

LCA BENEFITS AND LIMITATIONS FOR THE ASSESSMENT OF CARBON CAPTURE AND STORAGE (CCS) OR USE (CCU)

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SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

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- ✓ The views and recommendations expressed in this publication are those of the authors and do not necessarily reflect, unless otherwise stated, the views of all members of SCORE LCA.

- ✓ The information and conclusions presented in this document were established on the basis of scientific and technical data and regulatory and normative framework in force at the date of the publication of documents.

Context

To face the challenges raised by increased greenhouse gas (GHG) emissions, energy technology innovation is required to meet the given climate change mitigation goals while supporting economic and energy security objectives (IEA, 2015).

Amongst the possible innovations, carbon capture and sequestration (CCS) or carbon capture and use (CCU) are technologies that are believed necessary, in the energy and industrial sectors, to maintain global temperatures rise below 1.5 or 2°C.

However, the promotion of CCS/CCU is often solely based on climate change mitigation goals without consideration for other environmental impacts (e.g. smog, acidification, eutrophication, toxicity, ecotoxicity, etc.). While life cycle assessment (LCA) offers the ability to ascertain the environmental performance of technological systems regarding several impact categories, its use is not without challenges, from both methodological and interpretation perspectives.

Study's overall methodology

Given the lingering questions on LCA and its application, ScoreLCA mandated the CIRAIG to:

- 1) Provide an overview and critical analysis of the published and ongoing work on CCS and CCU systems in LCA;
- 2) List and identify LCA methodological issues for CCU and CCS systems;
- 3) Illustrate these challenges (and how best to tackle them) with different examples;
- 4) Provide methodological recommendations on applying LCA to CCU and CCS systems.

Carbon capture process – the basics

A literature review yielded that carbon capture has either been or is projected to be used in the power generation sector as well as for natural gas processing, fertilizer production, iron and steel production, chemical production, hydrogen production, oil refining, plastics, and concrete production. It should be noted that carbon capture deployment is lagging and well below the projected goals to mitigate temperature increases.

In these sectors, carbon capture is carried out with either:

- post-conversion capture: the separation of CO₂ from the flue gas after the conversion of a carbon source;
- pre-conversion: capture CO₂ through a chemical reaction before a conversion/combustion process. CO₂ is then an undesirable co-product of an intermediate reaction;
- oxyfuel: the fuel is burned with pure oxygen (instead of air) to produce a combustion gas with high a CO₂ concentration;
- direct air capture: CO₂ (and potentially other greenhouse gases) are removed directly from the atmosphere through fans that suck in the atmosphere. CO₂ is removed by a solvent.

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Among these carbon capture technologies, post-conversion with amine scrubbing as well as pre-conversion with solvents are the most mature while oxyfuel isn't much used, and DAC is mostly theoretical at this point.

Disposing of the captured CO₂: the carbon capture and storage (CCS) or carbon capture and use (CCU) pathway

Once captured, the CO₂ needs to be disposed of. Disposition of the captured CO₂ either follows a long-term storage (CCS) or use (CCU) pathways.

CCS is akin to waste sent to a landfill while CCU is akin to recycling since the captured CO₂ is used as a building block for making other products. Selection of one pathway over the other is left to the discretion of the industry but will typically be selected for economic purposes: captured CO₂ with CCS will cost money for its capture, compression/liquefaction, transport, and final injection in a long-term storage location while CCU allows to create value for CO₂ and allow to compensate, in some way, for the capture, compression, and transport costs.

Learning from past LCA studies

A literature review from 14 peer-reviewed papers on LCA applied to CCS and 22 papers on LCA applied to CCU yielded showed that the focus was mainly on GHG emissions and that carbon capture will decrease GHG emissions over a system without carbon capture. Since carbon capture also decreases NO_x, SO_x, and particulate matter emissions, indicator decrease is also expected for terrestrial and aquatic acidification, marine eutrophication, and respiratory inorganics impacts. This will be, however, at the expense of all other environmental indicators since one is increasing the energy consumptions, the operations, and their related emissions. The latter was only shown by a few papers since they focused on GHG emissions and left the other impact categories unassessed.

Past LCA CCU studies also showed more variability in their results due, in part, to the considered assumptions such as the capture efficiency, the energy consumption, the solvent types, etc.

CCS LCA studies showed little to no methodological issues apart from data acquisition - which is a consistent issue with most LCA, especially for emerging technologies (low technological readiness level (TRL)) for which operational data are scarce.

CCU on the other hand has several methodological issues ranging from the selection of the functional unit, the system boundaries, dealing with multi-functionality, data acquisition, and life cycle impact assessment interpretation.

Other methodological issues can also be raised if one is carrying a dynamic, consequential, or prospective LCA.

