)
PM removal (%)		50	Koornneef et al. (2008)
MEA consumption (kg/t CO2 captured)		2.34	Koornneef et al. (2008)
NH_3 emission (kg/t CO_2 captured)		0.21	Koornneef et al. (2008)
Compression			
Compression	-	Electric, from coal power plant	Koornneef et al. (2008)
Compression outlet pressure	-	110 Bar	Koornneef et al. (2008)
Compression energy requirement	-	111 kWh/ ton (electricity from power plant with capture)	Koornneef et al. (2008)

Two cases are assessed:

- The reference case without CCS is a state-of-the-art ultra-supercritical pulverized coal fired power plant. This power plant can be considered best available technology at present for firing coal.
- The case with CCS: a state-of-the-art coal fired power plant equipped with a post-combustion capture facility based on chemical absorption of CO_2 with monoethanolamine (MEA). The CCS chain further comprises compression, transport and underground storage of the CO_2.

The processes investigated in our assessment are depicted in Figure 5-2. For each process the full life cycle is considered where possible. Consequently, also direct, indirect and infrastructure emissions are included in the analysis[1]. The primary process in the electricity generation chain is the combustion process for which primarily coal supply and the power plant infrastructure are needed. Outputs of this process are heat and electricity (see green arrows), waste (bottom and fly ash) (see blue arrows) and flue gas.

The flue gas is fed into the electrostatic precipitator (ESP), followed by a selective catalytic reduction unit (SCR) and flue gas desulphurization section (FGD) where particulate matter (PM) and gaseous pollutants (NO_x and SO_x) are removed, respectively. These processes require material inputs (ammonia and limestone), and generate by-products and wastes (gypsum and fly ash) and emissions to environmental compartments (see red arrows). The flue gas emitted by the stack still contains environmental pollutants. Also, waste water effluent from the power plant is released into water bodies with potential environmental impacts.

Main performance parameters for the two cases are given in Table 5-3. This includes removal efficiencies assumed for the various flue gas cleaning technologies (including CO_2 removal). More detailed assumptions can be found in (Koornneef, 2008).

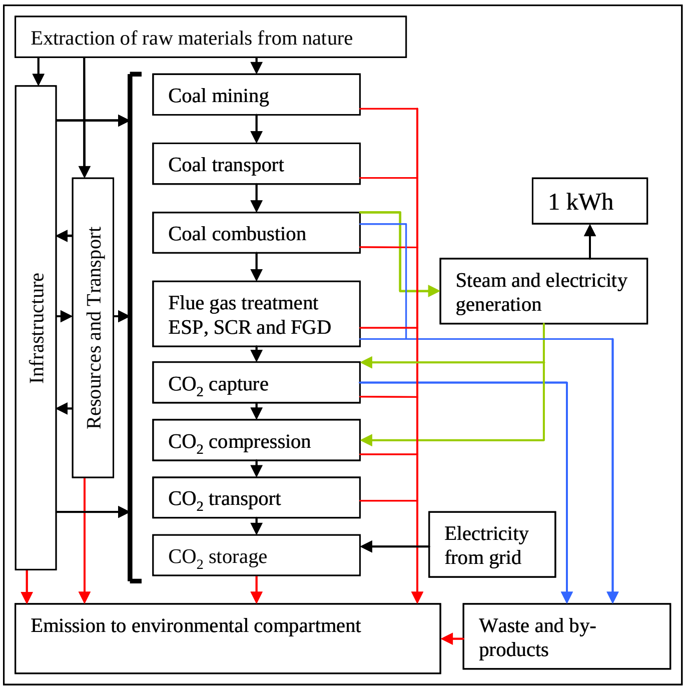


Figure 5-2 Product system for the coal fired power plant with post-combustion capture

[1] Direct, indirect and infrastructure emissions are not separately reported for these two cases.

5.3. NGCC post combustion

A natural gas combined cycle (NGCC) power plant is considered, with the possibility of post combustion capture using the solvent Monoethanolamine (MEA). A schematic overview of the different process steps is shown in Figure 5-3. Table 5-4 shows the main characteristics of the process.

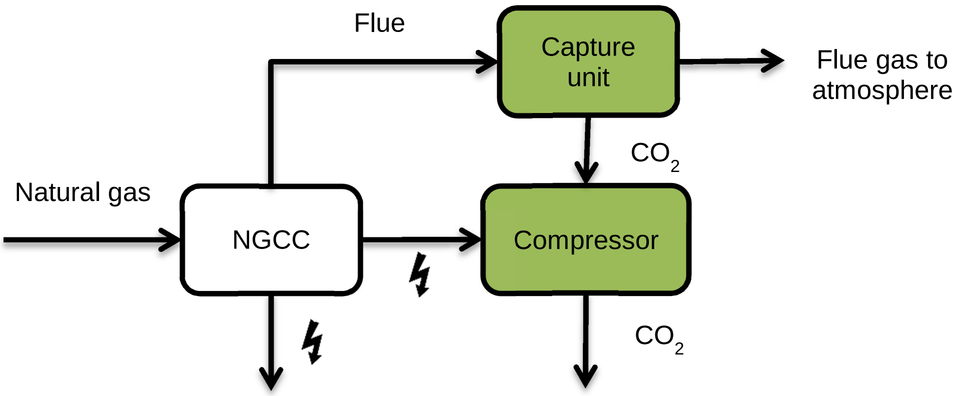


Figure 5-3 Schematic overview of the NGCC process as assessed in this study

Table 5-4 Main assumptions on the performance of the two scenarios based on NGCC power plants, with and without post combustion

Step in value chain	NGCC no CCS	NGCC + CCS	References - Comments
Fuel & transport			
Fuel type	Natural gas		
Origin	Dutch supply mix (2011)		CBS (2013)
Transport type	Pipeline, on- and offshore		EcoInvent (2010)
Conversion & capture & compression			
Power plant type	NGCC	NGCC	
Capacity (MWe)	406	342	Own calculation based on efficiency
Full load hours	7500	7500	Volkart et al. (2013)
Life time (yr)	25	25	Singh et al., 2011; Volkart et al. (2013)
Net electric efficiency	58.3%	49.2%	IEAGHG (2012)
Emission control	NO_x control by water injection	NO_x control by water injection	Faist-Emmenegger et al. (2007). No emission control for PM and SO_2 emissions necessary Faist-Emmenegger et al. (2007); EC (2006)
Capture technology	-	Post combustion MEA	
Removal efficiency CO_2	-	90%	IEAGHG (2012), Singh et al. (2011), Volkart et al. (2013), Veltman et al. (2010)
Compression	-	Electric, from NGCC	IEAGHG (2012)
Compression outlet pressure	-	110 bar	IEAGHG (2012)

The Ecoinvent (2010) dataset ‘Natural gas, burned in combined cycle plant, best technology/RER U’ is used as a basis for the modelling of the conversion step. However, a few adjustments are made to this dataset to account for a higher efficiency and life time operation according to the values in Table 5-4. For the carbon dioxide emissions from natural gas combustion the value 56.5 kg/GJ is used, which is the set emission factor for the Netherlands in 2013 (Zijlema, 2013). For the NGCC without CCS, all other emissions per GJ natural gas burned are from the EcoInvent database (Ecoinvent, 2010). Figure 5-4 shows the product system to produce 1 MWh of electricity.

LCI data from (Volkart, 2011) are used for the infrastructure of the capture unit. For the capture process additional resources are needed (e.g. solvent) and additional emissions and waste occur. The post-combustion capture process does not only influence the carbon dioxide emissions, but also influences other airborne emissions of the NGCC power plant.

The assumptions made regarding the operation of the MEA-based post combustion unit are shown in Table 5-5. The dataset ‘Natural gas, burned in combined cycle plant, best technology/RER U’ (Ecoinvent, 2010) is adjusted according to the values in Table 5-5. For the transport of resources for the capture process standard transport distances (100 km by truck and 600 km by train) are used. For the reclaimer waste a transport distance of 100 km by truck is used (Koornneef et al. 2008).

Table 5-5 Assumed operation parameters MEA-based capture unit (NGCC)

Parameter	Value	References - Comments
Resource consumption		
MEA (kg/tCO_2 captured)	1.79	IEAGHG (2012)
NaOH [1)] (kg/tCO_2 captured)	0.13	IEAGHG (2012), Veltman et al. (2010), Rao & Rubin (2002)
Activated carbon [2)] (kg/tCO_2 captured)	0.075	IEAGHG (2012), Rao & Rubin (2002)
Cooling water (m^3/tCO_2 captured)	73. 58	IEAGHG (2012)
Additional emissions		
MEA (kg/tCO_2 captured)	0.06	IEAGHG (2012), Veltman et al. (2010)
Ammonia (kg/tCO_2 captured)	0.034	Estimated from Veltman et al. (2010)
Formaldehyde (kg/tCO_2 captured)	0.00025	Estimated from Veltman et al. (2010)
Acetaldehyde (kg/tCO_2 captured)	0.00016	Estimated from Veltman et al. (2010)
Emission removal in capture unit		
CO_2 removal (%)	90	IEAGHG (2012), Veltman et al. (2010), Rao & Rubin (2002)
SO_2 removal (%)	99.5	IEAGHG (2012), Veltman et al. (2010), Rao & Rubin (2002)
NO_2 removal (%) [3)]	25	IEAGHG (2012); Veltman et al. (2010); Rao & Rubin (2002)
PM removal (%)	50	IEAGHG (2012); Koornneef et al. (2008)
Elemental Hg removal (%) [4)]	8	IEAGHG (2012)

Parameter	Value	References - Comments
Oxidized Hg removal (%) [4)]	76	IEAGHG (2012)
Wastes		
Reclaimer waste [5)] (kg/tCO_2 captured)	3.47	Own assumption based on Schakel et al. (2013) and IEAGHG (2012)[6)]

1) Approximated from the dataset ‘Sodium hydroxide, 50% in H_2O production mix, at plant/RER U’. Amount is doubled to account for the dilution in the dataset (Volkart, 2010).
2) The dataset ‘Charcoal, at plant, GLO U’ is used as a proxy for activated carbon as no data for activated carbon is available in the Ecoinvent database (Koornneef et al., 2008; Volkart, 2010)
3) 5% of the NO_x is assumed to be NO_2 (Rao & Rubin, 2002)
4) 75% of the mercury is assumed to be elemental and 25% to be oxidized (IEAGHG, 2012)
5) Modelled by the dataset ‘Disposal, hazardous waste, 25% water, to hazardous waste incineration/ CH U’.
6) IEAGHG (2012) reports a value of 3.47 kg/tCO_2 for a NGCC power plant and 3.94 kg/tCO_2 for a coal-fired power plant. Schakel at al. (2013) reports a value of 2.08 kg/tCO_2 for a coal-fired power plant. For consistency between the cases, tool the value provided by Schakel et al. (2013) is used. However, since reclaimer waste formation is expected to be lower for the NGCC power plant, the value is lowered using the ratio 3.47/3.94 provided by IEAGHG (2012).

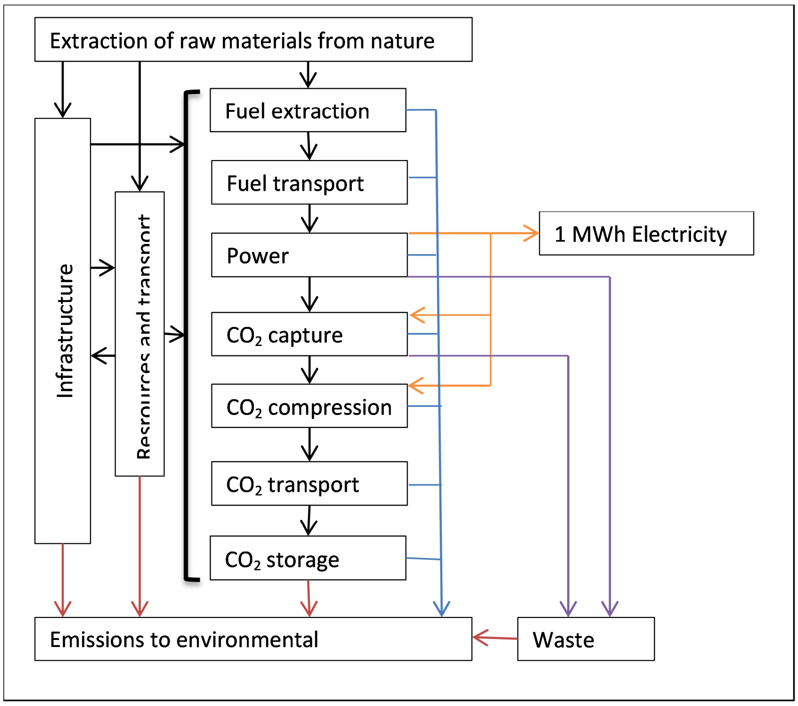


Figure 5-4 Product system for the natural gas fired power plant with post-combustion capture

5.4. Co-firing biomass post combustion

An ultra-supercritical pulverized power plant (PC) is considered, with the possibility of post combustion CO_2 capture using the solvent Monoethanolamine (MEA). A schematic overview of the different process steps is presented in Figure 5-5. This life cycle is very similar to that presented in section 2, but with some minor differences in assumptions on the environmental performance of the power plant with CO_2 capture.

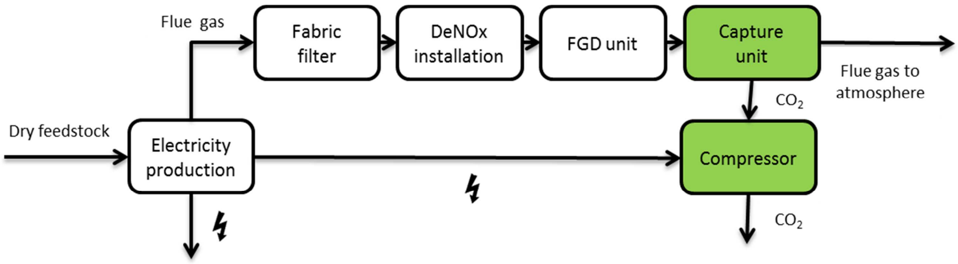


Figure 5-5 Schematic overview of PC process as assessed in this study. The green coloured box points out the new unit that is included when CCS is deployed. (Schakel et al, 2014)

When co-firing wood pellets, a slight drop in the efficiency of the power plant is expected due to the lower calorific value of wood pellets compared to coal. Besides, a substantial efficiency penalty occurs when CO_2 capture is added (this penalty includes the step of CO_2 compression). An overview of the used PC plant efficiencies is presented in Table 5-6. Other key parameters regarding system boundaries and flue gas treatment are presented in Table 5-7 for the scenarios without co-firing. When adding co-firing, most flue gas treatment efficiencies remain constant, except for the removal of NO_x (see footnote 3, Table 5-7). For a more detailed description regarding process parameters and estimations, please see (Schakel et al., 2014).

Table 5-6. Used power plant efficiencies for all PC scenarios. Note that efficiencies in CCS cases include efficiency drop due to CO_2 compression (NETL, 2012b; GCSSI, 2011).

CCS	No	Yes	No	Yes	No	Yes
Co-firing ratio (% energy)	0	0	15	15	30	30
η (HHV, %)	44.6	33.2	44.5	32.9	44.4	32.6
η (LHV, %)	46.8	34.8	46.8	34.6	46.8	34.4

Table 5-7. General parameters for 100% coal-fired PC with and without CO_2 capture technology.

Parameter	No CCS	CCS	Reference(s)
Fuel & Transport			
Fuel type	Illinois#6 coal		NETL (2012b)
Origin	Dutch imported coal mix		Smekens et al. (2013)
Transport type	Ship, transoceanic freighter		Smekens et al. (2013)
Plant			
Capacity (MW_e)	550	550	NETL (2012b)
Capacity Factor (%)	85	85	NETL (2012b)

Parameter	No CCS	CCS	Reference(s)
Efficiency (%) HHV [1)]	44.6	33.2	GCSSI (2011); NETL (2012b)
Flue gas cleaning equipment	Filter, DeNox, FGD	Filter, DeNox, FGD	NETL (2012b)
Capture technology	-	Post combustion MEA	NETL (2012b)
Flue gas			
SO_2 removal (%)[2)]	98	99.95	NETL (2012b); Koornneef et al. (2008); Rao et al. (2004)
NO_x removal (%) [3)]	86	87.8 [4)]	NETL (2012b); Koornneef et al. (2008); Rao et al. (2004)
PM removal (%)	99.8 [5)]	99.9 [6)]	NETL (2012b); Koornneef et al. (2008); Rao et al. (2004)
HCl removal (%)	90	99.5 [7)]	NETL (2012b); Koornneef et al. (2008); Rao et al. (2004)
HF removal (%)	70	97 [8)]	NETL (2012b); Koornneef et al. (2008)
Hg removal (%)	90	91.5 [9)]	NETL (2012b); Cui et al. (2010)
Se removal (%)	96	96	EH&H (2011)
DeNOx unit			
Ammonia consumption (kg/kg NOx removed)	0.3	0.3	Koornneef et al. (2008); Ecoinvent, (2010)
Ammonia emissions (kg/kg NOx removed)	0.003	0.003	Ecoinvent (2010)
TiO_2 consumption (kg/kg NOx removed) [10)]	0.025	0.025	Ecoinvent (2010)
Flue gas desulphurization unit			
Limestone consumption (kg/kg SO_2 removed)	4	4	Koornneef et al. (2008); Ecoinvent, (2010)
Quicklime consumption (kg/kg SO_2 removed)	0.20	0.20	Röder et al. (2007)
Sulphuric acid consumption (kg/kg SO_2 removed)	0.08	0.08	Röder et al. (2007)
Gypsum production (kg/kg limestone)	1.85	1.85	Koornneef et al. (2008); Ecoinvent, (2010)
Carbon capture			
CO_2 removal (%)	-	90	
Compression	-	Electric, from power plant	
Compression outlet pressure (MPa)	-	15.3	NETL (2012b)
Compression energy requirement	-	Included in efficiency drop	NETL (2012b)

1) Efficiency of the power plant solely combusting coal. In the co-firing case, the efficiency will drop with approximately a half %-point. (NETL, 2012b; NETL, 2013; Willeboer, 2013).
2) Efficiency of the flue gas desulphurization (FGD) unit (NETL, 2012b). When applying CCS, an extra desulphurization unit is implemented to further decrease the SO_2 content of the flue gas.

This unit removes 75% of the SO_2 that has passed the FGD. On top of that, 90% co-capture of SO_2 during the CO_2 capture phase is assumed (Koornneef et al, 2008).

3) NO_x (NO and NO_2) emissions for the co-firing cases are assumed to be equal to the base cases (sole coal combustion), since there is no need for extra reduction. This implies that the efficiency of the DeNOx installation in the co-firing cases is lower (since less NO_x needs to be removed from the flue gas).
4) Of the NO_x that is formed, 95% is assumed to be NO and 5% is assumed to be NO_2 (EPA, 2008; Koornneef et al, 2008; Dones et al, 2007; ICCI, 2000). 25% of NO_2 is assumed to be removed during the CO_2 capture process (Koornneef et al, 2008).
5) The following size distribution of the particle matter is assumed: 5% > 10 µm, 10% 2.5-10 µm and 85% < 2.5 µm (Ecoinvent, 2010).
6) 50% of the particle matter is assumed to be removed during the CO2 capture process (Koornneef et al, 2008). The PM size of the PM remained is assumed to be < 10µm (Koornneef et al, 2008).
7) 95% of HCl is assumed to be removed during the CO_2 capture process (Koornneef et al, 2008; Rao et al, 2004).
8) 90% of HF is assumed to be removed during the CO_2 capture process (Koornneef et al, 2008).
9) Mercury in the flue gas can occur in both elementary form (Hg^0) and oxidised form (Hg^{2+}). Only a minor part of Hg^0 can be removed in the carbon capture process, contrary to a large part of Hg^{2+} that can be removed (Cui et al, 2010). The removal efficiency of the capture unit therefore depends on the composition of mercury in the flue gas. Total removal is estimated to be 25%, which is a conservative estimate within the range of 23-31% (Corsten et al, 2013).
10) TiO_2 is a catalyst for removing NO_x. The lifetime TiO_2 spent is assumed to be landfilled. (Ecoinvent, 2010).

5.5. Co-firing biomass pre combustion

An integrated gasification combined cycle plant (IGCC) is considered, with the possibility of pre combustion CO_2 capture using the solvent Selexol. A schematic overview of the different process steps is presented in Figure 5-6.

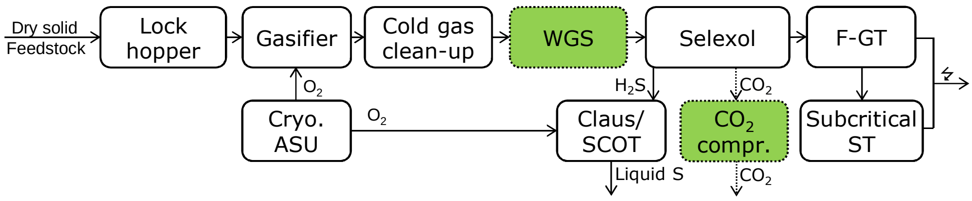


Figure 5-6 Schematic overview of IGCC process as assessed in this study. The green coloured box points out the new unit that is included when CCS is deployed (Meerman et al, 2013).

When co-firing wood pellets, a slight drop in the efficiency of the power plant is expected due to the lower calorific value of wood pellets compared to coal. Besides, a substantial efficiency penalty occurs when CO_2 capture is added (this penalty includes the step of CO_2 compression). An overview of the used IGCC plant efficiencies is presented in Table 5-8. Other key parameters regarding system boundaries and flue gas treatment are presented in Table 5-9 for the scenarios without co-firing. When adding co-firing, most flue gas treatment efficiencies remain constant. For a more detailed description regarding process parameters and estimations, please see (Schakel et al., 2014).

Table 5-8 Used power plant efficiencies for all IGCC scenarios. Note that efficiencies in CCS cases include efficiency drop due to CO2 compression.

CCS	No	Yes	No	Yes	No	Yes
Co-firing ratio (% energy)	0	0	15	15	30	30
η (HHV, %)	40.6	30.0	39.7	29.6	38.8	29.1
η (LHV, %)	42.6	31.5	41.8	31.1	41.0	30.7

Table 5-9 General parameters for IGCC with and without CO_2 capture technology.

