SCORE LCA

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LCA benefits and limitations for the assessment of CCS and CCU

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Responsables scientifiques :

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- ✓ Ces travaux ont reçu le soutien de l'ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) www.ademe.fr

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- ✓ Les informations et les conclusions présentées dans le présent document ont été établies au vu des données scientifiques et techniques et d'un cadre réglementaire et normatif en vigueur à la date de l'édition des documents.

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Summary

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 modeling and interpretation perspectives.

Given 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 is either carried out with either post-conversion capture (i.e. the separation of CO_2 from the flue gas after the conversion of a carbon source), pré-conversion (i.e. capture CO_2 through a chemical reaction before a conversion/combustion process. CO_2 is then an undesirable co-product of an intermediate reaction), oxyfuel (i.e. the fuel is burned with pure oxygen (instead of air) to produce a combustion gas with high a CO_2 concentration) or direct air capture (i.e. CO_2 (and potentially other greenhouse gases) are removed directly from the atmosphere). Among these carbon capture technologies, post-conversion with amine scrubbing as well as pre-conversion with solvents are more mature while oxyfuel isn't much used, and DAC is mostly theoretical at this point.

Disposition of the capture CO_2 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 CO_2 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 CO_2 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 CO_2 and allow to compensate, in some way, for the capture, compression, and transport costs.

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.

Past LCA CCS studies results typically show that carbon capture will decrease GHG emissions and, perhaps, terrestrial and aquatic acidification, and respiratory inorganics impacts over a system without carbon capture but at the expanse of all other environmental indicators since one is increasing the energy consumptions, the operations, and their related emissions. Past LCA CCU studies show more variability in their results due, in part, to the considered assumptions.

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.

This report analyzes each of these methodological issues, illustrated the challenges, and showed how best to circumvent them with different examples.

From these illustrations, a list of short-term and long-term recommendations was provided.

1 Introduction

Energy technology innovation is required to meet climate change mitigation goals while supporting economic and energy security objectives (IEA, 2015). Indeed, the deployment of proven, cost-effective technologies is what will make the energy system transformation possible (IEA, 2015). Figure 1-1 presents the International Energy Agency (IEA) proposed innovations, per sector, to limit the increase in global average surface temperature to 2°C by 2050.

As seen, **carbon capture and sequestration** (CCS) or **carbon capture and use** (CCU) is required in the power generation and industry sectors to help achieve the given GHG emissions reduction goals.

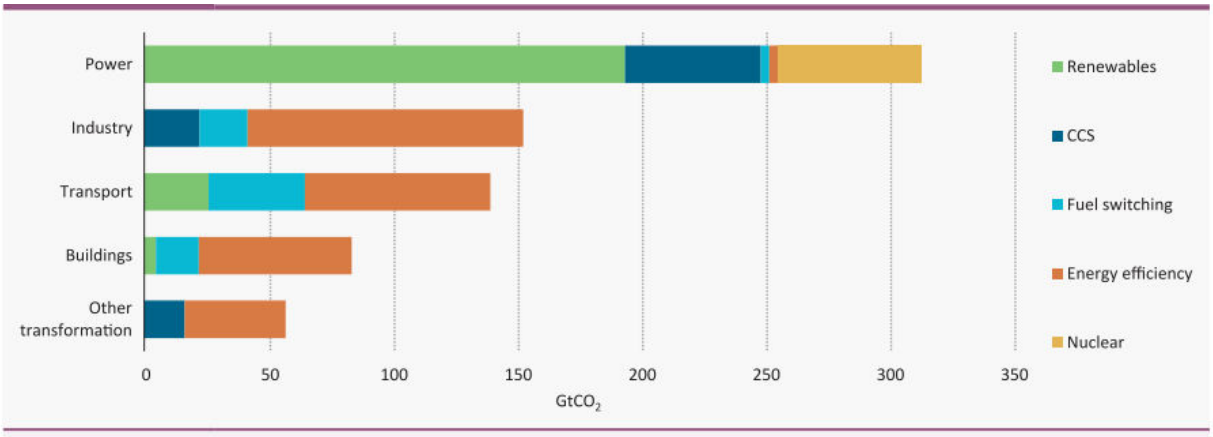

Figure 1-1: Cumulative carbon dioxide (CO_2) reductions by sector and technology in the 2DS to 2050 IEA scenario (IEA, 2015)

However, such a technological deployment is solely based on climate change mitigation goals and isn't necessarily an optimal solution for other environmental impact categories (e.g. smog, acidification, eutrophication, toxicity, ecotoxicity, etc.) or economically sound.

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 modeling and interpretation perspectives.

Therefore, ScoreLCA has 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

More specifically, this project will:

1) Provide a literature review to:
    a) Identify carbon capture technology families (i.e. post- and pre-conversion, oxyfuel combustion, direct air capture) and storage types or use;
    b) Describe the industrial systems implementing CCS and CCU;
    c) Identify existing CCS and CCU environmental assessments – relying on LCA or other approaches;
    d) Identify CCS and CCU potential to reduce GHGs, by 2050, to contribute to France's carbon neutrality commitments.
    e) Conduct a critical assessment of CCS and CCU LCA studies;
2) List and describe LCA methodological issues to address each industrial system implementing CCS and CCU;
3) Illustrate the methodological challenges with different case studies;
4) Develop practical methodological recommendations for CCU/CCS LCA in the form of a guide on how to apply LCA to these industrial systems.

This document represents the project's second milestone and presents:

- A literature review to provide SCORELCA members with the basic concepts associated with CCS and CCU (Section 2);
- A review of CO_2 emission sources for different industrial sectors (Section 3)
- A literature review of results from past LCA studies (Section 4);
- A list of methodological challenges when applying LCA to CCS/CCU illustrated with case studies (Section 5);
- A list of recommendations (Section 6).

2 Literature review – basic concepts

This section highlights the basic concepts and assumptions that are necessary for a better understanding of CCS and CCU technologies.

More specifically, this section aims to **identify, describe, and differentiate between carbon capture technology families (i.e. post- and pre-conversion, oxyfuel combustion, direct air capture) and storage types or use (i.e. the project's 1a objective).**

2.1 CCS and CCU: an overview

The following figure illustrates the distinction between CCS and CCU.

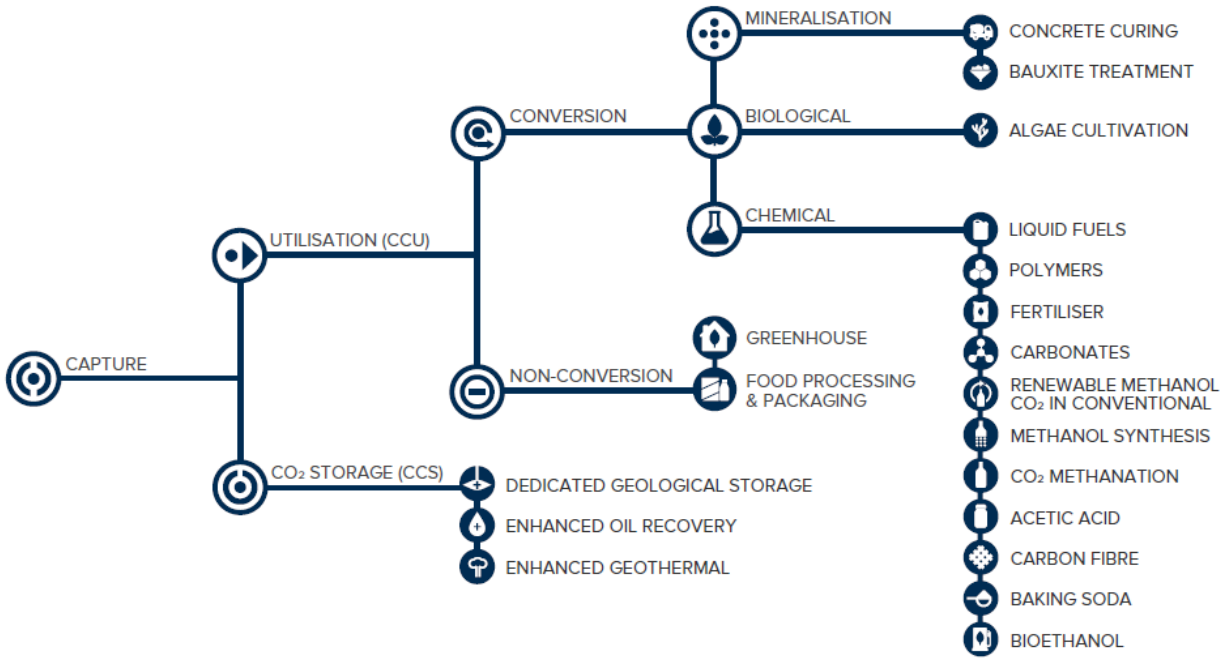

Figure 2-1: Overview of the carbon capture and storage (CCS) or use (CCU) processes (Global CCS Institute, 2019)

In summary, CCS and CCU pathways start from the capture process - the ability to isolate CO_2 either from a feed or from a combustion exhaust gas.

- If the CCS path is taken, the captured CO_2 is compressed and transported to a long-term storage solution (CCS).
- If the CCU path is taken, the captured CO_2 is compressed and transported to a facility that will use the capture CO_2 as a feedstock to generate other goods.

It should be noted that depending on the literature source, enhanced oil recovery (EOR) is classified as either storage or use. Indeed, EOR acts as long-term storage for the capture CO_2. However, as it helps extract more crude oil, it is also a use of the captured CO_2.

The following sub-sections will further detail the concepts of carbon capture, CO_2 storage, and CO_2 use.

2.2 Identification of the carbon capture families

Carbon capture technology aims to capture CO_2 emissions from feeds (e.g. natural gas treatment), point sources (such as power plants and industrial processes) to prevent their release into the atmosphere, or to extract CO_2 from the atmosphere.

Four types of capture processes are reported in the literature:

- Post-conversion capture;
- Pre-conversion capture;
- Oxy-fuel combustion;
- Direct air capture.

The following sub-sections present an overview of each capture family.

2.2.1 Post-conversion (combustion) capture

Post-conversion capture involves separating CO_2 from the flue gas after the conversion of a carbon source, for example, burning fossil fuels. Post-conversion capture can be used to eliminate CO_2 by various industrial sectors, including electrical power and heat generation, ethylene oxide, cement, fuels, and iron/steel production. When used in power plants, post-conversion capture is also known as post-combustion capture. The following figure illustrates the post-combustion capture process in a power plant relying on monoethanolamine (MEA) as the absorbing agent. Specific capture technologies are presented in sub-section 2.2.5

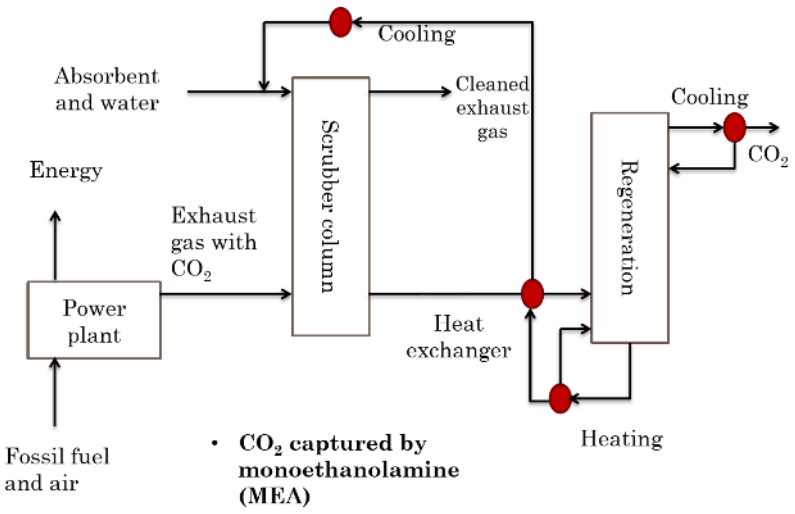

Figure 2-2: Illustration of a post-combustion capture process in a power plant relying on monoethanolamine (MEA) for the absorption of CO_2 (Zakuciova, 2016)

It should be noted that different solvent could also be used (Mumford et al., 2015):

- Advanced amine;
- Amino acid salt;
- Carbonates;
- Aqueous ammonia;
- Immiscible liquid;
- Ionic liquid.

2.2.2 Pre-conversion capture

Pre-conversion technologies capture CO_2 through a chemical reaction before a conversion/combustion process. CO_2 is then an undesirable co-product of an intermediate reaction. Examples include ammonia production and coal gasification in power plants. When used in power plants, pre-conversion capture is also known as pre-combustion capture. The following figure illustrates the pre-combustion capture process in a power plant relying on selexol as the absorbing agent. Specific capture technologies are presented in sub-section 2.2.5.

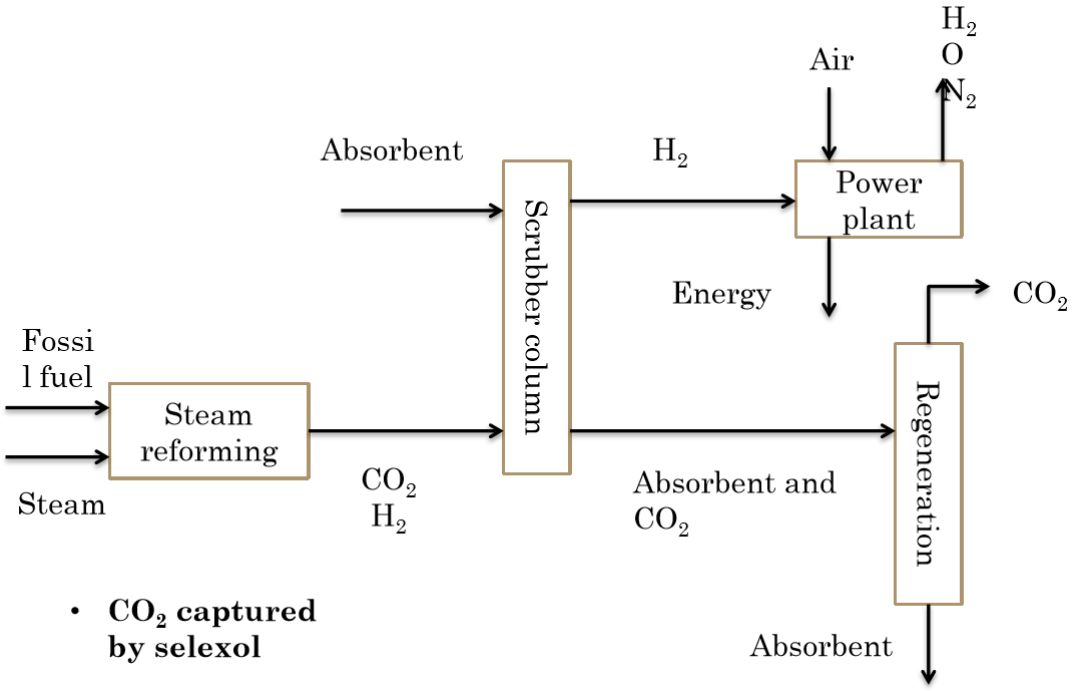

Figure 2-3: Illustration of a pre-combustion capture process in a power plant relying on selexol for the absorption of CO_2 (Zakuciova, 2016)

Other absorbents than selexol are possible (Mumford et al. 2015):

- Recticol;
- Sepaslov-MPE;
- Fluor solvent;
- Purisol;
- Morphysorb.

2.2.3 Oxyfuel combustion capture

Oxyfuel combustion can only be applied to combustion processes, such as electrical power generation using fossil fuel, cement or steel production.

In this process, the fuel is burned with pure oxygen to produce a combustion gas with high CO_2 concentration and free of nitrogen (N_2) – also limiting the generation of NO and NO_2 during combustion.

Although this simplifies the process of separating CO_2 from the combustion gas, oxygen is expensive, and the environmental impacts associated with its production can be significant due to the energy consumption required to separate oxygen from the air. The following figure illustrates the oxyfuel combustion process in a power plant. Specific capture technologies are presented in sub-section 2.2.5

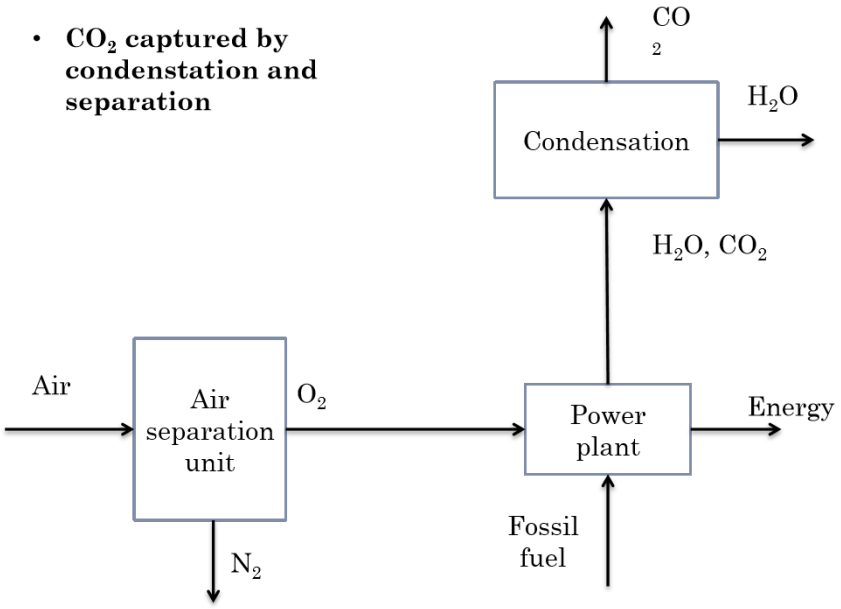

Figure 2-4: Illustration of an oxyfuel combustion capture process in a power plant (Zakuciova, 2016)

2.2.4 Direct air capture (DAC)

Direct air capture (DAC) is a technique in which CO_2 (and potentially other greenhouse gases) are removed directly from the atmosphere. The current technique uses large fans that move ambient air through a filter, using a chemical absorbent to produce a pure CO_2 stream that could be stored or used. The following figure illustrates the DAC process.

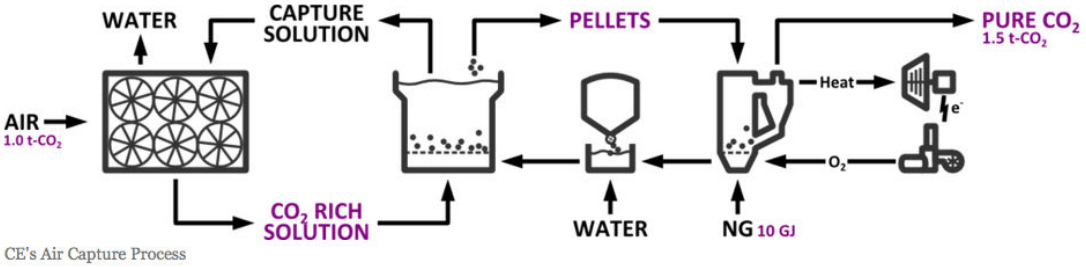

Figure 2-5: Illustration of a direct air capture (DAC) process (Geoengineering monitor, 2018)

DAC requires considerable energy input. When including all energy inputs for the capture-related processes, energy requirements reach, perhaps as much as 45 gigajoules per tonne of CO_2 extracted (Geoengineering monitor, 2018). Because of this huge energy demand, some geoengineering promoters have proposed to use “small nuclear power plants” connected to DAC installations.

Note: the previous figure only presents natural gas consumption for heating purposes (10 GJ/1.5 t CO2), but doesn’t present the energy requirements for the fan operations for directing air to the capture solution.

DAC also requires substantial water input. One study estimates that at implementation levels that would remove 3.3 gigatonnes of carbon (1 ton of carbon = 3.67 ton of CO2) per year, DAC could use up to 300 km^3 of water per year (assuming current amine technology) (Geoengineering monitor, 2018).

2.2.5 Capture technology commercial availability

Of the listed technology families, *post-conversion capture*, relying on chemical absorption, is the sole technology considered of sufficient maturity for large scale deployment (Gilbert, 2016).

Table 2-1 : Capture option and current availability

Capture option	Separation technology	Method	Commercial availability?
Post-conversion	**Absorption by chemical solvents**	**Amine-based solvent**	**Yes**
		Alkaline solvents	No
		Ionic liquid	No
	Adsorption by solid sorbents	Amine-based solid sorbents	No
		Alkali earth metal-based solid sorbents	No
		Porous organic frameworks-polymer	No
	Membrane separation	**Polymeric membranes**	**Yes**
		Inorganic membranes	No
		Hybrid membranes	No
	Cryogenic separation	Cryogenic separation	No
	Pressure/vacuum swing adsorption	**Zeolites**	**Yes**
		Activated carbon	**Yes**
Pre-conversion	Absorption by physical solvents	Selexol, recticol	No
	Absorption by chemical solvents	Amine-based solvent	No
	Adsorption by a porous organic framework	Porous organic frameworks membranes	No
Oxy-fuel combustion	**Separation of oxygen from the air**	**Oxy-fuel process**	**May be available around 2030**
		Chemical looping combustion	No
		Chemical looping reforming	No
Direct air capture	Largely theoretical/prototypes		

2.3 CO2 transport

Once CO_2 is separated it needs to be transported to the storage site or the facilities for its industrial utilization. Depending on the volumes involved a variety of means of transport may be utilized, ranging from road tankers to ships and pipelines.

Pipelines are the most viable method for onshore transport of high volume of CO_2 through long distances (as CCS would likely involve when widely deployed). Pipelines are also the most efficient way for CO_2 transport when the source of CO_2 is a power plant whose life is longer than 23 years. For a shorter period, road and rail tankers are more competitive. Supercritical is the preferred state for CO_2 transported by pipelines, which implies that the pipelines' operative temperature and pressure should be maintained within the CO_2 supercritical envelop, i.e. above 32.1°C and 72.9 atm. The typical range of pressure and temperature for a CO_2 pipeline is between 85 and 150 bar and between 13 °C and 44 °C to ensure a stable single-phase flow through the pipeline. The drop in pressure due to the reduction of the hydraulic head along the pipeline is compensated by adding recompression stations. Larger diameter pipelines allow

lower flow rates with smaller pressure drops and therefore a reduced number of recompression stations; on the other hand, larger pipelines are more expensive therefore a balancing of costs needs to be considered.

It should also be noted that pipelines have to be periodically monitored to assess their integrity and an accurate fiscal metering system is to be in place to assure the quantification of the stored fluxes. The equipment used for gas/oil pipelines needs to be modified to withstand the challenging environment experienced inside a CO_2 pipeline. Poor lubrication capacity of CO_2, high chemical reactivity, and high pressure may all affect the performance of both monitoring and metering equipment.

Leung et al. (2014)[1] report that only a few pipelines are used to carry CO_2 and are almost all for EOR projects. The oldest is the Canyon Reef Carriers pipeline, a 225 km pipeline built in 1972 for EOR in Texas (USA). The longest is the 800 km Cortez pipeline which is carrying 20 million tonnes/year of CO_2 from a natural source in Colorado to the oil fields in Denver City, Texas since 1983.

Leung et al. (2014) also report a study related to CCS in the North Sea highlights that CO_2 transport by ship tanker, using technologies derived from the LPG carriers, is feasible and cost-competitive with pipelines with a total cost ranging from 20 to 30 USD/tonne when more than 2MtCO_2/year are transported within the distances involved in North Sea storage.

The cost of transport varies considerably with the regional economic situation. Leung et al. (2014) mention a cost analysis study in China which showed that for a mass flow of 4000 t CO_2/day the use of ship tankers will cost 7.48 USD/tonne CO_2 compared with 12.64 USD/tonne CO_2 for railway tankers and 7.05 USD/tonne CO_2 for 300 km pipelines.

Leung et al. (2014) also note that other issues could arise from the trans-national transport of CO_2 and offshore storage due to legal aspects: "*The two key documents are the Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR Convention) and the London Protocol. These treaties do not allow waste dumping in marine environment and they also limit the cross-border transport of pollutants. In 2007 the OSPAR Convention was amended allowing sub-seabed CO_2 storage and entered into force following the needed ratification by seven countries on 23 June 2011. In 2006 an amendment was made to Annex 1 of the London Protocol allowing CO_2 to be injected in sub-seabed geological formations. Being an amendment to an Annex it does not need to be ratified and entered in force on 10 February 2007, 100 days after being proposed as for rules of the London Protocol. A second amendment was proposed in 2009 in order to remove the restriction for cross border transport of CO_2 for geological storage; this is an amendment to the Protocol itself and therefore needs to be ratified by two-thirds of the 42 contracting parties. So far only Norway and the UK have ratified the document. CO_2 transport for EOR is allowed under existing legislation both in USA and Europe, but there is no guarantee that the same approach will be maintained for the far larger volumes needed to be transported for large scale CCS operations.*"

2.4 CCS: sequestration options

Once captured, CO_2 – following the CCS pathway - is compressed and then transferred to a suitable site for long-term storage.

