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Determination of emissions related to CCS by LCA
Working document

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ccsp
Carbon Capture and Storage Program

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1 Introduction

Life cycle assessment (LCA) is a tool for quantitatively and systematically evaluating the environmental aspects of a product or system throughout its whole life cycle (e.g. Koskela et al. 2010). As LCA concentrates on all the inflows and outflows of substances, and the impacts of these, in a certain system, it provides means to identify effective policy options. Such knowledge also reduces the risk of simply shifting pollution from one environmental media to another. LCA has primarily been applied to assess the life cycle impacts of products but it can also be used for the assessment of services, technologies or regions. Typically, an LCA covers the life cycle of a product from ‘cradle to grave’ but it may also be limited to a certain part of the life cycle, for instance the use phase.

There are two standards on LCA :

- ISO 14040:2006 (Environmental management – Life cycle assessment – Principles and framework), which provides a clear overview of the practice, applications and limitations of LCA to a broad range of potential users and stakeholders, including those with a limited knowledge of life cycle assessment.
- ISO 14044:2006 (Environmental management – Life cycle assessment – Requirements and guidelines), which is designed for the preparation, conducting and critical review of life cycle inventory analysis. It also gives guidance on the impact assessment phase of LCA and on the interpretation of LCA results, as well as on data collection

There are four phases in LCA (Fig. 1):

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

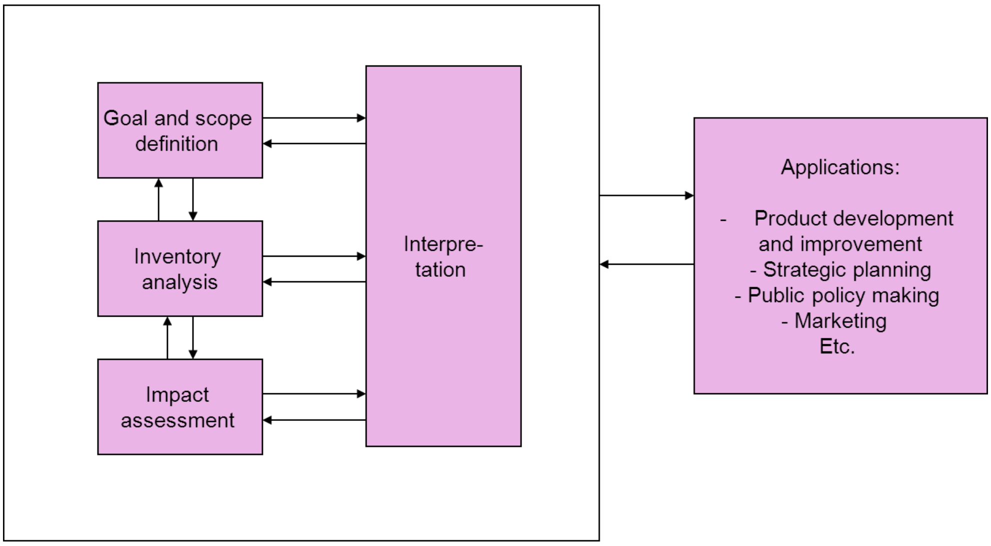

Figure 1. Stages of an LCA according to ISO 14040:2006

In the goal and scope definition phase, the aims, intended application and system boundaries of the study are defined. In this phase also the functional unit of the study is defined. In the life cycle inventory phase, data is collected on all the inputs and outputs related to the studied process or product. In life cycle impact assessment, the significance of the potential environmental impacts based on the LCI results is evaluated. Life cycle impact assessment consists of five phases, the first two of which are compulsory. First, LCI data is assigned into different impact categories (categorisation). Then category indicator results are calculated (characterisation). Characterisation can be followed by normalisation, which means that the magnitude of the category indicator results in relation to reference information is calculated. Results can then be grouped and weighed. Several different methods have been developed for life cycle impact assessments (e.g. Pennington et al. 2004). The choice of the appropriate LCIA methodology is always case-specific and depends on the purposes of the study. The final phase of LCA is interpretation, which is a systematic technique for identifying, quantifying and evaluating information from LCI or LCIA. As a result of the interpretation phase, conclusions and recommendations are given.