Parameter	Vent	CCS [1)]	Reference(s)
Fuel & Transport			
Fuel type	Illinois#6 coal		NETL (2012b)
Origin	Dutch imported coal mix		Smekens & Plomp (2013)
Transport type	Ship, transoceanic freighter		Smekens & Plomp (2013)
Plant			
Capacity (MW_e)	550	550	NETL (2012a)
Capacity Factor (%)	80	80	NETL (2012a)
Efficiency HHV (%)	40.6	30.0	NETL (2012a)
Flue gas cleaning equipment	Filter, scrubber, COS, WGS, Claus/SCOT	Filter, scrubber, COS, WGS, Claus/SCOT	NETL (2012a)

Capture technology	-	Pre combustion Selexol	NETL (2012a)
Flue gas			
SO_2 removal (%) [2)]	99.90	99.98	NETL (2010a); NETL (2013)
NO_x removal (%) [3)]	-	-	NETL (2010a); NETL (2012a)
PM removal (%) [4)]	99.8	99.8	Schoenmakers (2013)
HCl removal (%) [5)]	90	90	NETL (2010b); Schoenmakers (2013)
HF removal (%) [6)]	90	90	Schoenmakers (2013)
Hg removal (%) [7)]	99.34	99.34	Schoenmakers (2013)
Se removal (%)	99.7	99.7	Schoenmakers (2013)
NH_3 removal (%) [8)]	100	100	Schoenmakers (2013)
COS hydrolysis			
TiO_2 catalyst (kg/kWh) [9)]	$1.1e^{-5}$	-	NETL (2010b); Schoenmakers (2013)
Water-gas shift			
CoMo-oxide on alumina (kg/kWh) [10)]	-	$8.1e^{-6}$	NETL (2010b);
Acid gas removal			
Selexol (kg/kWh) [11)]	$1.2e^{-5}$	$3.1e^{-5}$	NETL (2013)
Claus/SCOT			
Claus catalyst (kg/kWh) [12)]	$2.6e^{-6}$	$3.5e^{-6}$	NETL (2010b);
Carbon capture			
CO_2 removal (%)	-	90	NETL (2012a)
Compression	-	Electric, from power plant	NETL (2012a)
Compression outlet pressure (MPa)	-	15.3	NETL (2012a)
Compression energy requirement	-	Included in efficiency drop	NETL (2012a)

1) As the main difference between the Vent and CCS cases is replacing the single-stage Selexol unit for a dual-stage Selexol unit, it is assumed that the CCS case has the same impurity removal efficiencies as the Vent case.
2) It is assumed that any sulphur that is not removed in the flue gas cleaning is emitted as SO_2. Additional SO_2 is co-captured with the CO_2 when CCS is applied.
3) NO_x formation is reduced by injecting steam or N_2 into the gas turbine. This eliminates the need for NO_x removal. [NETL 2010, 2012a]
4) The presented removal efficiency does not necessarily match the removal efficiency of this study. In this study, the environmental limits for PM emission (NETL, 2012a) have been used as actual emissions. It is unknown however how much PM is formed and what the exact removal efficiency is.
5) It is assumed that the wet scrubber removes 90% of all chloride compounds and that any remaining chloride is emitted as HCl. No co-capture in the AGR is assumed.
6) The removal efficiency of HF is assumed to be equal to the removal efficiency of HCl (Schoenmakers, 2013).
7) Mercury removal is assumed to be between 95%-99.34%. The higher value of Schoenmakers (2013) has been selected.
8) It is assumed that all ammonia formed in the gasifier is removed in the scrubbers or subsequently converted into N_2 in the COS hydrolysis or WGS reactors (Schoenmakers, 2013).
9) Catalyst consumption is between 1.2e-5 and 3.2e-6 L/kWh. Assuming a bulk density of 0.95 kg/L, this translates to a consumption rate of 3-11 mg/kWh. The higher value of the (NETL, 2010b) has been selected.

10) Catalyst consumption is 9.2e-6 L/kWh according to the (NETL, 2010b). The catalyst is assumed to be CoMo-oxide on an alumina support. The bulk density is conservatively estimated at 0.77 kg/L. This translates to a catalyst consumption of 8 mg/kWh.
11) Consumption is based on (NETL, 2010a) and is for a coal-fired IGCC with CCS 3.4e^{-5} kg/kg CO_2 captured. When not capturing CO_2, Selexol consumption drops by about 50%. These ratios are expected to remain constant when co-firing biomass.
12) The Claus catalyst is made from Al_2O_3. According to the (NETL, (2010a), catalyst consumption is 3.4e^{-6} L/kWh for Vent and 4.6e^{-6} L/kWh for CCS. Assuming a bulk density of 770 kg/m^3, this translated to 2.6e^{-6} kg/kWh and 3.5e^{-6} kg/kWh respectively. It is assumed that the same amount of catalyst is required when co-firing biomass and that the catalyst degradation rate is independent of the co-firing fraction.

6. Assessment of CCS chains

6.1. Coal post combustion

Life cycle assessment results for two state of the art coal fired power plants, with and without CCS, are presented in Figure 6-1. The figure clearly indicates a trade-off for the case with CCS between impacts on climate change and the other environmental themes. Climate change reduces with 76% and other environmental themes receive a higher score of at least 22%. This general increase of other environmental scores is mostly due to the drop in generating efficiency as a result of applying CCS. Ten environmental themes show a score increase of more than 30%: Agricultural land occupation, Natural land transformation, Ionising radiation, Ozone depletion, Particulate matter formation Metal & Water depletion, Marine Eutrophication, Terrestrial acidification, and Terrestrial ecotoxicity.

A process breakdown for all environmental themes is presented for the PC without CCS (Figure 6-2) and for the power plant including post-combustion CCS (Figure 6-3) to illustrate breakdown differences between the two cases. The process breakdown is divided into contributions from fuel extraction, fuel logistics, conversion & capture, waste from conversion, waste from capture, CO_2 transport and storage. With the use of these graphs it is possible to discuss the results in somewhat more detail and explain how the environmental scores can be attributed to different parts of the value chain.

The increase in agricultural land occupation for the case with CCS can be explained by the decrease in overall efficiency and the land requirement for the CCS infrastructure. For the themes Ionising radiation and Ozone depletion, increases in the impacts are the result of processes that enable the installation and use of the CCS infrastructure. Examples are the waste treatment from CO_2 capture waste and the injection of CO_2 into the underground. The increase in the score for Terrestrial acidification can be allocated to environmental impacts resulting from conversion and capture. More specifically, the change in emissions of NOx (although partially removed in capture process) and ammonia (emission profile changes due to capture) are the main factors. Terrestrial ecotoxicity increases also due to an increase in impacts in the CCS part of the chain. CO_2 transport and storage also seem to have a share in increasing metal depletion and natural land transformation.

The score for Natural land transformation for the scenario with CCS is highly influenced by our assumption related to the process that is used to describe the offshore storage of CO_2. The score for the process “Well for exploration and production, offshore/OCE/I U” as defined in the Ecoinvent database, dominates the score for natural land transformation. This process allocates 260 m^2 ‘transformation from sea and ocean to dump site benthos’ per meter of injection well. This seems very high, especially given information related to onshore wells where 90 m^2 of natural land transformation is allocated per meter of injection well. This anomaly in data, as it most likely is, should be considered when reviewing these results.

In general, the upstream steps of the life cycle - fuel production and logistics - are dominant in the scores for almost all environmental themes. When applying CCS, a further shift of environmental impacts from the conversion part of the chain to upstream and downstream can be seen. This is especially clear when comparing the results of the weighing sets A-E. This shows that overall weighed environmental burdens are dominantly shifted from the place of fuel conversion towards the upstream part of the value chain.

Figure 6-4 shows for example how the scores for various environmental themes can be weighed and summed using weighing set E. Results are shown in euros indicating environmental damage costs of producing 1 MWh of electricity. The scores are about 75 euro/MWh; the case without CCS just outperforming the case with CCS. The contribution of climate change, particulate matter and fossil depletion in the overall environmental costs are pivotal. This explains why for instance in weighing set B and C the CCS case outperforms the case without CCS while under weighing set A and D it is vice versa (see Figure 6-1). One main difference between the weighing sets is namely how the environmental damage costs of climate change are valued against the other environmental themes (see section 4.5 for details). Valuation of environmental themes, either via monetization or another method, thus determines whether the net balance between the advantages of CCS and its trade-offs are positive or negative.

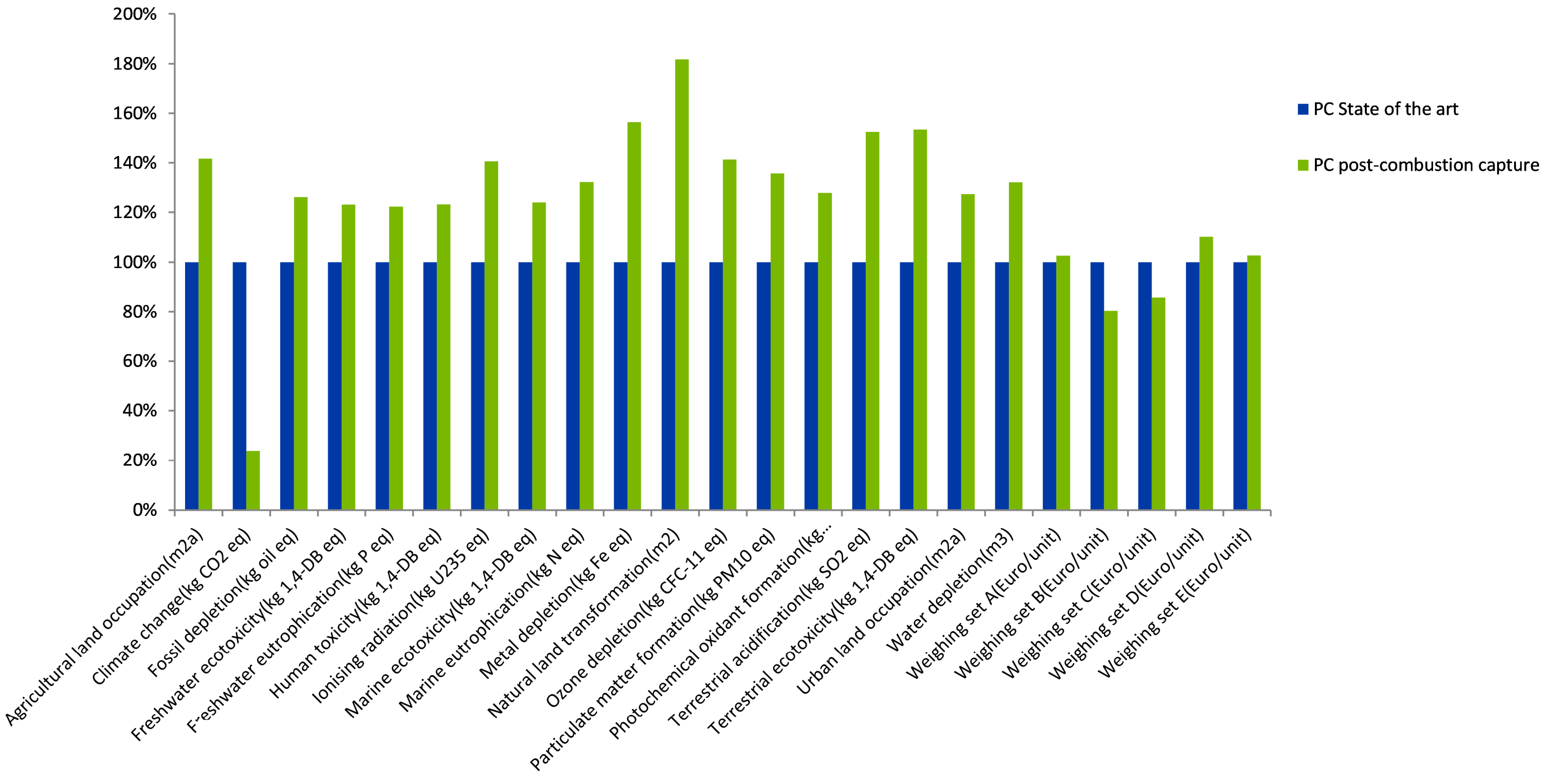


Figure 6-1 Relative life cycle results for 18 environmental themes and 5 weighing sets for two coal fired power plants, with and without CCS (based on Koornneef et al. 2008).

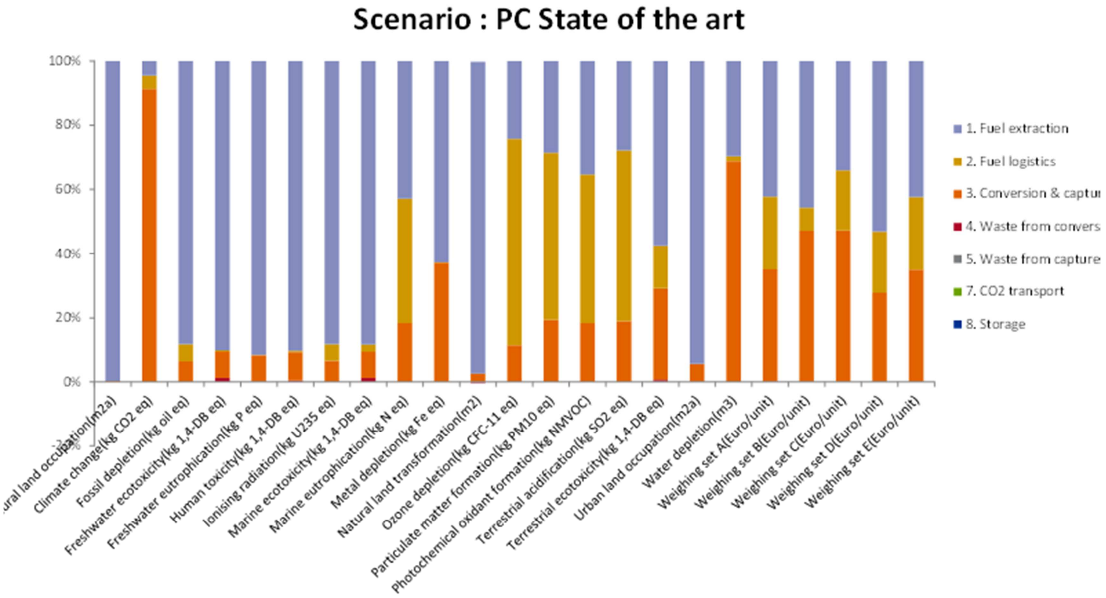


Figure 6-2 Process breakdown for all environmental indicators for the PC power plant without CCS. (*Note that the environmental interventions and impacts related to the compression of CO_2 are included in 'Step 3 Conversion and capture'. The legend of this figure therefore excludes 'Step 6 Compression')*

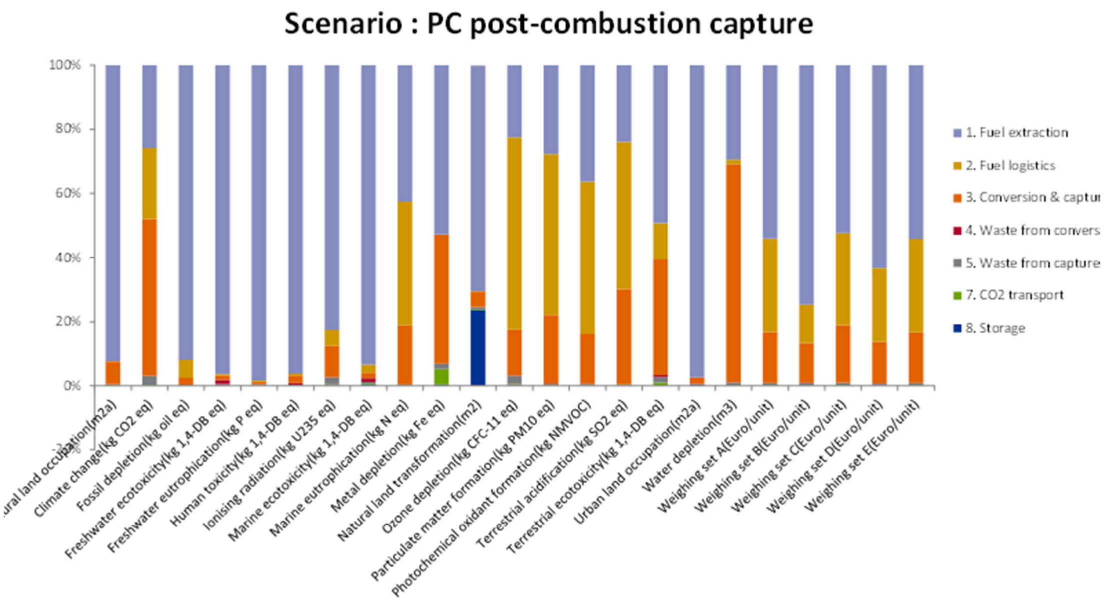


Figure 6-3 Process breakdown for all environmental indicators for the PC power plant including post-combustion CCS**.** (*Note that the environmental interventions and impacts related to the compression of CO_2 are included in 'Step 3 Conversion and capture'. The legend of this figure therefore excludes 'Step 6 Compression')*

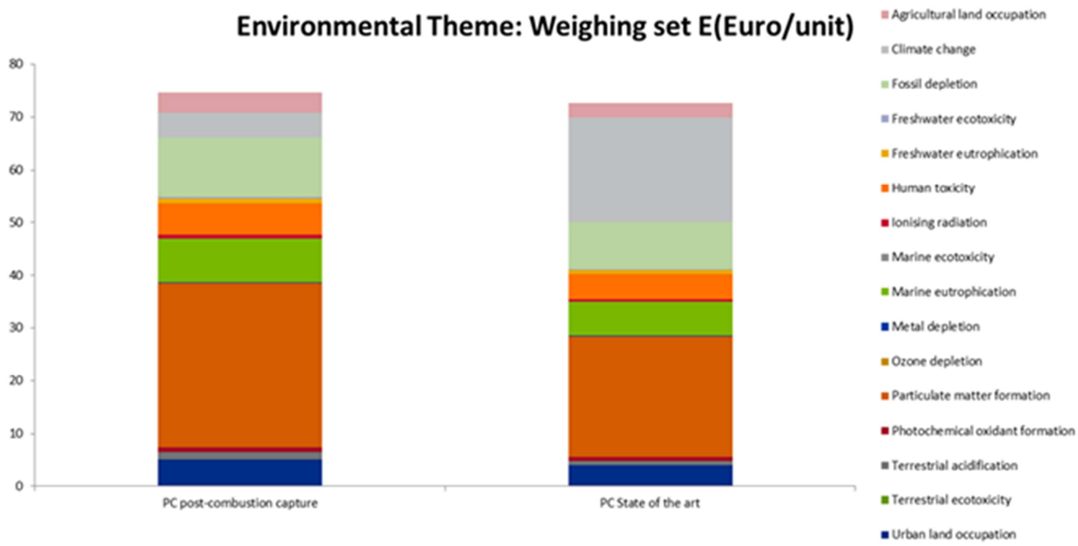


Figure 6-4 Distribution of contributions from environmental themes for PC power plant with and without post-combustion CCS. Results are shown for weighing set E indicating environmental costs of producing 1 MWh of electricity

6.2. NGCC post combustion

Life cycle assessment results for two NGCC power plants with and without post combustion capture, CO_2 transport and storage are presented in Figure 6-5 for all environmental themes and weighing sets. A process breakdown for all environmental themes is presented in Figure 6-6 and Figure 6-7.

Environmental trade-offs between the impact category climate change and the other impact categories when applying CCS are clearly visible in Figure 6-5. Results indicate that as a consequence of CCS, the impact in the category climate change decreases by 83% .The decrease is lower than the CO_2 capture rate of 90% because of the higher impact for fuel extraction and logistics due to the fuel penalty induced by CO2 capture as well as the additional impacts of the capture process. For all other impact categories, the impact of electricity generation with CCS is higher. This can partly be explained by the fuel penalty, which increases the impact of the upstream processes fuel extraction and transport. However, also during the conversion and capture stage the impact for all categories, except climate change, increases when applying post-combustion capture. For some impact categories the life cycle stages specific to CCS (e.g. waste from capture, storage) also have a significant impact (Figure 6-7). The main processes causing these increases in impact are the production of MEA and the disposal of the reclaimer waste. Note that for the impact categories agricultural land occupation, the strong increase is mainly caused by the production of activated carbon, and terrestrial acidification, which is mainly due to an increase in ammonia emissions. For both cases (without and with CCS), fuel extraction, conversion & capture are the life cycle stages with the highest contribution to the impacts. Ozone depletion is the only impact category that is dominated by the fuel logistics process (Figure 6-5 and Figure 6-6), this is due to emissions of the ozone depleting substance Halon-1211 during pipeline transportation.

Figure 6-8 shows that applying post-combustion capture to a NGCC power plant results in a lower shadow price independent of the weighing set applied. Without CCS, the shadow prices are in the range of 18-28 euro/MWh and they decrease to 12-15 euro/MWh with CCS, depending on the weighing set used. The decrease in carbon dioxide emissions due to the application of CCS thus outweighs the increase in other impact categories according to this weighing method. Figure 6-8 shows the breakdown into impact categories for weighing set E, which is used as an example. The categories climate change, particulate matter formation and fossil depletion dominate the shadow price. Climate change and fossil depletion are dominant in all weighing sets. Particulate matter formation is dominant in all weighing sets, except for weighing set B where particulate matter formation is not included. In weighing set B and D photochemical oxidant formation and terrestrial acidification also contribute significantly to the shadow price, although the impact categories mentioned previously are dominant. All other impact categories have minor impact on the shadow price of electricity from NGCC power plants with and without CCS.

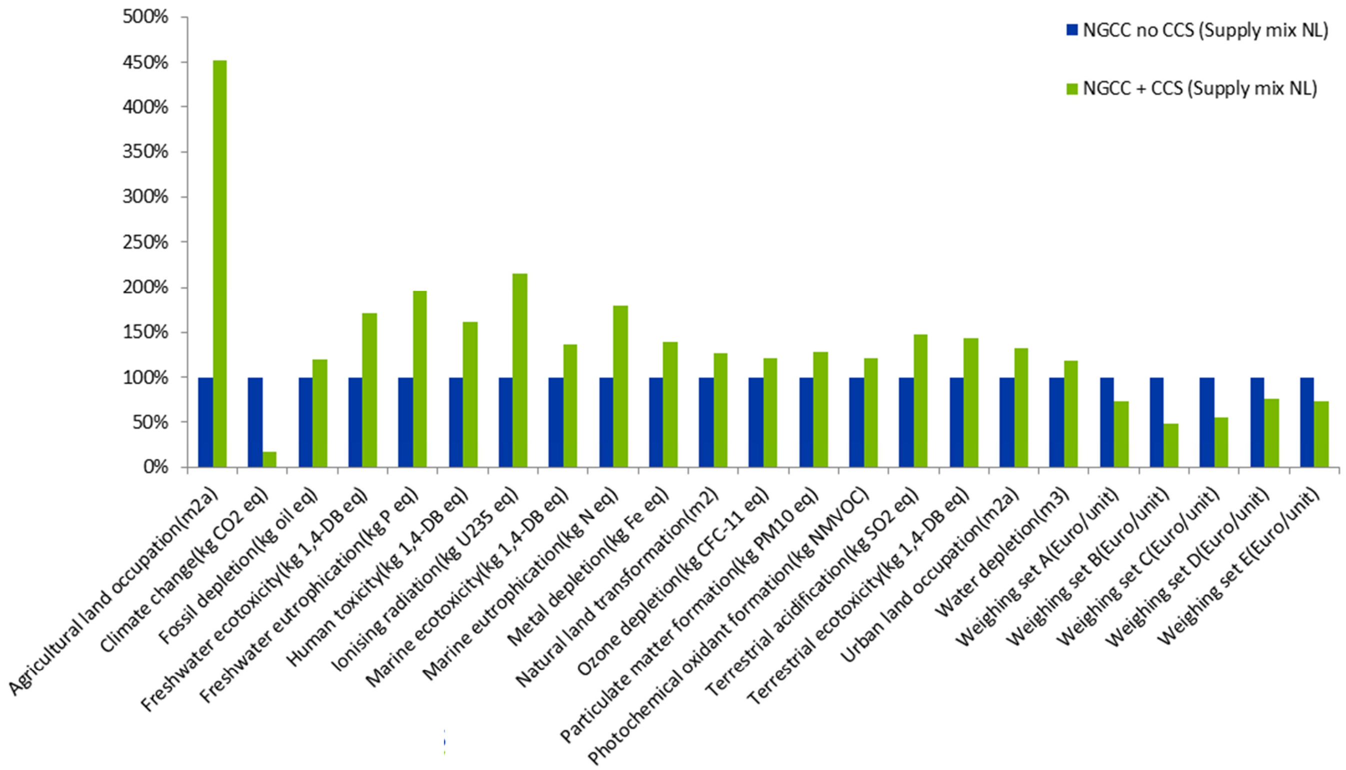


Figure 6-5 Relative life cycle results for 18 environmental themes and 5 weighing sets for two NGCC power plants, with and without CCS