Three different geological formations are commonly considered for CO_2 storage:

[1] https://www.sciencedirect.com/science/article/pii/S1364032114005450

- Depleted (or nearly depleted) oil and gas reservoirs (potential global capacity: 920 Gt). Extracting more oil from a nearly depleted oil and gas reservoir is called enhanced oil recovery (EOR).
- Unmineable coal beds (potential global capacity: 415 Gt).
- Saline aquifers (potential global capacity: 400–10,000 Gt).

Deep ocean storage may also be possible although environmental concerns (such as ocean acidification and eutrophication) will likely limit its application.

General requirements for geological storage of CO_2 include:

- appropriate porosity, thickness, and permeability of the reservoir rock;
- a caprock with good sealing capability;
- a stable geological environment.

The following figure illustrates the world's potential CO_2 storage areas.

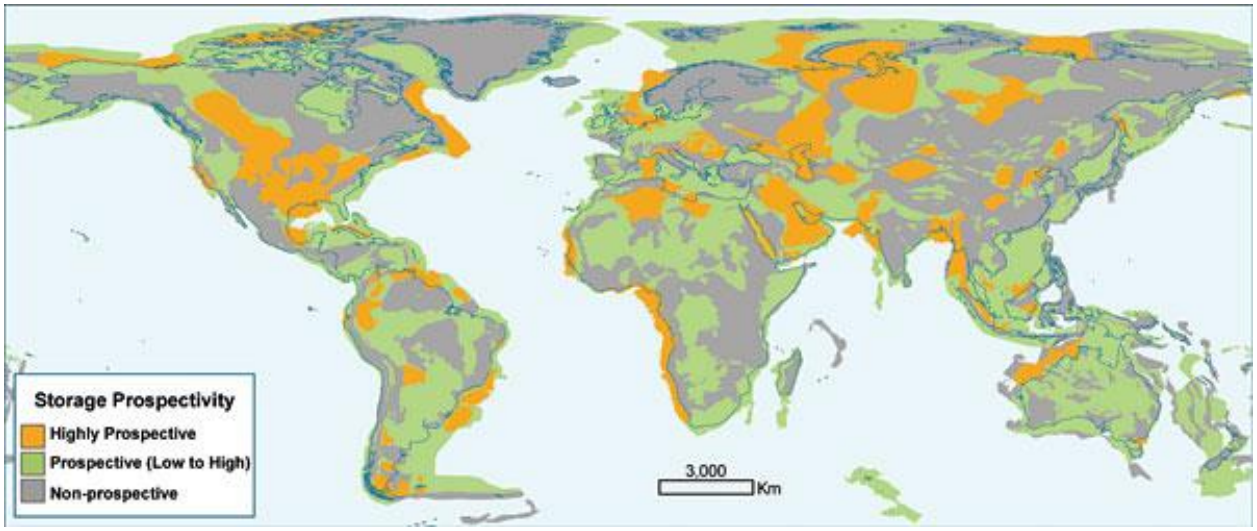

Figure 2-6: Potential CO_2 storage areas[2]

Over time, stored CO_2 is still expected to leak: The National Energy Technology Laboratory (NETL) estimates the leakage to be between 0 and 1% (with an average of 0.5%) over a 100-yr horizon (Cooney et al. 2015). NETL states that this remains an assumption until measurements from operating storage sites can validate the leakage rate. They also state that geologic formations with a potential leakage rate greater than 1% would be discarded for CO_2 storage.

A 2005 IPCC report on carbon capture and storage stated that it was "very likely" that 99 percent of stored CO2 would stay in place over the first 100 years and "likely" that the same percentage would stay in place over 1,000 years.

Several potential uses for captured CO_2 have been reported. However, Mac Dowell (2017) surmises that it will either be sequestered or used to recover oil from nearly depleted reservoirs (EOR) (Figure 2-7).

[2] http://news.stanford.edu/news/2007/june13/gifs/carbon_map.jpg

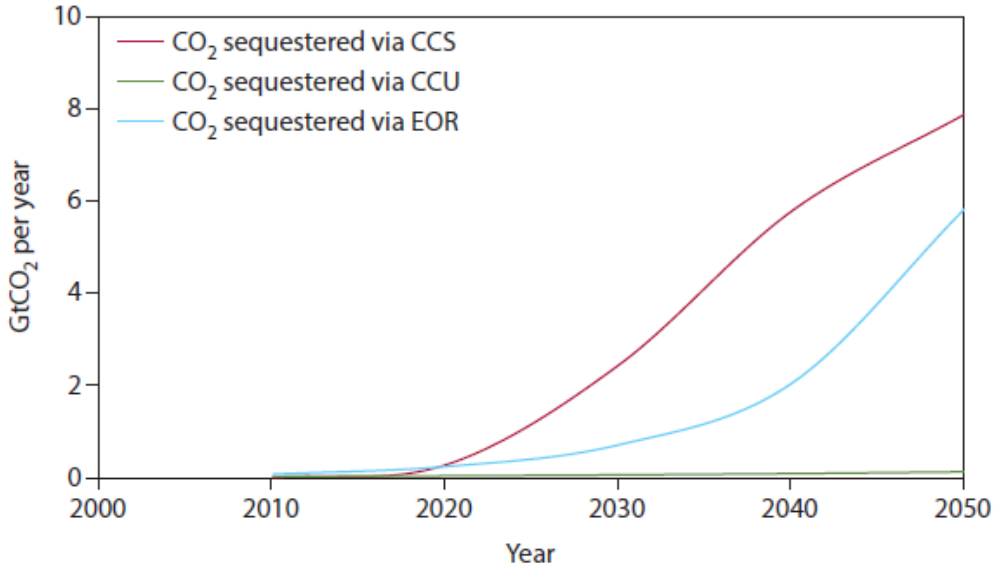

Figure 2-7: Most likely fate of captured CO_2 (Mac Dowell, 2017)

Finally, Figure 2-8 provides the EOR capacity per region and the CCS targets. As can be seen, CCS targets are higher than the capacity for numerous regions, especially Asia.

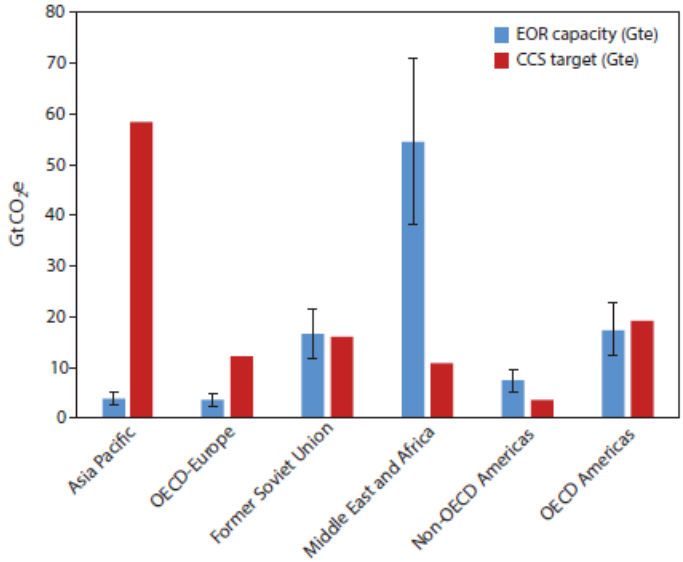

Figure 2-8: EOR Worldwide capacity and CCS targets (Mac Dowell, 2017)

Warning: the previous figure shows the storage capacity as EOR and not the overall storage capacity.

2.5 Use

Figure 2-9 presents an overview of different uses for captured CO_2 and their development level.

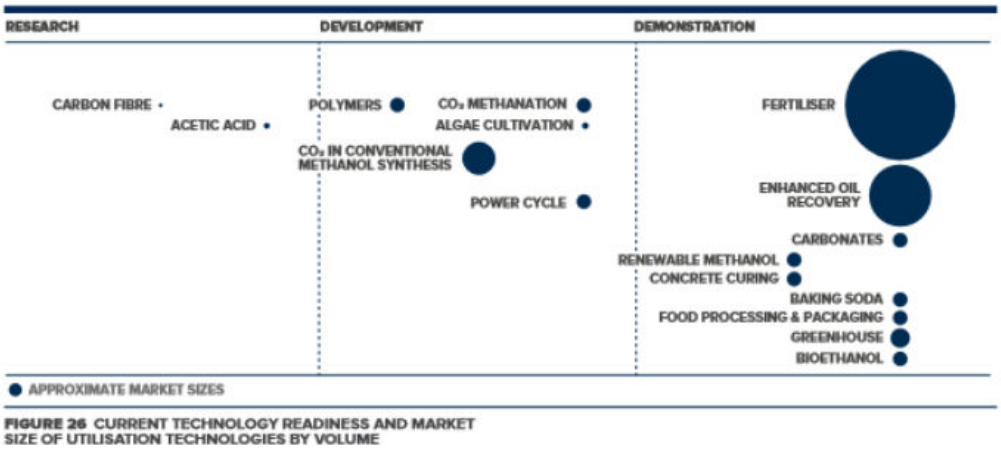

Figure 2-9: Technology readiness level (TRL) of captured CO_2 uses (Global CCS Institute, 2019)

Uses can be differentiated between non-conversion (i.e. the use of CO_2 without any transformation) and conversion (i.e. the use of CO_2 as a feedstock to be transformed by different chemical reactions).

2.5.1 Non-conversion use

Reported non-conversion uses are presented in Table 2-2. Non-conversion uses are mostly limited to the food industry and feedstock for vegetation growth.

Table 2-2 : CO2 non-conversion uses and readiness level

	Technology	TRL	Estimated economic and commercial potential	Chemical reaction	Comment
Non-conversion	Food and beverage applications	9	Medium	CO_2 is used as is	CO_2 is dissolved in beverages
	Horticulture	9	Medium		CO_2 is used as an input for the **growth** (photosynthesis) of vegetation
	Other Industrial and technical uses	9	Medium		Too vague a term to comment

2.5.2 Conversion use

Reported conversion uses are presented in Table 2-3. The conversion uses range over different applications.

Table 2-3 : CO_2 conversion uses and readiness level[3]

CCU category	Technology	TRL	Estimated economic and commercial potential	Chemical reaction
Chemical conversion	Renewable methanol production	4-8	High	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$
	Méthane production	4-8	High	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
	CO2 to fuels (Fischer Tropsch syntetic fuels)	4-8	High	CO2 + CH4 -> H2 + 2CO $nCO + 2(n+1)H2 \rightarrow nH_2O + C_nH_{2n+2}$
	Formic acid production	5	Medium	electrochemical reduction $CO_2 + 2H + +2e- HCOOH$
				$CO_2 + H_2 \rightarrow HCOOH$
	Urea	9	Medium	$2NH_3 + CO_2 \rightarrow NH_2COONH_4$ $NH_2COONH_4 \rightarrow NH_2CONH_2(urea) + H_2O$
	Ethanol	4-8	High	$2CO_2 + 3H_2O \rightarrow C_2H_5OH + 3H_2 + 3O_2$
	Counter-rotating ring receiver reactor recuperator[4]	3	Low	Solar Energy + xCO_2 + (x+1) H_2O -> CxH2x+2(liquid fuel) + (1.5x+.5) O_2
	Photocatalytic reduction of CO_2 (metallic)	3	Low	See Yamazaki et al. (2015) for a more comprehensive list
	Photocatalytic reduction of $3CO_2$ (non-metallic)	3	Medium	See Shen et al. (2020) for a complete list of potential reactions
	Nanomaterial catalysts	2-3	Medium	
	Enhanced Geothermal System with CO_2[5]	4	Low	Injected pressurized (≈500 bars) CO_2
	Supercritical CO_2 power cycles	3	Medium	See Crespi et al. (2017) for a complete list of possibilities
	Polymer processing (polycarbonates)[6]	3-5	Medium	Propylene oxide + CO_2 -> polyethercarbonate polyol + cyclic propylene carbonate
	Polymer processing (polyurethanes)[7]	3-5	Medium	Polyol + isocyanate -> polyurethane
Biological conversion	Algae cultivation	3-5	Medium	$CO_2 + 2H_2O \rightarrow (CH_2O) + O_2 + H_2O$
	Helioculture	3	Medium	CO2 + light -> MO MO+ enzymes -> C2H5OH + 2CO2
CO_2 mineralization	Mineral carbonation	3-7	Medium	$MO + CO_2 \rightarrow MCO_3$ + heat
	Sodium bicarbonate[8]	6	Medium	$CO_2 + 2\,NaOH \rightarrow Na_2CO_3 + H_2O$ $Na_2CO_3 + CO_2 + H_2O = 2\,NaHCO_3$
	CO_2 concrete curing[9]	5	Medium	$CO_2 + H_2O = H_2CO_3$ $H_2CO_3 = HCO_3 + H+$ $HCO_3^- = CO_3 + H+$ $Ca + CO_3 \rightarrow CaCO_3$
	Bauxite residue carbonation[10]	8	Medium	$2OH^-(aq) + CO_2(aq) = CO_3^{2-}(aq) + H_2O$ $Ca_3Al_2(SiO_4)(OH)_8 + 12H^+ = 3Ca^{2+} + 2Al^{3+} + H_4SiO_4 + 8H_2O$ $Ca^{2+} + CO_{2(aq)} + 2OH^-(aq) = CaCO_{3(s)} + H_2O$

[3] European Commission (2020)
[4] Miller et al. 2010
[5] Pruess, 2006
[6] Von der Assen et al., 2014
[7] Orgiles-Calpena et al., 2016
[8] Bonaventura et al.
[9] https://pubs.acs.org/doi/10.1021/ef7003943

[10] Bauxite residue neutralization with simultaneous mineral carbonation using atmospheric CO2 - ScienceDirect

2.6 The CCS or CCU pathway?

Selection of one pathway over the other is left to the discretion of the industry but will typically be selected for economic purposes: capture CO2 with CCS costs 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 for the capture costs.

For captured CO2 to become economical over its counterpart (which doesn't capture CO2 and is the cheapest option between the two) then one need to attribute to the emitted CO2 according to the following equation:

$$CO_2\ Breakeven\ price$$
$$= Cost\ of\ plant\ with\ CC + cost\ of\ CO2\ transport + cost\ of\ CO2\ storage - cost\ of\ sold\ CO2$$
$$- \ Cost\ of\ power\ plant\ without\ CC$$

In a CCS scenario, the cost of sold CO2 is equal to zero and in a CCU scenario, the cost of CO2 storage is nearing zero (temporary storage cost is lower than long term storage).

Bains et al. (2017) provide an estimation of the carbon capture cost according to the input CO2 content (see Figure 2-10).

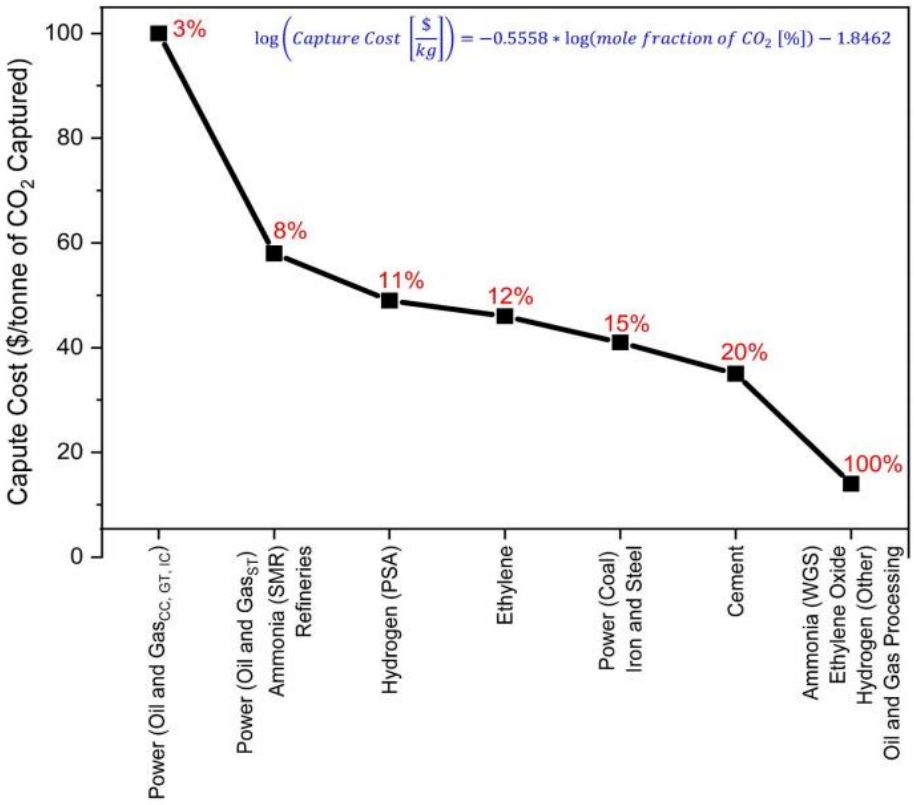

Figure 2-10: Carbon capture cost (y-axis) according to flue gas CO2 content (numbers in red) (Bains et al., 2017)

The EPA estimates pipeline transport and long-term storage at around 15$/ton CO2.

However, depending on the overall costs, the breakeven CO_2 prices could not be achieved before 2030 (and most likely before 2040 for power generation following a high CO_2 price trajectory) depending on the CO_2 price trajectory.

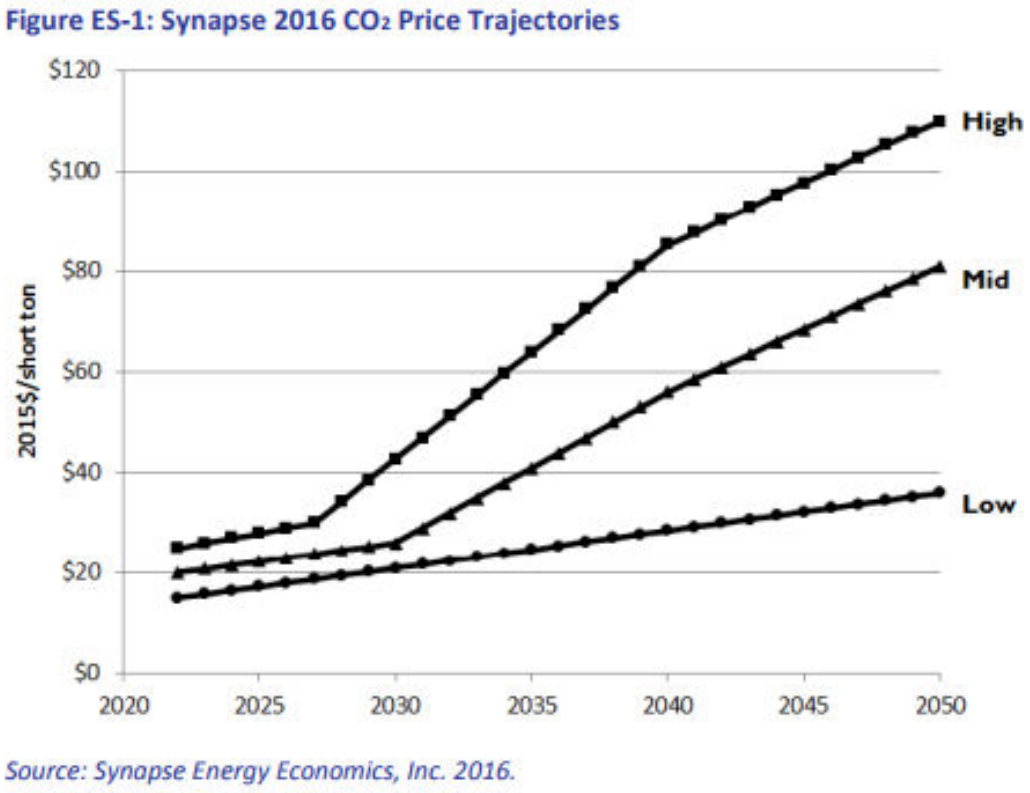

Figure 2-11: IEA's CO2 price trajectories[11]

[11] http://www.ieaghg.org/docs/General_Docs/Summer_School_2016/Presentations%20for%20web/07_Versteeg_Costs.pdf

3 Literature review: industrial CO_2 capture sources

This section aims to detail the industrial systems implementing CCS and CCU and identify CCS and CCU potential to reduce GHGs, by 2050, to contribute to France's carbon neutrality commitments (i.e. project's objectives 1b and 1d).

3.1 Current and future carbon capture projects

According to the Global CCS Institute, in 2019, 51 large-scale CCS facilities were recorded. Of these:

- 19 are in operation;
- 4 are under construction;
- 10 are in advanced development using a dedicated front-end engineering design (FEED) approach;
- 18 are in early development.

Right now, **those in operation and construction can capture and permanently store around 40 million tonnes of CO_2 every year**. This is expected to increase by about one million tonnes in the next 12-18 months. Also, there are 39 pilot and demonstration-scale CCS facilities (operating or about to be commissioned) and 9 CCS technology test centers.