There are two different approaches to system modelling in LCA (see e.g Ekvall & Weidema 2004; Thomassen et al., 2008): attributional or retrospective LCA, and consequential or prospective LCA. The choice between the two approaches depends first and foremost on the purpose of the study. The aim of attributional LCA is to assess the environmentally relevant physical flows of a product / system at a given point in time while consequential LCA aims to assess a change between two stable conditions. Attributional LCA represents the ’traditional’ way of conducting an LCA and its results describe the environmental impacts of the desired product. The method is stable and cannot describe the impacts of any changes. The key issues in consequential LCA on the other hand are how to define the change and the related environmental flows. Ideally in consequential LCA, all the activities (inside and outside the life cycle) affected by the change are included in the study. Due to the necessary system expansion, lack of information and data are typically encountered in consequential LCAs.

Within LCA, three different approaches to data collection have been developed (e.g. Suh & Huppes 2005). These are called process-based LCA, input-output LCA and hybrid LCA. The approaches differ from each other in the data used. In process-based LCA, environmental impacts are calculated on the basis of processes and summed up to the total environmental load of a product. In input-output LCA, data is taken from an environmentally extended input-output table. Hybrid-LCA is a combination of these two: part of the life-cycle is modelled with process-based data, which is then supplemented with input-output data.

2 Life cycle assessment for CCS

2.1 Literature review

Several life-cycle assessments have been performed for a variety of CCS cases. Here some of the observations made in these studies are discussed.

The studies show that CCS-technology is a trade-off between avoided greenhouse gas emissions and increased environmental effects in other impact categories and increased use of natural resources. When CCS is applied, less electricity is gained per unit of fuel. The studies conducted carry significant possibility of error because of assumptions made on the development of technology. However, LCA studies have given valuable information on the environmental effects of CCS.

CCS is used with the intention of mitigating climate change. LCA can be used to estimate whether the result of applying CCS is as planned: studies show that greenhouse gas emissions are avoided. A full LCA study can also give information about other environmental effects.

LCA studies have different scopes. As CCS is a large scale undertaking, policy makers must first make decisions whether to allow and support the application of CCS-technology. Some LCA studies strive to help these policy makers in making informed decisions whether to apply CCS. Other LCA studies give information for CCS plant designers on individual technical decisions such as which capture technology to use, or which solvent to select.

The studies conducted elsewhere can be used as examples and as sources for ideas to make CCS LCA studies in Finland as comparable as possible.

IEAGHG synthesis report on LCA studies states that while GWP is similar in all studies; other effects have significant differences suggesting that this could in part be caused by regional differences. Therefore study cases situated elsewhere in the world do not give accurate information on the environmental effects of a CCS plant in Finland. No CCS LCA studies have been published discussing Finland based cases. Studies of Finnish cases would help the international research effort.

Some further reading:

- Marx, J. et al., 2011, Environmental evaluation of CCS using Life-Cycle Assessment - a synthesis report
- Singh, B. et al., 2011, Comparative life-cycle environmental assessment of CCS technologies
- IEAGHG 2010-TR2, 2010, Comparative life-cycle environmental assessment of CCS technologies

2.1.1 General observations

Even though there are quite a few published life-cycle studies, e.g. a synthesis report by Marx et al compares the results of 15 different studies, comparing them is difficult as each case is different with different assumptions made. Therefore general conclusions should be made with caution. Even so, there are some conclusions that can be made with reasonable certainty. Some have been listed below:

- In general, the global warming potential is clearly decreased while other environmental effects increase with more uncertainty concerning the significance of the change.

- Increased environmental effects are formed by the increased use of fuel and the use of a solvent for CO_2 scrubbing. Construction of the plant and transport and storage of CO_2 have significantly smaller impacts.
- The effects growing include human toxicity potential.
- NOx emissions grow mainly because of the growing use of fuel and increased indirect emissions.
- In post combustion SOx and particle emissions decrease as both are caught with the solvent or are removed before the CO_2 scrubbing to lessen solvent loss.
- Acidification potential (AP) grows even though SOx emissions drop. This is likely due to the rise in NOx and NH_3 emissions and the SOx emissions from ship transport of fuel.
- Mining and transport of coal increases the eutrophication potential and Photochemical Oxidation Potential.

LCA can also bring out possible future research subjects.

Studies suggest that the environmental effects of the solvents used for CO2 scrubbing are not sufficiently known. Some studies have found that harmful substances are released in the manufacturing of MEA and that some of the solvent and its degradation products are released to the environment causing increases in different toxicity related impact categories, including human toxicity potential (HTP). The fate of MEA in the ecosphere, especially in the long dark winter of Finland, is not unequivocally known.