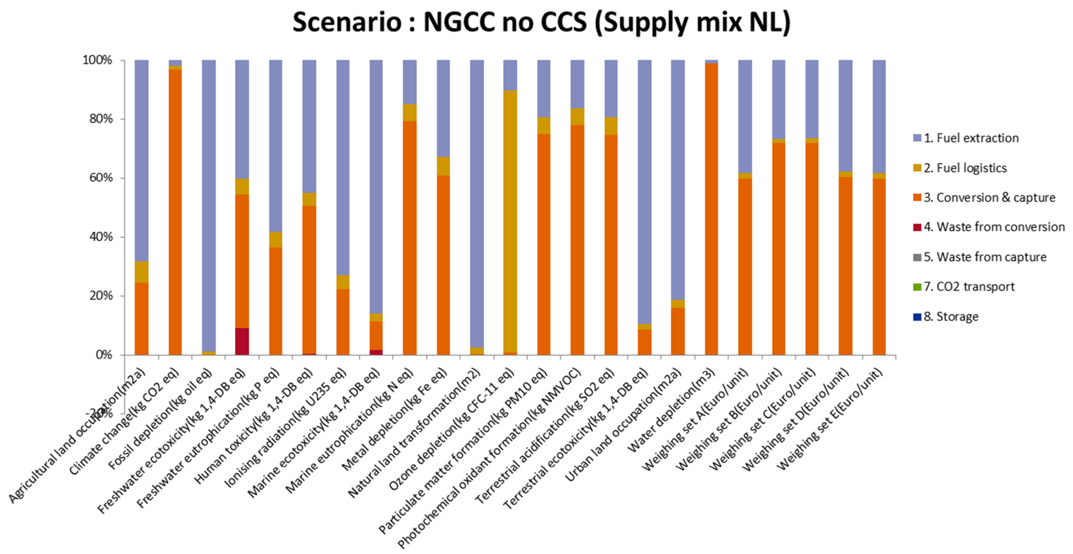


Figure 6-6 Process breakdown all environmental themes for the NGCC case without CCS. (*Note that the environmental interventions and impacts related to the compression of CO_2 are included in 'Step 3 Conversion and capture'. The legend of this figure therefore excludes 'Step 6 Compression')*

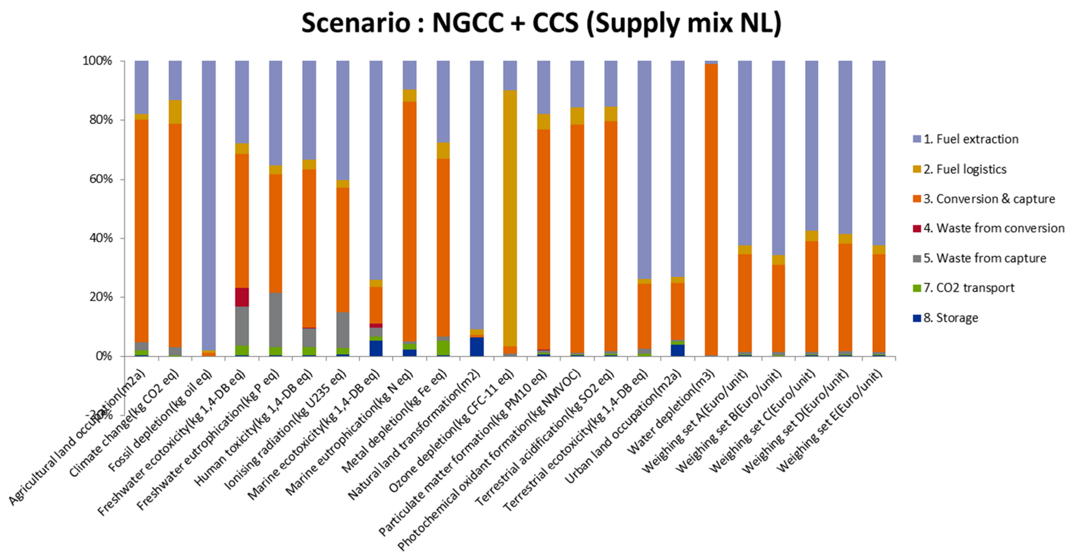


Figure 6-7 Process breakdown all environmental themes for the NGCC case with post combustion capture. (*Note that the environmental interventions and impacts related to the compression of CO_2 are included in 'Step 3 Conversion and capture'. The legend of this figure therefore excludes 'Step 6 Compression')*

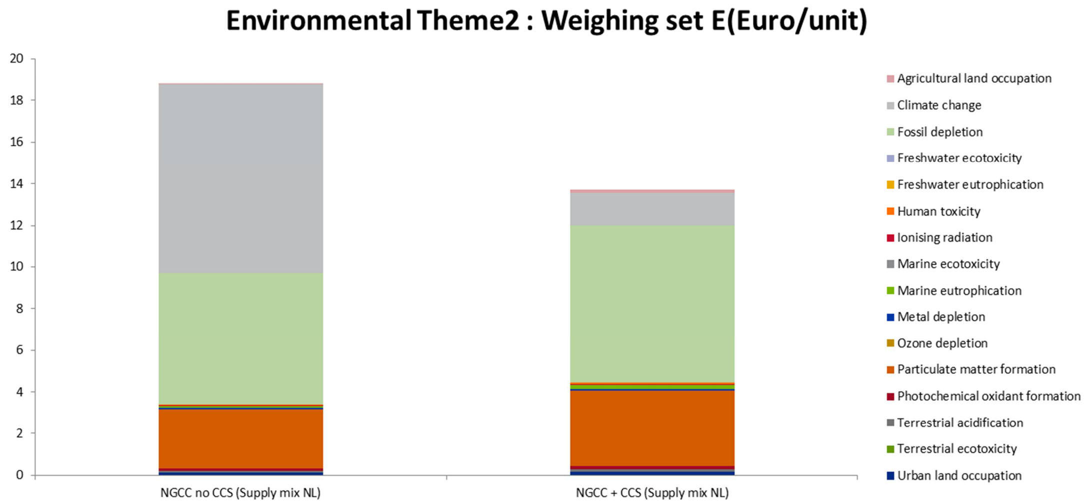


Figure 6-8 Distribution of contributions from environmental themes for NGCC power plant with and without CCS. Results are shown for weighing set E indicating environmental costs of producing 1MWh of electricity.

NGCC Uncertainties

The most important uncertainties regarding the NGCC power plant with post combustion capture concern the resource requirement for the capture process as well as the emissions and wastes from the capture process. This is due to a lack of experimental data from NGCC power plants, as the majority of CO2 capture pilot plants are currently coal fired power plants. Therefore, the values reported in literature for the MEA consumption in NGCC power plants are in fact derived from measurements at coal fired power plants. This could lead to either an overestimation or an underestimation of the actual MEA consumption and related impacts at NGCC power plants. It could be an overestimation because the flue gas of natural gas fired power plants contains less acid gases compared to the flue gas of coal fired power plant (Corsten et al., 2013). Therefore, MEA would react less with impurities in the flue gas. On the other hand, the amount of oxidative degradation of MEA could be much higher for natural gas fired power plants. The flue gas of a natural gas fired power plant typically contains 13% O_2 (IEAGHG, 2012; Veltman et al, 2010), while the values reported for MEA consumption are based on flue gas with an O_2 content of 4-5%. According to (IEAGHG, 2012) this could lead to a MEA consumption of 6 kg/tCO_2 captured instead of 1.79 kg/tCO_2 captured.

6.3. Co-firing biomass post combustion

Life cycle assessment results for all PC cases are presented in Figure 6-9. A process breakdown for all environmental themes is presented for the base case PC 100% coal without CCS (Figure 6-10) and for the case PC 70% coal and 30% wood pellets including CCS (Figure 6-11) to illustrate breakdown differences between the two most different cases. The process breakdown is divided into contributions from fuel extraction, fuel logistics, conversion & capture, waste from conversion, waste from capture, CO_2 transport and storage.

Adding CCS increases the impact scores for all environmental themes except climate change. As the majority of the category scores is dominated by contributions from fuel extraction and fuel logistics (Figure 6-11), the increases are a direct result of an increased fuel demand due to the efficiency drop in the power plant when adding CO_2 capture. As it is to be expected, the impact on climate change decreases when including CCS, although the decrease due to CO_2 capture (90%) is partly offset by the increased fuel demand. For the indicators ecotoxicity and eutrophication, a minor part of the increase when adding CCS comes from the conversion and capture process, namely from additional chemical use (MEA) and emissions (NH_3 and MEA). A larger impact, comparing to the other indicators, is observed for the environmental categories metal depletion, which is the result of additional required infrastructure, and natural land transformation, which is a direct result of the CO_2 storage process (see also Figure 6-11).

Co-firing wood pellets has a minor impact on the majority of the environmental categories. The slight differences are the result of changes in the amount of chemicals used and on the emissions profile due to the different composition of the wood pellets compared to coal. However, in some cases significant changes are observed: The most dramatic change is in the category agricultural land occupation, which is up to 617-1549% higher when co-firing wood pellets (617% for co-firing 15% without CCS, 1549% for co-firing 30% including CCS). The reason behind this is the substantial amount of agricultural land that is needed for the production of wood pellets, whereas agricultural land occupation for the extraction of coal as well as in other process steps, is negligible. The impact of climate change further decreases when including co-firing, because the amount of CO_2 coming from the combustion of biomass is compensated by “negative emissions” in the biomass production step. When co-firing 30% wood pellets and capturing CO_2, the total net CO_2 emissions almost drop to zero. The comparable (in size) decreases observed for the categories fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity and marine ecotoxicity are the result of the reduced coal demand when co-firing. These environmental themes are largely affected by coal mining (especially open mining), while the effect of the production of wood pellets on these themes is minimal. The score on ionising radiation increases when co-firing wood pellets due to a higher ionising radiation impact of wood pellets production compared to coal production (mainly because of the electricity used in the harvesting and pelletisation processes). The increase in the indicator metal depletion is primary the result of improved infrastructure requirements at the power plant when co-firing is considered.

Figure 6-12 presents the end scores for all cases for weighing set E. According to this weighing set, implementing CCS increases the environmental impact in all scenarios because the positive reduction of the climate change theme is not large enough to compensate the increase in all other themes. Besides, co-firing wood pellets further increases the impact due to a substantial increase in agricultural land occupation (which is only partly offset by the further decrease in climate change). Only when substantially decreasing the weighing of agricultural land occupation, compared to the weighing of climate change (weighing set B, see Figure 6-9), co-firing wood pellets decreases the total impact in the environment.

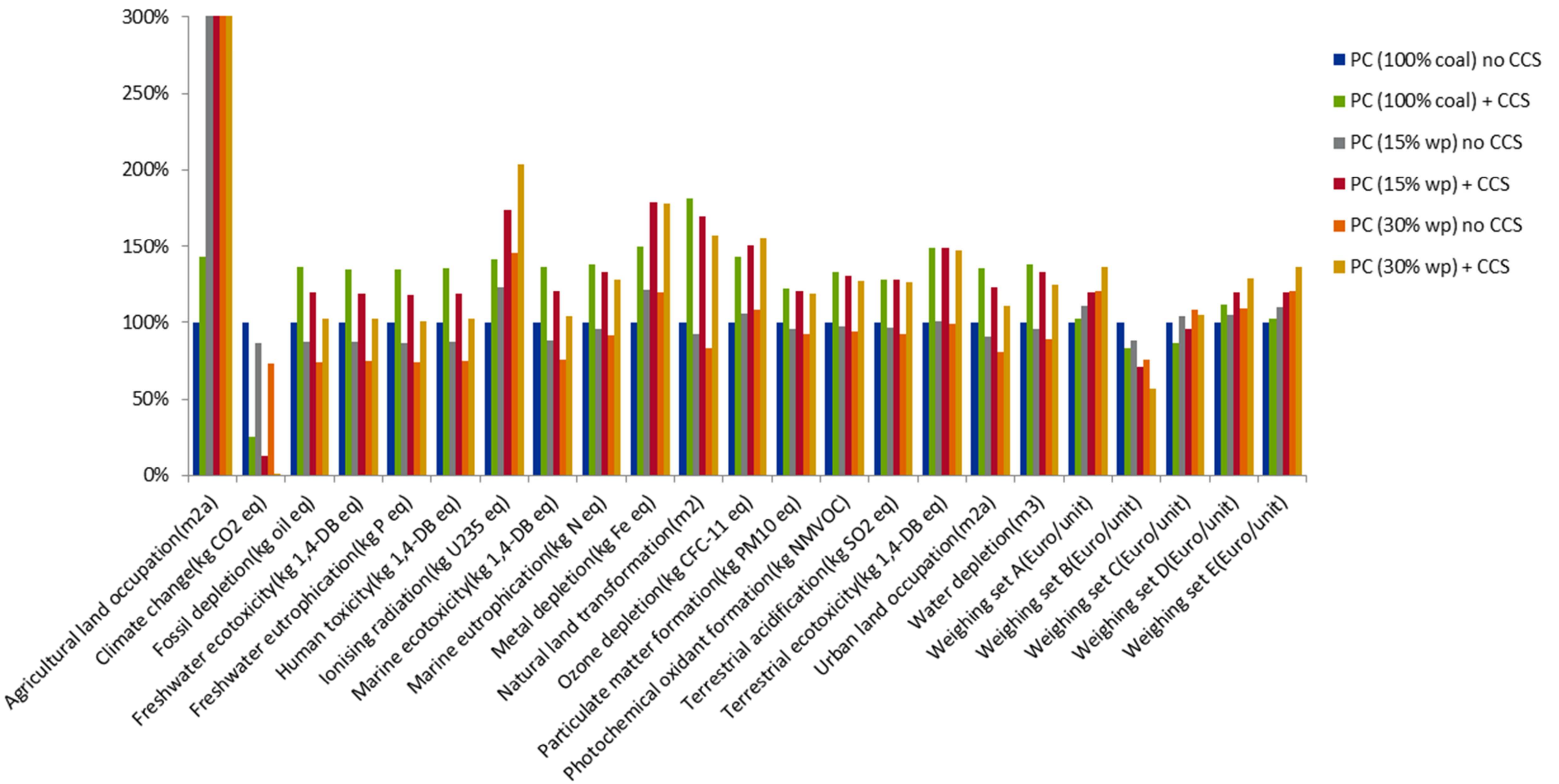


Figure 6-9 Life cycle results for all environmental themes for the PC scenarios. Note that the scores for agricultural land occupation for the co-firing cases are cut off, since the actual corresponding figures (in the range 617-1549%) largely exceed the other figures.

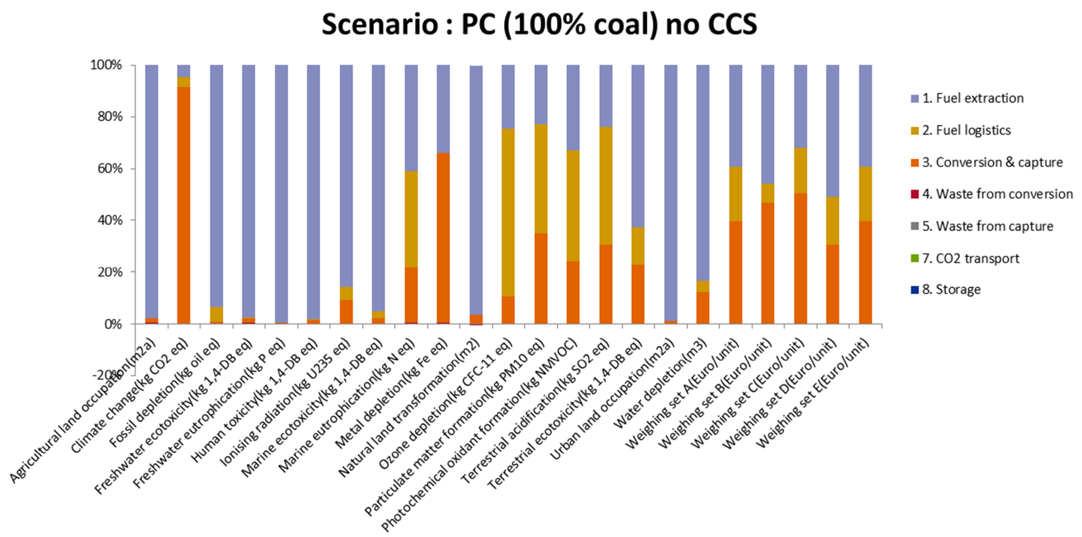


Figure 6-10 Process breakdown of all environmental indicators case PC 100% coal without CCS. (Note that the environmental interventions and impacts related to the compression of CO2 are included in 'Step 3 Conversion and capture'. The legend of this figure therefore excludes 'Step 6 Compression')

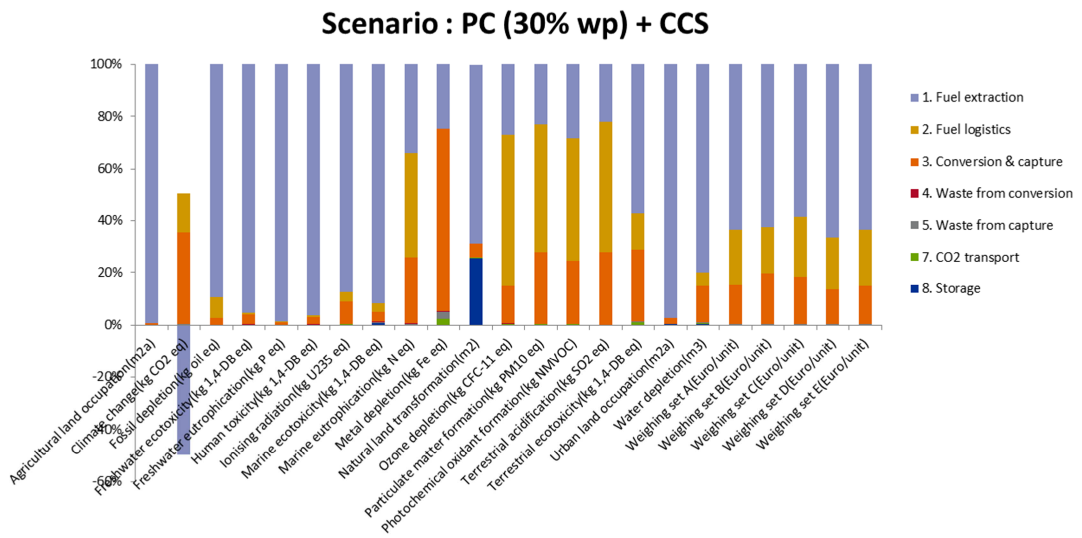


Figure 6-11 Process breakdown of all environmental indicators case PC 70% coal and 30% wood pellets including CCS. (*Note that the environmental interventions and impacts related to the compression of CO_2 are included in 'Step 3 Conversion and capture'. The legend of this figure therefore excludes 'Step 6 Compression')*

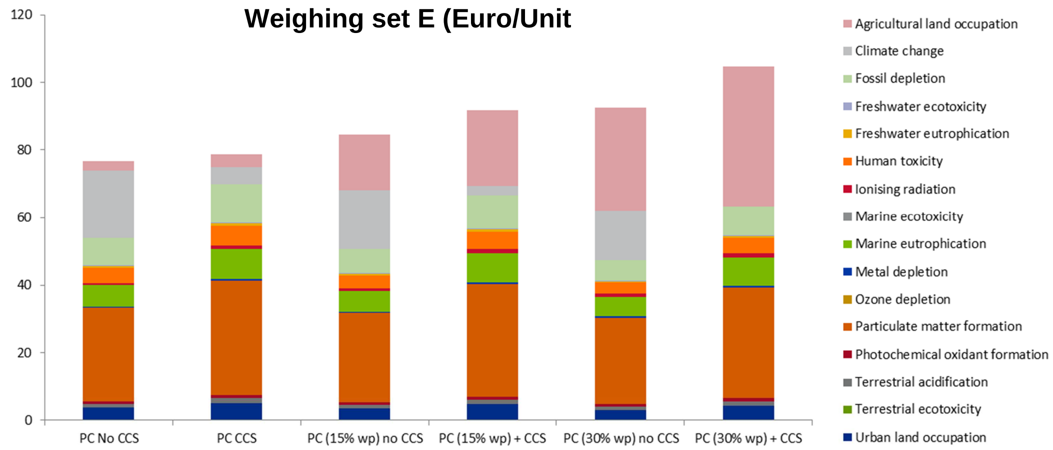


Figure 6-12 Distribution of contributions from environmental themes for all PC scenarios using weighing set E

6.4. Co-firing biomass pre combustion

Life cycle assessment results for all IGCC cases are presented in Figure 6-13. A process breakdown for all environmental themes is presented for the base case IGCC 100% coal without CCS (Figure 6-14) and for the case IGCC 70% coal and 30% wood pellets including CCS (Figure 6-15) to illustrate breakdown differences between the two most different cases. The process breakdown is divided into contributions from fuel extraction, fuel logistics, conversion & capture, waste from conversion, waste from capture, CO_2 transport and storage.

Adding CCS increases the impact scores for all environmental categories except climate change. As the majority of the category scores is dominated by contributions from fuel extraction and fuel logistics (Figure 6-14), the increases are a direct result of an increased fuel demand due to the efficiency drop in the power plant when adding CO_2 capture. The impact on climate change decreases when including CCS, although the CO_2 capture rate (90%) is partly offset by the increased fuel demand . The effect of additional chemicals when capturing CO_2 . does not significantly impact the conversion and capture step, as the contribution from this step does not change when going from the base case (Figure 6-14) to the 30% co-firing including CCS case (Figure 6-15). However, a larger increase, comparing to the other indicators, is observed in the categories metal depletion, which is the result of additional required infrastructure, and natural land transformation, which is a direct result of the CO_2 storage process (see also Figure 6-15).

Co-firing wood pellets only has a minor impact on the majority of the environmental categories. The slight differences that are noticeable are the result of changes in the amount of chemicals used and emissions profile due to the different composition of the wood pellets compared to coal. However, in some cases significant changes are observed: The largest change is in the category agricultural land occupation, which is upto 632-1583% higher when co-firing wood pellets (632% for co-firing 15% without CCS, 1583% for co-firing 30% including CCS). The reason behind this is the substantial amount of agricultural land that is needed for the production of wood pellets, whereas agricultural land occupation for the production of coal and in other process steps is negligible. The impact of climate change further decreases when including co-firing, because the amount of CO_2 coming from the combustion of biomass is compensated by “negative emissions” in the biomass production step. When co-firing 30% wood pellets and capturing CO_2, total net CO_2 emissions almost drop to zero. The comparable (in size) decreases observed for the themes fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity and marine ecotoxicity are the result of the reduced coal demand when co-firing. These environmental themes are largely affected by coal mining (especially open mining), while the effect of the production of wood pellets on these themes is minimal. The score on ionising radiation increases when co-firing wood pellets due to a higher ionising radiation impact of wood pellets production compared to coal production (mainly because of the electricity use in the harvesting and pelletisation processes). The increase in the indicator metal depletion is primary the result of improved infrastructure requirements at the power plant when co-firing is considered.

Figure 6-16 presents the end score for all cases for weighing set E divided in contributions to the environmental themes. According to this weighing set, adding CCS increases the environmental impacts in all scenarios because the positive reduction of the climate change theme is not large enough to compensate the increase in all other themes. Besides, co-firing wood pellets increases the impact further due to the substantial increase in agricultural land occupation (which is only partly offset by the further decrease in climate change theme). Only when substantially decreasing the weighing of agricultural land occupation compared to the weighing of climate change (weighing set B, see Figure 6-13), co-firing wood pellets decreases the total environmental impact.