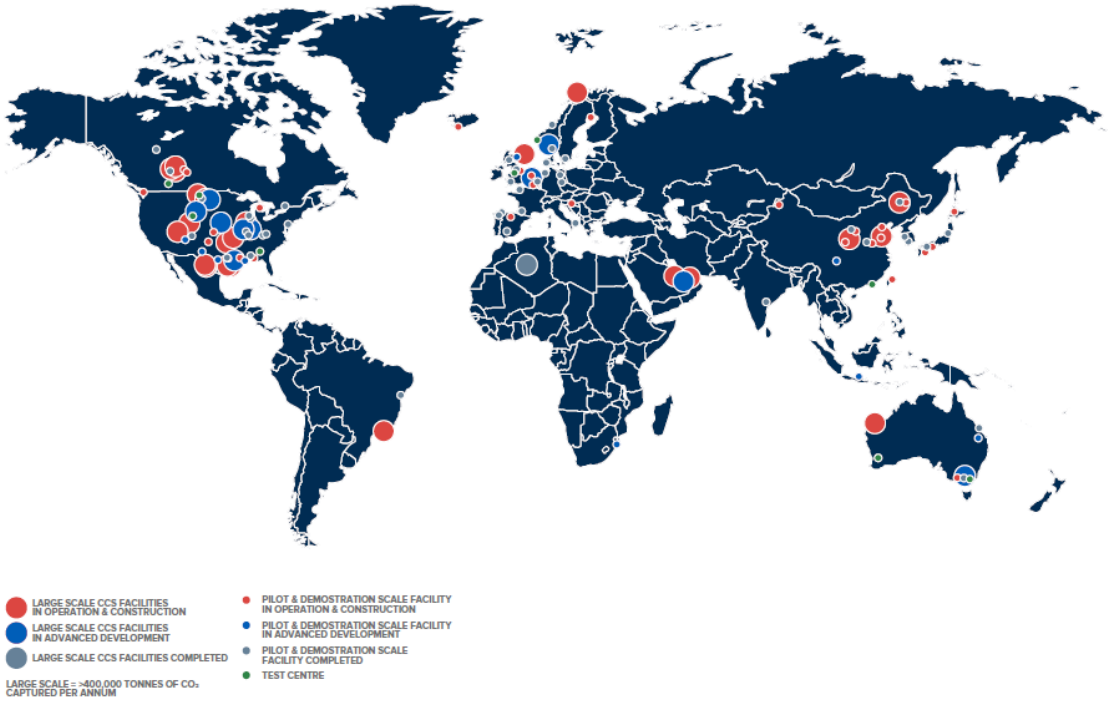

Figure 3-1: Location of current and future large-scale CCS facilities (Global CCS Institute, 2019)

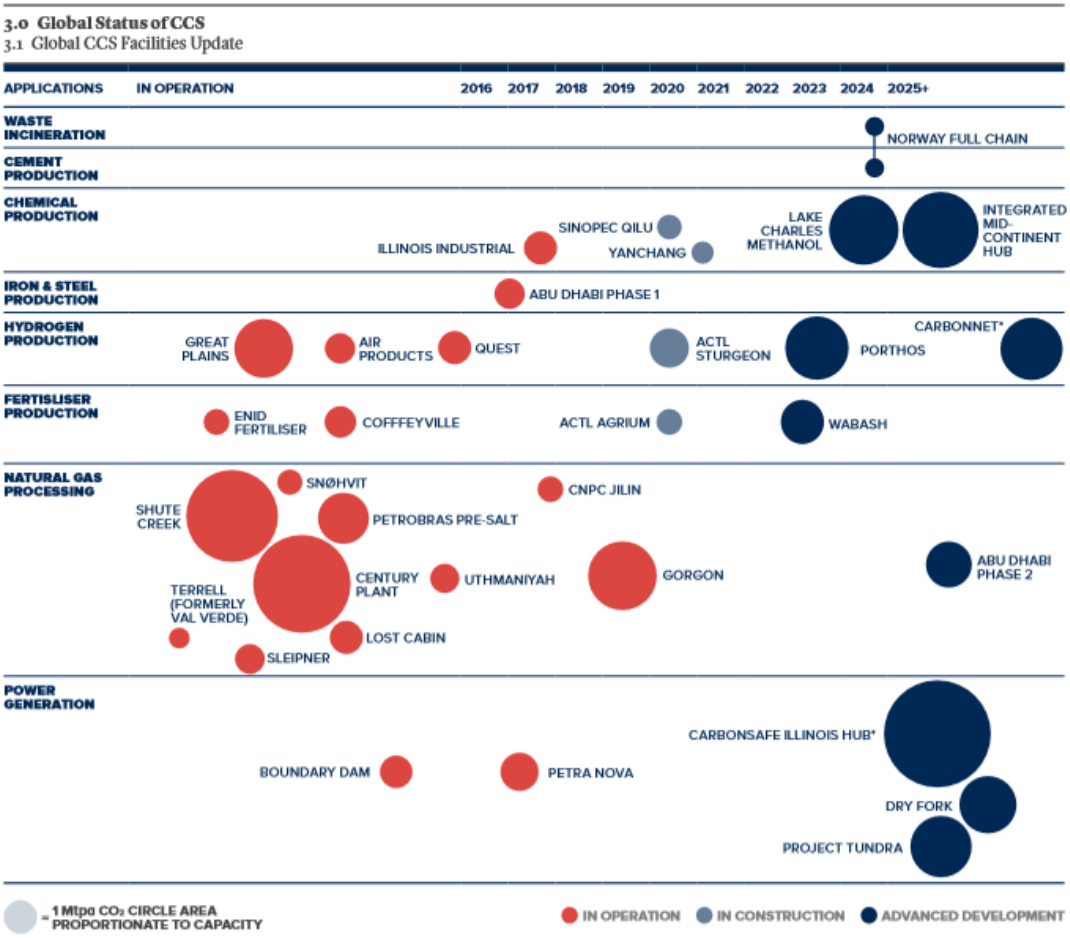

Figure 3-2: Details of current and future large-scale CCS facilities (Global CCS Institute, 2019)

However, considering current and proposed large-scale CCS facilities, climate change mitigation objectives will not be reached.

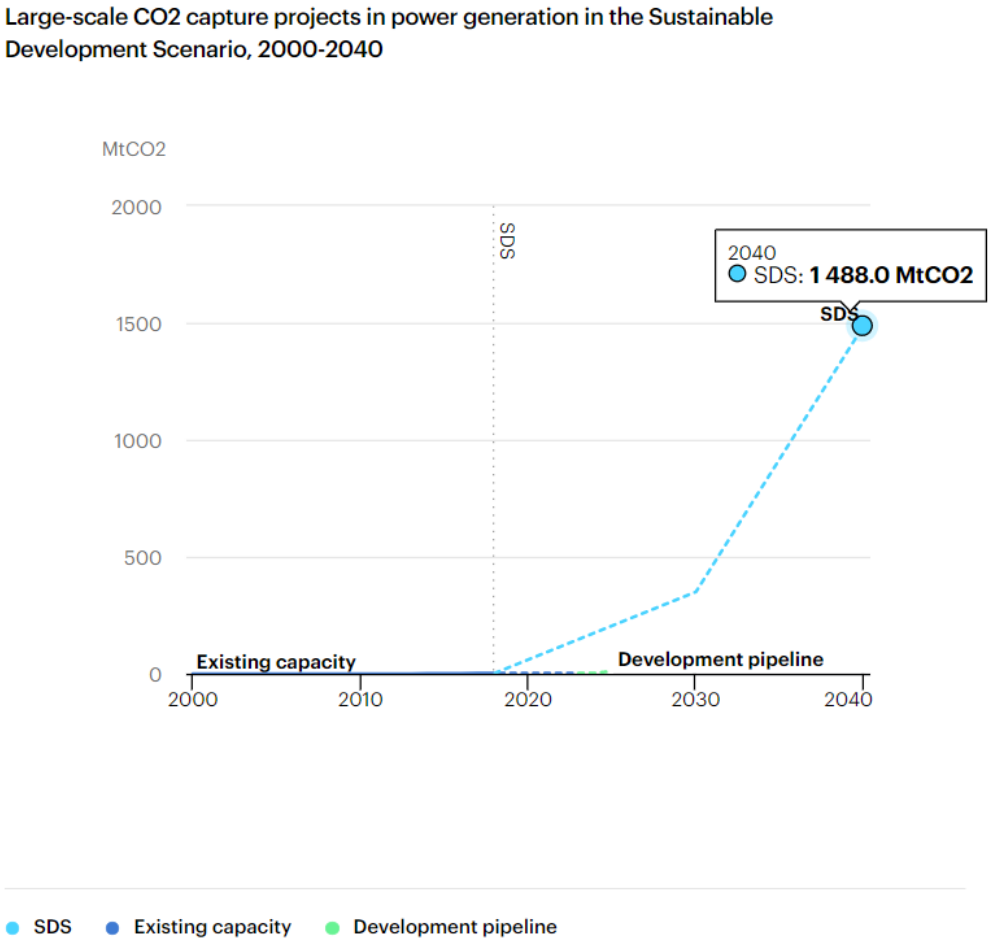

Figure 3-3: Large scale CO_2 projects objectives in the electrical power generation sector and the trend development pipeline must take to reach the climate change mitigation goals (IEA, 2020)

The following tables summarize the characteristics of 51 current (19) and upcoming (32) carbon capture projects around the world.

Table 3-1 : Characteristics of current carbon capture projects (Global CCS Institute, 2019)

	Name	Location	Year	Industry	Capture type	Capture capacity (Mtpa)	Storage
1	Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)	The United States	1972	Natural Gas Processing	Industrial Separation	0.4 - 0.5	Enhanced oil recovery
2	Enid Fertilizer	The United States	1982	Fertilizer Production	Industrial Separation	0.7	Enhanced oil recovery
3	Shute Creek Gas Processing Plant	The United States	1986	Natural Gas Processing	Industrial Separation	7	Enhanced oil recovery
4	Sleipner CO2 Storage	Norway	1996	Natural Gas Processing	Industrial Separation	1	Dedicated Geological Storage
5	Great Plains Synfuels Plant and Weyburn-Midale	Canada	2000	Synthetic Natural Gas	Industrial Separation	3	Enhanced oil recovery
6	Snøhvit CO2 Storage	Norway	2008	Natural Gas Processing	Industrial Separation	0.7	Dedicated Geological Storage
7	Century Plant	The United States	2010	Natural Gas Processing	Industrial Separation	8.4	Enhanced oil recovery
8	Air Products Steam Methane Reformer	The United States	2013	Hydrogen Production	Industrial Separation	1	Enhanced oil recovery
9	Coffeyville Gasification Plant	The United States	2013	Fertilizer Production	Industrial Separation	1	Enhanced oil recovery
10	Lost Cabin Gas Plant	The United States	2013	Natural Gas Processing	Industrial Separation	0.9	Enhanced oil recovery
11	Petrobras Santos Basin Pre-Salt Oil Field CCS	Brazil	2013	Natural Gas Processing	Industrial Separation	1	Enhanced oil recovery
12	Boundary Dam Carbon Capture and Storage	Canada	2014	Power Generation	Post-combustion capture	1	Enhanced oil recovery
13	Quest	Canada	2015	Hydrogen Production	Industrial Separation	1	Dedicated Geological Storage
14	Uthmaniyah CO2-EOR Demonstration	Saudi Arabia	2015	Natural Gas Processing	Industrial Separation	0.8	Enhanced oil recovery
15	Abu Dhabi CCS (Phase 1 being Emirates Steel Industries)	The United Arab Emirates	2016	Iron and Steel Production	Industrial Separation	0.8	Enhanced oil recovery
16	Petra Nova Carbon Capture	The United States	2017	Power Generation	Post-combustion capture	1.4	Enhanced oil recovery
17	Illinois Industrial Carbon Capture and Storage	The United States	2017	Chemical Production	Industrial Separation	1	Dedicated Geological Storage
18	Jilin oil field CO2-EOR	China	2018	Natural gas processing	Industrial Separation	0.6	Enhanced oil recovery
19	Gorgon Carbon Dioxide Injection	Australia	2019	Natural Gas Processing	Industrial Separation	3.4 - 4.0	Dedicated Geological Storage

Table 3-2 : Characteristics of upcoming carbon capture projects (Global CCS Institute, 2019)

	Name	Location	Year	Industry	Capture type	Capture capacity (Mtpa)	Storage
1	Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery CO2 Stream	Canada	2020	Hydrogen production for oil refining	Industrial Separation	1.2-1.4	Enhanced oil recovery
2	Alberta Carbon Trunk Line ("ACTL") with Agrium CO2 Stream	Canada	2020	Oil Refining	Industrial Separation	0.3 - 0.6	Enhanced oil recovery
3	Sinopec Qilu Petrochemical CCS	China	2020	Chemical Production	Industrial Separation	0.4	Enhanced oil recovery
4	Yanchang Integrated Carbon Capture and Storage Demonstration	China	2020-21	Chemical Production	Industrial Separation	0.41	Enhanced oil recovery
5	Wabash CO2 sequestration	USA	2022	Fertilizer production	Industrial Separation	1.5-1.75	Dedicated Geological Storage
6	Port of Rotterdam CCUS backbone initiative (Porthos)	The Netherlands	2023	Various	Various	2.0-5.0	Dedicated Geological Storage
7	Norway Full Chain CCS	Norway	2023-2024	Cement production and waste-to-energy	Various	0.8	Dedicated Geological Storage
8	Lake Charles Methanol	The United States	2024	Chemical Production	Industrial Separation	4.2	Enhanced oil recovery
9	Abu Dhabi CCS phase 2 – natural gas processing plant	United Arab emirates	2025	Natural gas processing	Industrial Separation	1.9-2.5	Enhanced oil recovery
10	Dry fork integrated commercial CCS	USA	2025	Power Generation	Post-combustion capture	3	Enhanced oil recovery or Dedicated Geological Storage
11	Carbonsafe Illinois – Macon county	USA	2025	Power generation and ethanol production	Post-combustion and industrial separation	2.0-5.0	Enhanced oil recovery and Dedicated Geological Storage
12	Project Tundra	USA	2025-26	Power generation	Post-combustion	3.1-3.6	Enhanced oil recovery or Dedicated Geological Storage
13	The integrated mid-continent stacked carbon storage hub	USA	2025-35	Ethanol production, power generation, and/or refinery	Various	1.9	Enhanced oil recovery or Dedicated Geological Storage
14	CarbonNet	Australia	2020's	Under evaluation	Under evaluation	3.0	Dedicated Geological Storage
15	Oxy and white energy ethanol EOR facility	USA	2021	Ethanol production	Industrial separation	0.6-0.7	Enhanced oil recovery
16	Sinopec Eastern China CCS	China	2021	Fertilizer Production	Industrial Separation	0.5	Enhanced oil recovery
17	Hydrogen 2 magnum (H2M)	Netherlands	2024	Power generation	Under evaluation	2.0	Dedicated Geological Storage
18	Clean gas project	UK	2024-2025	Power generation	Post-combustion capture	1.7-2.0	Dedicated Geological Storage
19	Caledonia Clean Energy	UK	2025	Power Generation	Post-combustion capture	3.0	Dedicated Geological Storage
20	Oxy and carbon engineering direct air capture and EOR facility	USA	2025	N/A	Direct air capture	1.0	Enhanced oil recovery
21	South West Hub	Australia	2025	Fertilizer Production and Power Generation	Industrial Separation	2.5	Dedicated Geological Storage
22	Hynet northwest	UK	Mid 2020's	Hydrogen production	Industrial separation	2.0	Dedicated Geological Storage
23	Project ECO2S : early CO2 storage complex in Kemper county	USA	2026	In evaluation	In evaluation	3	Dedicated Geological Storage

24	Northern gas network H21 North of England	UK	2026-2028	Hydrogen production	Industrial separation	1.5-20	Dedicated Geological Storage
25	Ervia cork CCS	Ireland	2028	Power generation and hydrogen production	Under evaluation	2.5	Dedicated Geological Storage
26	China Resources Power (Haifeng) – Demonstration	China	2020's	Power Generation	Post-combustion capture	1	Dedicated Geological Storage
27	Huaneng GreenGen IGCC Large-scale System (Phase 3)	China	2020's	Power Generation	Pre-combustion capture (gasification)	2	Enhanced oil recovery
28	Korea-CCS 1	South Korea	2020's	Power Generation	Post-combustion capture	1	Dedicated Geological Storage
	Korea-CCS 2	South Korea	2020's	Power Generation	Under evaluation	1	Dedicated Geological Storage
29	Shenhua Ningxia CTL	China	2020's	Coal-to-liquids (CTL)	Industrial Separation	2	Not specified
30	Sinopec Shengli Power Plant CCS	China	2020's	Power Generation	Post-combustion capture	1	Enhanced oil recovery
31	Net zero Teesside	UK	2020's	Various	Various	0.8-10	Dedicated Geological Storage
32	Acorn scalable CCS development	UK	End 2020's	Various	Under evaluation	3.0-4.0	Dedicated Geological Storage

The previous tables were updated from a literature review made at the end of 2017. Three main observations were made during that updating process:

- Most of the carbon capture projects which were projected for 2017-2018 were all pushed back to 2020.
- Three projects listed as upcoming in 2017 are now "abandoned" – including the only announced large scale oxy-fuel project

Table 3-3 : Characteristics of "abandoned" carbon capture projects (Global CCS Institute, 2019; Roy et al. 2018)

	Texas Clean Energy Project	The United States	2021 (Institute estimate)	Chemical Production	Industrial Separation	1.5 - 2.0	Enhanced oil recovery
	Riley Ridge Gas Plant	The United States	2020	Natural Gas Processing	Industrial Separation	2.5	Enhanced oil recovery
	Shanxi International Energy Group CCUS	China	2020's	Power Generation	Oxy-fuel combustion capture	2	Not specified

- Carbon capture, however, for hydrogen production has appeared – especially in the United Kingdom/Ireland.

In summary, the following industrial sectors have a concrete example of integrating carbon capture:

- Power generation
- Natural gas processing
- Fertilizer production
- Iron and steel production
- Chemical production
- Hydrogen production
- Oil refining
- Cement production

The following subsection will illustrate the opportunities in each of these sectors for carbon capture.

3.1.1 Carbon capture opportunities in the electrical power generation

Electrical power generation is one of the foremost examples of the use of carbon capture, especially for coal power plants. In those instances, post-combustion capture is currently the most popular option, even though pre-combustion and oxy-fuel combustion capture is possible. Figure 2-2 to Figure 2-4 illustrate power plant carbon capture examples.

3.1.2 Carbon capture opportunities for natural gas processing

When extracted, natural gas has a variable composition of methane, ethane, propane, butane, pentane, carbon dioxide, nitrogen, water, and hydrogen sulfur. The natural gas is then treated to remove the excess of some of the unwanted substances to bring the extracted natural gas up to a standardized composition of transmitted/distributed natural gas. The process is illustrated below.

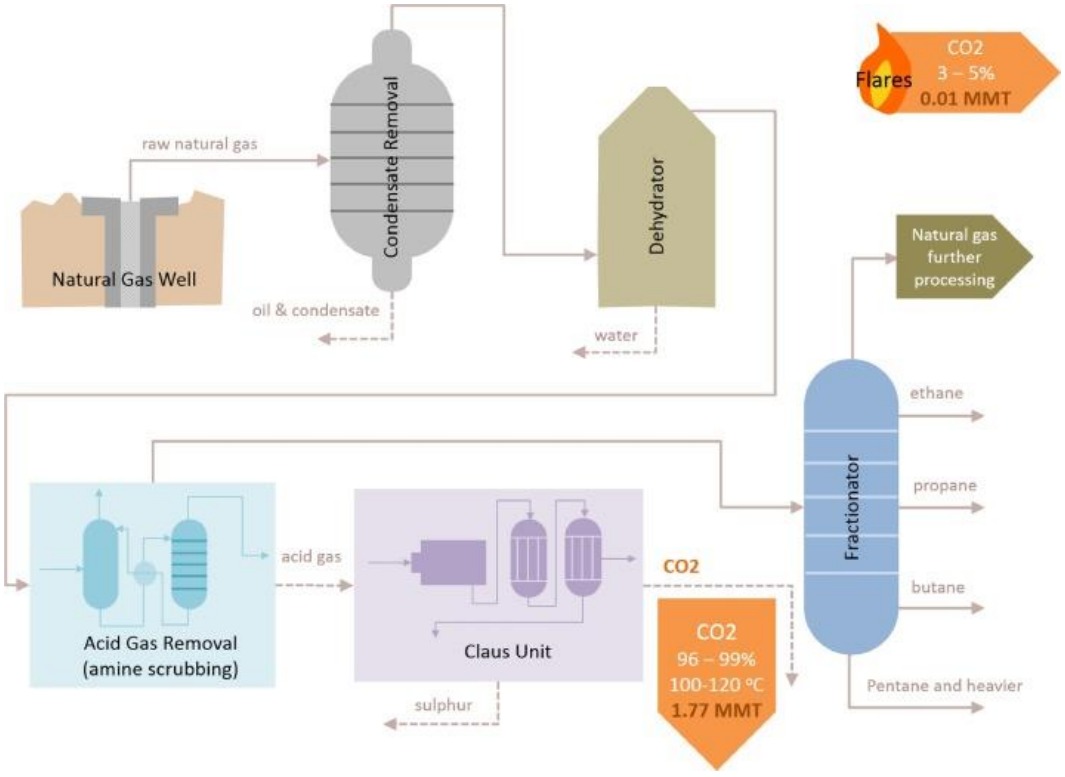

Figure 3-4: Natural gas treatment and CO_2 removal (Bains et al., 2017)

The removal of CO_2 from the extracted natural gas has been done by the gas industry for decades.

3.1.3 Carbon capture opportunities for fertilizer production

The fertilizer industry mentions the capture of CO_2 at the ammonia plant to then is used at the fertilizer plant instead of mined limestone.

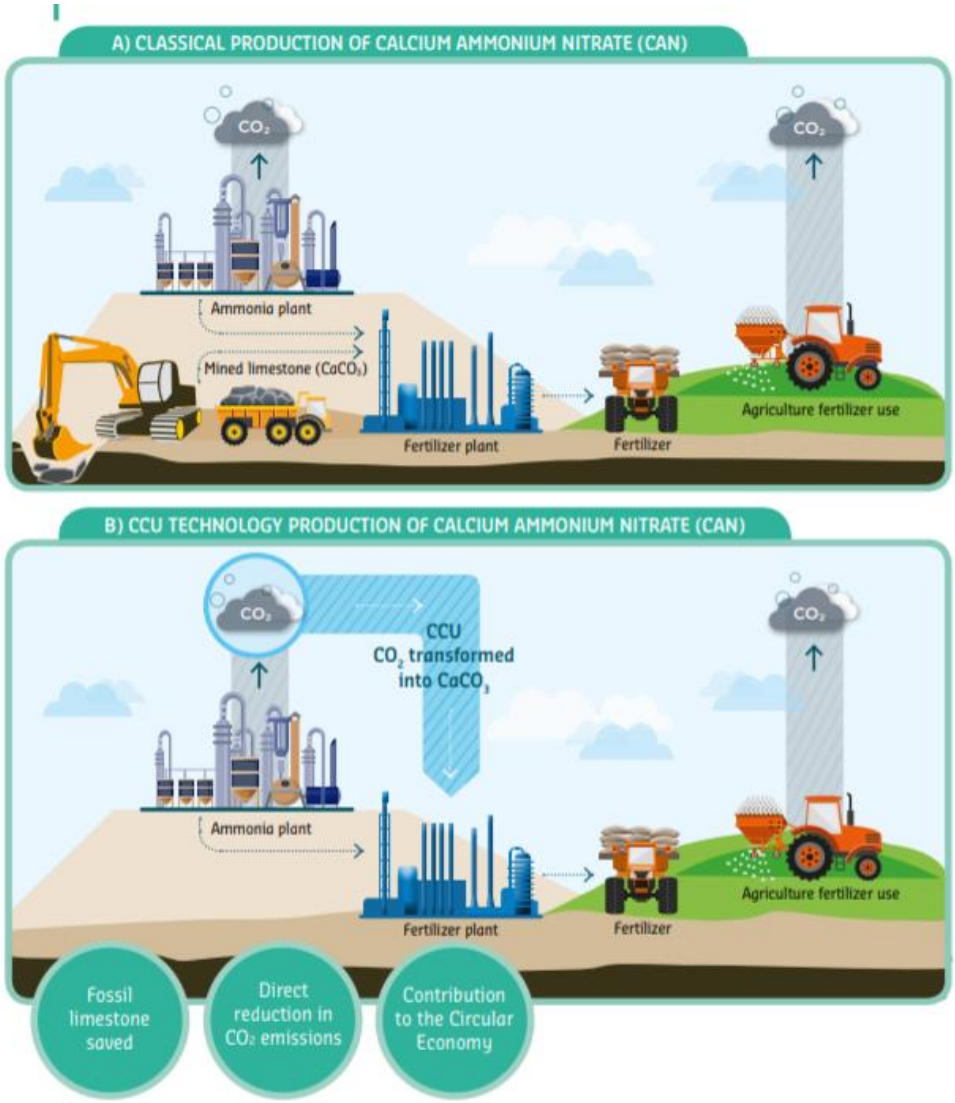

Figure 3-5: Illustration of the potential CO_2 capture and use associated with the fertilizer industry (Fertilizer Europe, 2019)

The ammonia process CO2 sources are illustrated in the following figure.

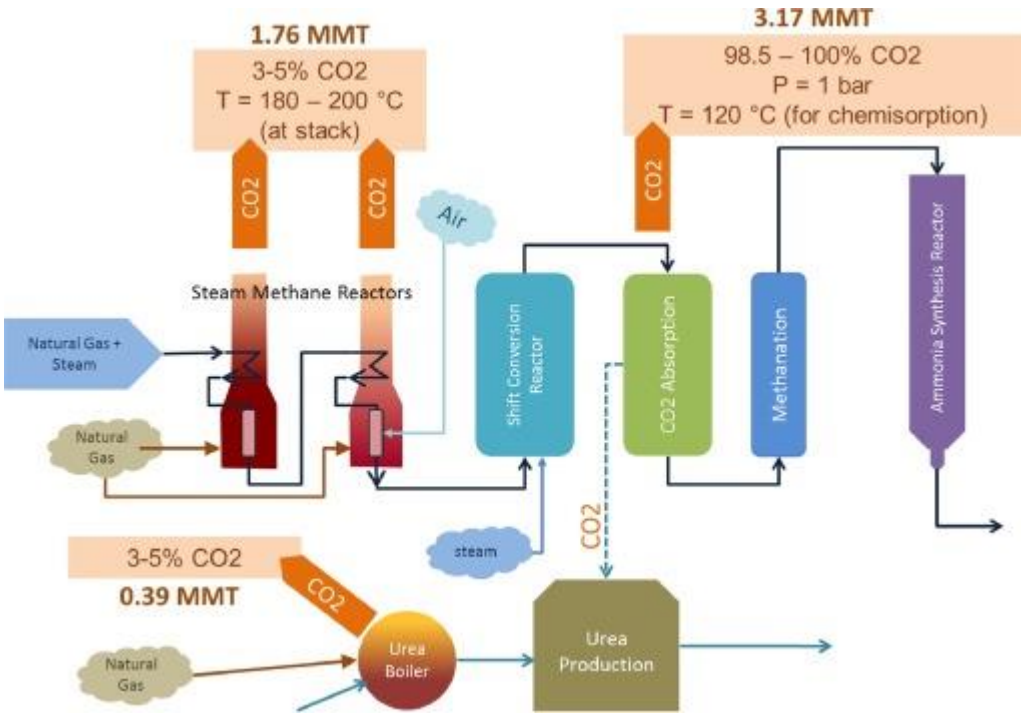

Figure 3-6: CO2 emissions from the ammonia production process (Bains et al., 2017)

3.1.4 Carbon capture opportunities in the steel industry

The following figure illustrates the operation of an integrated steel mill and the potential direct CO_2 emission point sources (illustrated by a red arrow) where carbon capture would be possible.

