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## Development of an Environmental performance assessment tool for Carbon Capture & Storage chains

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### Abstract

This paper reports the development of a tool to assess the environmental performance of carbon dioxide capture and storage (CCS) chains. The environmental assessment is done for the whole CCS chain. The tool has been designed to produce transparent and traceable results and is easy to work with. The tool is meant for a broad group of stakeholders for assessing CCS chains on their environmental performance. It provides insights into the environmental performance of CCS chains by using a learning-by-doing experience for users. It allows both knowledge sharing and stakeholder engagement so that view points of stakeholders are better understood and decision making on the deployment of CCS can be improved.

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### 1. Introduction

The overall environmental profile of a power plant - including its life cycle - changes when Carbon Capture and Storage (CCS) is applied to the plant. This effect is positive for greenhouse gases (i.e. overall greenhouse gas emissions are lower per MWh for plants equipped with CCS compared to a similar plant

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without CCS), but can be positive or negative for other environmental themes such as acidification and eutrophication [1].

Life cycle analysis (LCA) of Carbon Capture and Storage chains can provide a better understanding of the full environmental benefits and trade-offs of implementing CCS. It is also a suitable tool to screen CCS chains on possibilities for improvement on its total environmental performance. Although LCA is a powerful tool, there are some limitations when using it for assessing CCS chains. Assessments have been executed for only a few capture technologies; there is a lack of information on important toxic emissions and waste formation, and results are surrounded by large uncertainties due to a lack of (public) available measurements and due to methodological choices (e.g. the choice regarding system boundaries, unit of comparison, and impact assessment and methodologies). As a result, environmental performance assessments of plants equipped with CCS published in the literature show a wide range in outcomes, which in turn results in mixed messages about the environmental performance of CCS technologies. Finally, the assessments and data input are not easily accessible and transparent making it difficult to understand and discuss the results with stakeholders.

This paper reports the development of an accessible tool to support governmental bodies and companies with assessing the environmental performance of CCS chains. This tool has been developed as part of the efforts made within the Dutch CCS programme CATO2 to reduce the uncertainties and limitations mentioned above and deliver an accessible tool that can be used by a broad group of stakeholders.

## 2. Description of the tool

A *Strategic Environmental Performance Tool – version 1.0* has been developed to conduct environmental performance assessments for CCS chains. 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<sub>2</sub>
4. Waste from energy conversion
5. Waste from capture of CO<sub>2</sub>
6. CO<sub>2</sub> compression
7. CO<sub>2</sub> transport
8. CO<sub>2</sub> storage
9. Distribution of the energy carrier (e.g. electricity)

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 1. 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<sub>input</sub> or MWh<sub>output</sub>. 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 will include a number of weighting methodologies, including economic valuation. Alternatively, the user can also define its own weighting set.