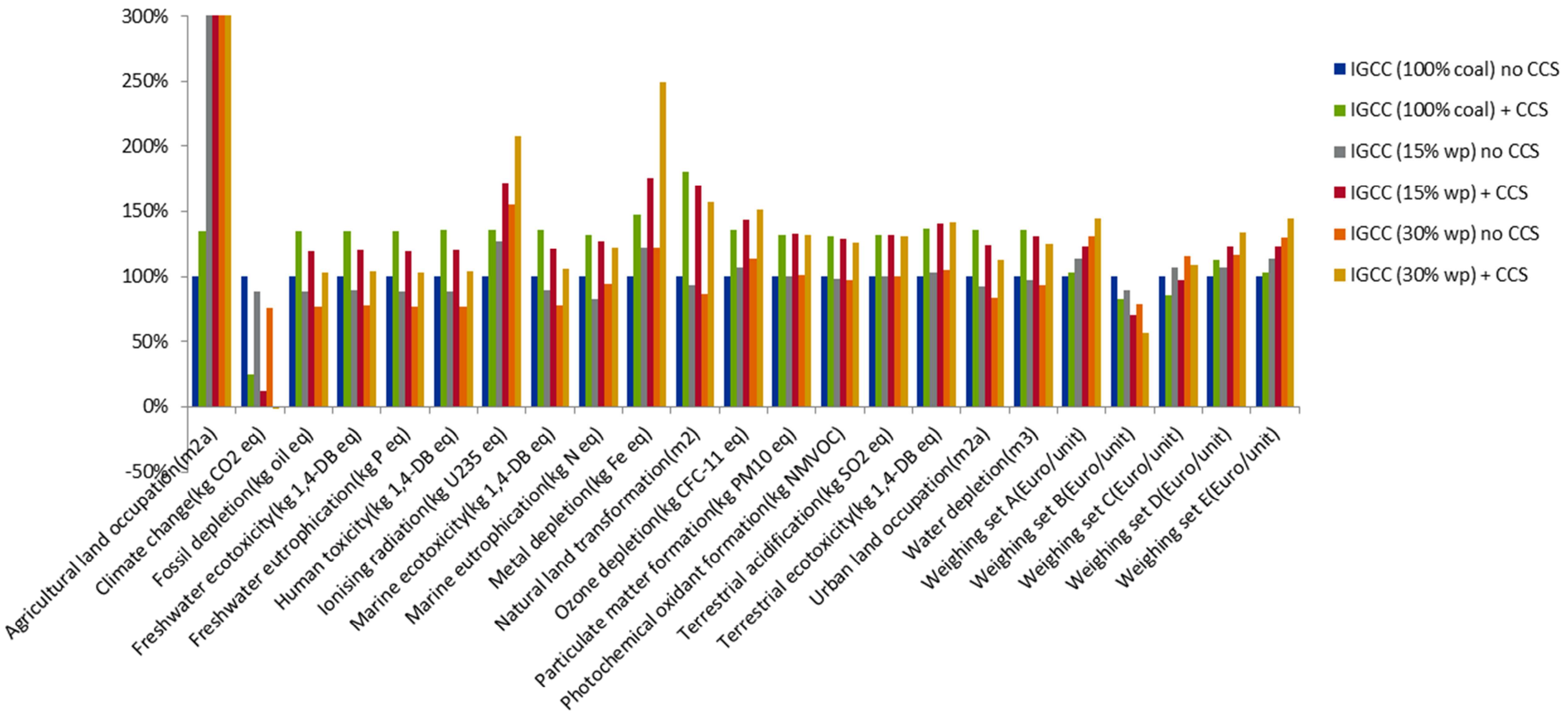


Figure 6-13 Life cycle results for all environmental themes for the IGCC scenarios. Note that the scores for agricultural land occupation for the co-firing cases are cut off, since the actual corresponding figures (in the range 632-1583%) largely exceed the other figures.

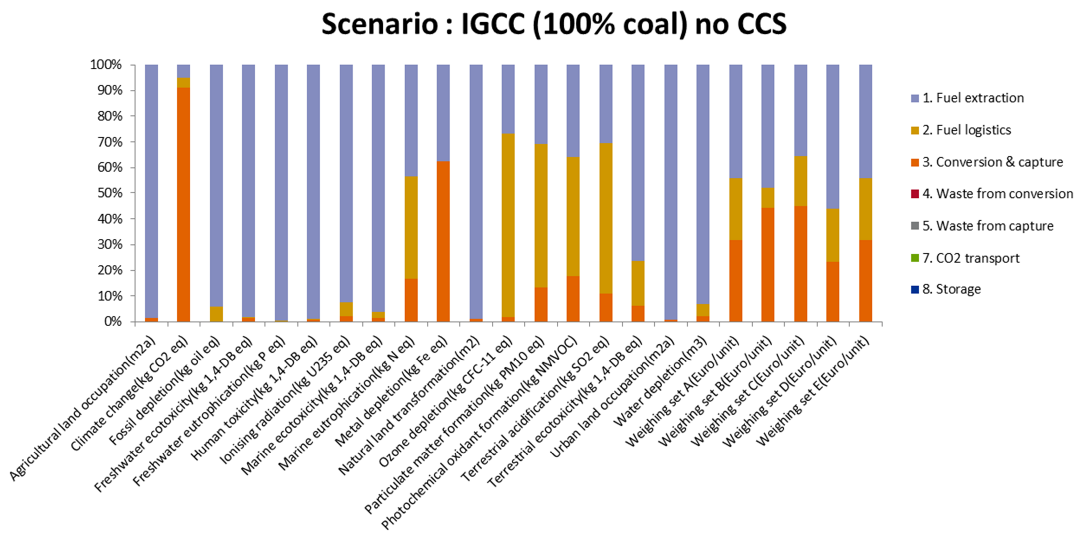


Figure 6-14 Process breakdown of all environmental indicators case IGCC 100% coal without CCS. (*Note that the environmental interventions and impacts related to the compression of CO_2 are included in 'Step 3 Conversion and capture'. The legend of this figure therefore excludes 'Step 6 Compression')*

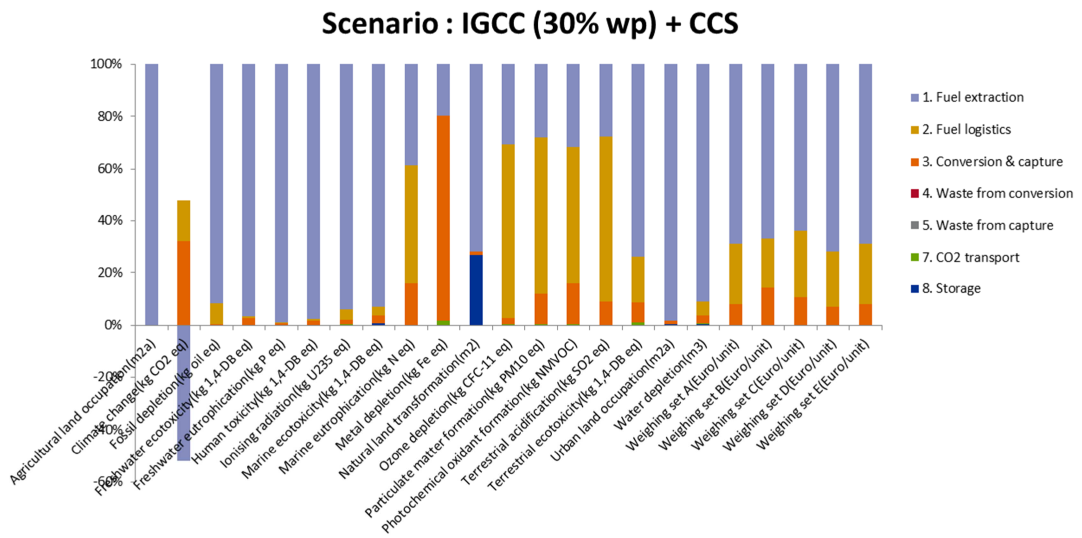


Figure 6-15 Process breakdown of all environmental indicators case IGCC 70% coal and 30% wood pellets including CCS. (*Note that the environmental interventions and impacts related to the compression of CO_2 are included in 'Step 3 Conversion and capture'. The legend of this figure therefore excludes 'Step 6 Compression')*

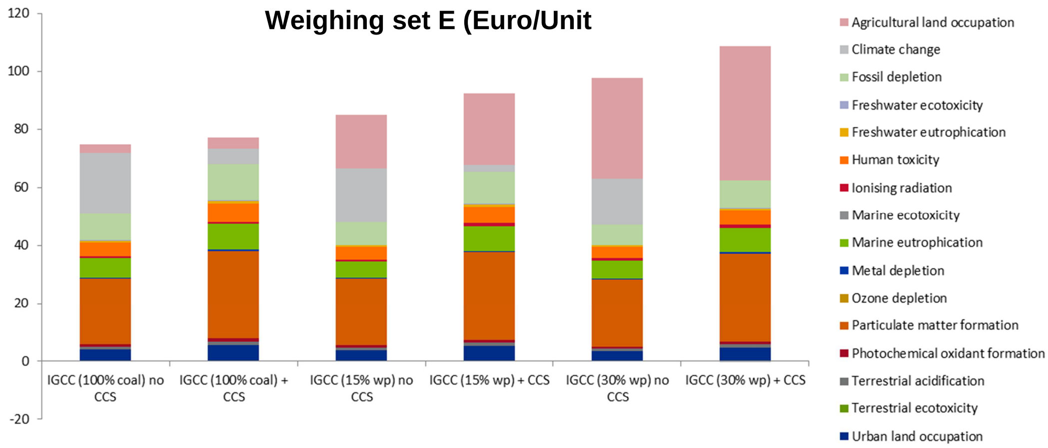


Figure 6-16 Distribution of contributions from environmental themes for IGCC scenarios using weighing set E

6.5. Comparison of CCS chains

6.5.1. Full chain

The previous sections have shown the assessment of the individual CCS chains. Within this paragraph the impacts are compared. For reasons of comparison and simplicity, a representative selection of the individual chains was made. They represent the different technologies, post and pre combustion, and the fuels, coal, gas and biomass. A comparison of the impacts, distributed over the process steps, for these main scenarios is given in Figure 6-17. The impacts are expressed in Euro/Mwh by using weighing set E. The figure shows that the impacts from the coal and biomass co-fired power plants are on average 5 times higher than the gas fired ones.

Fuel extraction, fuel logistics and the conversion and capture process dominate the environmental impact. Except for the gas fired power plant which uses the current Dutch natural gas mix. This mixture mainly consists out of domestic produced gas, meaning short transport distances resulting in a low impact to the transport step. The external costs of the coal and biomass fired plants are in the same order of magnitude for both post combustion and pre combustion.

The high scores of the biomass co-firing chains are caused by the agricultural land-use allocated to the residual wood and the corresponding monetisation value. Both the allocation of impacts to the use of residual wood as well as the monetary valuation of these impacts are surrounded with uncertainties. It is under discussion whether and to what extent impacts should be allocated to waste streams. Current monetary valuation methods for land use assume a complete loss ecological services, which might be an overestimation. CCS shows a decrease of the environmental cost for the NGCC chain, but an increase for the other chains, using weighing set E. The sensitivity to the weighing sets will be shown in section 6.6.3.

Figure 6-18 shows a comparison of the environmental costs of the main scenarios with a distribution over the environmental themes. The individual chains have been discussed in the previous sections. This comparison shows the relative high costs due to assumptions in the agricultural land occupation of the biomass production. CCS reduces the impacts from climate change for all chains, but except for the NGCC chain, this reduction does not compensate the additional impacts induced by the fuel penalty (additional fuel extraction and transport). Again these results are valid under the assumption that weighing set E is used.

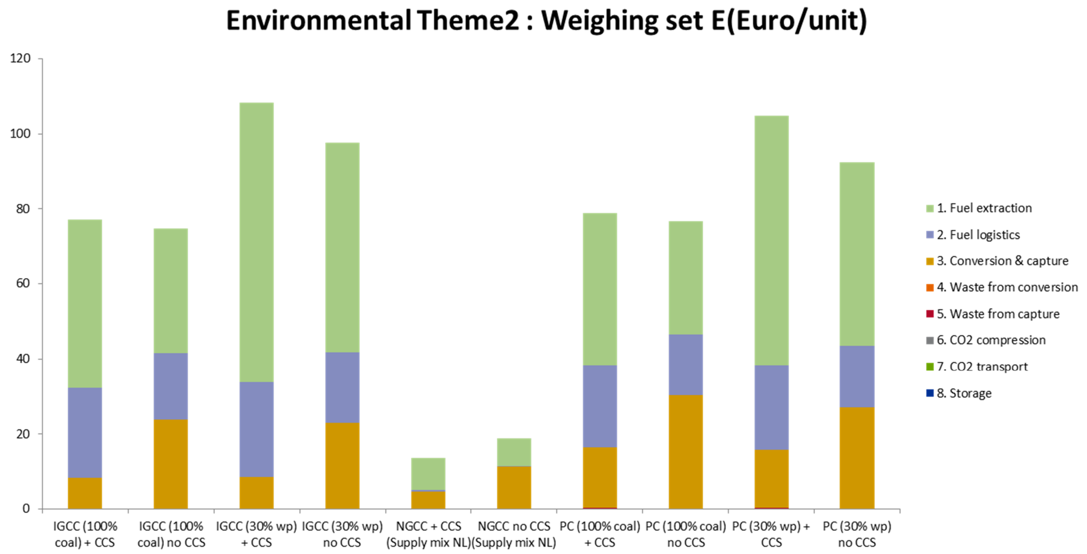


Figure 6-17 Comparison of the impacts of the main scenarios with distribution over the process steps, expressed in Euro/MWh (weighing set E)

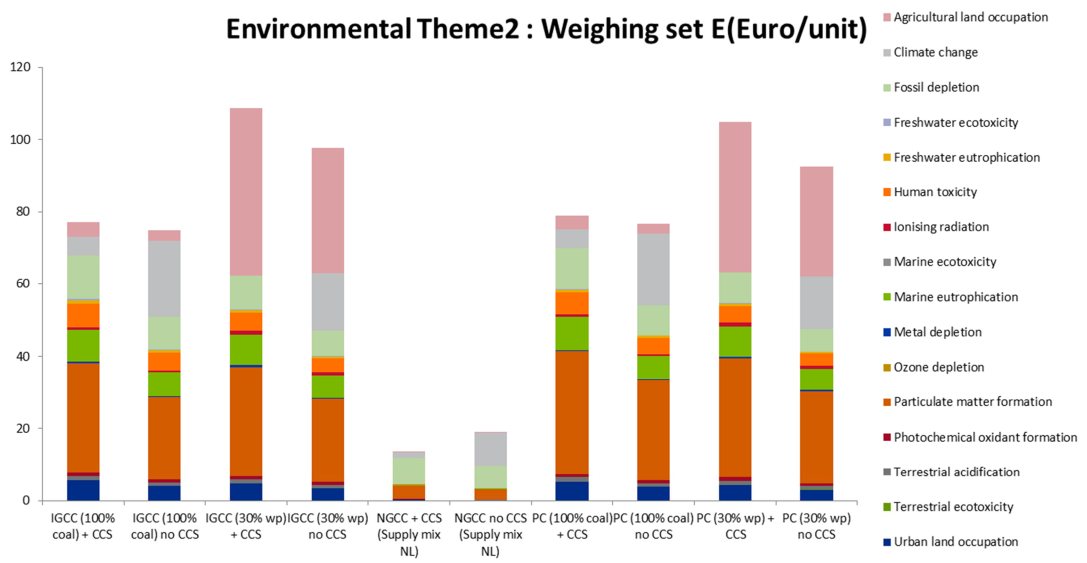


Figure 6-18 Comparison the impacts of the main scenarios with distribution over the environmental themes, expressed in Euro/MWh (weighing set E)

6.5.2. Fuel extraction and transport

Figure 6-19 shows the environmental impacts of the fuel extraction and logistics steps using weighing set E. The CCS scenarios have a higher impact due to the fuel penalty. The gas fired scenarios have low impacts, as explained in the previous section. About half of the impacts of the scenarios with co-biomass is caused by the agricultural land occupation. There is a negative impact, i.e. environmental benefit, in the theme of climate change from the use of biomass. The next important impact in the coal and biomass chains is particulate matter formation. The impacts from fuel extraction and transport are based on the

EcoInvent database. These data might be outdated to a certain extent, e.g. emissions from gas transport in Russia are based on 1994 data.

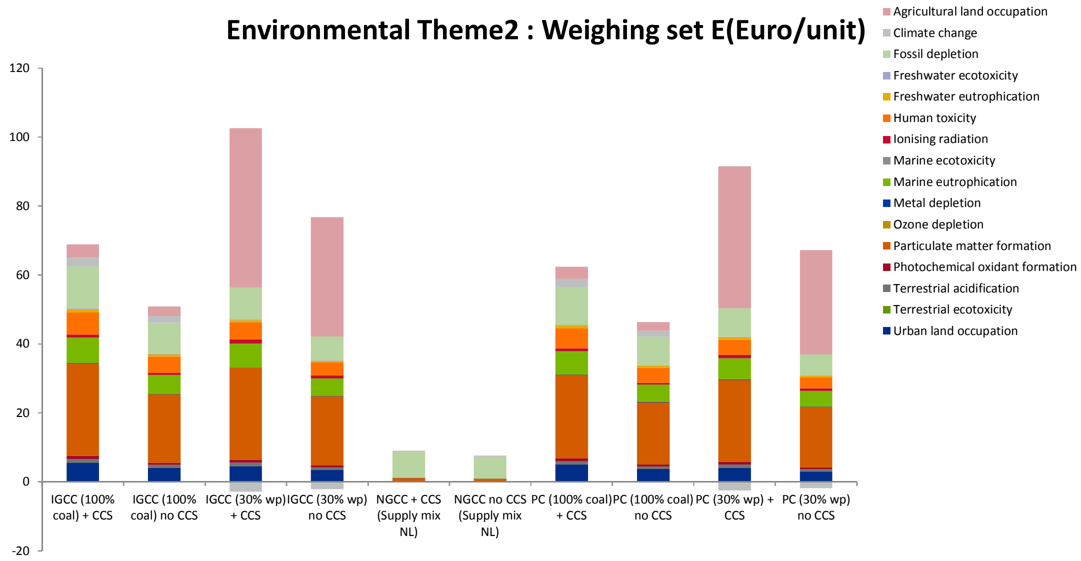


Figure 6-19 Environmental impacts, expressed in EUR/MWh (using weighing set E) for the fuel extraction and logistics steps

6.5.3. Power generation and capture

Figure 6-20 shows the environmental impacts of fuel conversion, CO_2 capture, compression and waste generation using weighing set E. The main contribution in the no CCS scenarios is from climate change. In the other scenarios particulate matter is the most important impact. The IGCC scenarios show a higher contribution to this theme than the other scenarios.

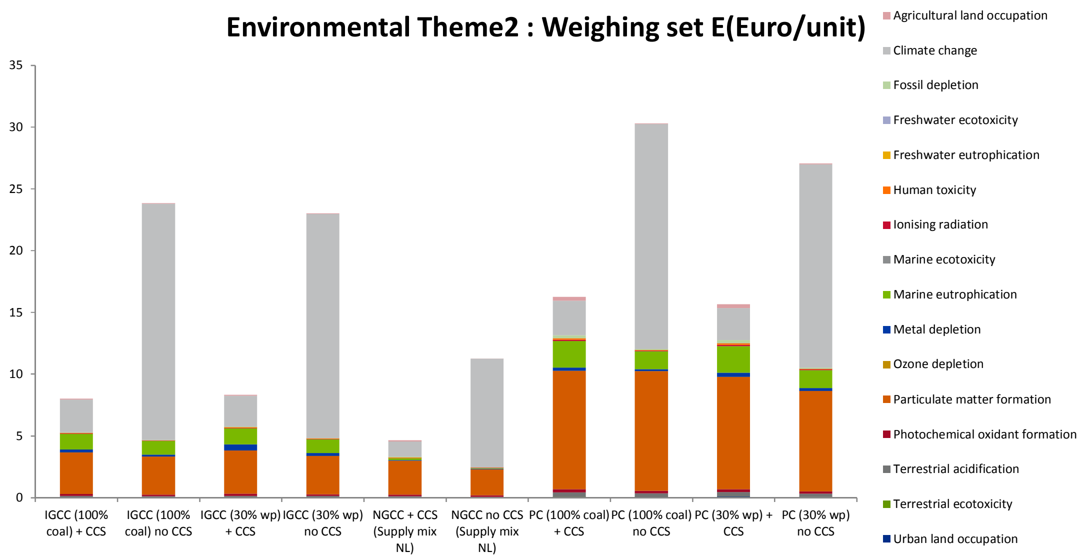


Figure 6-20 Environmental impacts, expressed in EUR/MWh (using weighing set E) for the conversion, capture, compression and waste steps

6.6. Sensitivity to fuels, extraction location and transport distances

6.6.1. Sensitivity to location of gas extraction

Figure 6-21 shows the environmental cost to produce 1 MWh off electricity with natural gas from Russia and the Netherlands with a NGCC with and without CCS. The extraction and transport of natural gas from Russia causes an additional 10 euros of environmental cost per MWh of electricity. This is a reflection of the impacts caused by leakage of natural gas, sweetening of the gas and the flaring of the gas in Russia. The Dutch natural gas mix, as used in this study, mainly consists out of the domestic NL gas mix as shown in the figure. However, these additional costs of 10 euros/MWh are small compared to the caste of coal fired power plants, which are in the order of 60 euros higher.

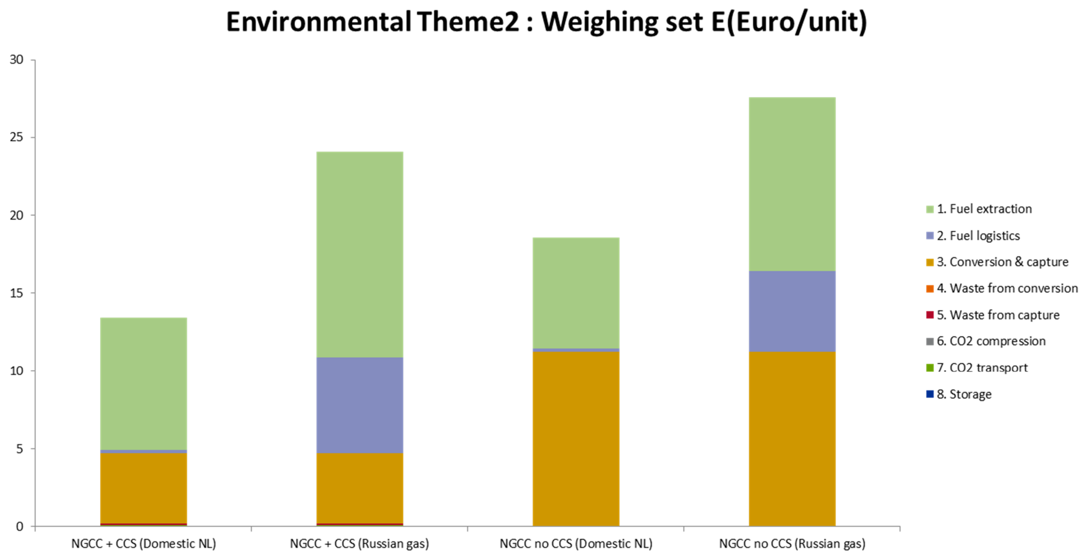


Figure 6-21 Environmental costs for the production of 1 MWh of electricity (weighing set E) via NGCC with and without post combustion CCS using NG from Russia and from the Netherlands

6.6.2. Sensitivity to coal import mix

Location and transport distances can have an impact on the environmental performance. The import mix of coal in the Netherlands varies over the years, see Table 6-1. From 2010 to 2011 the amount of coal from Russia halved and currently, almost three quarters comes from Colombian coal. Figure 6-22 shows the results of the production of 1 MWh of electricity by using the coal mix from 2010 versus 2011. The impacts are expressed in euro/MWh using weighing set E. The differences are marginal with only the agricultural land occupation showing a decrease of about 35%.

Table 6-1 Composition of the imported coal mix in the Netherlands (CBS, 2013)

	2009	2010	2011
South-Africa	16%	14%	9%
Colombia	61%	60%	73%
USA	4%	4%	4%
Russian Federation	13%	20%	10%
other	6%	3%	4%

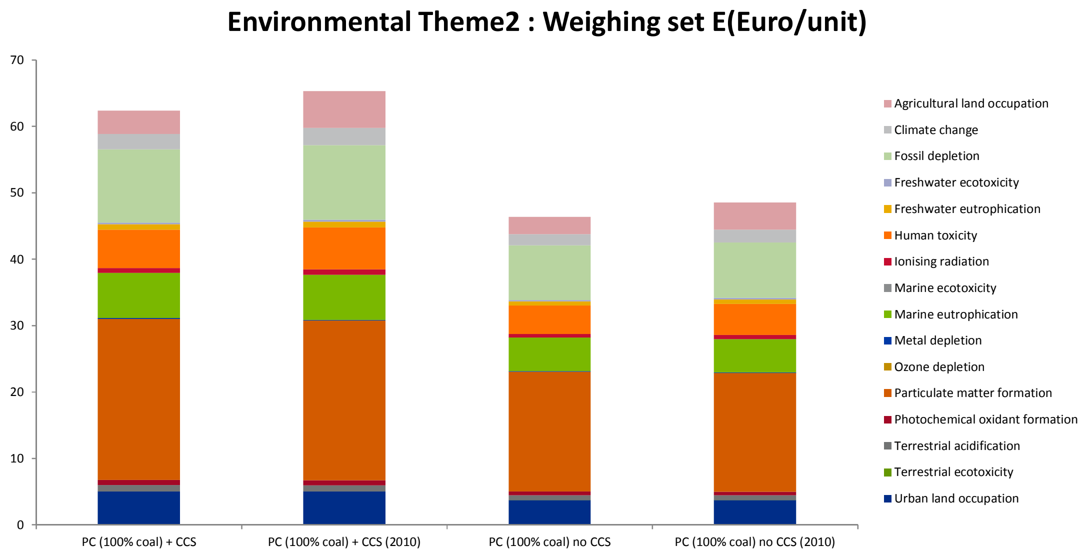


Figure 6-22 Environmental costs of fuel extraction and logistics needed for the production of 1 MWh of electricity (weighing set E) via PC with and without post combustion CCS using coal mix 2011 and 2010

6.6.3. Sensitivity to weighing set

Figure 6-23 shows the environmental costs of the production of 1 MWh of electricity for the main power generation chains when using the various weighing sets implemented in the environmental performance tool. The differences in the absolute value can be up to 80 euros per MWh. This is illustrated by the cases with 30wt% wood pellets, which is due to the absence in set B of a shadow price for agricultural land occupation.