Methodological challenges and recommendations

After a review of available guidelines, each step of an LCA has been thoroughly analyzed to highlight the most important methodological challenges and how to tackle them in CCS and CCU studies.

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The identified methodological challenges are:

- **Defining the goal of the study:** depending on the aim of the study, different LCA approaches could be used: attributional (classic LCA), consequential LCA (CLCA), dynamic LCA (DLCA), or prospective LCA (PLCA).
- Defining the scope of the study (all types of LCA's)
 - **Defining the functional unit:** CCS and CCU have very different functional units. Selecting one functional unit over another can lead to varying indicator results
 - **Defining the system boundaries:** special care needs to be taken when defining the system boundaries of CCU systems (especially). Indeed, a lack of included processes may lead to varying indicator results.
 - **Solving multi-functionality:** CCS is not burdened with multi-functionality issues; the captured CO₂ is considered a waste that needs to be eliminated. For CCU, the captured CO₂ now has a value since it will be used as an input in another process. Therefore, the system becomes multifunctional. Are there any special approaches that need to be considered?
- **Defining the scope of Consequential LCA (CLCA):** Consequential LCA captures environmental consequences that are often outside of the actual supply chain, and which instead result from market forces. They are often used to answer the question: *“What are the environmental consequences that are expected to occur following a change in production, consumption, and/or disposal of a product?”*. The identification of these market forces remains a challenge.
- **Defining the scope of Dynamic LCA (DLCA):** as a baseline, all emissions (be it past, present, or future) from the life cycle of a product occur at the same time (year 0). However, one could want to differentiate the timing of the individual emissions occurring during the life cycle of a product (e.g. I want to assess the effects of capture vs fugitive CO₂ emissions from long-term storage)
- **Defining the scope of Prospective LCA (PLCA):** the world is evolving. Something that holds now, might not be true tomorrow. For example, will the electricity consumed from the electricity mix by a process still be heavily dependant on coal, or, by the time this electricity is consumed, will society have shifted to a more renewable electricity mix? Foreseeing how and when the world will evolve is a challenge.
- Life cycle inventory
 - **Data acquisition:** finding representative technological, geographical, and temporal data is always a challenge in any LCA. It is even more of a challenge when evaluating emerging technologies with low technology readiness levels (TRL) such as some of the available carbon capture technologies.
 - **Data variability:** no single process works the same from one plant to the next – variations in the operations are to be expected and should be accounted for. How should they be accounted for?
 - **Regionalization:** if operations vary from plant to plant, they can also vary from country to country (especially when electricity is consumed from the country electricity mix which might be close to 100% renewable or depend heavily on coal), the supply chains which, are worldwide, can also vary. Selecting different suppliers may lead to varying life cycle indicators.
 - **Data acquisition for prospective LCA (PLCA):** emerging technologies will improve in time. Estimating how a process will evolve 10, 20 years from now is a challenge.
- Life cycle impact assessment

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- **Attributional impact assessment results:** In the literature, LCA of CCS has shown positive indicator results. For CCU, indicator results were shown to be positive or negative (they could even be theoretically neutral). Why are indicator results offer such variations?
- **Dynamic impact assessment results:** For the moment, only characterization factors for emissions related to the *Climate change* impact category has been developed.
- **Regionalization:** while the issue is not specific to CCS/CCU. Such impact categories as *Human toxicity, Ecotoxicity, Acidification, Eutrophication, Water scarcity, Particulate matter, SMOG, Land use, and Land transformation* are dependant on regional parameters. Current impact assessment methods typically assess impacts for a specific geographical location (e.g. Europe, Japan, the United States) even if the emission occurs somewhere else in the world. Therefore, the impact assessment could be improved if a coherent global impact assessment method with regional capabilities be used.
- Interpretation
 - **Contribution analysis:** are contribution analysis nice to have or should they be mandatory for a better understanding of the system indicator results?
 - **Sensitivity analysis:** which sensitivity should be carried out?
 - **Uncertainty analysis:** should uncertainty be carried out?
 - **Data quality assessment:** the ISO 14040: 14044 standards for LCA doesn't detail how data quality should be performed.
- **Who gets the environmental benefit of capturing CO₂?:** seeing that carbon capture reduces the GHG emissions, for CCU, who should claim – from a carbon footprint perspective – the benefits of capturing CO₂? The one who captures or the one who uses the CO₂?
- **LCA use for regulatory purposes:** can an LCA be used to assess the environmental impacts of the CCS and CCU project for regulatory purposes?

The following table list the short and long-term recommendations to tackle those methodological issues. For further details and illustration of the challenges and their effects through different examples, please consult the full report.