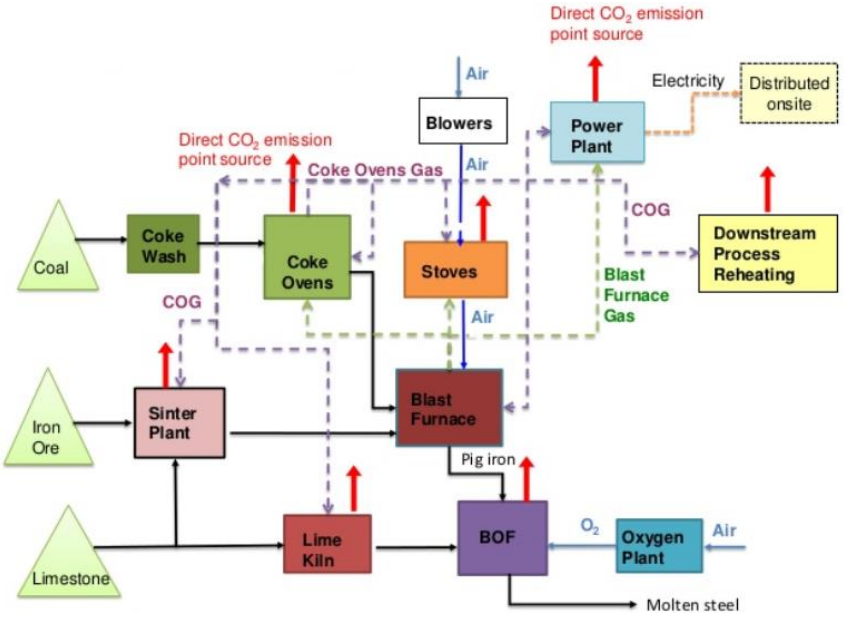

Figure 3-7: Illustration of the potential direct CO_2 emission point sources (red arrows from different processes) associated with a generic integrated steel plant (Wiley and Ho, 2014)

Wiley and Ho (2014) assessed for which process within this integrated steel plant would carbon capture be optimal (to decrease CO_2 emissions). As seen in the figure below, efforts should focus on the power

plant, stoves, coke ovens, and sinter plant, which account for nearly 95% of the overall direct CO_2 emissions.

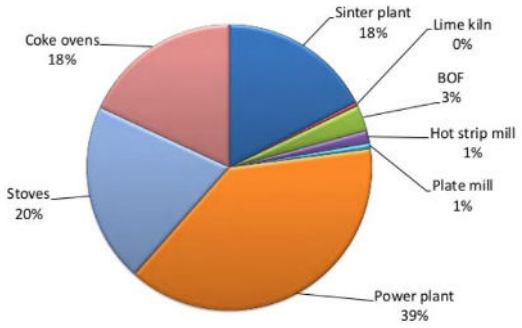

Figure 3-8: Direct CO_2 emissions associated with a generic integrated steel plant (Wiley and Ho, 2014)

3.1.5 Carbon capture opportunities for chemical production

The following figures illustrate the direct CO_2 emission point sources associated with ethylene and ethylene oxide production. Several other chemicals could also be considered.

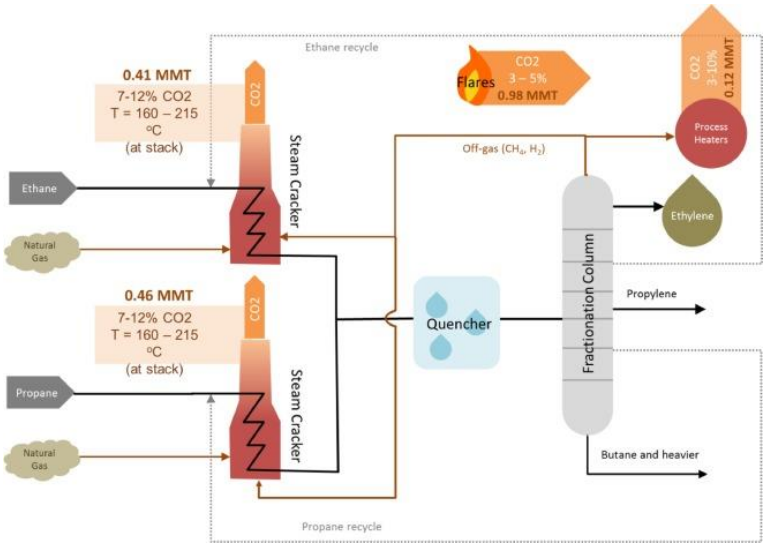

Figure 3-9: Identification of potential direct CO_2 emission point sources associated with ethylene production (Bains et al., 2017)

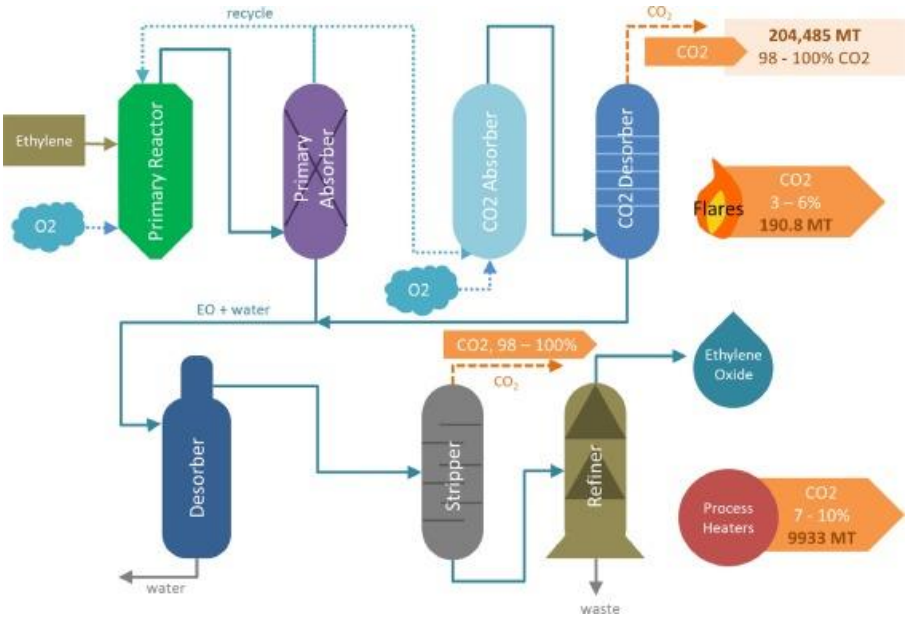

Figure 3-10: Identification of potential direct CO_2 emission point sources associated with ethylene oxide production (Bains et al., 2017)

3.1.6 Carbon capture opportunities for hydrogen production

There are many pathways to produce hydrogen; not all of which generate CO_2. Indeed, water electrolysis processes do not generate (at least directly) CO_2 emissions. However, the current most economic process to produce hydrogen is steam reforming of natural gas, which does generate CO_2 following the water shift gas reaction. CO_2 could therefore be captured after that reaction as illustrated in the figure below.

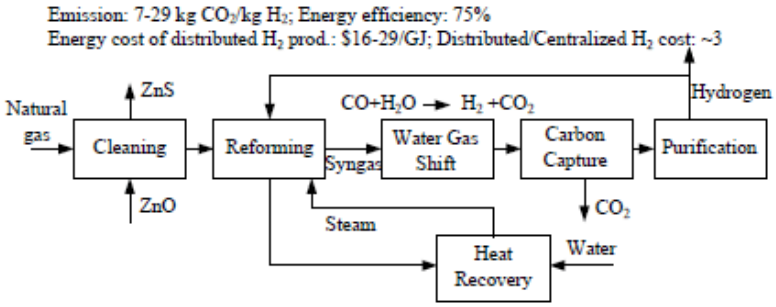

Figure 3-11: Identification of potential direct CO_2 emission point source s associated with the production of hydrogen from natural gas reforming (Matzen et al., 2015)

Other CO2 emissions occur in the steam reforming process as illustrated in Figure 3-12 and Figure 3-13.

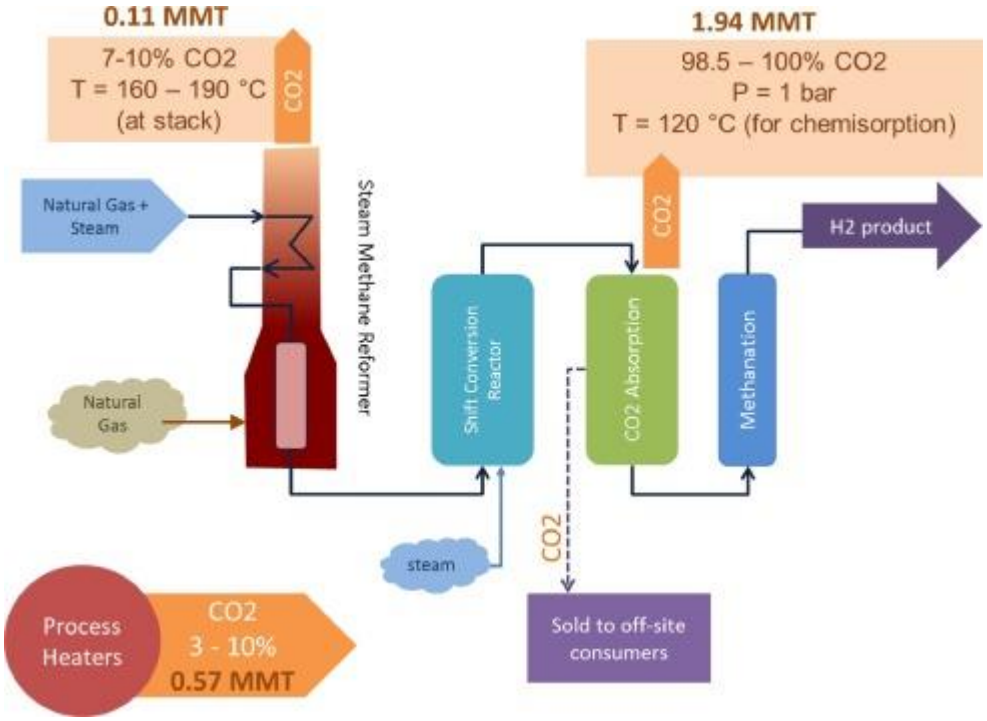

Figure 3-12: Identification of potential direct CO_2 emission point sources associated with hydrogen production with scrubbing technology (Bains et al., 2017)

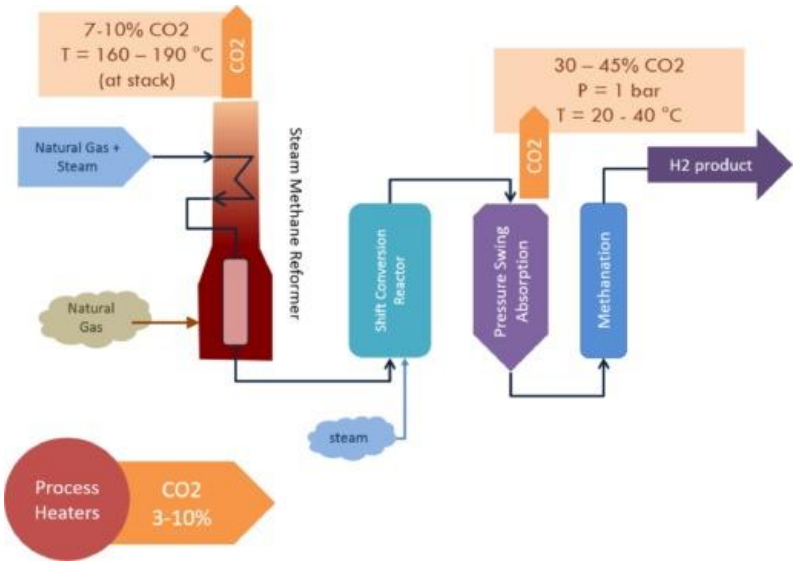

Figure 3-13: Identification of potential direct CO_2 emission point sources associated with hydrogen production with pressure swing absorption (Bains et al., 2017)

3.1.7 Carbon capture opportunities in oil refining (and plastic production)

The following figure presents direct CO_2 emissions related to oil refining which will produce naphtha (one of the petroleum products); a precursor to several polymers including polyethylene, polypropylene, and polystyrene.

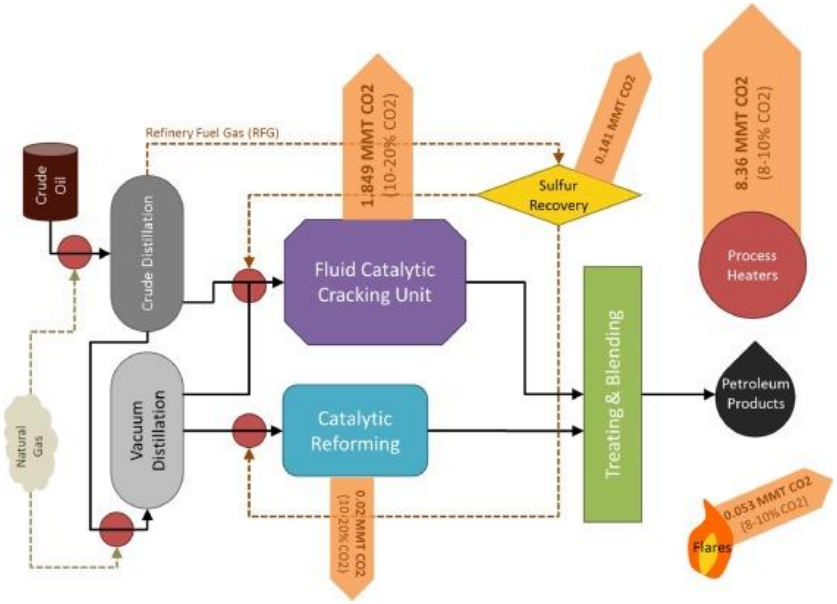

Figure 3-14: Identification of potential direct CO_2 emission point sources associated with oil refining (Bains et al., 2017)

3.1.8 Carbon capture opportunities for cement production

Cement is produced from calcium carbonate ($CaCO_3$). Raw materials such as limestone and the oxides of aluminum, silicon, and iron are first ground and then travel to the preheater and the precalciner, where it is preheated using flue gas from the rotary kiln. The limestone undergoes its initial calcination, or reduction, in the precalciner, where additional heat is provided via fuel combustion. After these preliminary processes, the limestone and other components enter the rotary kiln to undergo further reduction into lime (CaO). Pulverized coal or another fuel is blown into the kiln and combusted, providing the heat required for the reactions.

The major emitter of CO_2 in cement production is the rotary kiln. In the kiln, CO_2 is emitted from both fuel combustion (usually coal) and limestone calcination.

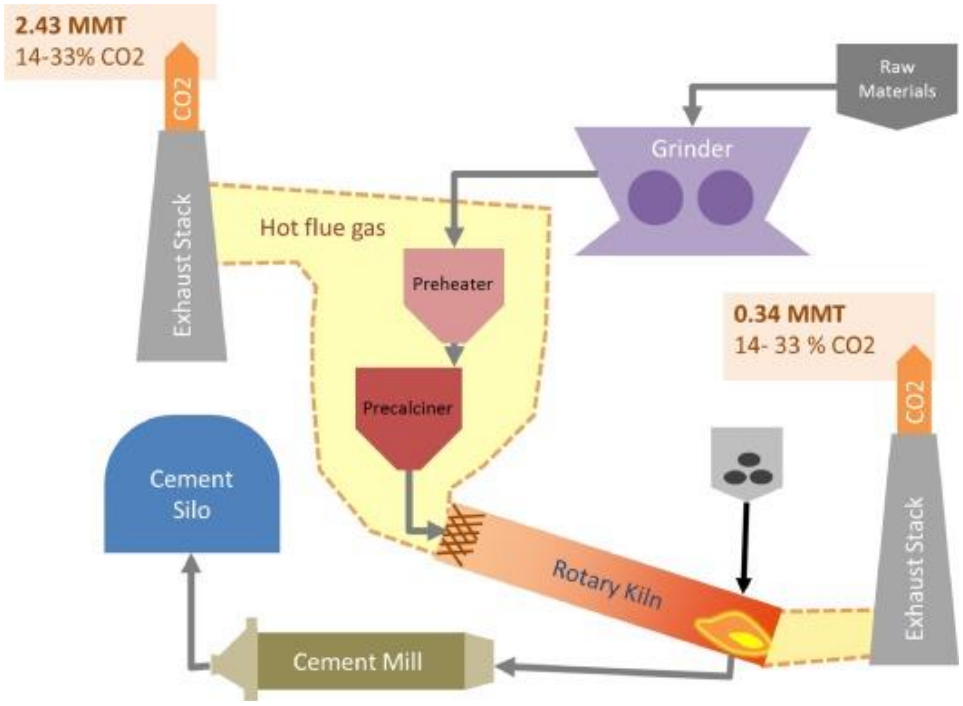

Figure 3-15: Identification of potential direct CO_2 emission point sources associated with cement production (Bains et al., 2017)

3.2 Summary of CO2 industrial process conditions

Table 3-4 presents a summary of CO2 from industrial process conditions and perhaps, more importantly, the CO2 flow content from these processes.

Table 3-4 : Summary of CO2 process conditions (Bains et al, 2017)

CO2 source	CO2 process unit	Flue gas component	CO2 content
Coal power plant	Steam boiler furnace	CO_2, NOx, SOx, CO, O_2, N_2, Hg, As, Se	10-15%
Natural gas power plant	Gas turbine	CO_2, NOx, SOx, CO, O_2, N_2, Hg, As, Se	3-5%
Petroleum power plant	Furnace	CO_2, NOx, SOx, O_2, N_2	3-8%
Cement production	Precalciner	CO_2, H_2O, N_2, hydrocarbons, volatiles (K_2O, Na_2O, S, Cl)	30%
	High T kiln		14-33%
Petroleum refineries	Process heaters	Depends on the fuel used	8-10%
	Utilities (steam, electricity)	Depends on the fuel used	3-5%
	Fluid catalytic cracker	O_2, CO_2, H_2O, N_2, Ar, CO, NOx, SOx	10-20%
	H2 purification - PSA	CO_2, H_2, CO, CH_4	30-45%
	H2 purification - chemisorption		98-100%
Iron/steel	Blast furnace	H_2, N_2, CO, CO_2, H_2S	20-27%
	Basic oxygen furnace	H_2, N_2, CO, CO_2, H_2S	16-42%
Ethylene	Steam cracking	H_2O, CO, NOx, SOx, O_2, N_2, CO_2	7-12%
Ethylene oxide	Water adsorption	Mainly CO_2, H_2O, N_2, (air oxidation) some CH_4, ethylene, EO	30%
	Chemisorption		98-100%
Ammonia	H2 purification	CO_2, H_2, O_2, CH_4	98-100%
Natural gas processing	Acid gas removal	96 - 99% CO_2, 1-4% CHx (mainly methane, trace amounts ethane, propane, butane), H_2O, N_2	96-99%
Hydrogen production	PSA	CO_2, H_2, CO, CH_4,	30-45%
	Chemisorption	~100% CO_2 (after)	98-100%
Ethanol	Fermentation	CO_2, ethanol, methanol, H_2S, dimethyl sulphide, acetaldehyde, ethyl acetate	98-99%

3.3 CO_2 capture opportunities in France

France's recent carbon neutrality target has pointed to CCS – as it was not part of the previous portfolio of technologies identified for reducing CO_2 emissions - to help achieve a balance between France's emissions and carbon sinks.

The stated target of reducing CO_2 emissions using CCS is 15 Mt CO_2/year, 5 Mt CO_2/year in the industrial sector starting in 2030 (ADEME, 2020). CCS is currently seen as a secondary solution, as emissions will first be reduced by other means such as less emitting technologies, development of renewable energies, electrification of transports and other industrial sectors, etc.

The ADEME (2020) estimates the potential for capture and storage at 24 Mt CO_2/year considering the development of CO_2 transport infrastructure, the establishment of geological CO_2 storage, and the low societal opposition. This potential has been estimated based on the technical and economic characteristics of emitting sites and CCS technologies.

This would allow France to meet its carbon capture objectives, which are still well below the capture potential of the industrial sector (see the following table).

Table 3-5 : CO2 emissions capture potential in the industrial sector (thus excluding the power generation) in France

Sectors	Number of sites	CO2 emission in 2017 [Mt CO_2]	"Capturable" CO2emissions [Mt CO_2]
Steel	11	23	17
Chemistry (without ammonia)	27	10.7	5.8
Ammoniac	4	1.9	1.9
Cement and other non-metallic	33	11	11.8
Refineries	9	10.3	5.6
Other	12	2.4	2.6
Food industry	14	2.5	2.6
Aluminium	4	1.2	0.9
Heat generation (industrial)	10	2.2	2.3
Total	120	≈65	≈51

Note: The table reflects the information found in ADEME (2020) table 3. As such, we didn't modify the capturable CO2 emission for the cement and other non-metallic which amounts to more CO2 emissions than what was emitted. This is most likely an error from the source material. In the source material's Table 2, the % of captured CO2 for the sector is equal to 90%. If we apply 90% to the CO2 emission in 2017, we obtain 9.9 Mt CO2 rather than 11.8.

4 CCS/CCU past LCA studies

This section conducts a critical assessment of CCS and CCU LCA studies (Objective 1e) and identifies the CCS and CCU environmental assessments (Objective 1c).

4.1 Carbon capture and storage

Table 4-1 provides a list of LCA studies related to carbon capture and storage. Table 4-2 details the studies compared systems, functional units, system boundaries, and intended locations. Table 4-3 presents the studies' data sources and used impact assessment method while Table 4-4 summarizes the investigated processes, the CO2 capture efficiency, and the energy requirements.

As seen:

- All CCS studies targeted the power generation sector and more specifically coal power plants. Some studies also considered natural gas power plants. Focus on coal can be explained by the belief that it has the worst carbon intensity of any fuel source, making carbon capture necessary for its continued use in a low-carbon economy (Gilbert, 2016).
- CCS studies generally targeted Europe and were published between 2006 and 2010. They mostly targeted the post-conversion carbon based on MEA which, according to Korre and co-authors, is convenient due to the low CO_2 partial pressure in the flue gas obtained in the coal-fired power plants (Korre et al., 2010). The amine technology suites well and is dedicated to the retrofitting of existing power plants. The major challenge, however, is minimizing the operating and investment costs (Pellegrini et al., 2010, Oyenekan and Rochelle, 2007).
- Data source between the different studies typically follows two trends:
    - All studies before Korre et al. (2010) are typically based on literature sources such as the IPCC report from 2005 and assumptions regarding the CO2 capture efficiency and the energy penalty used by different literature sources which can be traced back.
    - Starting from 2010, studies relied on process modeling (such as with the Aspen suite) or data from the plant which provides more robust or reliable data but at the expanse of transparency. For example, Korre et al. (2010) state that their process model can be used with 8 different solvents but only the results from MEA are presented.
- Regardless of the publication time, carbon capture is, for all investigated capture technology, between 85-95% with a reported energy penalty ranging between 5 and 14%.

It should be noted that the energy penalty is a function of many parameters including:

- the feed CO2 concentration,
- the feedstock type,
- the capture technology.

The following figure illustrates the energy penalty as a function of capture technology and feedstock type.