Set C has a high shadow price for climate change, while set D has a low price. The choice of the weighing is determinant for a positive or negative outcome in the assessment of CCS. For instance, by using set C the external cost of the CCS chains are lower than for the reference without CCS. When using set D the costs of the CCS chains are higher, except for the NGCC case.

The NGCC cases show a decrease of the environmental cost by the implementation of CCS for all sets of shadow prices. For the PC and IGCC cases the implementation can lead to a positive or negative effect, depending on the set of shadow prices used.

The assessments of the individual chains in section 6.1 to 6.4 show the impacts of applying CCS to the various environmental themes. In general the impacts to climate change are reduced by applying CCS, but all other impacts increase because of the fuel penalty (additional fuel extraction and transport). To assess the overall benefits and trade-offs the weighing sets can be used. However for the PC and IGCC cases the outcome depends on the weighing set, more specific on the valuation of the theme of climate change versus the other themes, especially particulate matter formation, fossil depletion and agricultural land occupation.

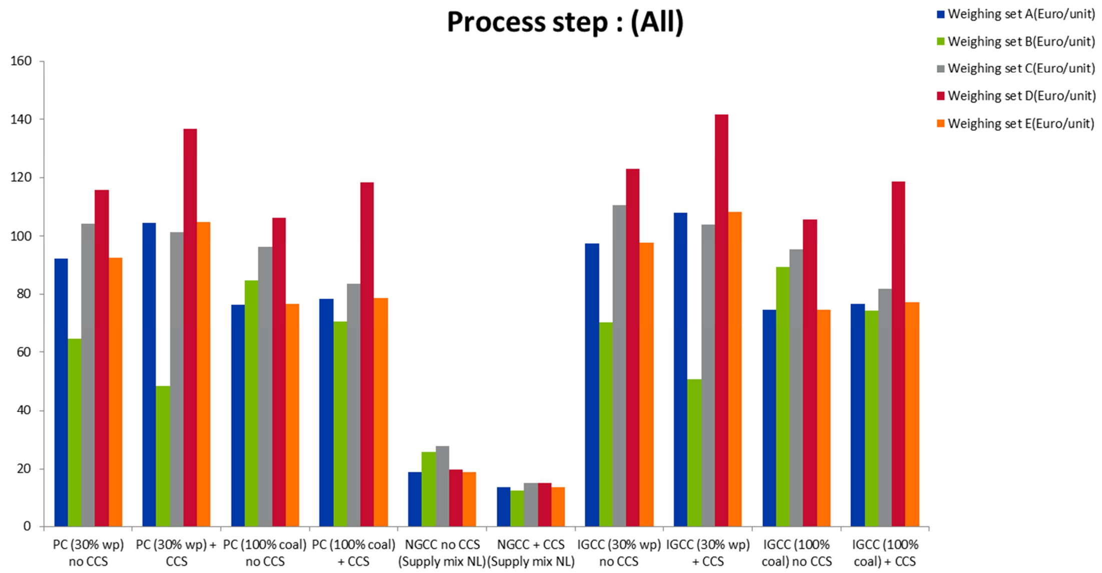


Figure 6-23 Environmental costs to produce 1 MWh of electricity for the various weighing sets included in the environmental performance tool

6.7. The environmental costs and benefits of CCS in deployment scenarios

Figure 6-24 shows the results from the three illustrative future scenarios. The first graph shows the total amount of electricity generated with the use of fossil fuel fired power plants (IGCC, PC, CHP and NGCC), with or without CCS. The reference scenario clearly shows the highest overall production of electricity with the use of fossil fired power plants. The lowest fossil based production is found in the scenario where CO_2 emissions are capped. Detailed results of the scenarios are included in the section 'Deployment scenarios' of this report.

In Figure 6-25 the total amount of electricity generated in coal fired power plants equipped with CCS is shown. Figure 6-26 is rather similar but it shows gas fired electricity generation with CCS.

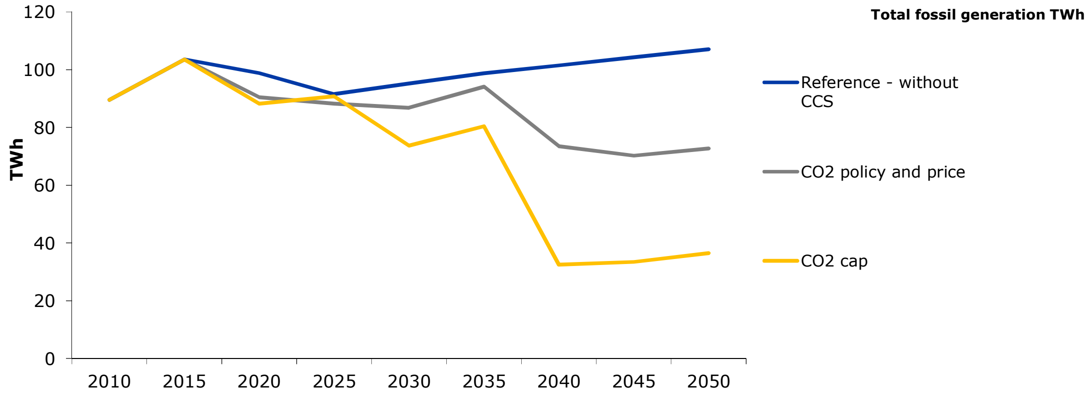


Figure 6-24 Annual electricity generated with fossil power plants (with and without CCS) under various scenarios

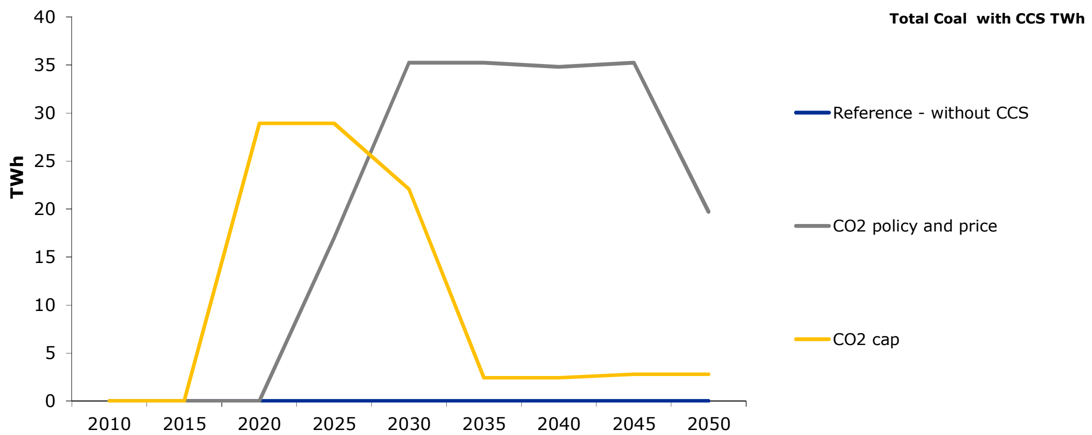


Figure 6-25 Annual electricity generated with coal fired power plants equipped with CCS under various scenarios

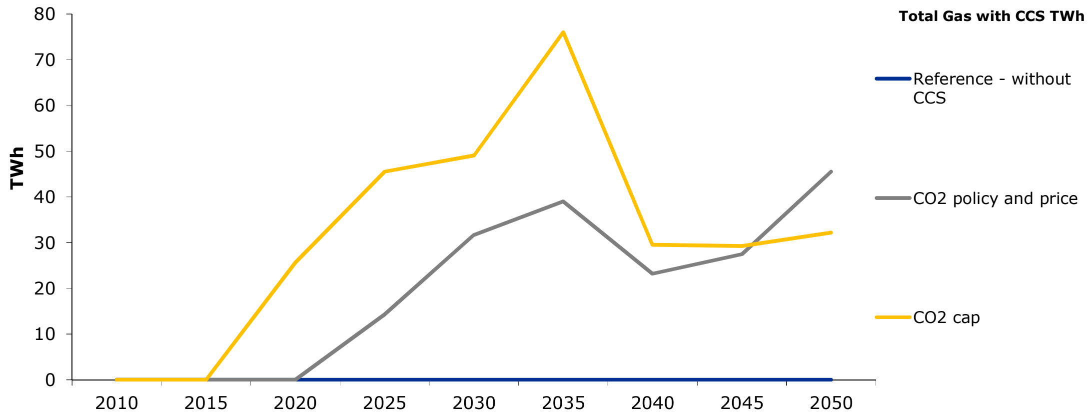


Figure 6-26 Annual electricity generated with gas fired power plants equipped with CCS under various scenarios

The results of this rough scenario modelling exercise shows a clear divergence in the deployment and operation of gas and coal fired power plants with CCS. A result which is not shown in the figures above is that IGCC power plants are not deployed in the Dutch power sector according to the scenario modelling. The capital cost are expected to be too high for the implementation of the IGCC technology. Pulverized coal fired power plants are the technology of choice (for firing coal) in the scenario model.

Total environmental costs and benefits of the scenarios are calculated by combining the total electricity production in a scenario with the technology specific environmental performance; see section 4.7 for methodological details.

Results are shown in Figure 6-27. Due to the high uncertainty of this exercise only indexed figures are shown to indicate the relative difference between the scenarios and focus less on the absolute environmental cost figures. To place the indexed values into perspective, the reference scenario results in environmental costs in the order of several hundred billions of euros.

Note that only the cumulative environmental damage costs of fossil based power generation is calculated. This is due to the fact that no environmental damage costs of (non-biomass) renewable and nuclear production technologies are included in the environmental performance tool.

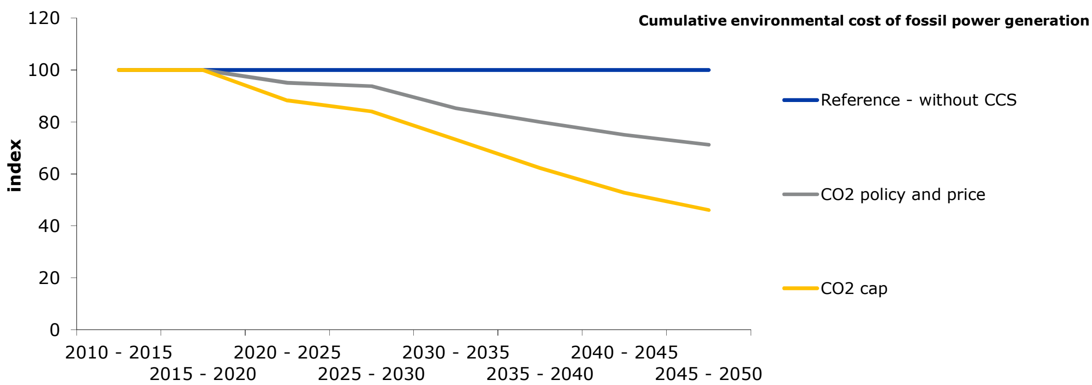


Figure 6-27 Cumulative environmental cost of fossil electricity generation. Results are normalised with ‘Reference’ set at 100. Results are based on using weighing set E to calculate technology specific environmental damage costs.

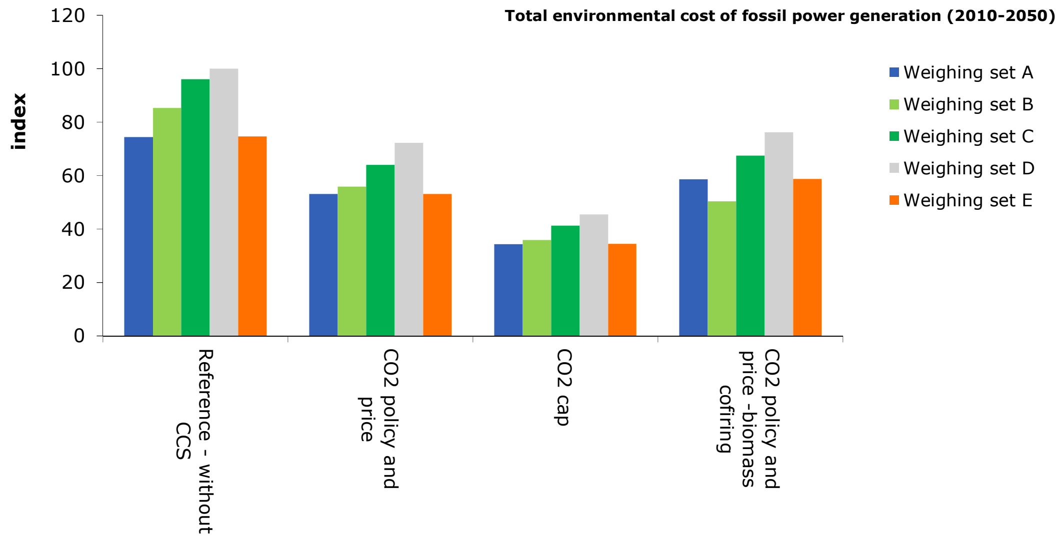


Figure 6-28 Cumulative environmental cost of fossil electricity generation in multiple scenarios under different weighing sets (A-E). The scenario with the highest environmental damage costs is set at 100.

Figure 6-28 shows the total environmental damage costs of fossil power generation over the full time period of the scenario modelling, 2010-2050. Here also a new scenario variant is introduced to show the impact of biomass co-firing. For this variant the 100% coal fired power generation in the 'CO_2 policy and price scenario' is replaced by 15% co-firing of biomass.

The results show that total environmental costs are lower when CO_2 mitigation policy is implemented. The reference scenario without strong mitigation policy has the highest environmental cost of all scenarios due to the deployment of coal fired capacity without CCS. The lowest environmental costs are found in the scenario that sets a CO_2 cap for the Netherlands. This leads to a strong reduction of CO_2 emissions with early deployment of low carbon technologies. This scenario has a high share of renewable generation and natural gas fired power plants with CCS. This combination leads to low environmental damage costs, although it should be again noted that no environmental costs has been included for renewable and nuclear electricity generation.

Another interesting result showed in Figure 6-28 is the difference between a scenario where power plants equipped with CCS are mostly gas fired (CO_2 cap) compared to the scenario that includes mostly coal fired power generation (CO_2 policy and price). The latter scenario results in a high deployment of coal fired capacity with CCS and it brings overall higher environmental damage costs compared to a scenario where the demand is met with mostly renewables and gas fired capacity, either or not equipped with CCS.

The biomass co-firing variant shows somewhat diverging results. The total environmental costs are comparable or higher than in the original 'CO_2 policy and price' scenario, except when applying weighing set B. With that weighing set the environmental damage cost decrease when co-firing biomass in coal fired power plants. The reason is that in weighing set B the environmental damage costs of climate change are higher than in set A, D and E; and no environmental damage costs are allocated to land-use. In set C the environmental damage costs of emitting CO_2 are equal to that in set B, but damage cost assumptions for other impact categories are higher than in set B. For detailed assumptions see section 4.5.

The assumption on the damage cost of emitting CO_2 relative to the damage costs of other impact categories is thus rather crucial when estimating the environmental costs of biomass co-firing in combination with CCS. The results vary considerably when changing the weighing set and can be crucial when ranking scenarios according to their (relative) environmental damage costs.

7. Conclusions & Recommendations

7.1. Environmental performance tool

An Environmental Performance Tool has been developed with WP4.3 of the CATO2 program. The tool is used within this study to assess the environmental performance of power plants with CCS over their complete life cycle. The tool has been further developed and improved - by practicing - during the assessments of CCS chains in this report. The number of output plots has been increased to be able to show the relevant results in a convenient format. A number of weighing sets has been included, based on monetization values from literature. The user is able to select a set or to add his own set which represents his or her own priorities.

7.2. Assessment of CCS chains

As with any technology, the implementation of CCS will lead to environmental trade-offs between climate change and all other themes. The CO_2 emissions will be reduced due to CCS, but all other impacts will increase. The valuation of environmental themes, either via monetization or another method, thus determines whether the net balance between the advantages of CCS and its trade-offs are positive or negative.

Fuel extraction, logistics and the conversion and capture process are the three dominating steps. Except for the gas fired chain, in which the logistics have a negligible impacts as the gas mainly originates from the Netherlands. The implementation of CCS will lead to a further shift from the conversion and capture step towards the fuel extraction and logistics step. This shows the importance of having an integrated view on the life cycle of a power generating technology also taking into account multiple environmental themes.

Climate change, particulate matter formation and fossil depletion are the dominating themes in all CCS chains. The coal fired plants additionally have impacts from human toxicity and marine eutrophication. Agricultural land occupation is a large additional impact in the chains based on the co-firing of biomass. Both the allocation of impacts to the use of residual wood as well as the monetary valuation of these impacts are surrounded with uncertainties. It is under discussion whether and to what extent impacts should be allocated to waste streams. Current monetary valuation methods for land use assume a complete loss ecological services, which might be an overestimation. The use of biomass reduces the impacts to climate change by the negative emission in the extraction step. At an amount of 30% biomass, the net CO_2 emissions in the CCS chain drop to zero. The overall environmental costs increase with an increasing amount of biomass.

The natural gas chains clearly outperform the coal fired and biomass co-fired chains. This is mainly due to fuel extraction and logistics step of the natural gas chain, which has far less impacts than the corresponding step in the coal chain. The overall environmental costs for the PC and IGCC chains are similar. The IGCC chain has lower impacts in the conversion and capture step (e.g., less particulate matter formation), but a higher impact in the extraction and logistics step, because of its slight lower efficiency.

The different sets of shadow prices currently included in the tool show mixed messages about the implementation of CCS to coal and biomass fired power plants. When the theme of climate change is relatively higher valuated than the others, e.g. those related to air pollution and toxicity, CCS shows environmental benefits. When climate change is lower valuated, CCS will show a negative environmental result. CCS implemented in the gas fired chain shows environmental benefits for all current sets of shadow prices.

The results also indicate that the gas chain is sensitive to the extraction location of the natural gas. The current Dutch natural gas mixture mainly originates from the Netherlands. A shift to Russian gas could lead to an increase in environmental impacts from extraction as well as a substantial increase in the impacts from pipeline transport, mainly caused by the leakage of natural gas.

The impacts from coal mining and transport vary from country to country and can contribute to variations in the environmental cost of the coal fired chains. The impacts due to variations in recent coal import mixes appear limited to a maximum of 5% of the environmental costs of the whole chain.

The assessment results of the reference chains are linked to the deployment scenarios as developed within WP2.4.3. The environmental costs due to fossil electricity generation decrease in the scenarios with a CO_2 policy or a CO_2 cap, in which respectively coal- and gas-fired power plants are equipped with CCS. The impacts from renewable energy sources, present in the mitigation scenarios are explicitly excluded.

7.3. Recommendations

The results of the EPT should not be used to place a definite value (in terms of absolute environmental damage costs) to a certain technology or life cycle. The EPT aims to facilitate a discussion on:

- How to compare climate change with other environmental concerns by different stakeholders?
- Where in the full life cycle are opportunities to further improve the environmental performance and should efforts be devoted to?
- Does the EPT flag issues regarding the environmental performance that require clarification or refinement of the research?

The impacts from the use biomass to agricultural land occupation are large. Furthermore, attention should be paid to what extent impacts should be allocated to waste streams like residual wood; and to the shadow price of agricultural land occupation. The current shadow price is based on a complete loss of ecosystem services and this assumption might not be realistic for all cases.

The theme of water depletion has not been valuated, due to absence of data in literature. Water as a scarce resource is gaining increased attention, especially in relation to biomass. It is recommended to develop a shadow price for the theme of water depletion.

Actual emission data for CCS pilot and demonstration projects is relative scarce and when it is available it should be used with care when implementing the data in a LCA tools like the EPT. However, inclusion of actual emission data in the tool would likely improve the estimates presented in this study and would give better insights into the actual environmental performance of power generation with CCS. Also, the tool can be used as a screening tool to study the emission profile of a power plant with CO2 capture and highlight potential concerns, and benefits.

Upstream effects of power generation seem to be very important in the end-results of this study. However, data regarding upstream environmental impacts are often scarce, outdated and of relative low quality. It is recommended to improve data gathering and validation on the upstream parts of the life cycle for the power generation concepts.

During workshops where the tool was presented and discussed, feedback was received to improve the weighing methodology for various environmental themes in the Environmental Performance Tool. It is recommended to develop a new set of weighing factors, or multiple sets, based on extensive stakeholder consultation. This would include consulting industry, government, NGO’s and scientific stakeholders to develop a robust weighing set, or sets that reflect their viewpoint on environmental themes, also in relation to CCS projects.

It is recommended to develop a web-based tool that shows results of life cycle assessment for CCS that can be altered based on the values of individual stakeholders. It can be a unique tool to facilitate a stakeholder discussion on the positive and negative effects of CCS.

A limitation of the methodology applied in the tool and study is that location specific environmental impacts are not properly accounted for. For some environmental themes the impacts are very much location dependent. Applying a general monetization factor thus neglects the location of an environmental intervention (e.g. the emission of NO_x or particulate matter in low or highly populated area). Although this is a well-known limitation of LCA methodology in general, in a next version of the EPT this local dependency of environmental impacts is recommended to study in more detail.