The use of CCS requires the use of more natural resources such as fossil fuels, metals and other building materials. Also CCS requires increases in land use.

2.1.2 Challenges CCS poses to LCA

LCA is often used to estimate the environmental effects of an existing product or service. When an LCA is performed, known inputs are inventoried and then calculated into impact categories. When assessing a new or not-yet-existing technology, the error potential is greater and the detail of the assessment should not be taken too far as some or all of the inputs and their impacts are unknown. When life-cycle assessments of CCS have been made, assumptions have also been made, some of which span over decades into future. Assumptions for post-combustion CCS include:

- What will the energy efficiency of the CO_2 scrubbing be in a production scale facility?
- Which solvent will be selected, most studies have chosen MEA
- Contents of the solvent, additives such as anti-corrosion and anti-foaming agents
- Environmental effects of the solvent used
- Toxicity related categories are the most difficult
- The availability and quality of the fuel
- Emissions from transportation of fuel
- Transportation of CO_2, the estimates depend on the method and the distance of transport and can vary tenfold.
- Stored CO_2 does not leak to the atmosphere
- Can test facilities be scaled to productions scale with linear environmental effects?

These assumptions, among others, cause uncertainty in the assessment and make the comparison of different assessment studies more difficult. When comparing different LCA studies, even though there is an ISO standard, it is hard to tell how a certain LCA study has been conducted. Any LCA study conducted should strive to be comparable to the academic studies conducted. It is crucial that the data sources, calculation procedures and assumptions are openly reported.

Energy efficiency of the carbon capture is not well known. CHP makes the LCA more difficult. A CHP power plant is considered energy efficient but some of that efficiency will be eaten by the CCS as some heat will be used to regenerate the solvent. For oxyfuel, the efficiency of the oxygen production is unclear. Studies suggest electricity consumption between 160-320 kWh/tO2. In the case of CHP, there seems to be significant potential to recover heat from air separation unit to be utilized as district heating. However, the environmental impacts of CCS in the CHP systems are strongly dependent on the properties of the existing CHP environment where CCS units would be located.

Other question that should be addressed:

- Geological storage includes possible environmental effects that cannot be properly analyzed with the current LCA methods.
- Regional normalization could pose difficulties
- Purity of CO_2
- If CCS is applied globally, how will it affect its own input data?

2.1.3 Effects of LCA on acceptability

CCS poses a great acceptability challenge. It is important that the LCA is credible so that decision makers can rely on the assessment. The LCA as a method is not easily understood by the great public and some of the numbers presented may seem unacceptable. As the LCA brings out possibly hidden environmental effects, they should be reported in such a manner that puts these effects to scale and perspective.

For example, the study “Environmental evaluation of CCS using Life-Cycle Assessment - a synthesis report” by Marx et al. states that Human Toxicity Potential (HTP), in many studies, shows an increase of 200% for systems with CCS compared to a conventional power plant. As a percent this rise seems significant. However it would seem that that the starting value is small and that the normalization shows that the effect is quite low. With careful reporting, misunderstandings can be avoided.

2.1.4 Uncertainty

Uncertainty management can be done with sensitivity analysis and data quality assessment. Also the case should be specified with more detail and attention should be given to the validity of the assumptions made.

Unknown technology or inputs may have environmental effects that are not known. Different studies have come to different assumptions regarding the environmental effects of the use of solvents such as MEA. Many of the solvents provided by the manufacturers now have unknown composition because of trade secrets. Also it would seem logical that the solvent used can change during the decades long lifetime of a power plant.

The long cold winter of Finland can have an effect on the environmental effects of CCS. Cold temperature effects the biodegradation of pollutants and less UV-radiation means less UV-degradation of pollutants. Because of this the LCA for CCS in Finland could contain significant uncertainties concerning the different environmental effects of the solvent.

Chosen system boundaries, especially the type of power production which is assumed to compensate the electricity production penalty resulted due to CCS, are essential regarding all impact categories. Emissions from compensating power production are affected by assumptions made for the future energy system, utilization rate of power plants with CCS and in the reference scenario, production efficiencies with and without CCS and the chosen approach to system modelling. For example, especially in the Nordic countries where large share of hydropower, nuclear and bioenergy are present, the average specific CO_2 emission for electricity production is about 100 – 200 g/kWh depending on for example weather. Average values are typically used in attributional LCA studies. If consequential LCA is used, specific CO_2 emissions of about 1000 g/kWh are justifiable, which obviously have huge effect on the avoided emissions in the case of CCS. On the other hand, the plant equipped with CCS may be utilized in significantly higher load than the reference plant which reduces production penalty but increases fuel use affecting emissions from fuel production.