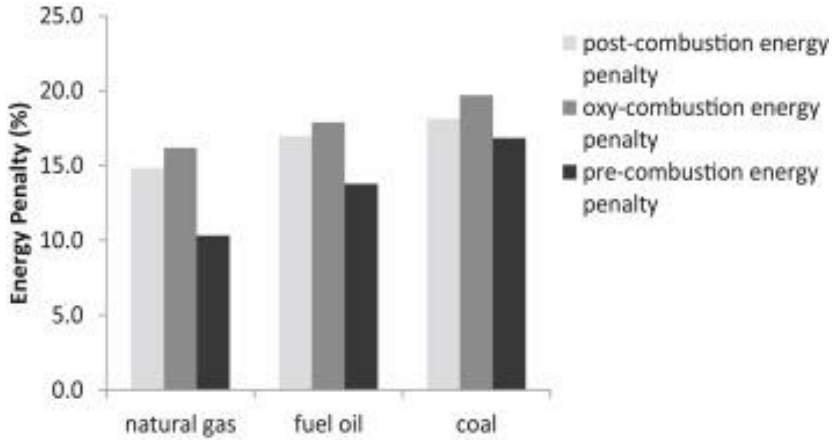

Figure 4-1: Energy penalty according to feed type and capture technology for power plant operations[12]

[12] https://www.sciencedirect.com/science/article/pii/S036054421630216X#tbl1

Table 4-1 : List of investigated CCS LCA studies

Study	Title
Khoo and Tan, 2006	Life Cycle Investigation of CO_2 Recovery and Sequestration[13]
Viebahn et al., 2007	Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany[14]
Koornneef et al., 2008	Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport, and storage of CO2[15]
Odeh and Cokerill, 2008	Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage[16]
Pehnt and Henkel, 2009	Life cycle assessment of carbon dioxide capture and storage from lignite power plants[17]
Korre et al., 2010	Life cycle modeling of fossil fuel power generation with post-combustion CO_2 capture[18]
Modahl et al., 2009	Only found as a work cited by Cuéllar et Azpagic (2015)
Schreiber et al., 2009	Environmental assessment of German electricity generation from coal-fired power plants with amine-based carbon capture[19]
Nie et al., 20011	Life cycle modeling and comparative assessment of the environmental impacts of oxy-fuel and post-combustion CO_2 capture, transport, and injection processes[20]
Singh et al., 2011	Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport, and storage[21]
Manuilova et al., 2014	Life Cycle Assessment of Post-Combustion CO2 Capture and CO2-Enhanced Oil Recovery based on the Boundary Dam Integrated Carbon Capture and Storage Demonstration Project in Saskatchewan[22]
Tang et al, 2014	Life cycle assessment of a pulverized coal-fired power plant with CCS technology in Japan[23]
Petrescu et al. 2017	Life Cycle Assessment for supercritical pulverized coal power plants with post-combustion carbon capture and storage[24]
Kim et al., 2019	Process-based life cycle CO_2 assessment of an ammonia-based carbon capture and storage system[25]

[13] https://pubs.acs.org/doi/10.1021/es051882a
[14] https://www.sciencedirect.com/sdfe/reader/pii/S1750583607000242/pdf
[15] https://reader.elsevier.com/reader/sd/pii/S1750583608000571?token=3D28E8CE599FCE65E385C13019CDF993298A4D40F18BF447E3758B72A81D8649BC932BFF672027ED24E83605ACA886AC
[16] https://www.sciencedirect.com/sdfe/reader/pii/S0301421507004120/pdf
[17] https://www.sciencedirect.com/sdfe/reader/pii/S1750583608000650/pdf
[18] https://www.sciencedirect.com/science/article/abs/pii/S1750583609000863
[19] https://link.springer.com/article/10.1007%2Fs11367-009-0102-8
[20] https://www.sciencedirect.com/science/article/abs/pii/S1876610211003444
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[22] https://reader.elsevier.com/reader/sd/pii/S1876610214025910?token=B90F7033B82FDD8B6C0D7E01B42D127ACE630323E577A1E4CD69086413506CAC5D25D76B65245CC28A1460DEDF0C2C08
[23] https://reader.elsevier.com/reader/sd/pii/S1876610214025958?token=BDF47965C5BB08D4565F95E92EEF60C70C23D89D04327A0A01BB05A38CDFCDB4994E7F0D31700C2B7049189C59834A82
[24] https://www.sciencedirect.com/science/article/pii/S0959652617307126
[25] https://www.sciencedirect.com/science/article/pii/S1226086X1930139X

Table 4-2 : Compared systems, functional units, system boundaries, and targeted location of different CCS LCA studies

Study	Compared systems	Reported functional unit	System boundaries	Location	Temporal representativity
Khoo and Tan, 2006	Coal power plant with/without CCS	1 MWh of electricity	Cradle-to-grave	Unspecified: U.S. power plants, storage in North Sea	Current
Viebahn et al., 2007	Coal and natural gas power plants with/without CCS	1 kWh of electricity	Cradle-to-grave	Germany	2020
Koornneef et al., 2008	Coal power plant with/without CCS	1 kWh of electricity	Cradle-to-grave	Netherlands	Near future
Odeh and Cokerill, 2008	Coal and natural gas power plants with/without CCS	1 kWh of electricity	Cradle-to-grave	United Kingdom	Current
Pehnt and Henkel, 2009	Coal power plants with/without CCS	1 kWh of electricity	Cradle-to-grave	Germany	2020
Korre et al., 2010	Coal power plants with/without CCS	1 MWh of electricity	Cradle-to-grave	Model	Current
Modahl et al., 2009	Natural gas power plants with/without CCS	1 TWh of electricity	Cradle-to-grave	?	Current
Schreiber et al., 2009	Coal power plants with/without CCS	1 kWh of electricity	Cradle-to-grave	Germany	2020
Nie et al., 20011	Coal power plants with/without CCS	1 MWh of electricity	Cradle-to-grave	Model	Current
Singh et al., 2011	Coal power plants with/without CCS	1 kWh of electricity	Cradle-to-grave	Norway	Current
Manuilova et al., 2014	Lignite power plants with/without CCS	1 GJ of electricity	Cradle-to-grave	Canada	Current
Tang et al, 2014	pulverized coal power plants with/without CCS	1 kWy of electricity	Cradle – to - grave	Japan	Current
Petrescu et al. 2017	Coal power plant with/without CCS	1 MWh of electricity	Cradle-to-grave	Model	Current
Kim et al., 2019	Coal power plant with/without CCS	CO_2 reduction from a coal-fired power plant generating 760 GW h per year and emitting 722,700 ton of CO_2 per year	Cradle-to-grave	South Korea *	Current

*the pilot project location was not specified in the paper. However, all authors' affiliations were from South Korean universities.

Table 4-3 : Capture process data sources and used impact assessment methods of different CCS LCA studies

Study	Cited data sources for the capture process	Used impact assessment method
Khoo and Tan, 2006	NETL for U.S. coal power plants; Different literature sources from the 1990's for capture efficiency and energy requirements; No efficiencies for other substances	EDIP 97
Viebahn et al., 2007	Capture process: Briem et al., 2004, IPCC, 2005, Göttlicher, 1999	UBA
Koornneef et al., 2008	Capture process: Abu-Zahra et al., 2007; Peeters et al., 2007; Rao and Rubin, 2002; Infrastructures: (Fluor Netherlands, 2007)	CML
Odeh and Cokerill, 2008	Calculations based on IOA (Proops et al, 1996) and process chain analysis (Dey and Lenzen, 2000)	N/A
Pehnt and Henkel, 2009	Idrissova, 2004, Feron et al., 2007	Mix of methods
Korre et al., 2010	Engineering models	CML
Modahl et al., 2009	Only found as a work cited by Cuéllar et Azpagic (2015) which did not provide this level of details	
Schreiber et al., 2009	Unspecified	CML
Nie et al., 20011	Korre et al, 2010 for post-conversion; engineering models for oxyfuel	CML
Singh et al., 2011	Process modeling data	ReCiPe
Manuilova et al., 2014	Data from the Boundary dam	TRACI
Tang et al, 2014	IPCC (2005) and Koornneff et al. (2008)	LIME
Petrescu et al. 2017	Process modeling and simulation	CML
Kim et al., 2019	pilot-scale ammonia-based CO_2 capture system	ReCiPe

Table 4-4 : Main parameter assumptions of different CCS LCA studies

Study	Capture Technology	CO2 removal efficiency	Energy requirement
Khoo and Tan, 2006	Chemical absorption	95-98%	330-340 kWh/ton CO2 recovered
	Membrane separation	82-88%	70-75 kWh/ton CO2 recovered
	Cryogenics	90-95%	600-660 kWh/ton CO2 recovered
	Pressure swing adsorption	85-90%	160-180 kWh/ton CO2 recovered
Viebahn et al., 2007	Post combustion (MEA)	88%	9-12% energy penalty
	Oxyfuel (only condensing)	99.5%	11% energy penalty
	Pre-combustion (Rectisol)	88%	8% energy penalty
Koornneef et al., 2008	Post-combustion (MEA)	90% [85-96%]	11% energy penalty
Odeh and Cokerill, 2008	Post-combustion (MEA)	90%	5-14% energy penalty
	Pre-conversion (Selexol)	90%	5-14% energy penalty
Pehnt and Henkel, 2009	Post-conversion (MEA)	90%	15-18% energy penalty
	Pre-conversion (selexol)	90%	10% energy penalty
	Oxyfuel	90-95%	4-10% energy penalty
Korre et al., 2010	MEA, Hindered amine (K/PZ), Promoted potassium carbonate (KS-1)	95%	14-25% energy penalty (14% was used)
Modahl et al., 2009	Only found as a work cited by Cuéllar et Azpagic (2015) which did not provide this level of details		
Schreiber et al., 2009	Post-conversion (MEA)	84-90%	14% energy penalty
Nie et al., 2011	Post-conversion (MEA)	95%	14-25% energy penalty (14% was used)
	Oxyfuel	95%	Unspecified
Singh et al., 2011	Post-conversion (MEA)	90%	8% energy penalty
Manuilova et al., 2014	Post-combustion (MEA)	90%	N/D
Tang et al, 2014	Post-combustion (MEA)	90%	8-12% energy penalty
Petrescu et al. 2017	MDEA	90.5%	9% energy penalty
	Aqueous NH3	85%	8.2% energy penalty
	Ca-based CL	92.66%	7.4% energy penalty
Kim et al., 2019	Ammonia	95%	Calculated (unspecified in the paper)

4.1.1 Impact assessment of coal-generated electricity with CCS

Figure 4-2 presents the GHG emissions reported by different LCA studies (with and without CCS) for coal power plants. As expected, CCS technologies decrease (by approximately 75 %) the life cycle GHG emissions of coal-generated electricity.

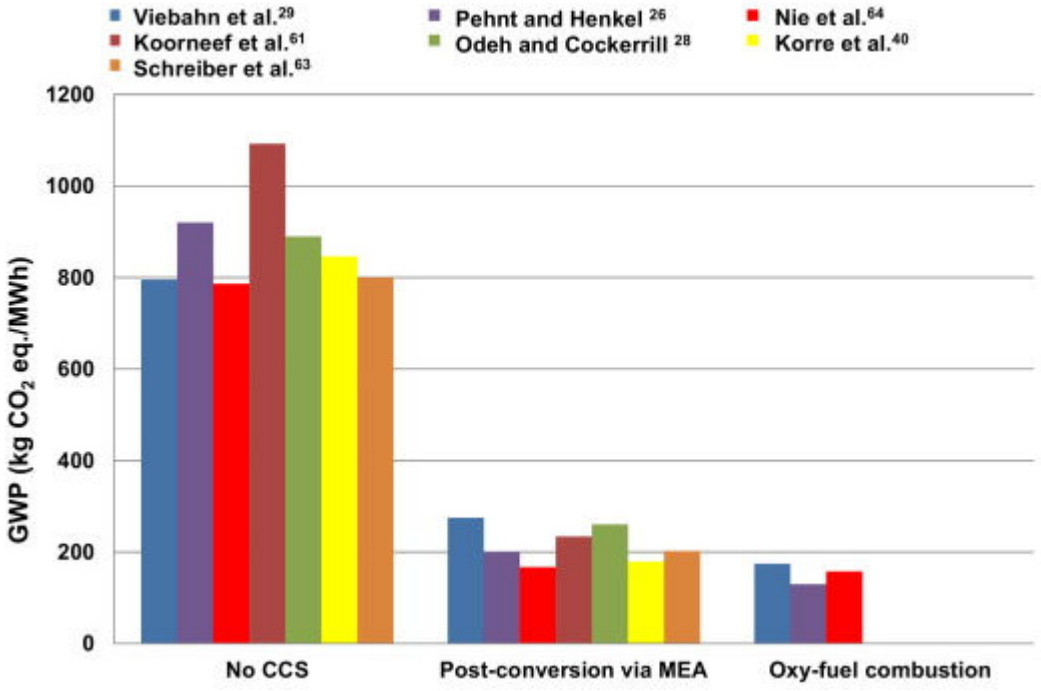


Figure 4-2: Reported life cycle GHG emissions for coal-generated electricity with no CCS, post-conversion and oxy-fuel combustion capture (Cuéllar-Franca, R.M., Azapagic, A., 2015)

Figure 4-3 presents coal-generated electricity, with and without CCS, life cycle environmental profile reported by different LCA studies for the following impact categories:

- AP, *Acidification* impact category;
- ADP, *Abiotic resources depletion* impact category;
- EP, *Eutrophication* impact category;
- ODP, *Ozone layer depletion* impact category;
- HTP, *Human toxicity* impact category;
- FAETP, *Freshwater aquatic ecotoxicity* impact category;
- MAETP, *Marine aquatic ecotoxicity* impact category;
- TETP, *Terrestrial ecotoxicity* impact category;
- POCP, *Photochemical ozone creation* impact category.

As can be seen, indicator results for coal CCS technologies were rarely reported, apart from the *Acidification* impact category.

Furthermore, for nearly all impact categories, studies have reported higher, lower, or nearly identical indicator results for systems with CCS compared to the reference system without CCS.

An overall conclusion on the environmental performance of CCS is thus impossible.

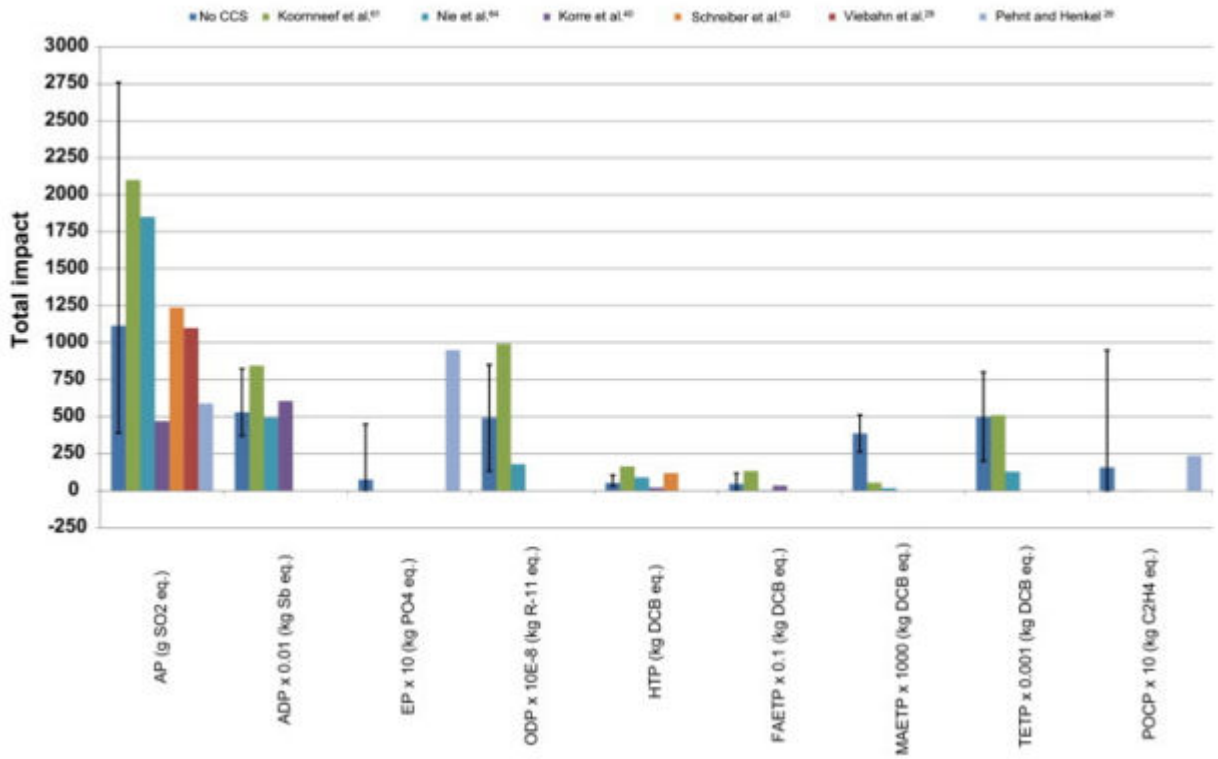


Figure 4-3: Environmental profile (other than *Climate change* impact categories) for coal-generated electricity with no CCS and different CCS technologies (Cuéllar-Franca, R.M., Azapagic, A., 2015)

4.1.2 Impact assessment of natural gas-generated electricity with CCS

Figure 4-4 presents the GHG emissions reported by different LCA studies (with and without CCS) for natural gas power plants. As expected, CCS technologies decrease (approximately 50 %) the life cycle GHG emissions of natural gas-generated electricity.

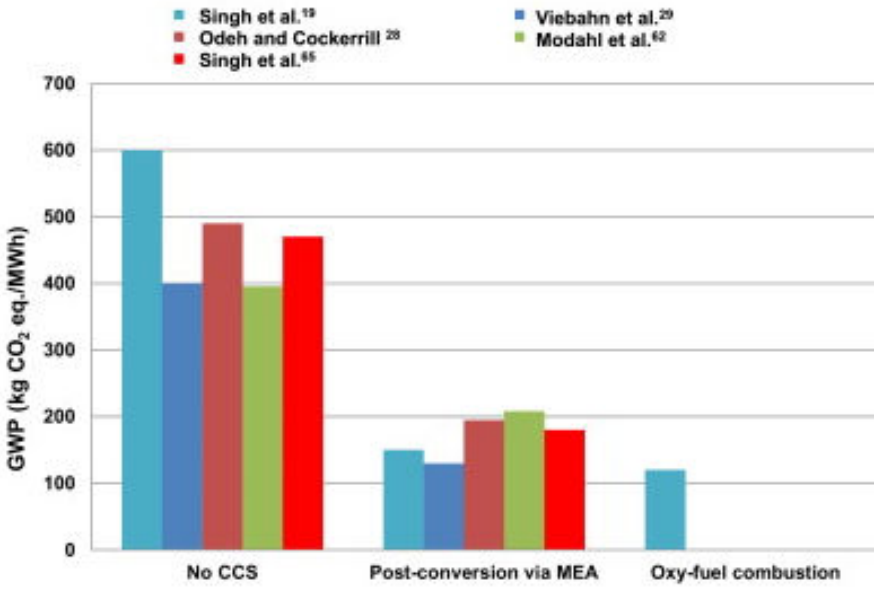


Figure 4-4: Reported life cycle GHG emissions for natural gas-generated electricity with no CCS, post-conversion and oxy-fuel combustion capture (Cuéllar-Franca, R.M., Azapagic, A., 2015)

Figure 4-5 presents natural gas-generated electricity, with and without CCS, life cycle environmental profile reported by different LCA studies for the following impact categories:

- AP, *Acidification* impact category;
- EP, *Eutrophication* impact category;
- HTP, H*uman toxicity* impact category;
- FAETP, *Freshwater aquatic ecotoxicity* impact category;
- MAETP, *Marine aquatic ecotoxicity* impact category;
- TETP, *Terrestrial ecotoxicity impact* category.

As can be seen, indicator results for natural gas CCS technologies were rarely reported, but when they were, they tend to be higher compared to the reference system without CCS

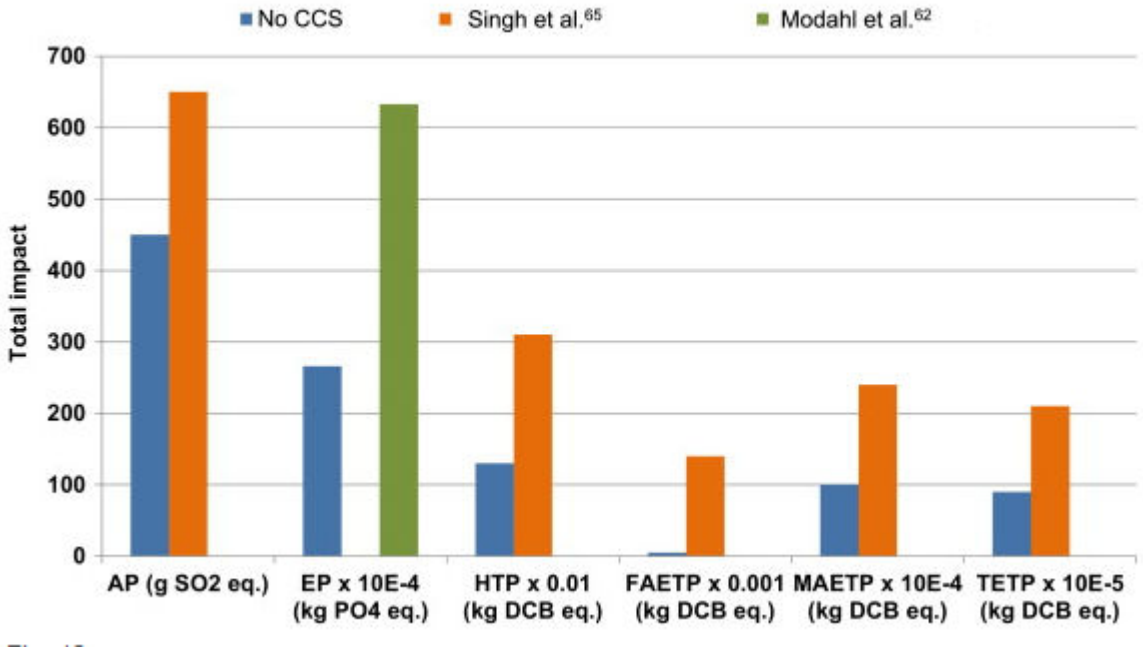


Figure 4-5: Environmental profile (other than *Climate change* impact categories) for natural gas-generated electricity with no CCS different CCS technologies (Cuéllar-Franca, R.M., Azapagic, A., 2015)

4.2 Carbon capture and use

Table 4-5 provides a list of LCA studies related to carbon capture and use. Table 4-6 details the studies compared systems, functional units, system boundaries, and intended locations. Table 4-7 presents the studies' data sources and used impact assessment method while Table 4-8 summarizes the investigated processes, the CO2 capture efficiency, and the energy requirements.

As seen:

- CCU studies targeted different uses.
- CCU studies generally targeted Europe or the United States of America (especially for the fuel-based use of CO2);
- System boundaries of CCU studies are typically cradle-to-grave;
- Data sources and assumptions regarding carbon capture are typically less transparent with CCU studies compared to CCS studies. For several studies, assumptions or technical data regarding carbon capture are not reported. The word "capture" is often not even mentioned, and the reader must understand that a capture process has occurred with such sentences as "*co-product utilization options include an adjacent coal-fired power system that co-fires biomass residues*". The focus of the studies is much more centered on the use of CO2 rather than the capture process.