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Table S-1 : CCS/CCU LCA studies methodological recommendations

Life cycle step	Methodological challenge	CCS		CCU	
		Short-term recommendations	Long-term recommendations	Short-term recommendations	Long-term recommendations
Goal and scope	Defining the goal of the study	<p>the most common research questions for attributional CCS LCA studies are:</p> <ul style="list-style-type: none"> ▪ How does CCS improve the life cycle environmental profile of a product or service based on fossil carbon sources? ▪ What are the contributions to the life cycle environmental profile of a CCS process and where are hot spots to improve the environmental performance? ▪ What are the environmental trade-offs of CCS implementation? <p>Application of CLCA for CCS shows little interest since the likely consequence is the replacement of an existing process without carbon capture – a calculation that can be made with the information from the attributional LCA</p> <p>DLCA should be used if the study aims to differentiate the timing of the individual emissions occurring during the life cycle of a product (i.e. the effects of capture vs long-term storage)</p> <p>PLCA should be used if one needs to ascertain a specific technology that would be employed in the mid to long-term.</p>		<p>the most common research questions for attributional CCU LCA studies are:</p> <ul style="list-style-type: none"> ▪ What is the life cycle environmental profile of a CCU-based product or service compared to that of the same product or service derived from fossil carbon sources? ▪ What are the contributions to the life cycle environmental profile of a CCU-based product/service and where are hot spots to improve the environmental performance? ▪ Which CCU technology to use to make efficient use of renewable energy? ▪ What are the environmental footprints of products or services used as a basis for consumer decisions (product declarations)? <p>CLCA should be used if one wants to assess the environmental consequences that are expected to occur following a change in production, consumption, and/or disposal of a product</p> <p>DLCA should be used if the study aims to differentiate the timing of the individual emissions occurring during the life cycle of a product (i.e. short vs long-term storage in different products)</p> <p>PLCA should be used if one needs to ascertain a specific technology that would be employed in the mid to long-term.</p>	
	Defining the functional unit	<ul style="list-style-type: none"> • Functionally equivalent • Quantifies the function and defines both geographical and temporal contexts • Based on the product where capture technology is deployed unless the comparison is for capture process across several industry types. In which 		<ul style="list-style-type: none"> • Functionally equivalent • Quantifies the function and defines both geographical and temporal contexts <p>Varies according to the study's context</p>	

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		case, the quantity of captured carbon should be the focus.	
Defining the system boundaries of attributional LCA	Cradle-to-grave should always be considered unless processes of compared systems are identical in which case they can be removed from the analysis since they do not participate in the system differentiation. Doing so may limit the identification of other factors that would lead to greater decrease in indicator results.		
Defining the system boundaries of CLCA	<ul style="list-style-type: none"> Limited application to carry out a CLCA with CCS. Indeed, the displaced technology is assuredly the same technology without carbon capture. An attributional LCA often compares the two. One would simply need to take the indicator result for the CCS system and subtract the attributional indicator results of the process without carbon capture, compression, transport, and injection to obtain a CLCA result 	<ul style="list-style-type: none"> Attributional challenges apply Build “addition”, “net substitution”, and “substitution with rebound effect” scenarios based on a series of assumptions. The scenarios are most likely incomplete since all ripple effects wouldn’t have been considered. 	Use general or partial equilibrium models to ascertain the ripple effects of introducing CCU
Defining the system boundaries of DLCA	<ul style="list-style-type: none"> Same as with attributional LCA. The life cycle emissions are now time-dependent (which wasn’t the case with attributional LCA) 		
Defining the system boundaries of PLCA	<ul style="list-style-type: none"> Assessment of all possible futures improvements of CCS 	<ul style="list-style-type: none"> One should consider the use of the Shared Socioeconomic Pathways (SSP) 	<ul style="list-style-type: none"> Assessment of all possible futures improvements of CCU One should consider the use of the Shared Socioeconomic Pathways (SSP)
Solving multi-functionality	Doesn’t apply. CO ₂ is a waste that must be eliminated (akin to “waste sent to a landfill”)		<p>System expansion should always be considered. Captured CO₂ doesn’t come unburdened. Indicator depends on the process in which CO₂ was captured.</p> <p>If product-specific, allocation according to several bases (mass, volume, energy, economic) should be considered to ascertain the potential</p>

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				variations from selecting one basis over the other
Life cycle inventory	Obtaining life cycle inventory data for attributional LCA	<ul style="list-style-type: none"> • Data should be representative of geographical and temporal context • Data quality should be assessed • Life cycle inventory data are taken from the literature <ul style="list-style-type: none"> ▪ Pros: Easy ▪ Cons: Study must have already been carried out and only provides a “picture” of a specific process ▪ Challenge: If technology hasn’t been documented, such as with technologies at low TRL, then finding data will be harder and most likely the LCA will have to rely on assumptions which, of course, will impact the reliability of the resulting environmental indicators. 	<ul style="list-style-type: none"> • Data should be representative of geographical and temporal context • Data quality should be assessed • Life cycle inventory data are obtained from process modeling <ul style="list-style-type: none"> ▪ Pros: Reliable and flexible ▪ Cons: Requires in-depth operational knowledge; ▪ Challenges: Reliant on chemical engineers and, most likely their Aspen Tech suite (which is costly) which then needs to be translated into useable life cycle inventory 	See CCS