2.1.5 Lessons learned from previous LCA studies

The specific attention should be paid on following issues when comparing the studies and reporting of the results:

Which capture technology will be used?

> Studies conducted by the international community provide point of comparison for post-combustion, oxyfuel and pre-combustion capture. For the solvent used in post-combustion capture, the choice often falls upon MEA. Also comparative studies and synthesis reports are

available.

Which fuel will be used?

The most common fuel found in LCA CCS studies is hard coal. Other fuels used are lignite and natural gas. Fuel specifications should be presented clearly. These specifications should include net calorific value, composition and transport distance. In addition production phase may be important, for instance in the case of coal mining significantly higher CH4 emissions may occur in the case of underground mining than open pit mines. An estimate of how long the selected fuel will be available considering future demand should be made.

What happens when technology develops?

It is usually assumed that the energy efficiency of the process will improve. Will other environmental effects drop? When looking at the publications of CCS LCA, it is not easy to find a consensus on the technological development of the future or the emissions of a production scale facility.

What are the quality demands for captured CO_2?

Compression, transport and storage can pose demands on the CO2 quality. The required quality of CO_2 could affect the selection of the technology used. Also it could affect the emissions of the selected technology.

How is the efficiency penalty compensated?

What are the properties of the energy system where CCS is located and how application of CCS effects on the system level. What are the utilization rates of the plants with and without CCS (or before and after application of CCS in the case of retrofit studies). In CHP environment it is essential to consider effects on the other plants in the heating network. In Finland, question related to biomass availability, sustainability etc. are of specific importance.

2.2 LCA in the CCSP program

2.2.1 CCS from-cradle-to-grave

For LCA, the most significant inputs with environmental effects are collected over the products life-cycle. For carbon capture facility, the main phases of the life-cycle are: raw-material production, building phase, use phase and demolition. The use phase clearly dominates as a source of environmental effects. This is explained by the huge amounts of energy and solvent used over the entire lifespan of the power plant.

2.2.2 Goal and scope

According to the ISO 14040 and 14044 standards a life-cycle assessment study must include a statement of the goal and the scope of the study. The following questions must be answered:

What is the goal of the LCA?

> An LCA could be performed to help the designer of the plant to make environmentally friendly decisions. Or it could have the goal of helping a power company in decision making. It could also be aimed at helping policy-makers make informed decisions. This could easily slip into the question of how to mitigate climate change and the acceptability of CCS.
>
> On a more technical level, some studies aim to quantify the changes in emissions while others are more interested in the changes for different impact categories. The level of detail should be carefully considered. The LCA studies already performed can help in narrowing down the environmentally most important parts of the CCS
>
> For the program, the LCA considerations should be aimed towards forming the policy in Finland and cases significant to the program and Finland.

What is the functional unit?

> Captured CO_2
>
> - Important for the operator

- Not widely used in LCA studies
- Has monetary value (included to economic case studies)

Avoided CO_2

- Used in most of the case studies conducted in CCSP
- Has value in mitigating climate change
- Often presented also for other GHG emission reduction methods
- Difficult to compare because of the case dependency, different boundary settings, assumptions included and other uncertainties presented earlier

What are the system boundaries?

System boundaries can have significant effects on the results. They can even change the results from positive to negative.

The assessment should not be limited inside the power plant but upstream and downstream processes should also be taken into consideration.

The assessment could be done for a single plant or considering wider entities such as the electrical grid. Chosen boundaries effect on the question that study answers.

Utilization of captured CO_2, for example EOR, complicates the assessment. If significant use for the Finnish CO_2 is found, then the benefits should be split between CCS and the process benefiting from the captured CO_2. For example cash flows can be used as a basis for the allocation.

Timescale of the assessment must be carefully set. A power plant has a lifespan of decades. When will the plant be build and how far has the technology been developed by then? CO_2 storage leakage forces LCA to an unfamiliar territory when it has to face a lifecycle of thousands of years. On the other hand, climate change is often considered to be a problem of ongoing century and therefore small leakages after thousands of years can be ignored.

The relevancy of all impact categories should be conducted. If the toxicity effects of a solvent used can be found as insignificant, the LCA can be simplified. This requires further study beyond LCA.