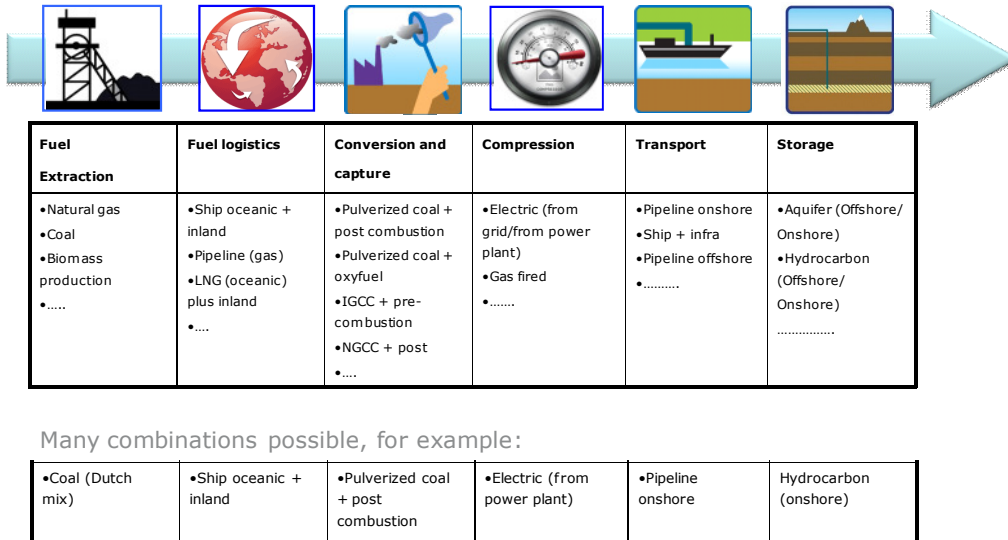


Fig. 1 Overview of steps of the life cycle for power generation with and without CCS. Note that for simplicity the steps ‘waste from conversion’, ‘waste from CO<sub>2</sub> capture’ and ‘distribution of energy carrier’ are not shown in the graph.

The basic philosophy of the tool consists of the following pillars:

*Accessible:* The user does not need to have specialised knowledge of environmental impact assessment and is able to assess the environmental performance of CCS chains in three simple steps (review data, define scenarios and assess outcome). No special software packages are needed as the tool is based on standard MS Office software. The user can easily create CCS chains he/she wants to analyse.

*Transparent & Traceable:* Data on the environmental performance of CCS technologies (capture, transport and storage) has been collected in a central database (e.g. emissions, water use, and waste generation). Comments and literature references can be added to track-and-trace the origin of the data under the premise that this does not conflict with the confidentiality of sources or information.

*Flexible:* The scientific knowledge on the environmental performance of CCS chains develops through time. The database and the tool should thus be flexible enough to integrate new environmental information and methodologies. The tool is also flexible in the output it generates in terms of graphs and data tables. The output and input can thus be adjusted to the user’s preferences so that the tool can be used for multiple purposes and perspectives.

*Reflect uncertainty:* An important function of the environmental performance tool is that it allows the user to perform a detailed sensitivity and uncertainty analysis. In literature often uncertainty ranges for the performance indicators (e.g. emissions, material use, efficiencies etc) for steps in the life cycle are reported. These ranges are also reported in the developed database so that an analysis of CCS chains can be performed based on a proper understanding of the knowledge base.

### 3. Tool design and use

A general overview of how the tool works is graphically presented in figure 2. 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 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.