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Annex A. Deployment scenarios

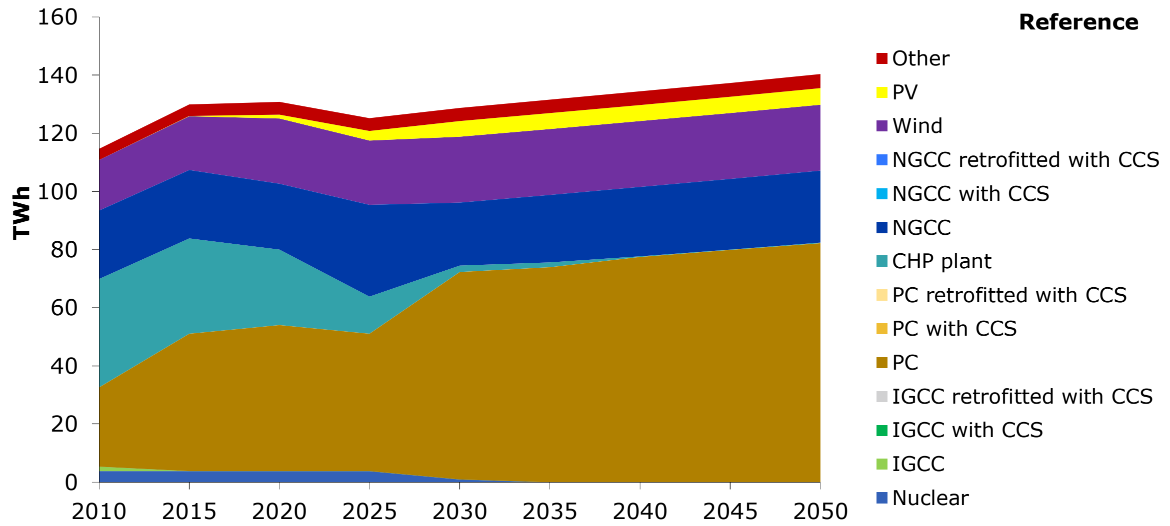


Figure A-1 Electricity production in the Netherlands under the 'Reference' scenario

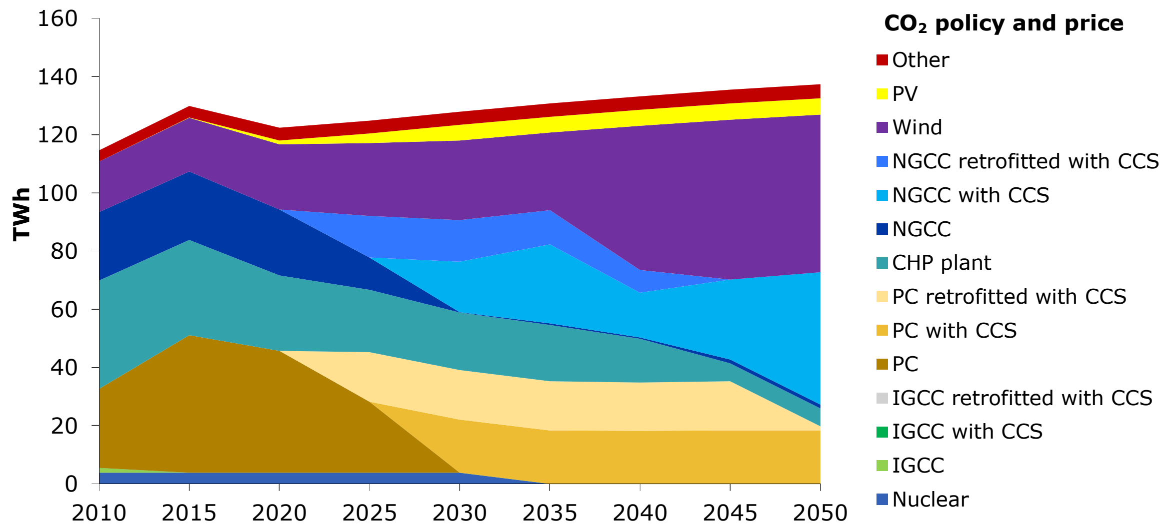


Figure A-2 Electricity production in the Netherlands under the 'CO2 policy and price' scenario

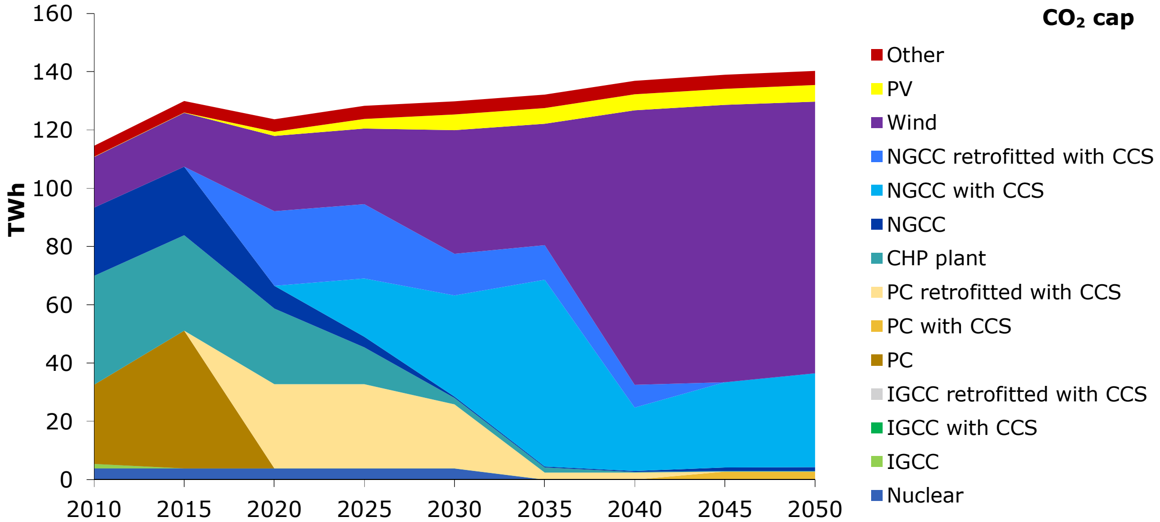
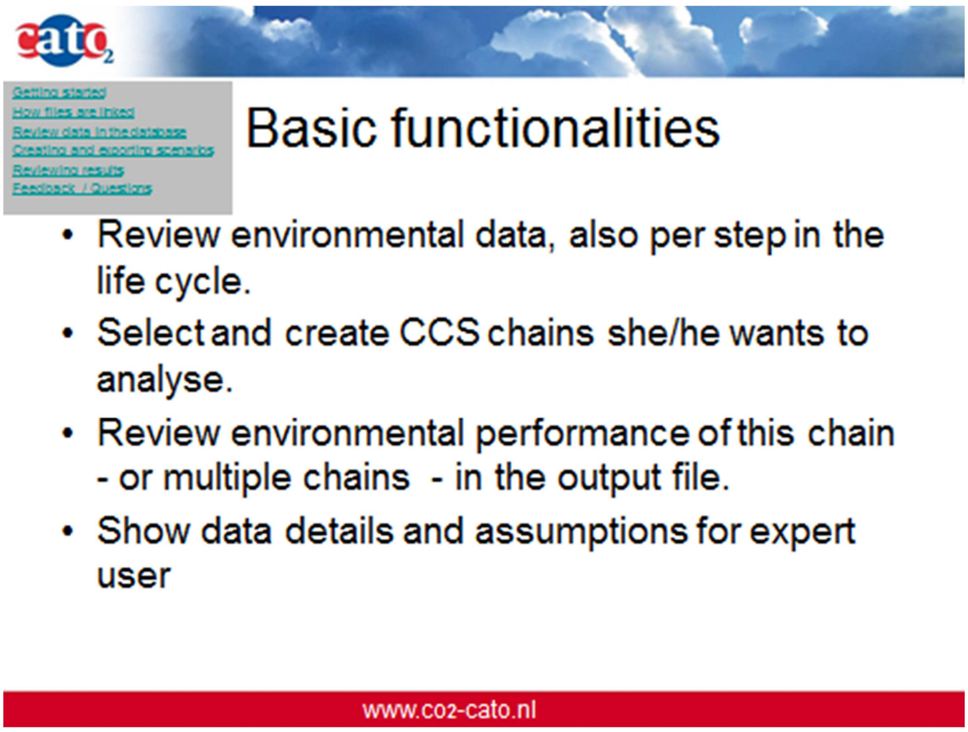


Figure A-3 Electricity production in the Netherlands under the 'CO2 cap' scenario

Annex B. Manual of Environmental Performance Tool



Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions

Three step tool

The user basically has to walk through three steps when using the tool.

1. The user opens the Excel interface of the tool and reviews the environmental performance data on steps in the life cycle of CCS chains that are already defined in the database.
2. The user selects or builds its own scenario (CCS chain from cradle to grave) in the Excel interface of the tool and exports the scenarios with the tool.
3. An export file is generated in MS Excel that allows analysing and comparing the performance of the scenarios. In this step also major assumptions can be changed to allow for sensitivity analysis.

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Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions

Content

- Getting started
- How files are linked
- Review data in the database
- Creating and exporting scenarios
- Reviewing results
- Feedback / Questions

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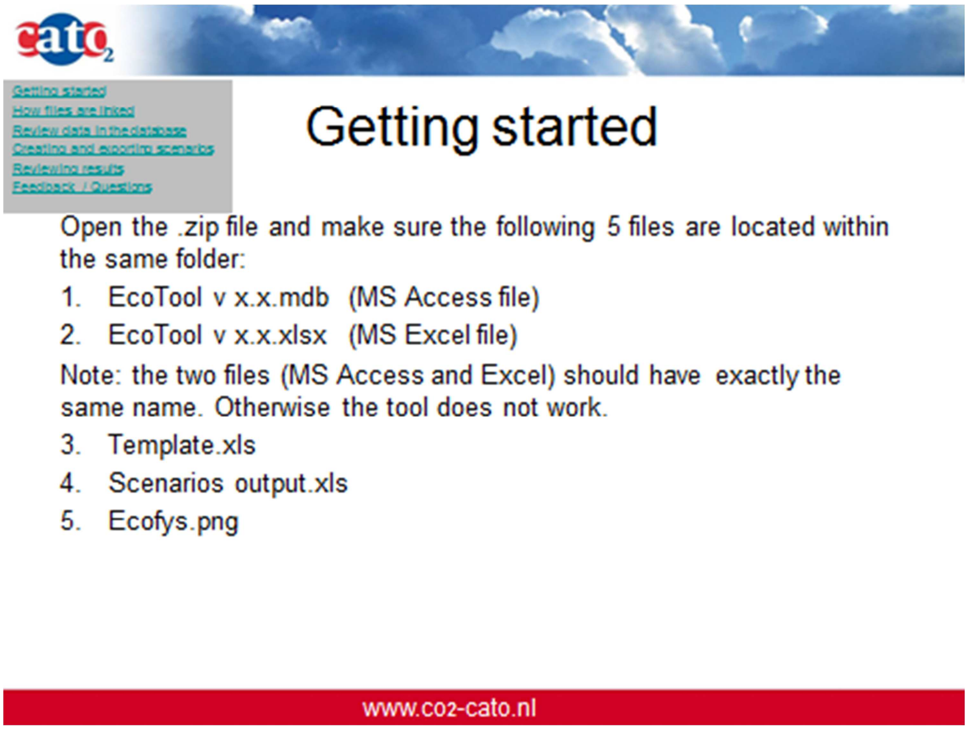
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Getting started
Download the latest version of the tool:
https://ecity.tno.nl/sites/CATO2/WP4.3/default.aspx
www.co2-cato.nl


Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Getting started
Open the .zip file and make sure the following 5 files are located within the same folder:
1. EcoTool v x.x.mdb (MS Access file)
2. EcoTool v x.x.xlsx (MS Excel file)
Note: the two files (MS Access and Excel) should have exactly the same name. Otherwise the tool does not work.
3. Template.xls
4. Scenarios output.xls
5. Ecofys.png
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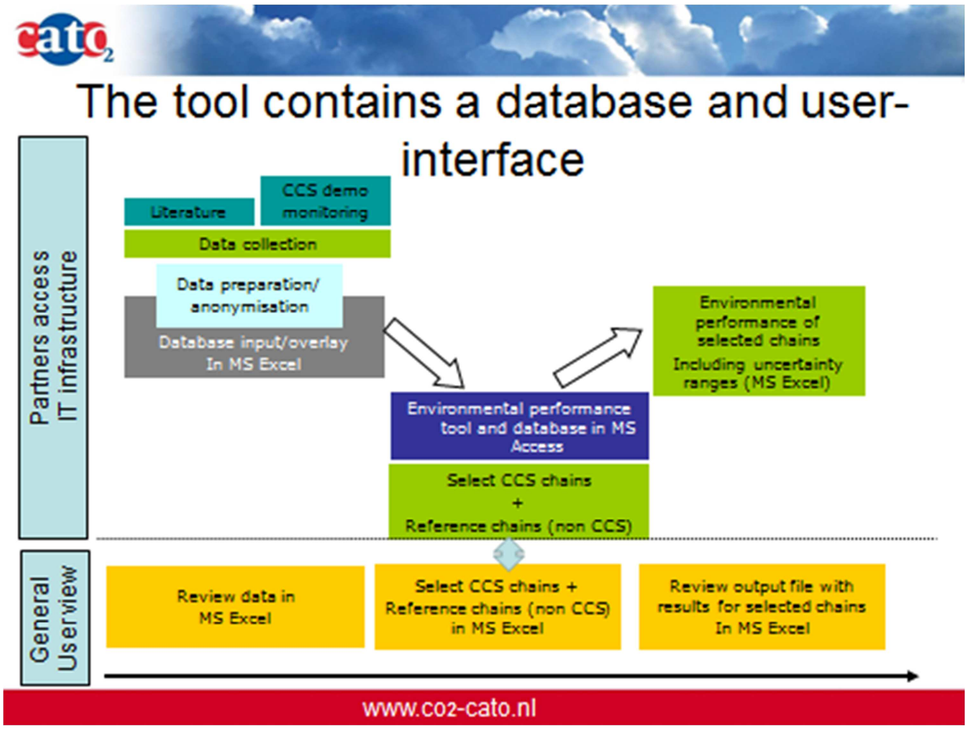
The tool contains a database and user-interface
Partners access IT infrastructure
General User view
Literature
CCS demo monitoring
Data collection
Data preparation/ anonymisation
Database input/overlay In MS Excel
Environmental performance tool and database in MS Access
Select CCS chains + Reference chains (non CCS)
Environmental performance of selected chains Including uncertainty ranges (MS Excel)
Review data in MS Excel
Select CCS chains + Reference chains (non CCS) in MS Excel
Review output file with results for selected chains In MS Excel
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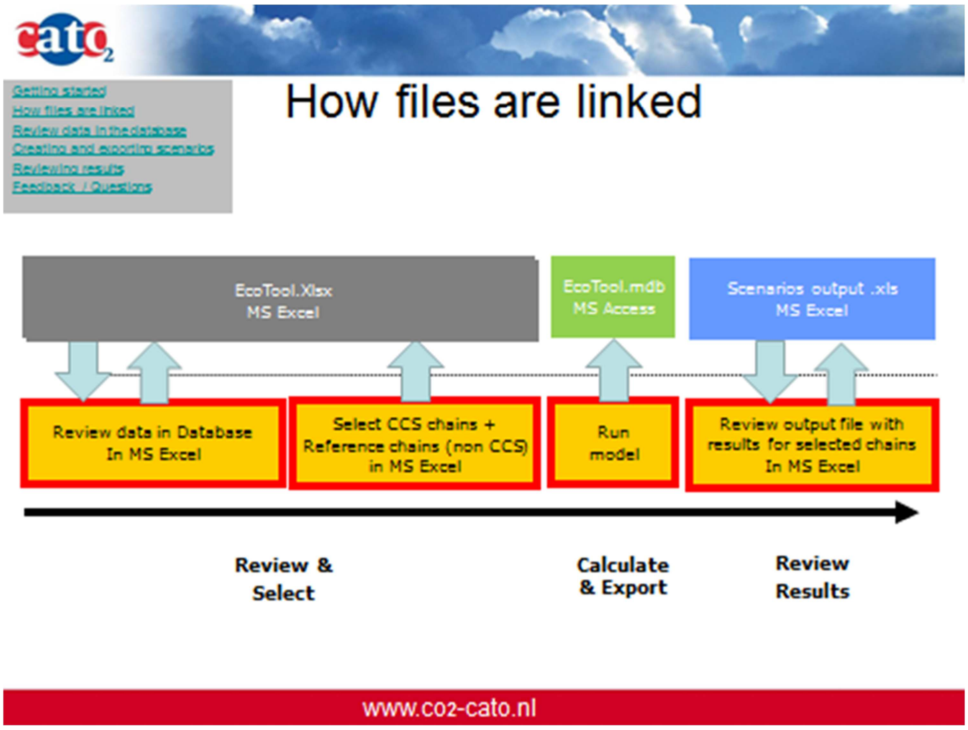
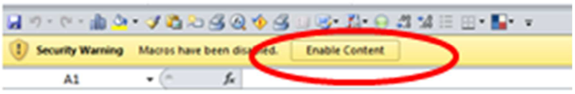

How files are linked
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
EcoTool.Xlsx MS Excel
EcoTool.mdb MS Access
Scenarios output .xls MS Excel
Review data in Database In MS Excel
Select CCS chains + Reference chains (non CCS) in MS Excel
Run model
Review output file with results for selected chains In MS Excel
Review & Select
Calculate & Export
Review Results
www.co2-cato.nl

Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions

Review data in Database

- Open file 'EcoTool v x.x.xlsx'
- Enable content



- Wait until the tool is fully loaded

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Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions

Steps in the life cycle

The life cycle of a CCS chain comprises 9 steps in this tool. The following steps in the life cycle are defined:

1. Fuel extraction
2. Fuel logistics
3. Conversion and capture of CO_2
4. Waste from energy conversion
5. Waste from capture of CO_2
6. CO_2 compression
7. CO_2 transport
8. CO_2 storage
9. Distribution of the energy carrier (e.g. electricity)