Table 4-5 : List of investigated CCU LCA studies

Study	Use type	Title
Khoo et al, 2011	Mineral carbonation	Carbon capture and utilization: preliminary life cycle CO2, energy, and cost results of potential mineral carbonation[26]
Khoo et al, 2011b		Carbon Capture and Mineralization in Singapore: Preliminary Environmental Impacts and Costs via LCA[27]
Nduagu et al., 2012		Life cycle assessment of CO2sequestration in magnesium silicate rock – A comparative study[28]
Aresta and Galatola, 1999	Production of chemicals	Life cycle analysis applied to the assessment of the environmental impact of alternative synthetic processes. The dimethylcarbonate case: part 1[29]
Honda et al. 2014		Catalytic CO2 conversion to organic carbonates with alcohols in combination with dehydration system[30]
Hoppe et al, 2017		Life Cycle Assessment of Carbon Dioxide–Based Production of Methane and Methanol and Derived Polymers[31]
Elbashir et al. 2018		CO2 Utilization through Dry Reforming of Methane Process[32]
Aldaco et al., 2019		Bringing value to the chemical industry from capture, storage and use of CO_2: A dynamic LCA of formic acid production[33]
Thonemann et Pizzol, 2019		Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry[34]
Jaramillo et al., 2009	Enhanced oil recovery	Life Cycle Inventory of CO_2 in an Enhanced Oil Recovery System[35]
Herwich et al., 2008		Life-cycle Assessment of Carbon Dioxide Capture for Enhanced Oil Recovery[36]
Mora et al. 2016		Life cycle assessment of carbon capture and utilization from ammonia process in Mexico[37]
Lardon et al., 2009	Diesel production from microalgae	Life-Cycle Assessment of Biodiesel Production from Microalgae[38]
Brentner et al., 2011		Combinatorial life cycle assessment to inform process design of industrial production of algal biodiesel[39]
Campbell et al., 2011		Life cycle assessment of biodiesel production from microalgae in ponds[40]
Clrens et al., 2011		Environmental impacts of algae-derived biodiesel and bioelectricity for transportation[41]
Shirvani et al., 2011		Life cycle energy and greenhouse gas analysis for algae-derived biodiesel[42]
Borkowski et al., 2012		Only found as a work cited by Cuéllar et Azpagic (2015)
Passel et al., 2013		Algae biodiesel life cycle assessment using current commercial data[43]
Soratana et al, 2013		Re-envisioning the renewable fuel standard to minimize unintended consequences: A comparison of microalgal diesel with other biodiesels[44]
Zaimes and Khanna, 2013		Environmental sustainability of emerging algal biofuels: A comparative life cycle evaluation of algal biodiesel and renewable diesel[45]
Stephenson et al., 2010		Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors[46]

[26] https://reader.elsevier.com/reader/sd/pii/S1876610211003420?token=0E800E0EBF495BE44C524AF5765DDAC3AEBFD242091EB43F20B8F9D79B1A40CF2C1718669E89A814441A9A7C4ED126AE
[27] https://pubs.acs.org/doi/10.1021/ie200592h
[28] https://reader.elsevier.com/reader/sd/pii/S0196890411003074?token=3FC22D08FA05563F9120868F5CACAC1420A98161CCBAEAD2A956B722167ED7DAA53DAB8F816774EBAB0CC353FAFBA4B2
[29] https://reader.elsevier.com/reader/sd/pii/S0959652698000742?token=2E6BA50498FBC17D1BC0DF2F08631A6C5951324A3C270F3F62A38CB84932EBFA96BF8C793E473093E66FAD4159BE69D1
[30] https://pubs.rsc.org/en/content/articlelanding/2014/cy/c4cy00557k#!divAbstract
[31] https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12583
[32] https://www.qscience.com/content/papers/10.5339/qfarc.2018.EEPP1093
[33] https://www.sciencedirect.com/science/article/pii/S0048969719304437?via%3Dihub
[34] https://pubs.rsc.org/en/content/articlepdf/2019/ee/c9ee00914k
[35] https://pubs.acs.org/doi/10.1021/es902006h
[36] https://reader.elsevier.com/reader/sd/pii/S1004954108600853?token=BC8865E4DB5480C25619398285EA6B30007C7F6BE7A17FC1FCA8A05441A7973B19469099D64F92C3ED709F4058C502FE
[37] https://www.sciencedirect.com/science/article/pii/S0301479716307113
[38] https://pubs.acs.org/doi/abs/10.1021/es900705j
[39] https://pubs.acs.org/doi/10.1021/es2006995
[40] https://reader.elsevier.com/reader/sd/pii/S0960852410010291?token=CCD2388DA0BB2598B1E86D43F54B316AD57142973E9597232579BA24A550B0E5BC0952609FA6290DDCF202435B05BFED
[41] https://pubs.acs.org/doi/abs/10.1021/es200760n
[42] https://pubs.rsc.org/en/content/articlelanding/2011/ee/c1ee01791h#!divAbstract
[43] https://reader.elsevier.com/reader/sd/pii/S0301479713004647?token=92906A550434CB08E14679A2F79C2AD7B470CCA1FEB96CC2141FE39F4EA8091DC9A9D8D77C1C50F23D45563AD4B390DA
[44] https://reader.elsevier.com/reader/sd/pii/S0306261913005059?token=D066D672225554499B8F8B9C0862BE74EE5985BFF39C1C40196D21A851C773787FFD5F27AD62055E6008DA33A3106CC7C
[45] https://aiche.onlinelibrary.wiley.com/doi/full/10.1002/ep.11810
[46] https://pubs.acs.org/doi/pdf/10.1021/ef1003123

Table 4-6 : Compared systems, functional units, system boundaries, and targeted location of different CCU LCA studies

Study	Use type	System	Functional unit	System boundaries	Location
Khoo et al, 2011	Mineral carbonation	Natural gas power plant	Supply of 1 MWh of electricity from CCGT	Cradle-to-gate (cradle-to-grave but without including the carbonate application)	Singapore
Khoo et al, 2011b		Natural gas power plant	Supply of 1 MWh of electricity from CCGT		Singapore
Nduagu et al., 2012		Coal power plant	Sequestration of 1 tonne of CO_2 in a mineral silicate		Canada
Aresta and Galatola	Production of chemicals	Production of DMC	Production of 1 kg of DMC	Cradle-to-grave	Europe
Honda et al. 2014		Production of DMC	Production of 1 kg of DMC	Unspecified	Japan*
Hoppe et al, 2017		Production of methane, synthesis gas, methanol, POM, PE or PP	Production of 1 kg of methane, synthesis gas, methanol, POM, PE, or PP	Cradle-to-gate	Germany
Elbashir et al. 2018		CO_2 reforming of CH_4	Production of 1 kg of syngas	Unspecified	Qatar*
Aldaco et al., 2019		Production of formic acid and electricity generation	Production of 350 kt of formic acid at a commercial concentration of 85% wt associated with a 500 MW capacity coal plant (for the electricity supply and required CO_2)	Cradle-to-gate	Europe
Thonemann et Pizzol, 2019		Several products: CO, formic acid, MeOH, CH4, ethanol, DME, DMC, DMM, Fischer-Tropsch products, Polyols	Treatment of 1 kg of CO2	Unspecified but seems Cradle-to-grave	Germany
Jaramillo et al.	Enhanced oil recovery	Coal power plants	Total production of electricity over the projected lifetime	Cradle-to-grave	United States of America
Herwich et al.		Natural gas power plant	Production of 1 MWh of electricity and extraction of 1 m^3 of oil	Cradle-to-grave	Norway
Mora et al. 2016		Ammonia plant	Production and use of 1 bbl of crude oil	Cradle-to-grave but excludes the capture infrastructure	Mexico
Lardon et al.	Diesel production from microalgae	Biodiesel production	Production and use 1 MJ of fuel	Cradle-to-grave	Europe
Brentner et al.		Biodiesel production	Production of 10 GJ of fuel	Cradle-to-gate	United States of America
Campbell et al.		Biodiesel production	Provide 1 tkm of transport	Cradle-to-grave	Australia
Clarens et al.		Biodiesel production and electricity	Vehicle kilometer traveled	Cradle-to-grave	United States of America
Shirvani et al.		Biodiesel production	Production and use of 1 MJ of fuel	Cradle-to-grave	UK, France, Brazil, China, Nigeria and Saudi Arabia
Borkowski et al.		Biodiesel and renewable diesel production	Production of 1 MJ of fuel	Cradle-to-gate	N/D
Passel et al.		Biodiesel production	Production and use of 1 MJ of fuel	Cradle-to-grave	United States of America
Soratan et al		Biodiesel production	Production and use of 8,94 x 10^{10} MJ of diesel/year	Cradle-to-grave	United States of America
Zaimes et al.		Biodiesel production	1 MJ of final fuel	Cradle-to-grave	United States of America
Stephenson et al.		Biodiesel production	Production and use of 1 t of biodiesel	Cradle-to-grave	United Kingdom

* not mentioned in the paper but follows author university affiliation

Table 4-7 : Capture process data sources and used impact assessment methods of different CCU LCA studies

Study	Use type	Data sources for the capture	Impact assessment method
Khoo et al, 2011	Mineral carbonation	IPCC, 2005	No method used
Khoo et al, 2011b		IEA, 2002	EDIP 2003
Nduagu et al.		Mix of data from Korre et al. 2010, Khoo and Tan 2006 and Röder et al. 2004 (i.e. ecoinvent)	IPCC 2001
Aresta and Galatola	Production of chemicals	Mimura et al., 1997	CML
Honda et al. 2014		N/D	N/D
Hoppe et al, 2017		Rochelle et al. (2011), MT biomethan GmbH (2012), Wurzbacher (2014), Element Energy Ltd et al. (2014)	N/D
Elbashir et al. 2018		N/D	N/D
Aldaco et al., 2019		N/D	CML
Thonemann et Pizzol, 2019		N/D	International Life Cycle Data system
Jaramillo et al.	Enhanced oil recovery	Specific data from 5 different sites	N/D
Herwich et al.		Solli, 2003	N/D
Mora et al. 2016		Process simulation	IPCC 2007; ReCiPe
Lardon et al.	Diesel production from microalgae	N/D	CML
Brentner et al.		N/D	BEES and Cumulative demand in Energy
Campbell et al.		N/D	IPCC 2001
Clarens et al.		N/D	Mix of inventory results and unknown GWP from the IPCC
Shirvani et al.		N/D	Unknown GWP
Borkowski et al.		Only found as a work cited by Cuéllar et Azpagic (2015)	
Passel et al.		GREET	GREET
Soratan et al		ecoinvent	TRACI
Zaimes et al.		N/D	Unknown GWP
Stephenson et al.		N/D	EDIP 2003

Table 4-8 : Main parameter assumptions of different CCU LCA studies

Study	Use type	Capture technology	CO2 capture efficiency	Energy requirement	Substitution
Khoo et al, 2011	Mineral carbonation	amine scrubbing technology	90%	Energy penalty of 16%	No substitution; reference is a NGCC power plant without carbon capture
Khoo et al, 2011b		amine scrubbing technology	90%	Energy penalty of 16%	No substitution; reference is a NGCC power plant without carbon capture
Nduagu et al.		MEA	N/D	N/D	No substitution; test of two different MgCO3 process
Aresta and Galatola	Production of chemicals	MEA	N/D	900 kcal/kg-CO_2	Comparison of phosgene route vs urea with capture CO2.
Honda et al. 2014		N/D	N/D	N/D	N/D
Hoppe et al, 2017		Amine scrubbing	N/D	0.02-0.24 kWh_{elec}/kg CO2	Conventional production of methane, methanol, synthesis gas, polyethylene, polyoxymethylene, and polypropylene
Elbashir et al. 2018		N/D	N/D	N/D	N/D
Aldaco et al., 2019		MEA	89%	N/D	Conventional methyl formate to the formic acid pathway
Thonemann et Pizzol, 2019		N/D	N/D	N/D	Conventional methanol, methane, polyol, ethanol, DMC, CO, DME, formic acid, Fischer-Tropsch products, DMM
Jaramillo et al.	Enhanced oil recovery	Selexol	90%	14%	1 bbl of crude oil (average U.S.)
Herwich et al.		Amine based	90%	N/D	No substitution
Mora et al. 2016		MEA	95.7%	2.85 MJ/ton CO2	No substitution
Lardon et al.	Diesel production from microalgae	N/D	N/D	N/D	N/D
Brentner et al.		N/D	N/D	N/D	N/D
Campbell et al.		N/D	N/D	N/D	Substitution of fossil-based fuels
Clarens et al.		N/D	N/D	N/D	No substitution
Shirvani et al.		N/D	N/D	N/D	Substitution of fossil-based fuels; depletion of conventional oil and increased use of shale oil
Borkowski et al.		Only found as a work cited by Cuéllar et Azpagic (2015)			
Passel et al.		N/D	N/D	N/D	Comparison to biomass-based fuels
Soratan et al		N/D	N/D	N/D	Substitution of other biomass-based fuels
Zaimes et al.		MEA scrubbing	N/D	N/D	Comparison of different production pathways
Stephenson et al.		N/D	N/D	N/D	Compared with fossil-based diesel

Figure 4-6 presents the GHG emissions reported by different LCA studies for different CCU scenarios compared to CCS. As shown, CCS, on average, generates less GHGs emissions than most CCU scenarios.

It also shows the wider range of GHG emissions range which is mostly related to the assumptions of substitution associated with dealing with multi-functionality.

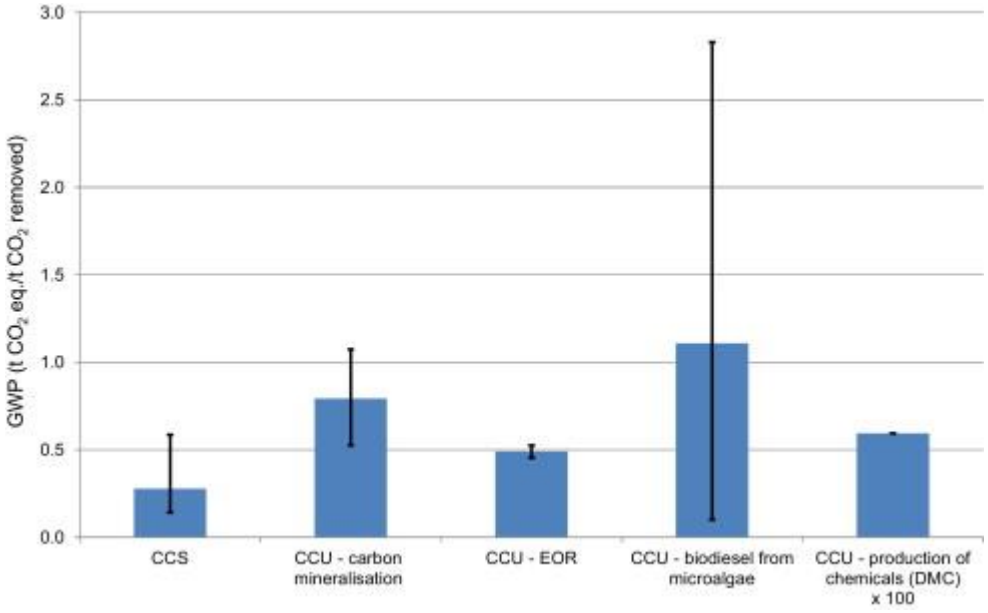


Figure 4-6: Reported life cycle GHG emissions for CCS and CCU scenarios (Cuéllar-Franca, R.M., Azapagic, A., 2015)

The following figure presents the reported life cycle GHG emissions for the CO_2-based production of basic chemicals and polymers, from different CO_2 sources, and for their conventional production method.

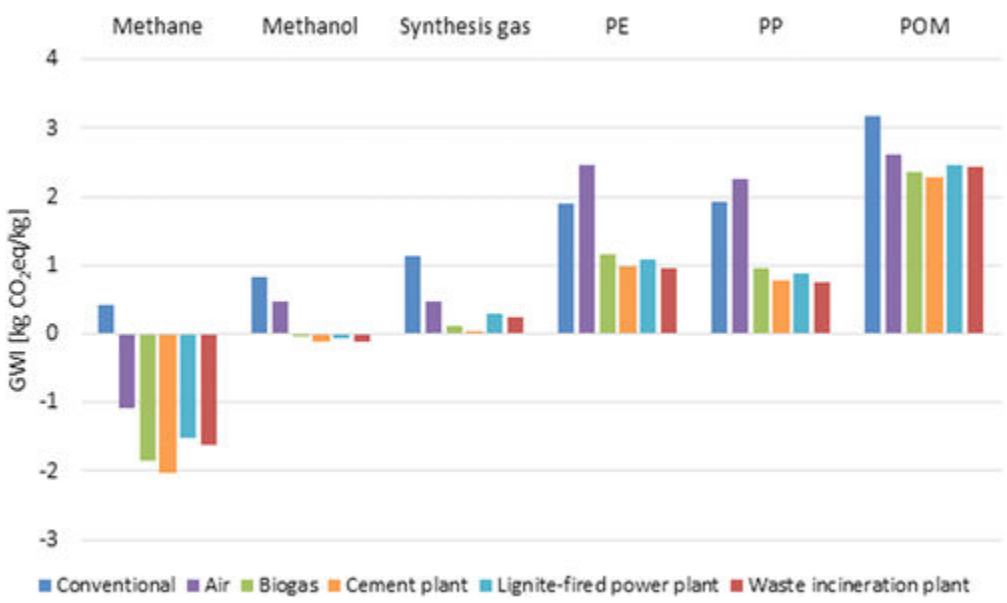


Figure 4-7: Reported life cycle GHG emissions for CO_2-based production of basic chemicals and polymers, from different CO_2 sources, and for their conventional production method. PE=polyethylene, POM = polyoxymethylene, and PP = polypropylene (Hoppe et al., 2017).

As seen, CO_2-based products typically showed lower GHG emissions than their conventional counterpart. Some of the alternatives even showed negative indicator results. The authors explain the negative values for the CO_2-based methane and methanol "*because of the input of CO_2, whereas 2.75 kg of CO_2 is used for the CO_2-based production of 1 kg of methane and 1.37 kg of CO_2 for the CO_2-based production of 1 kg of methanol*".

Note: Negative results in Figure 4-7 depends on the system expansion calculations which have been presented in a non-transparent way. System expansion calculation should be presented in a way that would be easy for the reader to understand.

Finally, Figure 4-8 shows the reported very limited life cycle environmental profile for some CCU applications in comparison with CCS. It typically shows that CCU obtains higher indicator results than CCS. These conclusions must be taken lightly as there are several methodological challenges when comparing CCS and CCU and it is unsure, at this point, if these challenges were met satisfactorily.

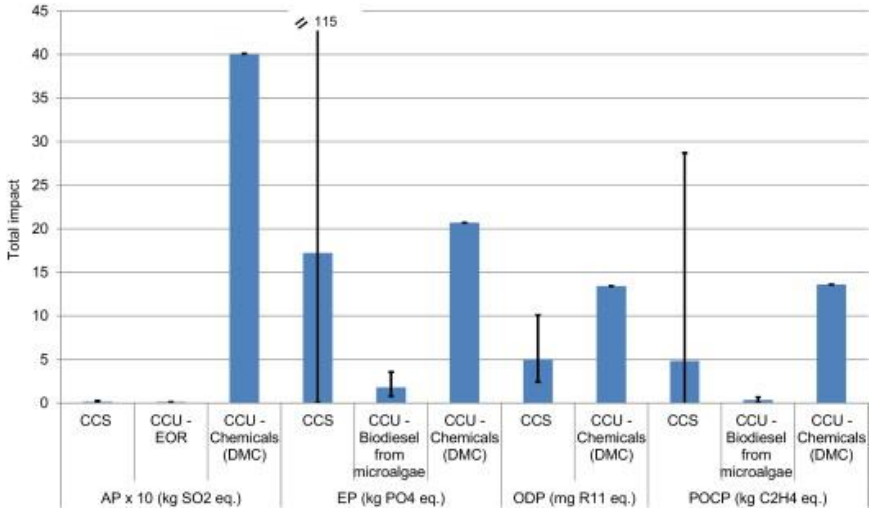


Figure 4-8: Environmental profile (other than Climate change impact categories) for CCS and CCU (Cuéllar-Franca, R.M., Azapagic, A., 2015)

5 Identifying and overcoming methodological challenges when applying LCA to CCS and CCU

When modeling of CCS and CCU systems in LCA studies, several challenges arise. Some of these challenges are faced by practically every LCA, but others are specific to CCS/CCU studies.

The following sub-section reviews each phase of an LCA and some of the generic and specific challenges when applying LCA to CCS/CCU.

5.1 Review of existing CCS and CCU guidelines

No specific guidelines were found for CCS. Two reviews of existing studies were found:

Table 5-1 : LCA critical reviews of CCS

Author	Title
Corsten et al. 2013	Environmental impact assessment of CCS chains – Lessons learned and limitations from LCA literature[47]
Cuéllar-Franca and R.M., Azapagic, A., (2015)	Carbon capture, storage, and utilization technologies: A critical analysis and comparison of their life cycle environmental impacts[48].

The reasons why there are no guidelines are simple: CCS typically doesn't provide any methodological challenges apart from data availability and the assumption accounting for the energy penalty in the event when a retrofitted power plant cannot provide the same energy output as before and requires additional energy production from the grid or marginal energy sources (see section 5.2.2).

The same cannot be said about CCU for which numerous guidelines have been published (see table below) in recent years (essentially the last two years). Most notably among them are the guidelines related to the *Global CO2 initiative*; a series of guidelines and applied examples that ultimately cumulated into the paper by Müller et al. (2020).

[47] https://reader.elsevier.com/reader/sd/pii/S1750583612003143?token=6C59F254DBDBB922F1D868BA0AB982E091FA826EB63B061B091B55A337A45A798789CCD14C3E20212EAA7D51BE410AB1

[48] https://www.sciencedirect.com/science/article/pii/S2212982014000626

Table 5-2 : List of CCU LCA guidelines

Author	Title
Von der Assen et al. 2014	Life cycle assessment of CO_2 capture and utilization: a tutorial review[49]
IEA, 2018	Greenhouse gas emissions accounting for CO2 capture and utilization (CCU) technologies[50]
NETL, 2019	Carbon dioxide utilization life cycle analysis guidance for the U.S. DOE office of fossil energy
LCA4CCU, 2020	Guidelines for Life Cycle Assessment of Carbon Capture and Utilisation [51]
Global CO2 initiative's LCA and TEA guidelines series	
Müller et al., 2020	A Guideline for Life Cycle Assessment of Carbon Capture and Utilization[52]
Zimmermann et al, 2018	Techno-economic assessment & life cycle assessment guidelines for CO2 utilization
Michailos et al., 2018	Methanol worked examples for the TEA and LCA guidelines for CO2 utilization
McCord et al., 2018	Mineralization worked examples for the TEA and LCA guidelines for CO2 utilization
Zimmermann et al, 2019	OME worked example for the TEA guidelines for CO2 utilization
Zaragoza et al, 2020	Building an LCA inventory: a worked example on a CO2 to fertilizer process
Zaragoza et al, 2020	Interpretation of LCA results: a worked example of a CO2 to fertilizer process
McCord et al., 2020	A worked example considering CO2 use in the Domestic heating sector

Note: Only the life cycle assessment part of the Global CO2 initiative's LCA and TEA guidelines series has been reviewed for this project; the Technico-Economic Assessment (TEA) being out of the scope of the study. Useful information regarding technical-economic assessment studies could be found in those references.

It should be noted that not all guidelines are of equal quality. While the Global CO2 initiative and LCA4CCU guidelines provide (generally) quality guidelines, others typically offer a flavor to what would otherwise be an introductory guide on how to conduct an attributional LCA. None of this seems truer than the guideline from von der Assen et al. 2014 as the discussion topics, while true, are not as relevant for the realization of an LCA on CCU as what is found in other guidelines.

The following sections provide the main findings from these guidelines and offer a step-by-step overview of the methodological challenges one could encounter when producing an LCA about CCS and/or CCU.

5.2 Goal and scope definition of CCS and CCU LCA studies

5.2.1 The purpose of the step in an LCA

In an LCA, this phase aims to define the methodological framework of the study, namely:

- define the goal of the study (and which type of LCA is best suited to answer the goal of the study);
- the functional unit (which ensures the comparability of products/processes/services);
- the system boundaries;
- define how to deal with multi-functionality (if applicable)
- the data sources and assumptions;
- the included and excludes processes (and the reason for their exclusion if applicable);
- the life cycle impact assessment method;
- the subsequent analysis to ensure the robustness of the obtained conclusions.

[49] https://pubs.rsc.org/en/content/articlepdf/2014/cs/c3cs60373c

[50] https://www.ieaghg.org/publications/technical-reports/reports-list/10-technical-reviews/929-2018-tr01c-ccu-technology-review-synthesis

[51] https://www.ifeu.de/wp-content/uploads/LCA4CCU-March-2020-Release-v1-0.pdf

[52] https://www.frontiersin.org/articles/10.3389/fenrg.2020.00015/full

In other words, this is where all the required information to carry out the LCA is listed.

5.2.2 Defining the goal of CCS/CCU LCA studies

Every LCA study starts with the goal definition by unambiguously stating "*the intended application of the study, the reasons for carrying out the study, the intended audience of the study and whether the results are to be used in comparative assertions disclosed to the public*" (European Committee for Standardisation, 2018). In other words, the central question of the study is defined.