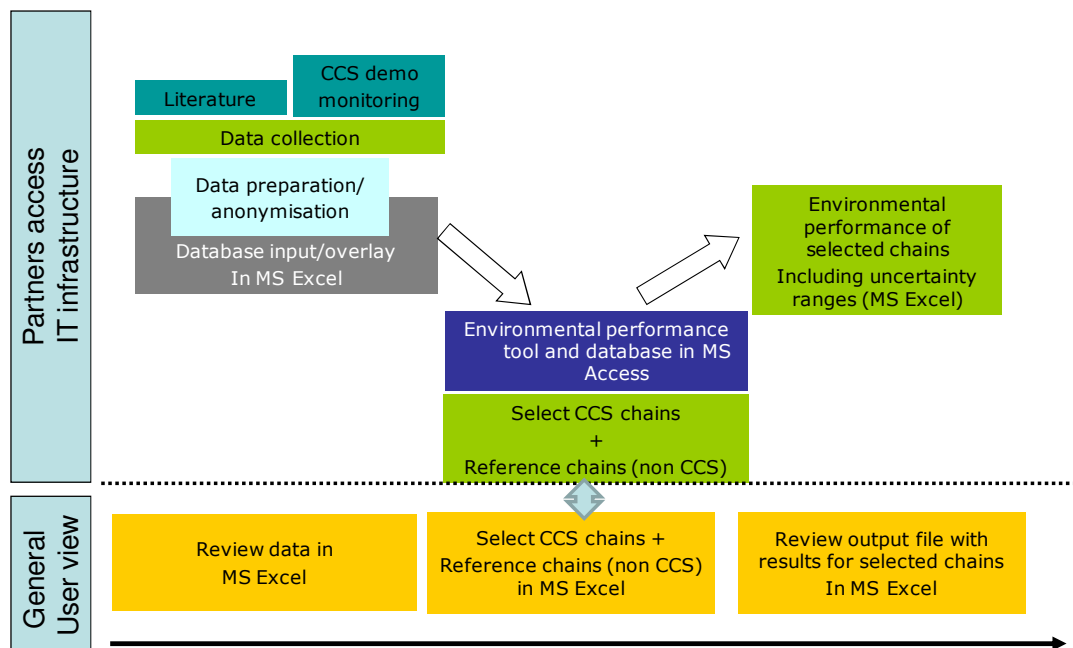


Fig. 2 Schematic overview of the general workflow to fill the database and allow general users to assess the environmental performance of CCS and reference chains. Note that the tool has different levels of user rights. Advanced users are allowed to change and/or add data to the database and extract more detailed information from the database.

#### 3.1. Database with information on environmental performance of steps in the CCS life cycle

An environmental performance database of energy conversion supply chains including carbon capture and storage is 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 [2]) 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.

### *3.2. Translating environmental performance into environmental impact categories*

Life cycle inventory 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. The grouped LCI data can be characterized with the use of characterization factors. Characterization factors are used to sum different LCI data into one common denominator, such as expressing methane emissions into CO<sub>2</sub> 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 tool the ReCiPe (ReCiPe Midpoint (H) V1.05) methodology is used by default, which includes a set of 18 environmental impact categories [3].

### *3.3. Review data by the user*

The user of the tool can add, change and/or review information on environmental performance of steps of the life cycle and add comments for further detail. The user can also add new (sets of) environmental categories.

Environmental default data is already included for a number of steps of the life cycle (e.g., different types and origins of fossil fuels and biomass, fuel transport modes, power generation facilities, capture technologies and storage reservoirs).

### *3.4. Select and build scenarios*

In a next step, the CCS scenarios are built by the user. The user can build one or multiple scenarios simultaneously to allow direct comparison. An example of building a CCS chain, or scenario, was shown in figure 1. For every step of the life cycle a choice has to be made starting with the fuel. Selecting multiple fuels (biomass, coal, natural gas) simultaneously is also possible, allowing for instance the environmental performance assessment of co-firing of biomass and coal in a power plant with CCS.

The tool then calculates life cycle emissions (and other defined environmental interventions) and translates this into impact scores for multiple environmental themes or categories (e.g. acidification, eutrophication, global warming potential, etc).

Additional insights can be obtained by grouping or weighting the different environmental impacts according to predefined set of weighting factors or to the preference of the user. Also, a multi criteria analysis and/or economic valuation of the environmental effects can be done with the tool. Valuation or weighting of scores from a life cycle assessment is an important step in the overall analysis as it allows translating stakeholder perspectives into weighting sets. Such analyses may show under what conditions the benefits of CCS outweigh the trade-offs.

### 3.5. Review results from various perspectives and modify major assumptions

The results of the calculations are presented in a separate output file generated in MS Excel. Easy to review data on the created/selected scenarios (with or without CCS) are presented in this file, but for the advanced user also the detailed data are included. In figure 3 the environmental performance of a pulverized coal power plant with and without post-combustion capture of CO<sub>2</sub> is shown. The screenshot in figure 3 shows that the user can directly change the information by modifying the functional unit of analysis (the default is 1 MWh<sub>final</sub>, the alternative is 1 GJ<sub>primary</sub>), changing the set of environmental themes shown, selecting the amount of scenarios shown, modifying the amount of steps of the life cycle and by changing the reference scenario.