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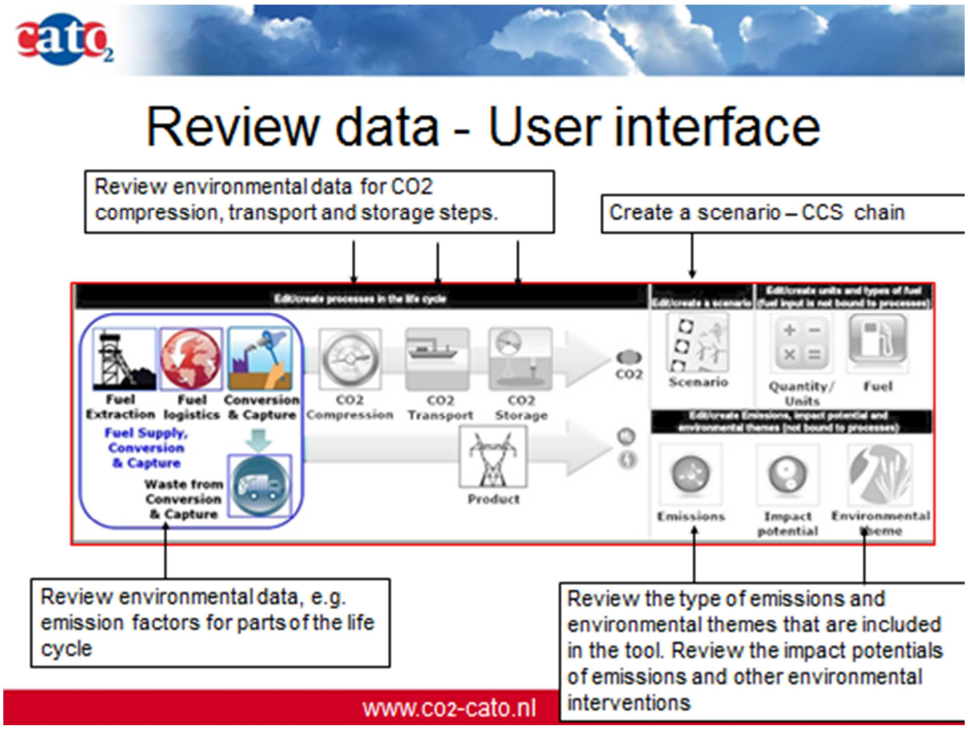
Review data - User interface
Review environmental data for CO2 compression, transport and storage steps.
Create a scenario – CCS chain
Edit/create processes in the life cycle
Edit/create a scenario
Edit/create units and types of fuel (fuel input is not bound to processes)
Fuel Extraction
Fuel logistics
Conversion & Capture
Fuel Supply, Conversion & Capture
Waste from Conversion & Capture
CO2 Compression
CO2 Transport
CO2 Storage
CO2
Product
Scenario
Quantity/ Units
Fuel
Edit/create Emissions, impact potential and environmental themes (not bound to processes)
Emissions
Impact potential
Environmental theme
Review environmental data, e.g. emission factors for parts of the life cycle
Review the type of emissions and environmental themes that are included in the tool. Review the impact potentials of emissions and other environmental interventions
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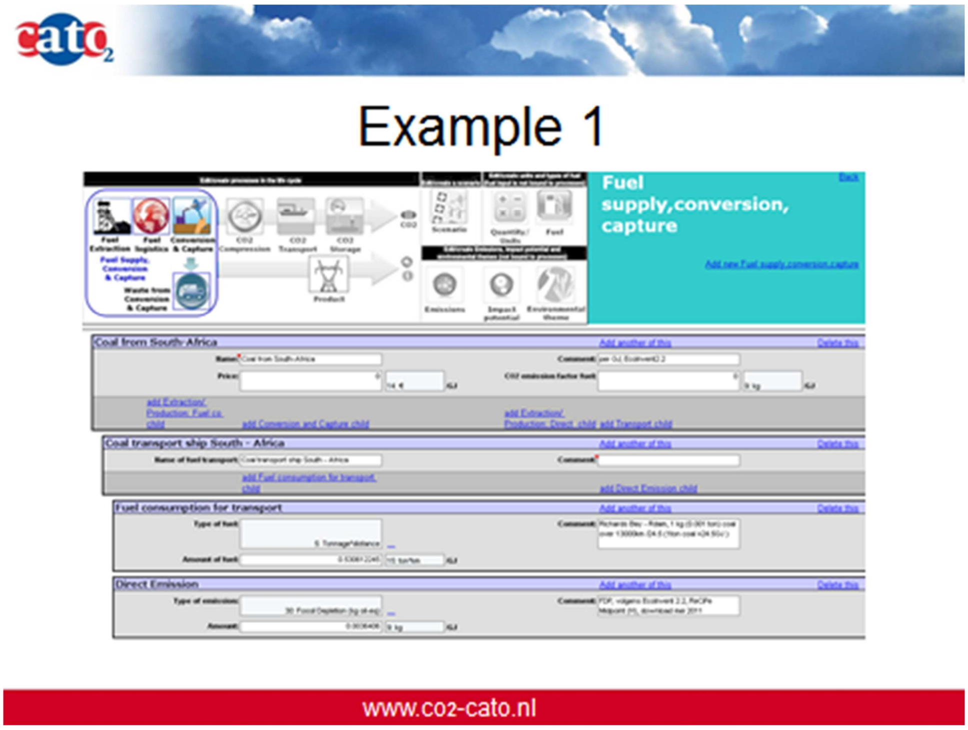
Example 1
Fuel supply,conversion, capture
Coal from South Africa
Coal transport ship South - Africa
Fuel consumption for transport
Direct Emission
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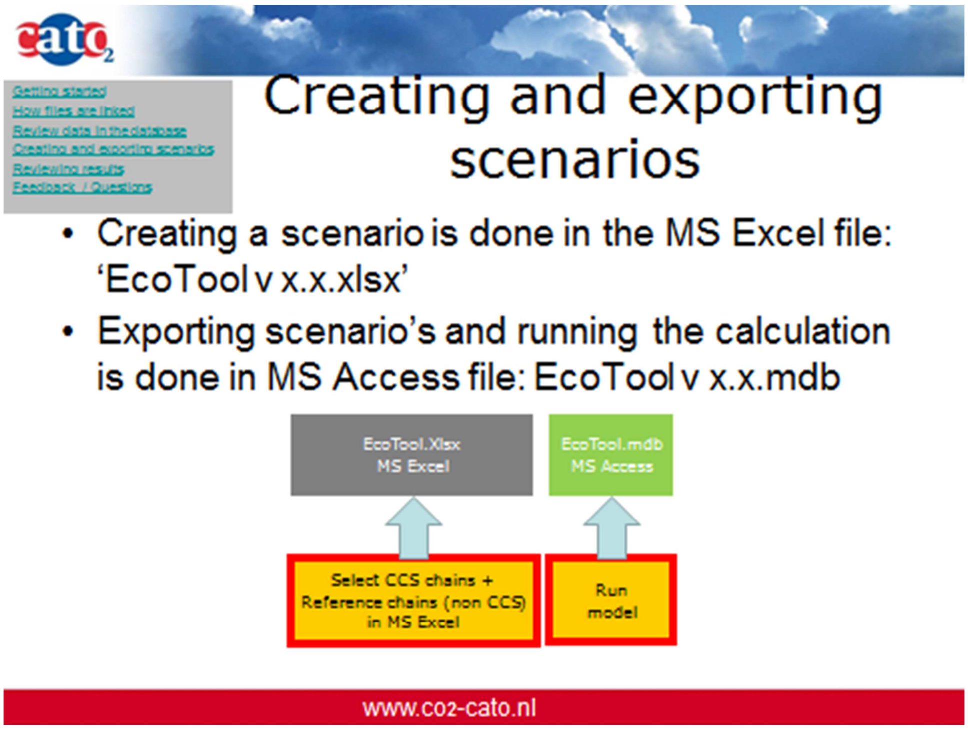
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Creating and exporting scenarios
• Creating a scenario is done in the MS Excel file: 'EcoTool v x.x.xlsx'
• Exporting scenario's and running the calculation is done in MS Access file: EcoTool v x.x.mdb
EcoTool.Xlsx MS Excel
EcoTool.mdb MS Access
Select CCS chains + Reference chains (non CCS) in MS Excel
Run model
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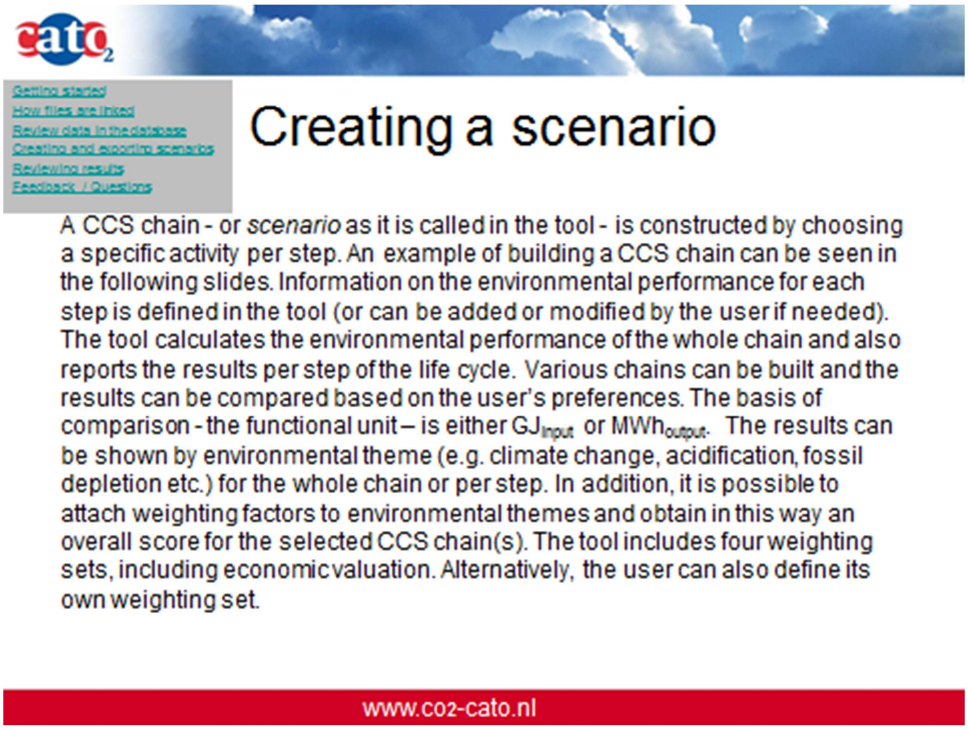
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Creating a scenario
A CCS chain - or scenario as it is called in the tool - is constructed by choosing a specific activity per step. An example of building a CCS chain can be seen in the following slides. Information on the environmental performance for each step is defined in the tool (or can be added or modified by the user if needed). The tool calculates the environmental performance of the whole chain and also reports the results per step of the life cycle. Various chains can be built and the results can be compared based on the user's preferences. The basis of comparison - the functional unit – is either GJ_{input} or MWh_{output}. The results can be shown by environmental theme (e.g. climate change, acidification, fossil depletion etc.) for the whole chain or per step. In addition, it is possible to attach weighting factors to environmental themes and obtain in this way an overall score for the selected CCS chain(s). The tool includes four weighting sets, including economic valuation. Alternatively, the user can also define its own weighting set.
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Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Create scenarios
• Go to scenario button
Edit/create a scenario
Scenario
• Create new scenario
Scenario
Back
Add new Scenario
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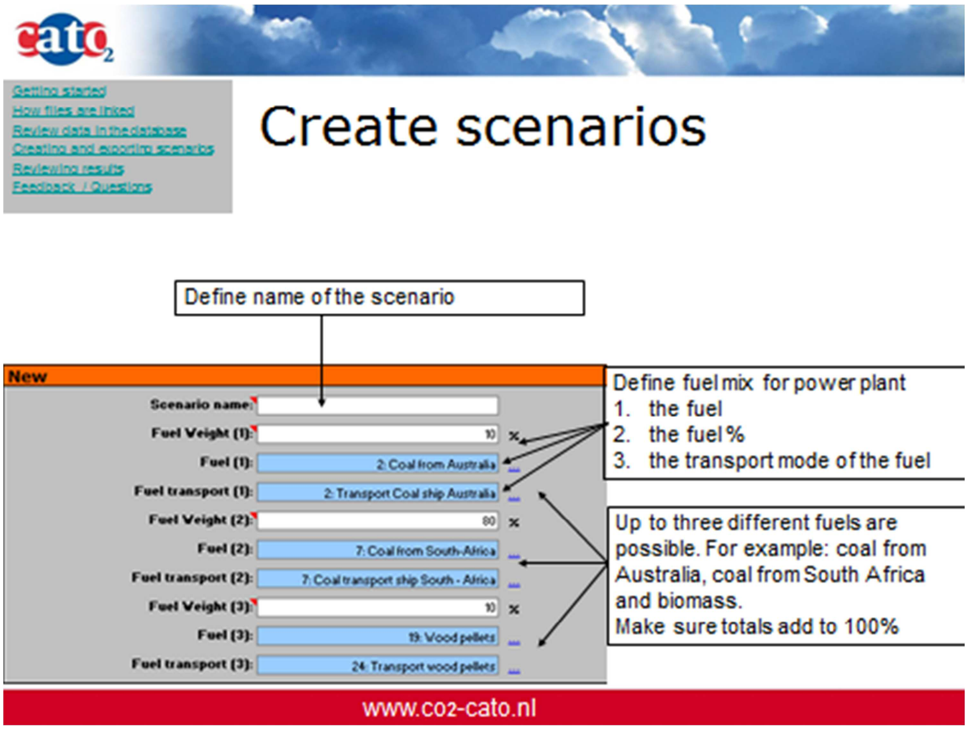
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Create scenarios
Define name of the scenario
New
Scenario name:
Fuel Weight (1): 10 %
Fuel (1): 2: Coal from Australia
Fuel transport (1): 2: Transport Coal ship Australia
Fuel Weight (2): 80 %
Fuel (2): 7: Coal from South-Africa
Fuel transport (2): 7: Coal transport ship South - Africa
Fuel Weight (3): 10 %
Fuel (3): 19: Wood pellets
Fuel transport (3): 24: Transport wood pellets
Define fuel mix for power plant
1. the fuel
2. the fuel %
3. the transport mode of the fuel
Up to three different fuels are possible. For example: coal from Australia, coal from South Africa and biomass.
Make sure totals add to 100%
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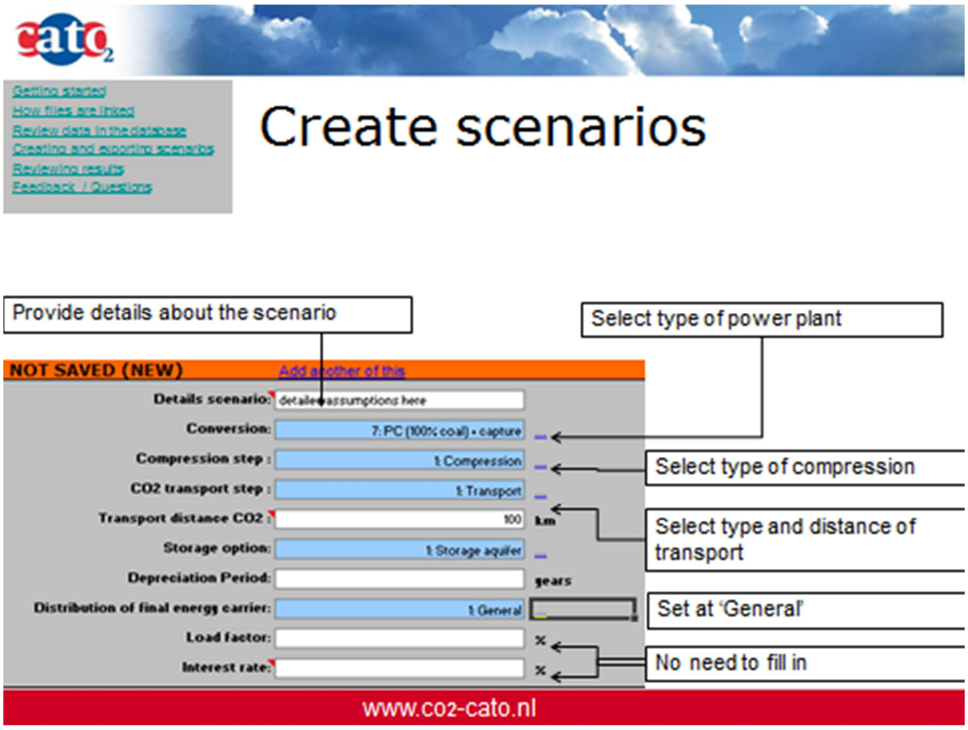
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Create scenarios
Provide details about the scenario
Select type of power plant
NOT SAVED (NEW)
Add another of this
Details scenario:
detailed assumptions here
Conversion:
7: PC (100% coal) + capture
Compression step:
1: Compression
CO2 transport step:
1: Transport
Transport distance CO2:
100
km
Storage option:
1: Storage aquifer
Depreciation Period:
years
Distribution of final energy carrier:
1: General
Load factor:
%
Interest rate:
%
Select type of compression
Select type and distance of transport
Set at 'General'
No need to fill in
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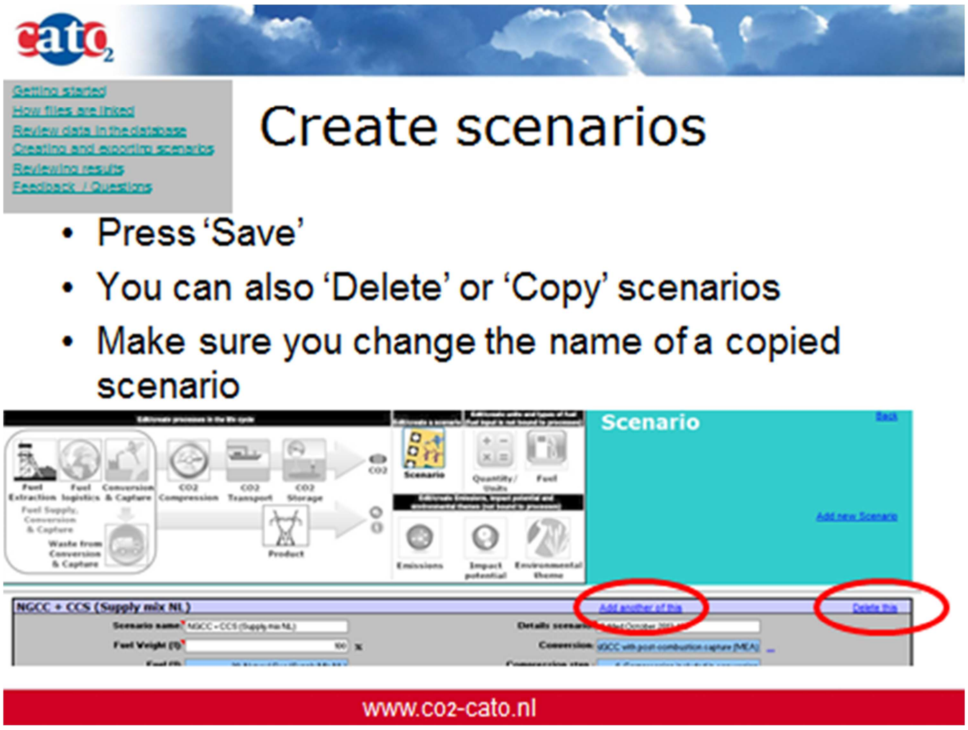
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Create scenarios
• Press 'Save'
• You can also 'Delete' or 'Copy' scenarios
• Make sure you change the name of a copied scenario
Scenario
Add new Scenario
NGCC + CCS (Supply mix NL)
Add another of this
Delete this
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Selecting and Exporting scenarios

- Make sure that the Excel file (EcoTool v x.x.xlsx) is saved and closed
- Open the file: EcoTool v x.x.mdb (MS Access file)

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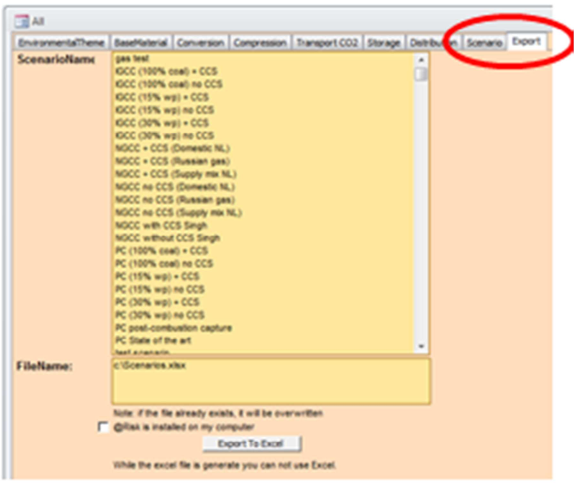
Selecting and Exporting scenarios

- Go to the 'Export' tab
- Select the scenarios you want to export (hold 'Ctrl' to select multiple scenarios



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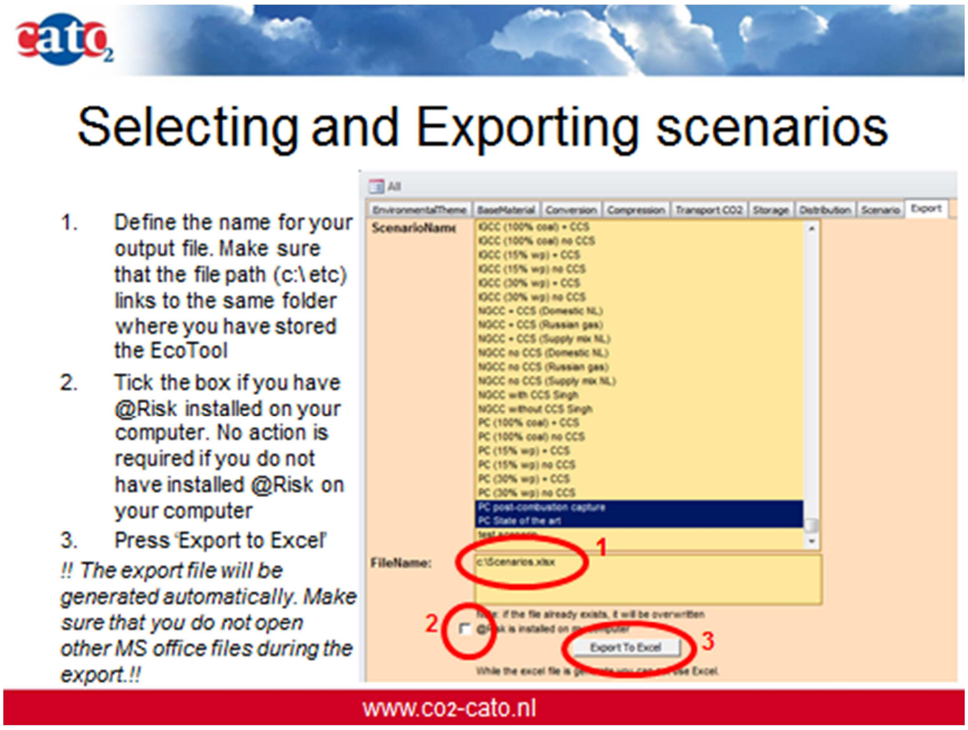
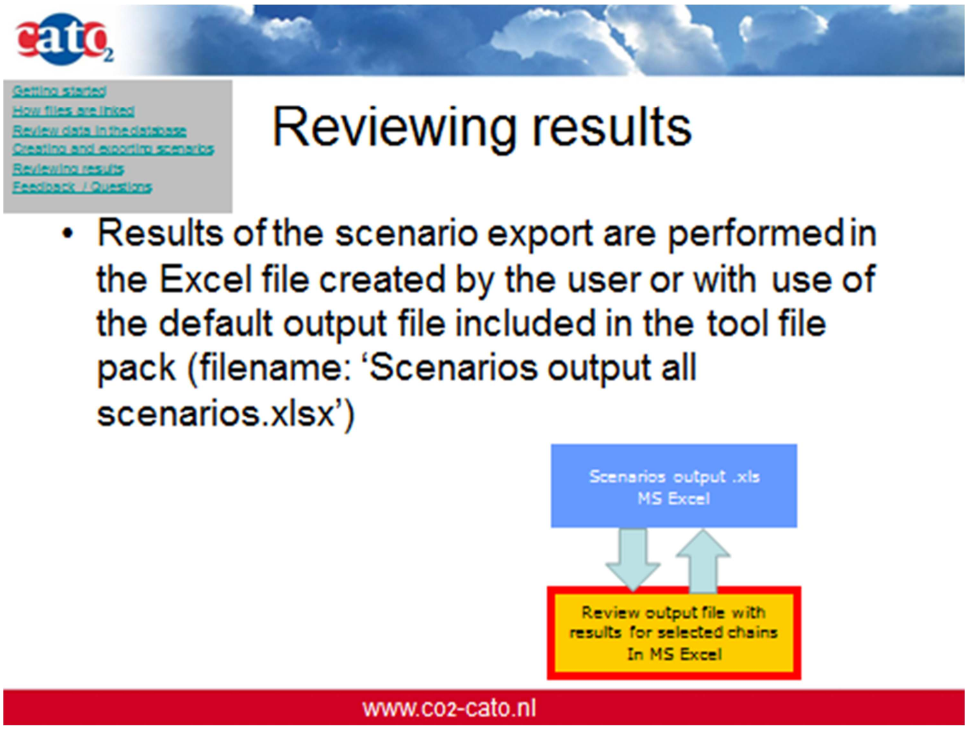

Selecting and Exporting scenarios
1. Define the name for your output file. Make sure that the file path (c:\ etc) links to the same folder where you have stored the EcoTool
2. Tick the box if you have @Risk installed on your computer. No action is required if you do not have installed @Risk on your computer
3. Press 'Export to Excel'
!! The export file will be generated automatically. Make sure that you do not open other MS office files during the export.!!
ScenarioName
FileName:
Export To Excel
1
2
3
www.co2-cato.nl


Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Reviewing results
• Results of the scenario export are performed in the Excel file created by the user or with use of the default output file included in the tool file pack (filename: 'Scenarios output all scenarios.xlsx')
Scenarios output .xls
MS Excel
Review output file with results for selected chains
In MS Excel
www.co2-cato.nl

The output file 1/3

The output file contains the following sheets

- Intro: with a base description of the output file. Please review carefully
- Environmental Theme: by default the tool shows the result for 18 environmental themes. This sheet contains an explanation of the themes.
- Orange sheets: for every scenario a detailed result sheet is created. Within the worksheets showing the names of the scenarios the user can review the emissions (and other data) and the most important assumptions. Some assumptions can be changed by the user. These assumptions are shown as 'White cells' in these worksheets.

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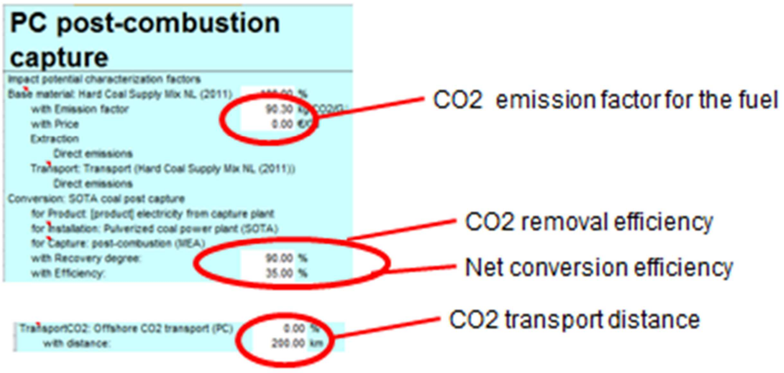
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions

The output file 2/3

- Orange sheets: some important assumptions can be changed by the users, for example:



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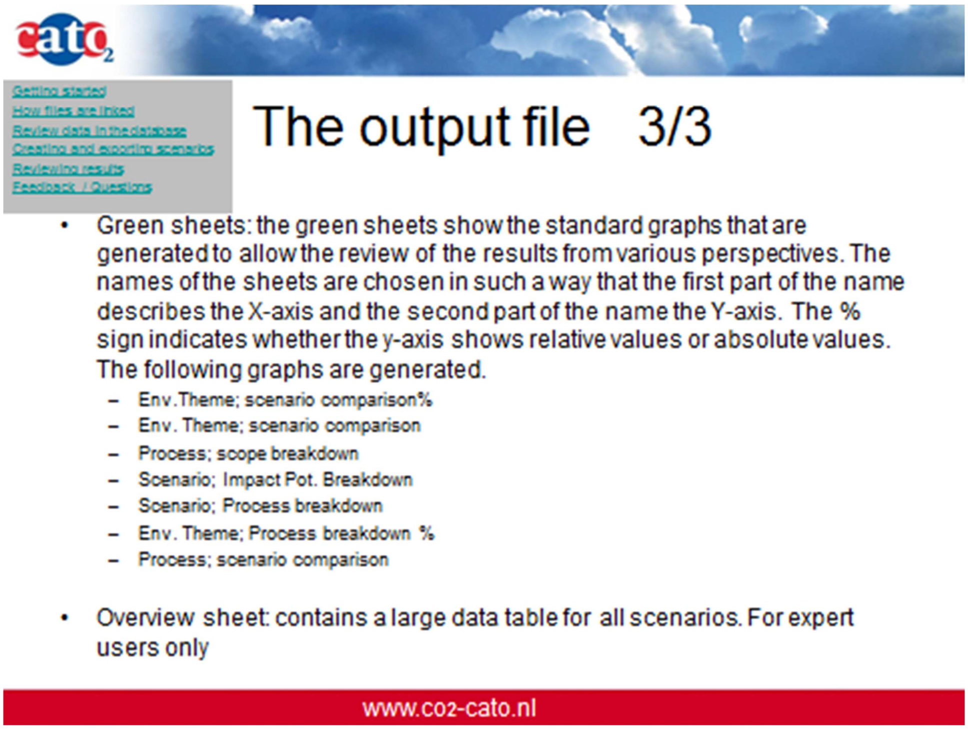
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
The output file 3/3
Green sheets: the green sheets show the standard graphs that are generated to allow the review of the results from various perspectives. The names of the sheets are chosen in such a way that the first part of the name describes the X-axis and the second part of the name the Y-axis. The % sign indicates whether the y-axis shows relative values or absolute values. The following graphs are generated.
Env.Theme; scenario comparison%
Env. Theme; scenario comparison
Process; scope breakdown
Scenario; Impact Pot. Breakdown
Scenario; Process breakdown
Env. Theme; Process breakdown %
Process; scenario comparison
Overview sheet: contains a large data table for all scenarios. For expert users only
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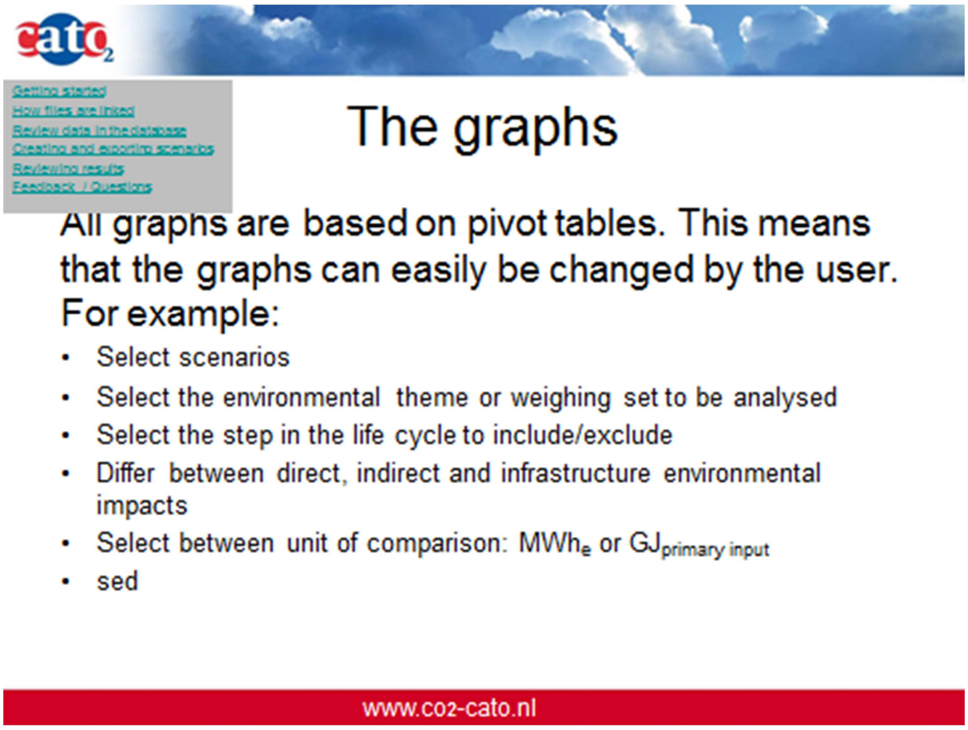
Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
The graphs
All graphs are based on pivot tables. This means that the graphs can easily be changed by the user. For example:
Select scenarios
Select the environmental theme or weighing set to be analysed
Select the step in the life cycle to include/exclude
Differ between direct, indirect and infrastructure environmental impacts
Select between unit of comparison: MWhe or GJprimary input
sed
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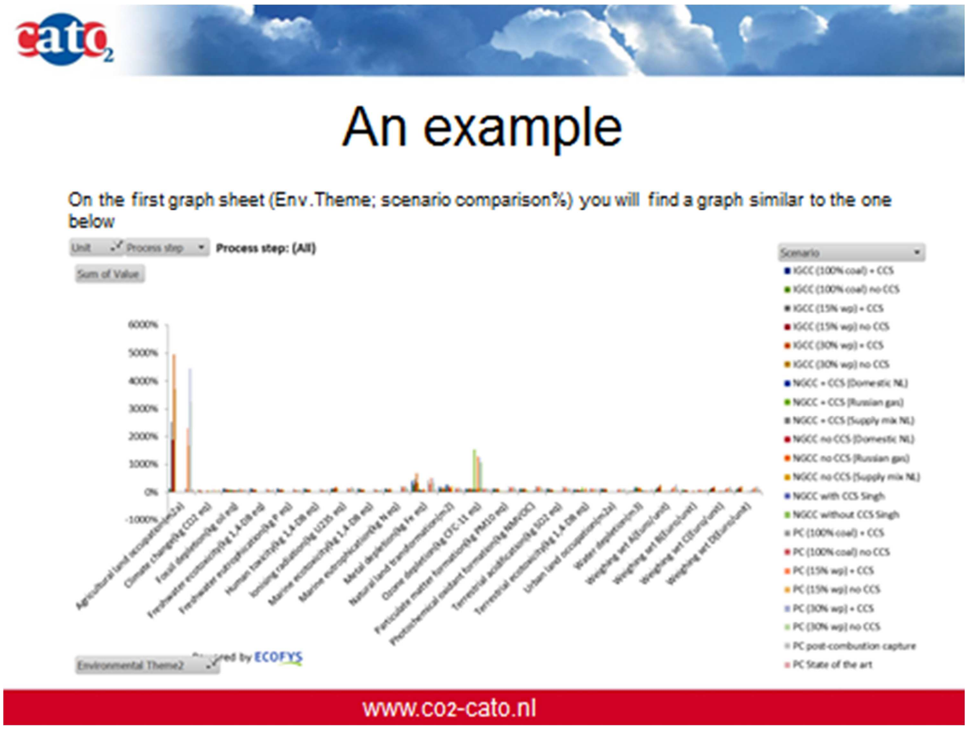
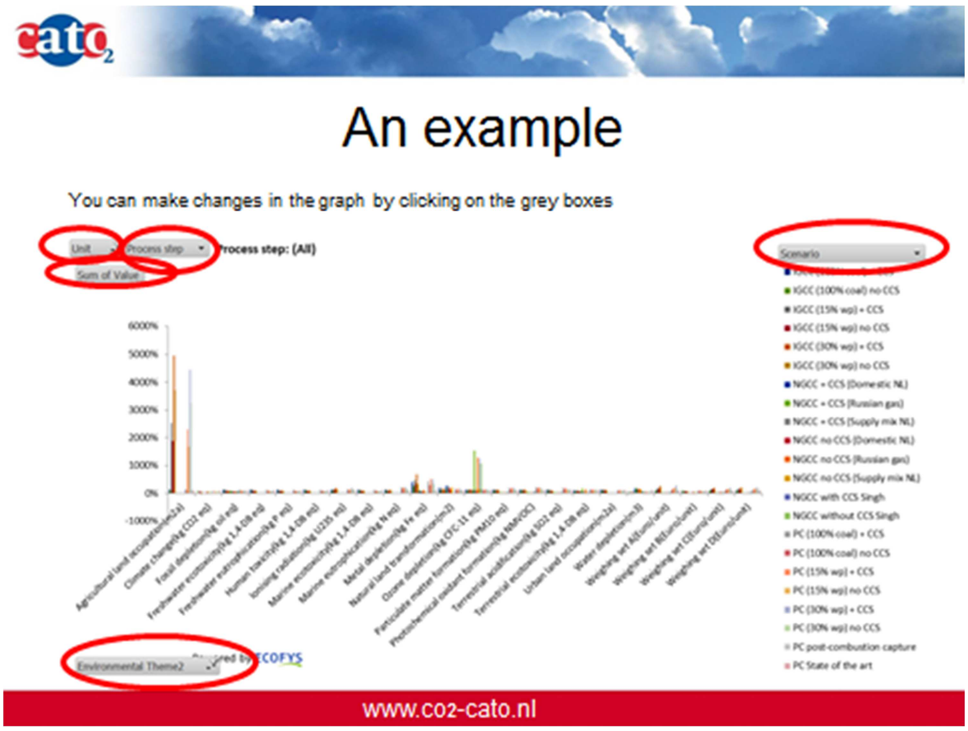
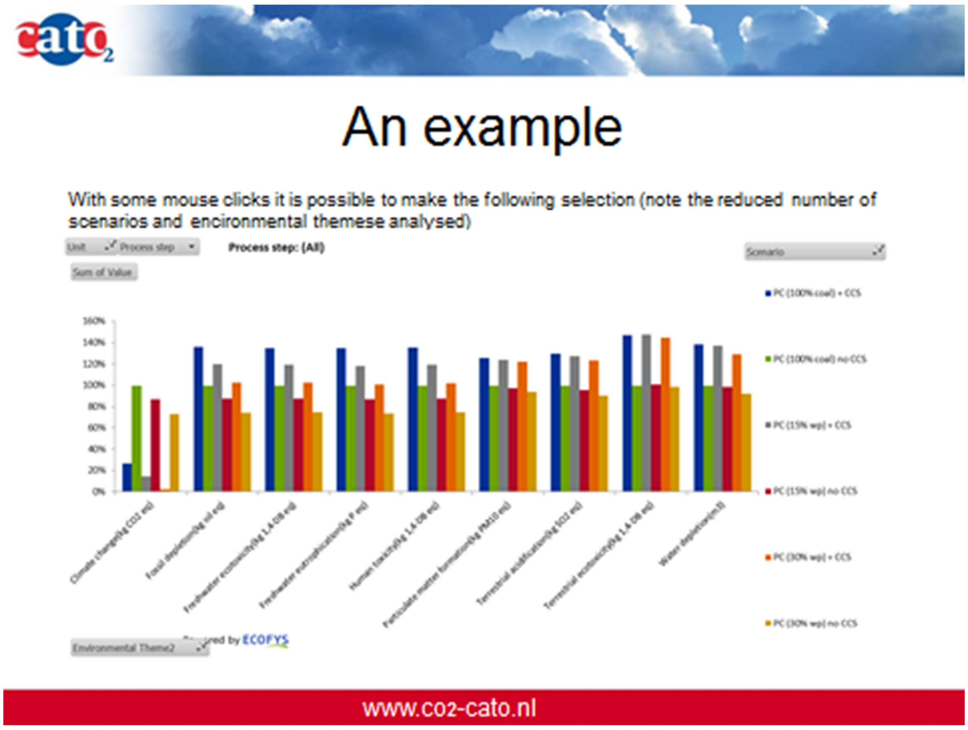
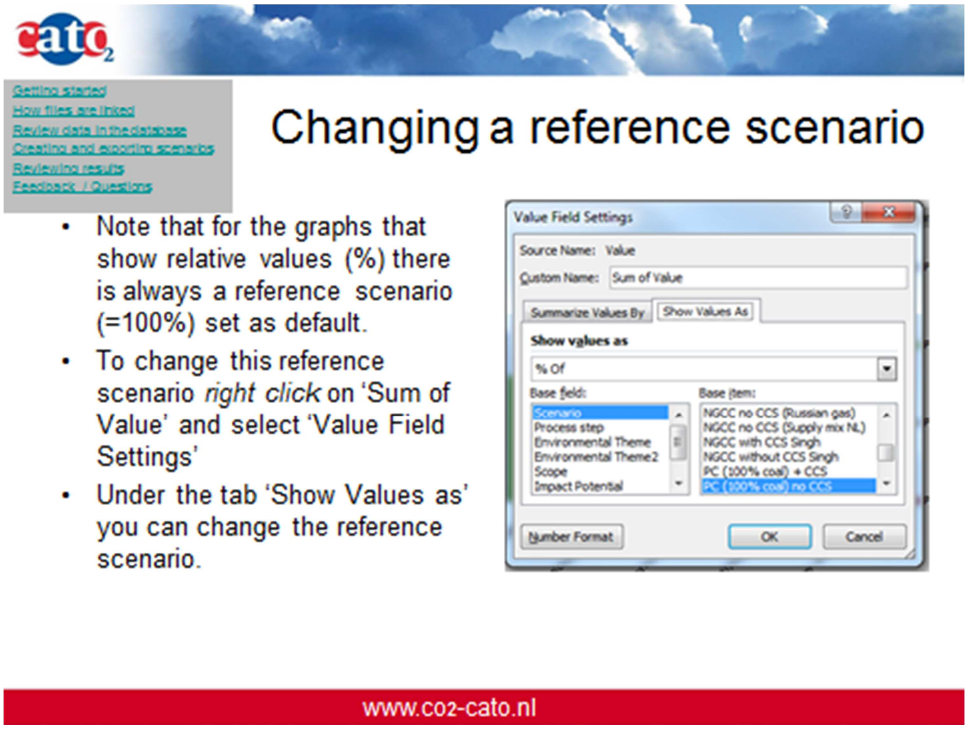

An example
On the first graph sheet (Env.Theme; scenario comparison%) you will find a graph similar to the one below
Process step: (All)
Scenario
www.co2-cato.nl


An example
You can make changes in the graph by clicking on the grey boxes
Process step: (All)
Scenario
www.co2-cato.nl


An example
With some mouse clicks it is possible to make the following selection (note the reduced number of scenarios and encironmental themese analysed)
Unit
Process step
Process step: (All)
Scenario
Sum of Value
160%
140%
120%
100%
80%
60%
40%
20%
0%
PC (100% coal) + CCS
PC (100% coal) no CCS
PC (15% wp) + CCS
PC (15% wp) no CCS
PC (30% wp) + CCS
PC (30% wp) no CCS
Environmental Theme2
ECOFYS
www.co2-cato.nl


Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Changing a reference scenario
Note that for the graphs that show relative values (%) there is always a reference scenario (=100%) set as default.
To change this reference scenario right click on 'Sum of Value' and select 'Value Field Settings'
Under the tab 'Show Values as' you can change the reference scenario.
Value Field Settings
Source Name: Value
Custom Name: Sum of Value
Summarize Values By
Show Values As
Show values as
% Of
Base field:
Base item:
Scenario
Process step
Environmental Theme
Environmental Theme2
Scope
Impact Potential
NGCC no CCS (Russian gas)
NGCC no CCS (Supply mix NL)
NGCC with CCS Singh
NGCC without CCS Singh
PC (100% coal) + CCS
PC (100% coal) no CCS
Number Format
OK
Cancel
www.co2-cato.nl


Getting started
How files are linked
Review data in the database
Creating and exporting scenarios
Reviewing results
Feedback / Questions
Feedback / Questions
Ecofys
Joris Koornneef
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www.co2-cato.nl

Annex C. Stakeholder Workshop

On February 16th TNO, Ecofys, UU and ECN organized a workshop on the environmental performance tool for Carbon Capture and Storage chains. The aim of the workshop was to receive feedback from the stakeholders on the content, look & feel and functionality of the environmental performance tool.

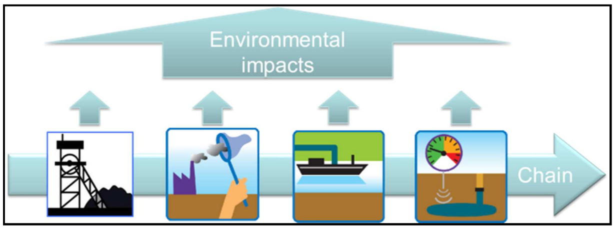

Figure C-1 Environmental impacts of Carbon Capture and Storage chain

The environmental performance tool aims to support governmental organizations as well as companies to assess the environmental performance of CCS chains. The tool has been developed from a life cycle perspective; it considers all processes ranging from fuel extraction to CO_2 storage. The tool offers the possibility to design, select and compare CCS chains. It presents the environmental performance for the whole chain as well as for each process step. This allows the user to identify the parts of the chain contributing the most to each environmental impact category. Examples of impact categories are global warming potential, acidification, eutrophication and toxicity.

A mix of industrial and governmental parties attended the workshop. It was designed around an interactive session in which the participants used the tool to do some exercises. Step by step the users were guided through the functionalities of the tool.


Figure C-2 Interactive session on the environmental performance tool

The tool was seen by the participants as an excellent medium to understand and communicate on environmental performance of CCS chains, because of its transparent way in reporting the results and how these are obtained. One of the participants mentioned the results of the environmental impacts of additional primary energy use in CCS chains as an eye-opener. Some participants suggested adding the possibility to weigh the different environmental impacts to more easily compare the CCS chains. In addition, they highlighted the need for reliable data, e.g. by involving industrial partners to provide, verify and where possible improve the data available in the tool. The current dataset is based on publicly available literature. Other suggestions on the look & feel and the functionality will be used to develop and improved version of the tool. Additional suggestions are to include industrial CCS chains and alternative renewable energy options. However, these options are currently out of the scope of the project.

Detailed account of stakeholder workshop

Date: 16 – feb-2012
Place: Ecofys (Utrecht)
Participants:

Stakeholders
Duco Drenth - Air Liquide
Gerdi Breembroek - Agentschap NL
Ruurt Heijsman - dcmr
Sjoerd Harkema commisie mer
Lianda Sjerps-Koomen – Essent
Tanya Tuurling - ROAD

WP partners
Toon van Harmelen - TNO
Arjan van Horssen - TNO
Arjan Plomp – ECN
Jeroen van Deurzen – former ECN
Andrea Ramirez –Utrecht University
Ali Talaei–Utrecht University
Chris Hendriks - Ecofys
Ruut Brandsma - Ecofys
Joris Koornneef - Ecofys
Anouk Florentinus – Ecofys

Agenda of the workshop

Arrival	13.30 – 14.00
Welcome & Introduction	14.00 – 14.30
Introduction and presentation of beta-version “Environmental Performance Tool”	14.30 – 15.00
Trial Run	15.00 – 16.00
Coffee break	16.00 – 16.15
Feedback on tool: - Functionality - Look and feel - Content	16.15 – 17.00
Summary and way forward	17.00 – 17.30
Closing and drinks	17.30

Annex D. Coal origin

Table D-1. Dutch coal import shares by country of origin (CBS, 2013 cited in Smekens & Plomp, 2013).

	2008	2009	2010	2011
South-Africa	18.9%	16.1%	14.0%	8.7%
France	0.0%	0.0%	0.0%	0.1%
Colombia	57.1%	60.5%	60.1%	73.0%
Venezuela	0.2%	0.2%	0.0%	0.7%
Canada	0.1%	0.2%	0.0%	0.5%
Belgium	2.4%	1.9%	0.3%	0.5%
USA	4.6%	3.8%	3.8%	4.4%
Germany	0.8%	0.6%	0.6%[1)]	0.3%
Spain	0.0%	0.0%	0.0%	0.0%
Norway	1.1%	1.3%	1.3%[1)]	2.1%
Russian Federation	11.7%	13.2%	19.5%	9.7%
Tanzania	0.0%	0.0%	0.0%	0.0%
UK	0.1%	0.1%	0.2%	0.0%
Poland	0.0%	0.0%	0.0%	0.0%
Indonesia	2.1%	1.2%	0.2%[1)]	0.0%
China	0.2%	0.0%	0.0%	0.0%
Australia	0.7%	0.9%	0.0%	0.0%
New-Zealand	0.0%	0.0%	0.0%	0.0%

1) for these countries the 2010 amount is estimated from the world total import as CBS did not provide country specific values.

Table D-2. Coal distribution as input data for the LCI (CBS, 2013)

	NL mix	CBS	2010	2011
Australia (AU)	15.00%	0.7%	0.0%	0.0%
Central Pacific Asia (CPA)	12.20%	2.2%	0.2%	0.0%
West Europe (WEU)	0.20%	4.4%	2.4%	2.9%
Latin America (RLA)	19.90%	57.3%	60.1%	73.7%
North America (RNA)	16.60%	4.8%	3.8%	4.9%
Russia (RU)	1.90%	11.7%	19.5%	9.7%
South Africa (ZA)	25.80%	18.9%	14.0%	8.7%
Eastern Europe (EEU)	8.70%	0.0%	0.0%	0.0%
Total	100.30%	100.0%	100.0%	100.0%

Table D-3. Share open cast mining and underground mining Dutch coal mix in 2011 (Ecoinvent, 2010).

Country	Share 2011 (CBS, 2013)	Open Cast Mining	Underground Mining
Latin America (RLA)	73.7 %	100 %	0 %
Russia (RU)	9.7 %	33 %	67 %
South Africa (ZA)	8.7 %	50 %	50 %
North America (RNA)	4.9 %	58 %	42 %
West Europe (WEU)	2.9 %	0 %	100 %
Total	**100.0 %**	**84 %**	**16 %**

Annex E. Comparison pulverised coal plant cases

In this report, two different supercritical coal fired power plants are presented, namely based on the study of Koornneef et al (2008) and Schakel et al (2014). In this section, differences in results between the two cases are assessed. Figure presents both cases with identical upstream assumptions (equal coal production and transport). Besides, assumed efficiencies are almost equal (difference less than 0.3 %point for both cases). Therefore, noticeable differences are the result of different assumptions regarding the conversion and/or capture processes in the power plant.

According to Figure significant changes only occur in the themes particulate matter formation and marine eutrophication. Both impacts are larger in cases Schakel et al, 2014, regardless whether CCS is included. The main emissions that contribute to particle matter formation are particulate matter (PM), NH_3 and NOx. The main emissions that contribute to marine eutrophication are NH_3 and NOx. Table shows the differences in assumptions for the key parameters regarding these emissions.

Relative large differences are shown for emissions of particulate matter and NOx. In all cases, Koornneef et al (2008) have assumed lower emissions for coal fired power plants without CCS. This explains why the higher scores for particulate matter formation and marine eutrophication in the cases by Schakel and shows the importance of variance in assumptions on these key parameters.

Table E-1. Comparison between key parameters for the PC no CCS case.

Parameter	Koornneef et al (2008)	Schakel et al (2013)
PM removal efficiency (%)	99.95	99.8
NOx removal efficiency (%)	85	86
PM emitted (g/kWh$_e$)	$1.7*10^{-3}$	0.053
NOx emitted (g/kWh$_e$)	0.16	0.28
NH_3 emitted (g/kWh$_e$)	$3.15*10^{-3}$	$1.5*10^{-3}$

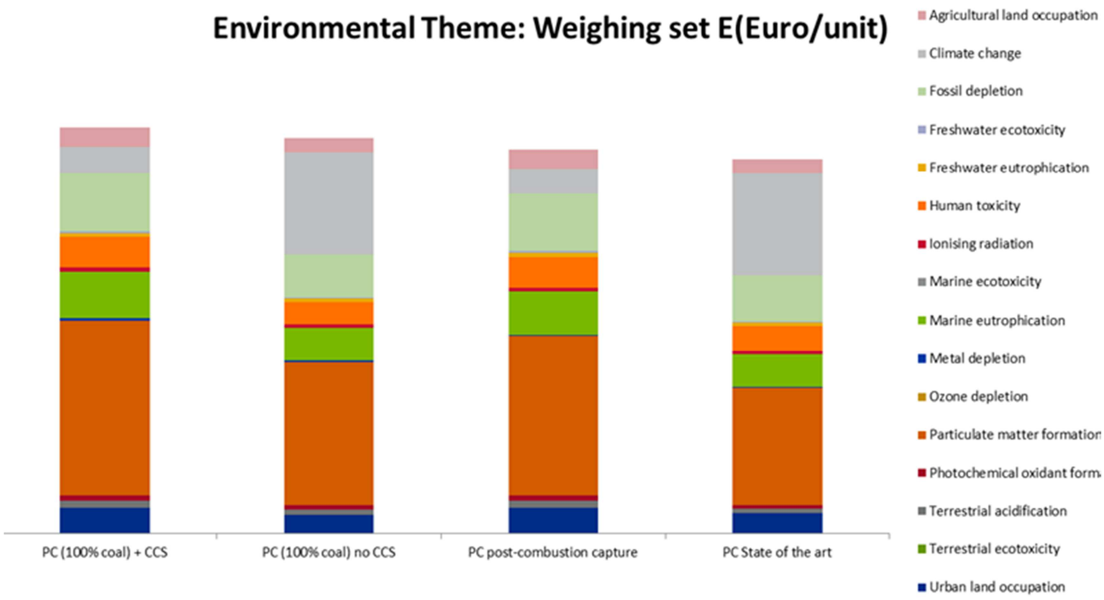

Figure E-1 Total environmental impact (using weighing set E) for supercritical pulverised coal power plant cases A (Koornneef et al, 2008) and B (Schakel et al, 2013) when using equal assumptions regarding upstream processes (coal production and transport).

Annex F. Sensitivity wood pellet production process

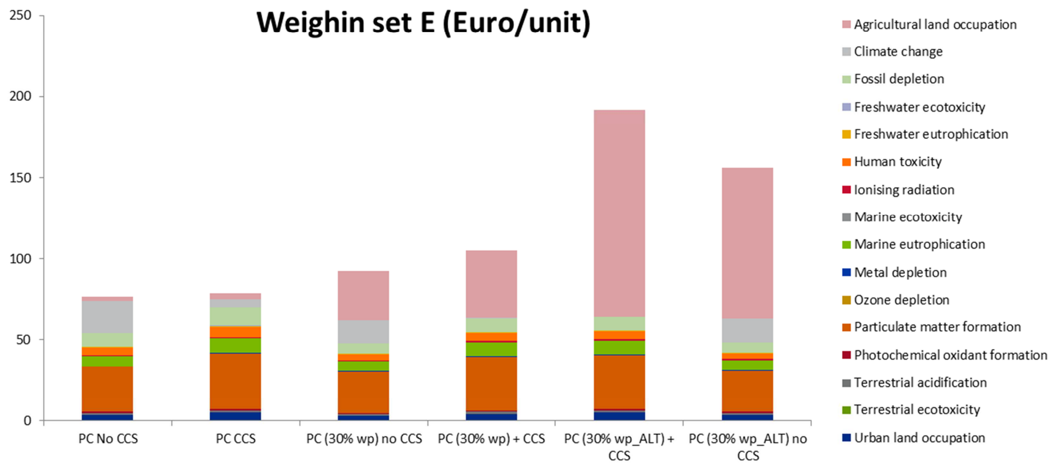

Figure F-1 Total environmental impact (using weighing set E) for supercritical pulverised coal power plant cases without co-firing, with 30% co-firing wood pellets used in Schakel et al, 2014 and with 30% co-firing alternative wood pellets