From the identified CCS and CCU studies as well as the guidelines, the most common research questions for CCS LCA studies are:

a. How does CCS improve the life cycle environmental profile of a product or service based on fossil carbon sources?
b. What are the contributions to the life cycle environmental profile of a CCS process and where are hot spots to improve the environmental performance?
c. What are the environmental trade-offs of CCS implementation?

While the most common research questions for CCU LCA studies are:

a. 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?
b. 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?
c. Which CCU technology to use to make efficient use of renewable energy?
d. What are the environmental footprints of products or services used as a basis for consumer decisions (product declarations)?

Cuéllar-Franca and R.M., Azapagic, A., (2015) also noted an underlying question:

- Between CCS and CCU, which will decrease GHG emissions the most?

All of these research questions imply a comparison between alternatives (explicit or implicit) and thus, intends to support decision making, e.g., which process to use, how can technology be improved. All of which can be answered with an attributional (classic) LCA and therefore implies the use of the inherent LCA assumptions:

- They only look at the involved processes and not the potential alteration to the market resulting from these involved processes.
- All emissions, be they past, present, or future, necessary to fulfill the function occurs at the same time.
- The study is made in accordance with the defined period which is typically close to the time in which the study is being carried out

If one would want to answer those types of questions, then other types of LCA are required such as:

- Consequential LCA: *What are the environmental consequences that are expected to occur following a change in production, consumption, and/or disposal of a product?*
- Dynamic LCA: *What is better to limit climate change issues: long-term storage or reuse of CO_2?*
- Prospective LCA: *What are the environmental impacts of deploying carbon capture technology in the (long-term) future?*

5.2.3 Defining the functional unit of CCS in attributional LCA studies

LCA compares different alternatives based on the function of a product. For example, the function of a product could be generating electricity, producing steel, producing hydrogen, producing fertilizers, etc.

Note that in these examples, that we do not offer a basis of comparison or the processes that will be compared which will fulfill the different functions.

The quantification of the function is obtained through the so-called functional unit. The functional unit is a quantified description of the performance requirements that the product system fulfills with the product's function(s). A good functional unit should cover three important aspects:

- The function quantification: e.g. 1 kWh of electricity, 1 kg of steel, 1 kg of hydrogen, etc.
- The geographical location in which the function will be fulfilled.
- The time in which the function will be fulfilled.

The definition of a functional unit must be done in a way that will ensure the functional equivalency between compared systems.

From the identified CCS studies as well as the guidelines, the functional unit is related to the "original product" (e.g. 1 kWh of electricity, 1 m^3 of natural gas, 1 kg of fertilizer, 1 kg of hydrogen, 1 kg of steel, etc.).

As shown in Table 5-3, all identified CCS studies pertained to electricity generation The following table provides suggestions for the useable functional unit for CCS studies depending on the industrial sector.

Table 5-3 : Defining the functional units

Industrial sector	Functional unit example
Power generation	1 kWh of electricity generation in [year] in [country/continent]
Natural gas processing	1 kg of natural gas produced in [year] in [country/continent]
Steel	1 kg of steel produced in [year] in [country/continent]
Fertilizer	1 kg of fertilizer produced in [year] in [country/continent]
Chemicals	1 kg of [chemical] produced in [year] in [country/continent]
Hydrogen	1 kg of hydrogen produced in [year] in [country/continent]
Oil refining/fuels	1 kg of [fuel] produced in [year] in [country/continent]
Plastics	1 kg of [plastics] produced in [year] in [country/continent]
Cement	1 kg of cement produced in [year] in [country/continent]
Different sectors	1 kg of CO2 captured in [year] in [country/continent]]

Note: terms in "[]" needs to be specified according to the study's context.

One potential issue is the variations in indicator results resulting from the definition of a functional unit. Indeed, different functional units, for the same compared systems, can lead to different results. The following example illustrates the GHG results based on electricity generation with, alternatively, a functional unit of "*1 kWh of electricity generation from coal with an MEA-based post-conversion capture in 2018 in Germany"* and *"1 kg of captured CO2 from MEA-based post-conversion capture in a coal power plant in Germany in 2018"*. While both functional units are sound from a method standpoint, they do not fulfill the same function: one generates electricity the other focuses on the captured carbon. Indicator results for both functional units are shown in Figure 5-1.

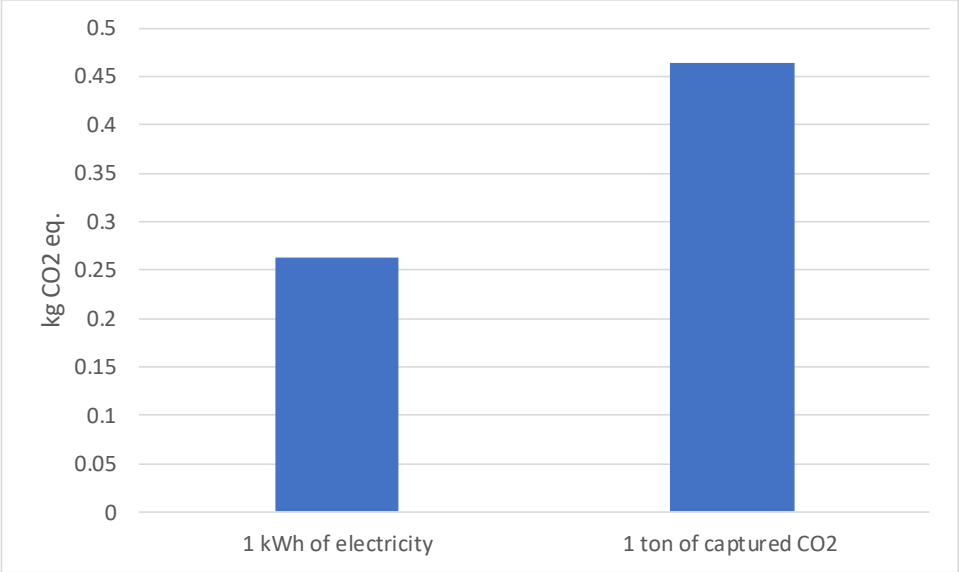


Figure 5-1: LCA carbon footprint related to coal-generated electricity according to two different functional units

As seen, the selection of a functional unit leads to a potential increase of the reported GHG emissions by 77% (if 1 kg of captured CO2 was chosen over the generation of 1 kWh of electricity).

5.2.4 Defining the functional unit of CCU in attributional LCA studies

In a study about CCU, contrarily to CCS, the captured CO_2 now has a "value". **The CO_2 is not a waste that needs to be disposed of but rather an input to other industrial processes**.

In LCA terms, the system is now multifunctional (see the following section for "*solving CCU multifunctionality*"); a carbon capture system will not only generate or produce the original product (i.e. electricity, steel, hydrogen, etc.), it will also help produce other products as well.

The figure below illustrates this.

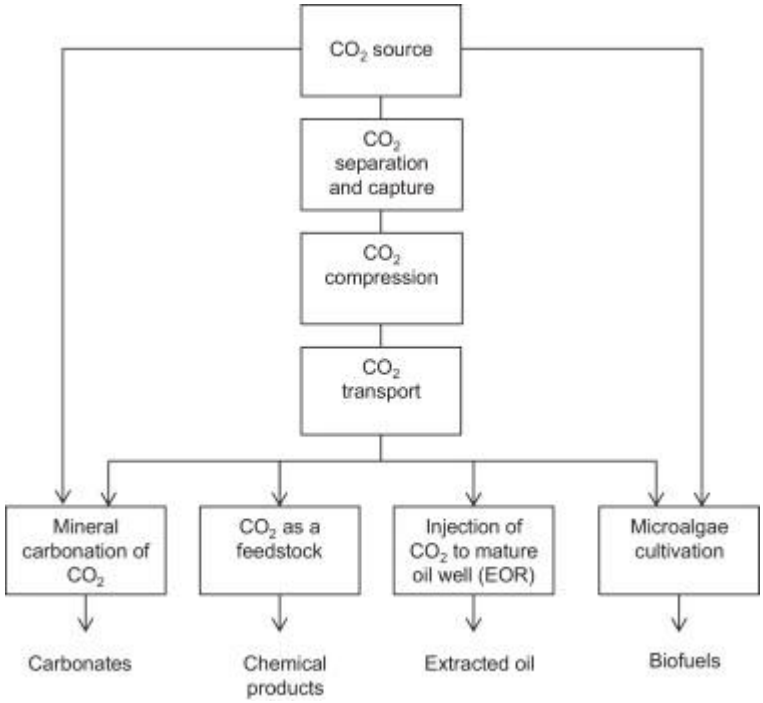


Figure 5-2: CO_2 as a feedstock for different uses

Given the wide range of possible captured CO_2-based products and their associated functions **defining a single universal functional unit for CCU studies is nearly impossible**. This has been illustrated in the review of CCU attributional LCA studies.

As such, the guidelines provide the following information regarding the definition of an LCA for CCU:

- Von der Assen et al. (2014) states that "*comparative LCA of processes has to provide the same functions*".
- Likewise, the IEA (2018) doesn't provide any specific recommendations regarding the selection of functional unit; only that "compared products should be "*functionally equivalent*"
- The NETL (2019) only states that "*the functional unit shall include all of the services and/or functions being provided by the products exiting the system boundary. The functional unit may have one or more products exiting the system boundary. Most, if not all, CO2U projects will have more than one output flow leaving the system boundary, this is referred to as a multiproduct functional unit*".
- LCA4CCU (2020) recommends the following functional units based on different products:

Table 5-4 : LCA4CCU functional unit recommendations for CCU LCA studies

	Recommended FU
Product: Energy carrier - Transportation fuel	1 vehicle km (or 1 tonne km) using a specified means of transport
Product: Energy carrier - Other	Define FU quantifying the energy service
Product: Chemical/material - chemically identical	1 kg of product
Product: Chemical/material - chemically different	Define FU based on equal technical performance
Energy storage system	Define FU quantifying the storage characteristics
Comparison of various CCU processes	1 kg of CO_2 input

- Müller et al. (2020) (for the Global CO2 initiative's), essentially agreed with the recommendations of LCA4CCU for the selection of the functional unit but presented it in the form of a decision tree to help users define the functional unit, depending on the goal of the CCU LCA study.

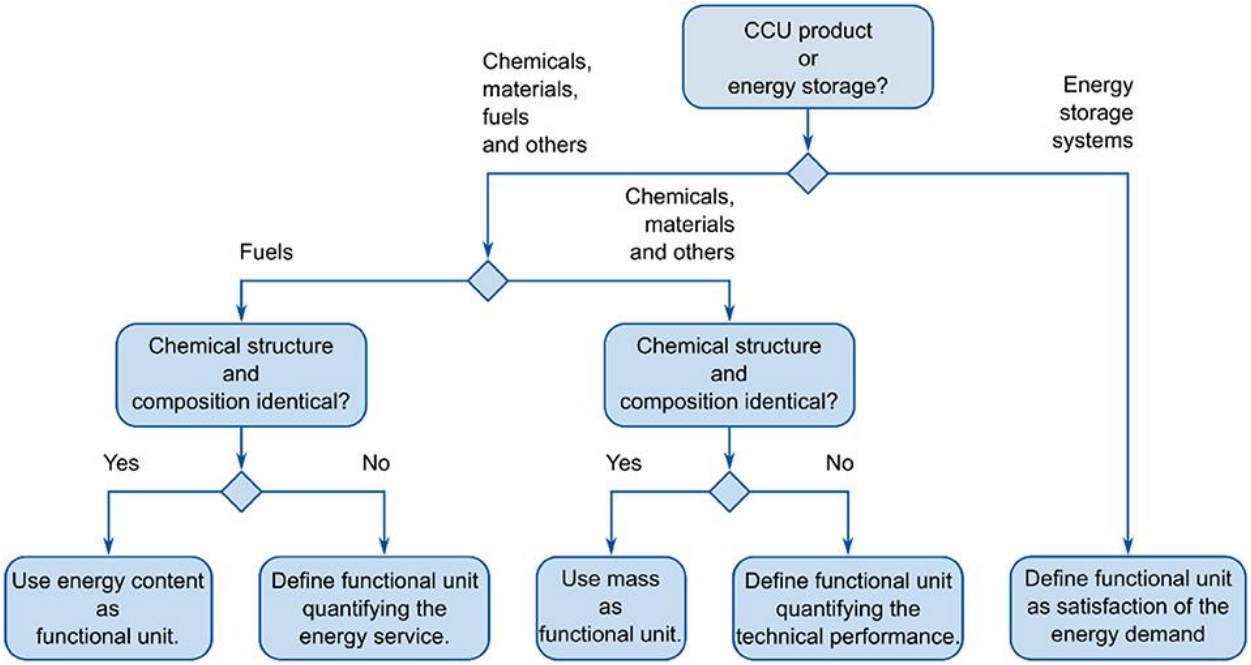


Figure 5-3: Decision tree to define the functional unit of CCU LCA studies (Müller et al., 2020)

5.2.5 Defining the system boundaries of CCS in attributional LCA studies

Once the basis of comparison (i.e., the functional unit) has been established, one must now detail the "story" of the compared products. The "story" of a product is defined through the so-called system boundaries which illustrate the processes comprising the entire life cycle of the investigated product. Depending on the intended objective of the study, the system boundaries can be gate-to-gate (i.e. the process at a specified factory), cradle-to-gate (i.e. from raw material extraction to the end product from a specified factory), or cradle-to-grave (i.e. from raw material extraction to the product end-of-life). When

comparing systems, identical processes between the systems can be omitted from the comparison (as they are identical, they generate the same impacts and therefore will not be a differentiating source).

Figure 5-4 illustrates the cradle to grave system boundaries of a system with and without CCS, related to coal electricity generation, for the reader's convenience.

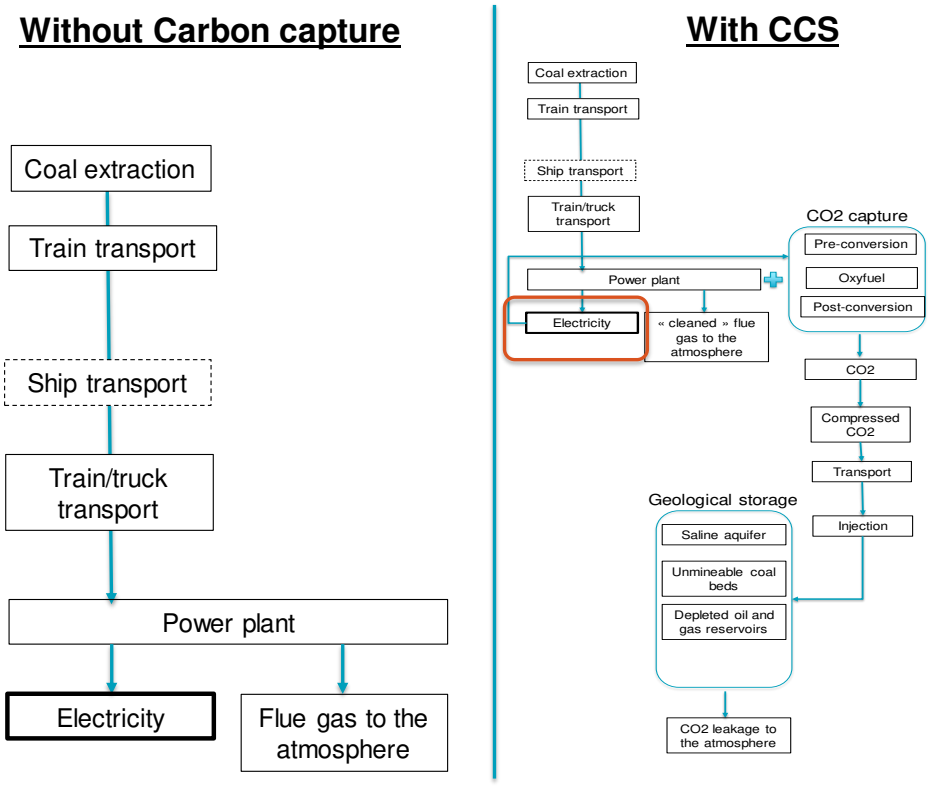


Figure 5-4: Cradle-to-grave system boundaries with and without CCS for electricity generation in a coal power plant

As such, a comparison between systems "with CCS" and "without CCS" is relatively straightforward. The cradle-to-grave system boundaries for all other industrial sectors (than electricity generation) would be similar; the life cycle of compared systems, with and without carbon capture, would be similar at the exception of decreased emissions to the atmosphere and the following additional life cycle stages for the system with carbon capture:

- The carbon capture;
- The CO_2 compression before its transport;
- The CO_2 transport - be it by pipeline or ship transport - to a dedicated long-term storage facility;
- The CO_2 injection.

With CCS, the system is not multifunctional, only the original product is considered. **The captured CO_2 can then be considered as a "waste" that needs to be disposed of much like "*waste sent to a landfill*"**.

5.2.2.1 Potential methodological issues: the capture energy requirement

This sub-section highlights a potential issue that wasn't mentioned in the review of listed CCS studies. Indeed, while these studies essentially targeted the potential impacts of coal or natural gas power plant

they mostly limited their assessment to a "new power plant" scenario which doesn't raise a methodological issue.

Indeed, carbon capture requires energy; energy that is provided on-site. This additional energy may be accounted for differently depending on the power plant assumptions:

- A new power plant with carbon capture, by design, accounts for the carbon capture power requirement. Therefore, the plant will provide a certain amount of electricity all the while capturing CO_2. This situation does not pose a methodological issue.
- A retrofitted power plant that provides the same output of electricity but uses additional energy input (i.e. more coal, more natural gas) to operate its on-site carbon capture and compression would not likewise pose a methodological issue.
- A retrofitted plant that diverts part of its energy output to operate the carbon capture and/or the compression processes -without an increase in coal or natural gas consumption - will decrease its electrical power output to the grid comparatively to its prior set-up. Therefore, depending on the functional unit, an additional amount of electricity generated elsewhere would be required to maintain the same electricity supply. The grid mix can generally be assumed to provide the necessary additional electricity (if it can), otherwise the marginal generation technology(ies). Currently, the grid mix will largely exclude any carbon capture technology.

The concept is illustrated in Figure 5-5.

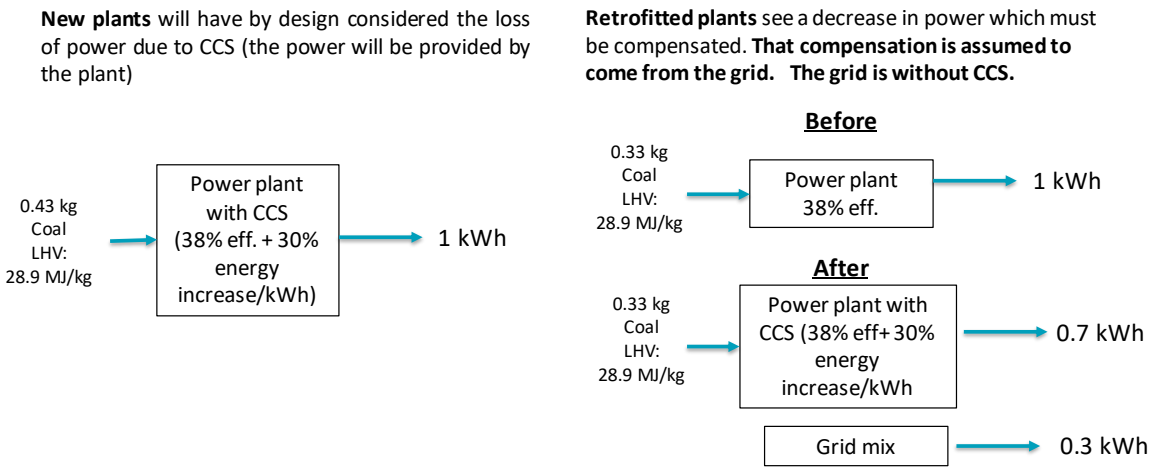


Figure 5-5: Challenge: accounting for the energy penalty associated with carbon capture. Difference between new and retrofitted plants – an example with coal-generated electricity

This assumption of considering either a new or retrofitted plant may influence the life cycle impact assessment. Figure 5-6 illustrates this effect with GHG life cycle emissions. In this example, coal power plants located in Germany with and without CCS are compared, with one CCS scenario requiring an increase in electricity output (equivalent to 0.3 kWh) from the German electrical grid to compensate for the decrease in electrical power output from the coal power plant. Carbon capture is based on the MEA solvent in this example.

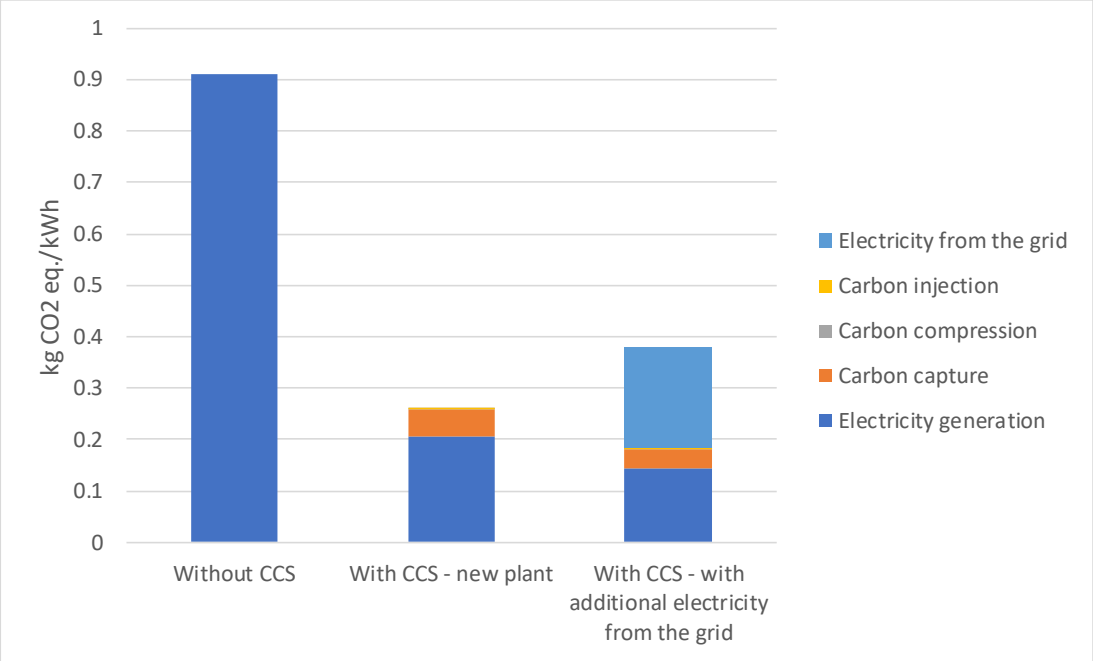


Figure 5-6: An example of the effect of new vs retrofitted plant related to electricity generation: 1 kWh of generated electricity in a coal power plant in Germany – GWP 100 years factors from the IPCC AR-5 report

As seen, the decrease in GHG emissions associated with CCS is lower with a retrofitted plant whose decreased electrical power output needs to be compensated with electricity from the grid. That observation would only be true if the electricity grid is still high in carbon emission. Indeed, different results and conclusions can be obtained depending on the carbon intensity of the grid mix. While Germany has a relatively high carbon intensity grid mix (with several coal/lignite power plants), France electricity mix is composed largely of nuclear power plant with lower levels of GHG emissions resulting in lower GHG emissions if the grid is used rather than a coal power plant equipped with carbon capture. The previous assertion is illustrated in Figure 5-7.