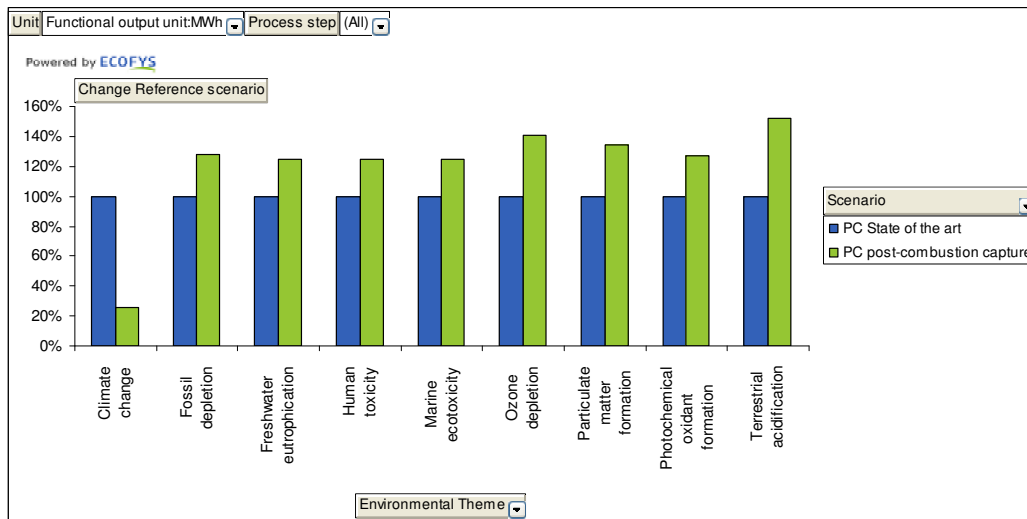


Fig. 3 Example of an output figure generated by the environmental performance tool showing the comparison of scenarios with and without CCS for various environmental themes.

The user can also analyse the breakdown of environmental performance over the steps in the life cycle. An example is shown in Figure 4 A. The user is able to modify the functional unit of analysis, the set of environmental themes shown, the shown scenario and the amount of steps of the life cycle.

In a third and final pre-defined figure, Figure 4 B, the user gets insights into how different parts of the life cycle contribute to the final score and how this differs depending on the scenario. The user is able to modify the functional unit of analysis, the environmental theme shown, the amount of scenarios shown and the amount of steps of the life cycle.

Once the output file is generated, it is standalone. Major assumptions can be changed to see their effect on the end result without changing the data in the core database. Examples of assumptions that can be changed in the output file are: energy conversion efficiency, fuel transport distance, CO<sub>2</sub> transport distance and CO<sub>2</sub> removal efficiency.

The fact that the tool is fully based on widely used software means that it is plug-and-play. The major benefit is that no additional software is needed and that most users are accustomed to working with the software.