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			datasets		
	Obtaining data for CLCA	<ul style="list-style-type: none"> Attributional LCA comments apply Additional data needs to be gathered for all processes affected by the captured carbon. 			
	Obtaining data for DLCA	<ul style="list-style-type: none"> Attributional LCA data needs to be assigned by hand to their respective timeframe. 	<ul style="list-style-type: none"> Build a dynamic LCA database 	See CCS	
	Obtaining data for PLCA	Assumptions need to be made about technological improvements. If history is any indication, those assumptions are likely to be wrong	Build an uncertainty assessment that would allow assessment for “all possible futures” – the answer being one of the “possible futures”	Assumptions need to be made about technological improvements. If history is any indication, those assumptions are likely to be wrong	Build an uncertainty assessment that would allow assessment for “all possible futures” – the answer being one of the “possible futures”
Life cycle impact assessment	Attributional LCA impact assessment/regionalization	<ul style="list-style-type: none"> Apply existing LCIA methods as is Regionalization capabilities are limited now Indicator results are positive 	Apply worldwide regionalized impact assessment methods that provide an overall coherent framework all the while accounting for a regionalized life cycle inventory database.	<ul style="list-style-type: none"> Apply existing LCIA methods as is Regionalization capabilities are limited now When applying system expansion, indicator results can be: <ul style="list-style-type: none"> Negative: the process used to subtract the unwanted function, indicator results are higher than the indicator 	Apply worldwide regionalized impact assessment methods that provide an overall coherent framework all the while accounting for a regionalized life cycle inventory database.

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				<ul style="list-style-type: none"> ■ r results from the CCU system ■ Neutral: the process, used to subtract the unwanted function, indicator results are identical to the indicator results from the CCU system ■ Positive: all other possibilities 	
	CLCA impact assessment/regionalization	See Attributional LCA impact assessment/regionalization			
	DLCA impact assessment/regionalization	Dynamic characterization factors are only available for the <i>Climate change</i> impact category	Dynamic characterization factors need to be developed for all impact categories	See CCS	
	PLCA impact assessment/regionalization	See Attributional LCA impact assessment/regionalization	Adapt environmental models to reflect future conditions and provide new (reliable and coherent) characterization factors	See CCS	
Interpretation	Analysis contribution	Contribution analysis should be performed to provide a better understanding of the compared systems.		Due to the application system expansion, results should only be presented in a contribution analysis to highlight the contribution of the process, used to subtract the unwanted function	

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	Sensitivity analysis	<p>The following sensitivity analysis should be considered as best practices:</p> <ul style="list-style-type: none"> • Impact assessment method • The CO₂ capture efficiency; • The CO₂ capture process energy consumption; • The type of capture process (pre-conversion, post-conversion, oxy-fuel combustion or DAC); • The type of solvent used (if applicable) during carbon capture; • The efficiency of the electricity generation process (if applicable) or the amount of input; • The CO₂ transport option: pipeline, ship, road, or freight transport (if applicable); • The leakage rate of the CO₂ storage geological formation (if applicable); • Methane fugitive emissions associated with coal or natural gas systems (if applicable); • The allocation rules (if applicable) such as mass, energy, or economic; • The avoided process(es) for CCU systems in consequential LCA (if applicable).
	Uncertainty assessment	<p>Monte-Carlo uncertainty analysis is the most efficient way to assess all the LCI data variability and/or uncertainty related to possible technological leap throughs.</p>
	Data quality assessment	<p>Though ISO does not propose a method for such inventory data quality assessment, the Pedigree matrix approach, as employed in the <i>ecoinvent</i> life cycle inventory database, is one of the most recognized, systematic, approaches to describe data quality. In addition to the pedigree matrix criteria, one should also assess the contribution of the data. Indeed, if data is of poor quality but its contribution is low, then its effect on the overall conclusions should be insignificant.</p>
Regulatory purposes	Who gets the credit?	<p>Akin to the issues of recycling, the credit could be allotted to the one who captures CO₂, the CO₂ user, or split between the one who captures or the user. This is not a methodological issue and is more likely to be politically driven.</p>
	LCA recommendations for regulatory purposes	<p>A series of methodological recommendations and best practices can be established but due to the high variability of potential outcomes, LCA CCS/CCU studies should be considered on a case by case basis.</p>