What are the impact categories?

Selection of impact categories is important. If a comparison between a new LCA and existing ones is planned, the categories should be selected accordingly. The exact impact categories and the emissions included in them, depend on the chosen impact assessment method. All LCA studies for CCS include global warming potential (GWP). Other common categories are acidification potential (AP), eutrophication potential (EP), photochemical oxidation potential (POCP), human toxicity potential (HTP), cumulative energy demand (CED) and abiotic depletion potential (ADP).

2.2.3 Streamlined LCA utilised in case studies

In LCA case studies conducted during the first period of CCSP so called streamlined LCA regarding GHG emissions only was utilised. The streamlined method was chosen because comprehensive LCA is laboured and typically over 90 % of the GHG impact is resulted from few phases of CCS life cycle, namely fuel production, combustion, capture and compensation of the energy penalty of CCS. The phases of CCS life cycle are presented in the Figure 2.

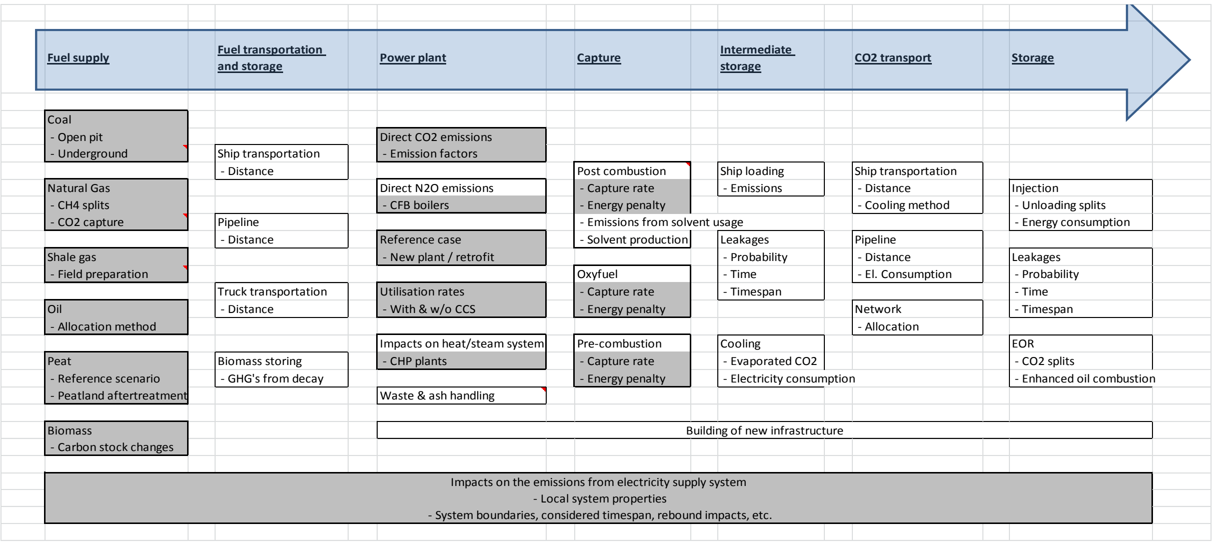

Figure 2. The phases of CCS chain. Potentially significant phases in terms of GHG emissions

are indicated by grey colour.

In streamlined LCA only the phases which are known to be significant are included in detailed analysis. For the other phases for example constant and very uncertain values from literature are used.

3 Discussion

Despite of the standards, LCA can be utilised in many ways leading to different results. For example term “avoided CO_2 emissions” which is often presented as one of the main results of the CCS studies, is not unambiguous but depending significantly on chosen system boundaries, electricity production system and utilisation rates. Therefore comparison of different technologies from different studies may be challenging.

Several LCA studies for CCS have been made and despite of different assumptions, boundaries and other uncertainties, some general conclusions can be made. The global warming potential is clearly decreased while other environmental effects increase with more uncertainty concerning the significance of the change. Increased environmental effects are formed by the increased use of fuel (in the same or some other plant) and the use of a solvent for CO_2 scrubbing. Construction of the plant and transport and storage of CO2 have significantly smaller impacts.

It has been found, that typically over 90 % of the GHG impact of CCS is resulted from few phases of life cycle, namely fuel production, combustion, capture and compensation of the energy penalty of CCS. Therefore in the case studies conducted during the first period of CCSP streamlined LCA regarding GHG emissions only was utilised. The results are presented in context of the economic case studies.

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