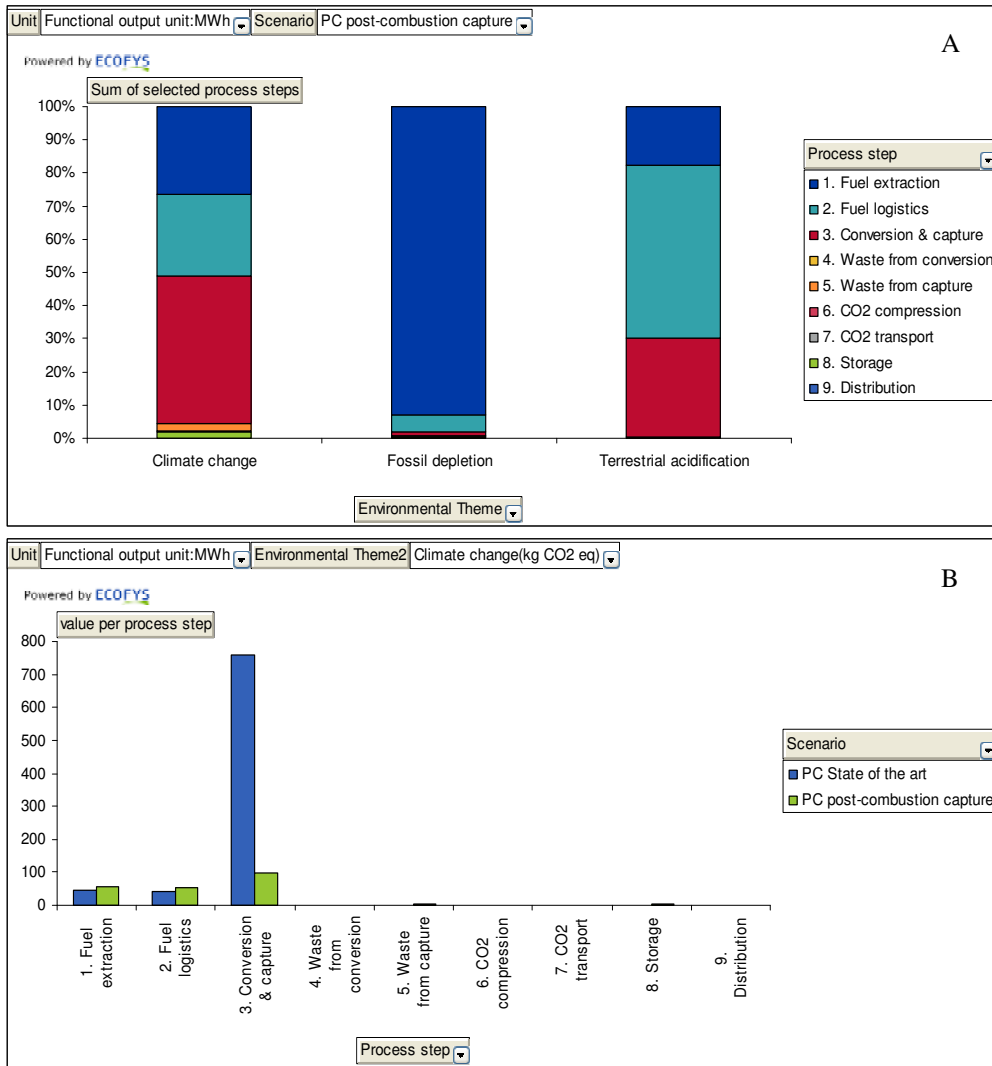


Fig. 4 Example of output figure generated by the environmental performance tool. **A** shows the breakdown of the scores for environmental performance into the steps of the lifecycle. **B** shows contribution of steps to overall score for multiple scenarios.

#### 4. Conclusions and way forward

We have developed an environmental performance assessment tool for CCS chains which is accessible to a broad group of stakeholders. It provides insight into environmental performance of steps in the life cycle for power generation with and without CCS using a learning-by-doing approach. It allows both knowledge sharing and stakeholder engagement so that decision making on the deployment of CCS can be improved.

Continuous improvement efforts in the near term will be devoted to:

- Improve the user interface of the tool.
- Continue to collect data on environmental performance of CCS technologies across the chain, preferably based on RD&D programs, both national as international. The focus will be on information on solvent related emissions (such as nitrosamines); waste and by-product formation as a result of CO<sub>2</sub> capture; (additional) water consumption and information on emissions to water.
- Expand the set of CCS technologies included in the tool.
- Expand and improve the options of weighting and valuing environmental themes.

Possible improvements and additions that could enhance the abilities and robustness of the tool on the longer term:

- For the future the tool could be an excellent platform to share information on the environmental performance of CCS technologies while keeping a life cycle perspective.
- Adding chains devoted at understanding the environmental performance of CCS in industry.
- Adding chains devoted at understanding environmental performance of CO<sub>2</sub> reuse.
- Screening second generation CCS technologies on their environmental performance.
- Compare CCS technologies in power generation with other low-carbon energy technologies.

#### Acknowledgement

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