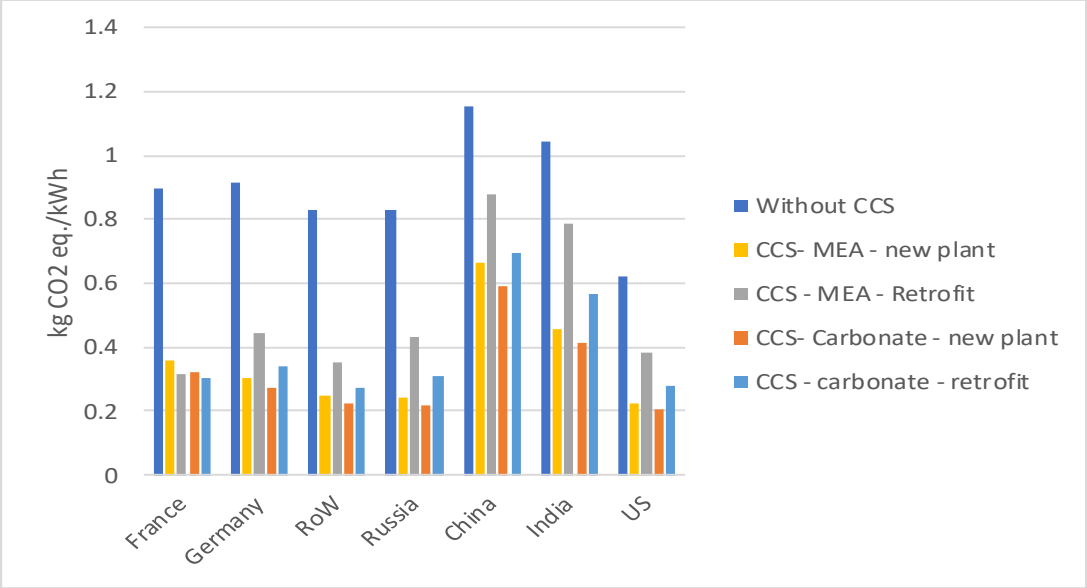


Figure 5-7: GHG emissions from electricity generation from a coal conventional power plant with and without carbon capture adapted to different countries

Note: new plants generate 1 kWh of electricity while retrofitted plants provide 0.7 kWh from the plant and require compensation of 0.3 kWh of electricity from the investigated country's electricity grid mix.

5.2.6 Defining the system boundaries of CCU in attributional LCA studies

In a study about CCU, contrarily to CCS, the captured CO_2 now has a "value". **The CO_2 is not a waste that needs to be disposed of but rather an input to other industrial processes**.

In LCA terms, the system is now multifunctional (see the following section for "*tackling CCU multifunctionality*"); a carbon capture system will not only generate or produce the original product (i.e. electricity, steel, hydrogen, etc.), it will also help produce other products as well.

The figure below illustrates this.

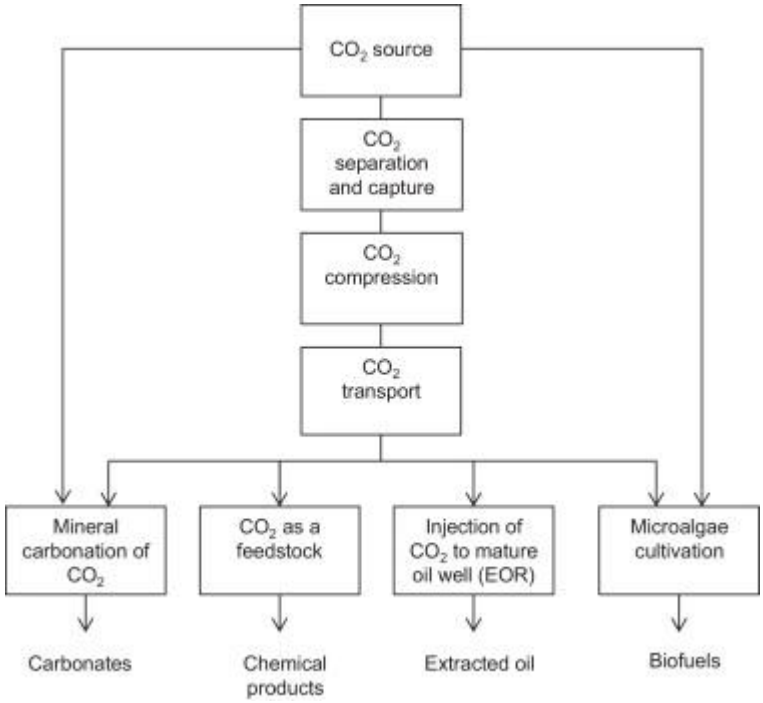


Figure 5-8: CO_2 as a feedstock for different uses

Given the wide range of possible captured CO_2-based products and their associated functions, as well as different goal and scope definitions, **defining a single universal functional unit for CCU studies is nearly impossible**. This has been illustrated in the review of LCA studies on CCU.

As such, the guidelines provide the following information regarding the definition of an LCA for CCU:

- Von der Assen et al. (2014) states that "*comparative LCA of processes has to provide the same functions*".
- Likewise, the IEA (2018) doesn't provide any specific recommendations regarding the selection of functional unit; only that "compared products should be "*functionally equivalent*"
- The NETL (2019) only states that "*the functional unit shall include all of the services and/or functions being provided by the products exiting the system boundary. The functional unit may have one or more products exiting the system boundary. Most, if not all, CO2U projects will have more than one output flow leaving the system boundary, this is referred to as a multiproduct functional unit*".
- LCA4CCU (2020) recommends the following functional units based on different products:

Table 5-5 : LCA4CCU functional unit recommendations for CCU LCA studies

	Recommended FU
Product: Energy carrier - Transportation fuel	1 vehicle km (or 1 tonne km) using a specified means of transport
Product: Energy carrier - Other	Define FU quantifying the energy service
Product: Chemical/material - chemically identical	1 kg of product
Product: Chemical/material - chemically different	Define FU based on equal technical performance
Energy storage system	Define FU quantifying the storage characteristics
Comparison of various CCU processes	1 kg of CO_2 input

- Müller et al. (2020) (for the Global CO2 initiative's), essentially agreed with the recommendations of LCA4CCU for the selection of the functional unit but presented it in the form of a decision tree to help users define the functional unit, depending on the goal of the CCU LCA study.

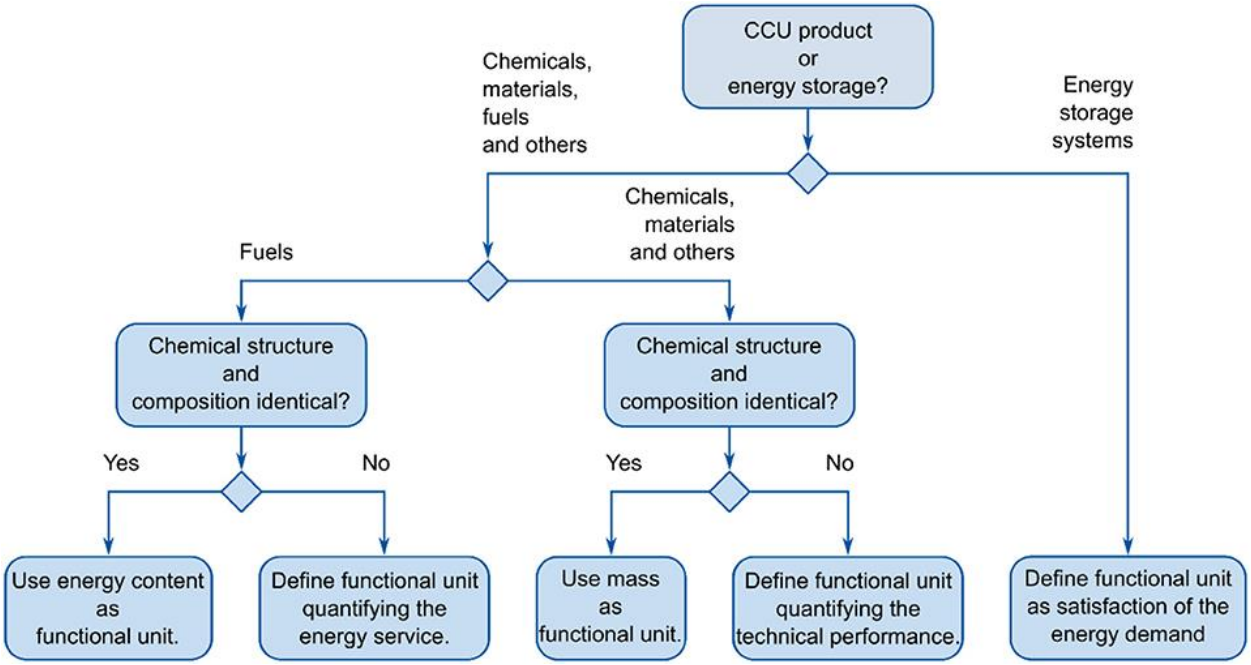


Figure 5-9: Decision tree to define the functional unit of CCU LCA studies (Müller et al., 2020)

For the system boundaries of CCU LCA studies, **all guidelines conclude – in various terms – that they should <u>always</u> cover the entire life cycle from cradle-to-grave unless common processes between systems are identical and therefore can be omitted from the system boundaries**. In other words, in situations where technical performance and, thus, downstream processes are identical, a cradle-to-gate approach is sufficient, for comparative studies.

The following figure presents Müller et al. (2020) decision tree defining a set of system boundaries for CCU LCA studies.

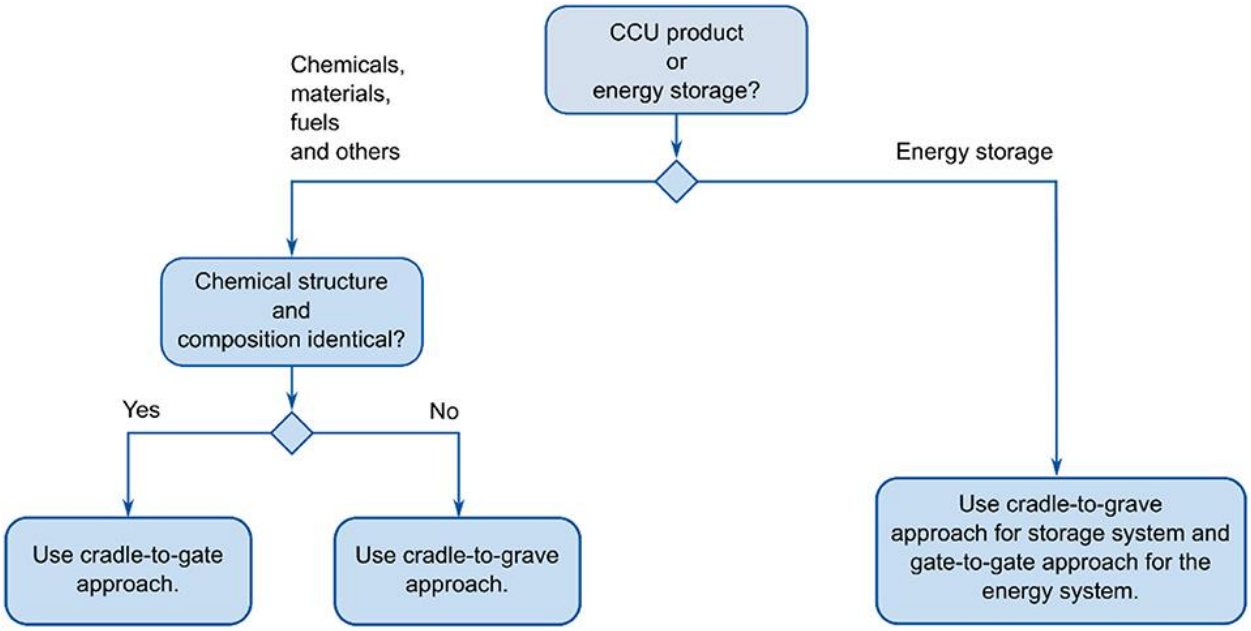


Figure 5-10: Decision tree to define the system boundaries in CCU LCA studies

Figure 5-11 illustrates the new system boundaries for a system with CCU, for the reader's convenience using the previous "electricity generation" example. In this figure, the outputs of the systems are "electricity" and "an existing product" (highlighted with blue arrows).

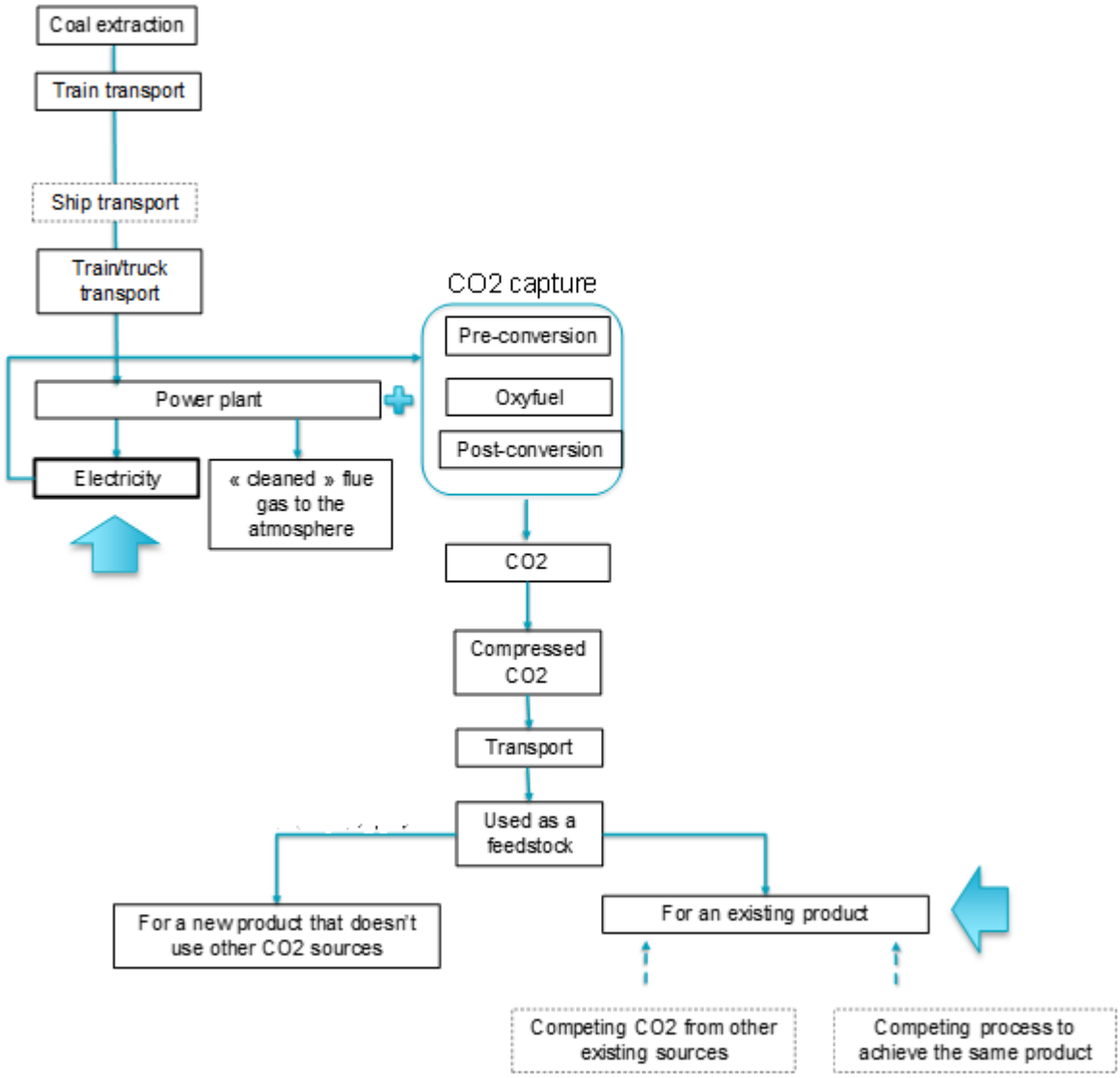


Figure 5-11: Accounting for the multifunctionality of CCU systems; a generic example with CO2 captured from a coal power plant (dashed line processes only pertain to system expansion or consequential LCA – see below for information regarding those approaches)

Note: as with CCS, the issue regarding the CO_2 capture energy penalty in the retrofitted power plant is still in effect.

Note: The CCU pathway entitled "*for a new product that doesn't use other CO2 sources*" is purely theoretical since no known product could only be produced from captured CO2 (and no other CO2 sources).

5.2.7 Defining the system boundaries for direct air capture (DAC) LCA studies

This subsection highlights additional methodological issues inherent to the direct air capture (DAC) technologies. It should be noted that all previously mentioned challenges may also arise with direct air capture, whether the captured CO_2 follows the CCS or CCU pathway.

With DAC, the additional challenge stems from the disconnect between the emission and capture location. Indeed, contrary to post-conversion, pre-conversion, and oxyfuel combustion capture related processes, DAC can be deployed anywhere in the world and captures the CO_2 from the atmosphere where it is located. Therefore, while DAC will capture CO_2, it will be from the atmosphere – the sum of all biological and industrial processes CO_2 outputs and not from a specific process.

5.2.8 Defining the system boundaries of CCS/CCU consequential LCA studies

A consequential life cycle assessment (CLCA) aims at assessing the environmental consequences of a specific decision affecting a product system and is 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?*"

Consequential LCA captures environmental consequences that are often outside of the actual supply chain, and which instead result from market forces (e.g. product substitution) (Ekvall, 2000). Therefore, in a CLCA, all activities within and outside the life cycle that are affected by a change within the life cycle of the investigated product are included (Ekvall and Weidema, 2004). In many cases, this implies the use of marginal process data and multifunctionality is typically treated through system expansion (Ekvall and Weidema, 2004; Weidema2003)

The debate on how and when to perform attributional life cycle assessment (ALCA, the type of the LCA studies mentioned in the previous sections of this report) versus CLCA is not yet resolved (Zamagni et al.2008). The identification of affected technologies, collection of marginal data, and associated uncertainties are still debated (Earles and Halog, 2015).

With CLCA, the consequences are traced forward in time, which means that it is relevant to **use data on marginal suppliers and substitution of displaced activities**.

Therefore, **the system boundaries need to account for more than the carbon capture, compression, transport, injection, or use in an industrial process**. The processes that need accounting for will vary depending on the market for the new CO2-based product. There are three possible outcomes for the introduction of a "new" product or process (i.e. based on captured CO_2) on the market:

I. The captured CO_2-based product is used in addition to the product from the conventional production method – i.e. the market for product X is not saturated. The burdens (i.e. resource use and emissions) of the captured CO_2-based product are added to the overall pool of burdens. This increases overall burdens. The system boundaries are the same as with an attributional LCA.
II. The captured CO_2-based product completely substitutes the product from the conventional production method – i.e. the market for product X is saturated; any additional production of captured CO_2-based product X translates into a decrease in the production of product X from the conventional method. The burdens of the captured CO_2-based product are added to the overall pool of burdens, but the burdens of the conventional product are subtracted from the overall pool of burdens. The system boundaries need to include the products/processes that it substitutes. This may lead to a net increase, decrease, or no change of the overall burdens.
III. The captured CO_2-based product partially substitutes the product from the conventional production method – i.e. the market for product X is locally saturated but unsaturated in other parts of the world; any additional production of captured CO_2-based product X translates into export of product X from the conventional method to other parts of the world with a potential cascade of effects due to the introduction of product X in a new market. In such circumstances, the actual ripple effects are difficult to anticipate, and economic modeling may be required with

models such as GTAP. The system boundaries will need to account for all affected products/processes by the introduction of the new process.

To date, notes The National Academy of sciences, engineering, and medicine (2019)[53], consequential LCA has been sparingly applied to carbon utilization because:

- Carbon-derived fuels, materials, and chemicals need to be produced at volumes that are disruptive to current markets to provide valuable information.
- Partial and general equilibrium models used for consequential LCA lack the level of details required to track the influence of captured carbon-derived products, fuels, and materials on existing supply chains and markets. The development of more detailed models is thus required.
- Market such as production volumes and market prices are often outdated and should be updated to provide accurate information for consequential LCA.
- Uncertainty assessment of consequential LCA is a field of research on its own.

For the reader's convenience, the following table provides the most likely avoided conventional production for several products produced from captured CO_2.

Table 5-6 : Identification of most likely avoided conventional production depending on the captured CO_2-based product

CCU category	Technology	Chemical reaction	Most likely avoided conventional production
Chemical conversion	Renewable methanol production	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$	Methanol is commercially produced from synthesis gas containing CO and H_2. As an intermediate product, methanol is used in a variety of chemical syntheses, mostly for the production of formaldehyde, methyl tert-butyl ether, and acetic acid
	Methane production	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	Natural gas mainly contains methane with a molar fraction of up to 0.99. Conventionally, natural gas is extracted either from reservoirs containing oil and gas or from reservoirs containing only gas. Natural gas can be used either as a fuel or as a feedstock in the chemical industry (e.g. to produce methanol).
	Formic acid production	electrochemical reduction $CO_2 + 2H + +2e^- \rightarrow HCOOH$ $CO_2 + H_2 \rightarrow HCOOH$	European formic acid is mostly used in the feed industry and as a silage aid. The potassium salt of formic acid is used on a large scale for the de-icing of aircraft
	Urea	$2NH_3+CO_2 \rightarrow NH_2COONH_4$ $NH_2COONH_4 \rightarrow NH_2CONH_2(urea)+H_2O$	The most popular way of producing CO_2 for urea production is the thermal decomposition of carbonates following the chemical reaction: $CaCO_3+heat \rightarrow CO_2 + CaO$
	Ethanol	$2CO_2 + 3H_2O \rightarrow C_2H_5OH + 3H_2 + 3O_2$	Fermentation accounts for 90% of the total ethanol production share whereas 10% of the total ethanol production is produced synthetically from ethylene or as a by-product of specific industrial processes. Ethanol from fermentation is traditionally used for beverages and specialty chemicals whereas ethanol from chemical synthesis is used for industrial purposes. CO_2-based ethanol is produced from CO_2 and H_2O via synthesis gas using co-electrolysis and by fermentation of CO_2 containing syngas in particular in steel mills
	Synthetic fuels	$CO2 + CH4 \rightarrow H2 + 2CO$ $nCO + 2(n+1)\ H2 \rightarrow nH_2O + C_nH_{2n+2}$	Conventional syngas production follows the following chemical reaction: $2CH4 + O2 \rightarrow 4H2 + 2\ CO$.
	Counter-rotating ring receiver reactor recuperator	TRL currently to low to identify a specific current market	

[53] https://www.nap.edu/read/25232/chapter/10

	Photocatalytic reduction of CO_2 (metallic)	TRL currently to low to identify a specific current market	
	Photocatalytic reduction of CO_2 (non-metallic)	TRL currently to low to identify a specific current market	
	Nanomaterial catalysts	TRL currently to low to identify a specific current market	
	Enhanced Geothermal System with CO_2	TRL currently to low to identify a specific current market	
	Supercritical CO_2 power cycles	TRL currently to low to identify a specific current market	
	Polymer processing (polycarbonates)	Polyether polyols conventionally are produced by a synthesis of propylene oxide, glycerol, and monopropylene glycol	
	Polymer processing (polyurethanes)		
Biological conversion	Algae cultivation	TRL currently to low to identify a specific current market	
	Helioculture	TRL currently to low to identify a specific current market	
CO_2 mineralization	Mineral carbonation		Uncertain but most likely source of competing CO2 is from the heat destruction of calcium carbonate (limestone)
	Sodium bicarbonate		
	CO_2 concrete curing		
	Bauxite residue carbonation		

5.2.9 Defining the system boundaries of CCS/CCU of dynamic LCA studies

In an attributional LCA, all emissions for a given pollutant throughout the life cycle are typically added into a single aggregated life cycle inventory (LCI) emission. Then, during the life cycle impact assessment (LCIA) phase, the potential impacts of the aggregated LCI emissions are characterized, i.e. converted into impact indicator results. The timing of the individual emissions occurring during the life cycle of a product is not considered; an emission occurring today is treated the same way as an emission that will occur 20 years from now, i.e. the same characterization factor is used for both.

Indeed, the selection of a time horizon is equivalent to giving weight to time and is one of the most critical parts of carbon accounting processes. Indeed, the shorter the time horizon, the greater the importance given to the impacts closer in time, because impacts occurring after the defined time horizon is not considered. Most LCIA methods use 100 years as the time horizon for GWP. The use of a fixed time horizon for GWP in LCA results in an inconsistency between the time horizon chosen for the analysis in a given LCA study and the period covered by the results, especially for long-lasting products or projects.

The following figure illustrates this inconsistency by using the example of a building with a 75-year lifetime. A cradle-to-grave LCA will account for every pollutant released during the entire life cycle of the building, from its construction to destruction, including the use phase, which considers maintenance, heating, and air-conditioning activities. During these 75 years, GHGs will be released and will generate an impact on the climate. By choosing an impact assessment method that uses GWP with a time horizon of 100 years, one might think that this LCA study considers the global warming impacts over 100 years. However, that is not the case. The impact of an emission that occurs 50 years after construction, for example, will be considered from year 50 to year 150.

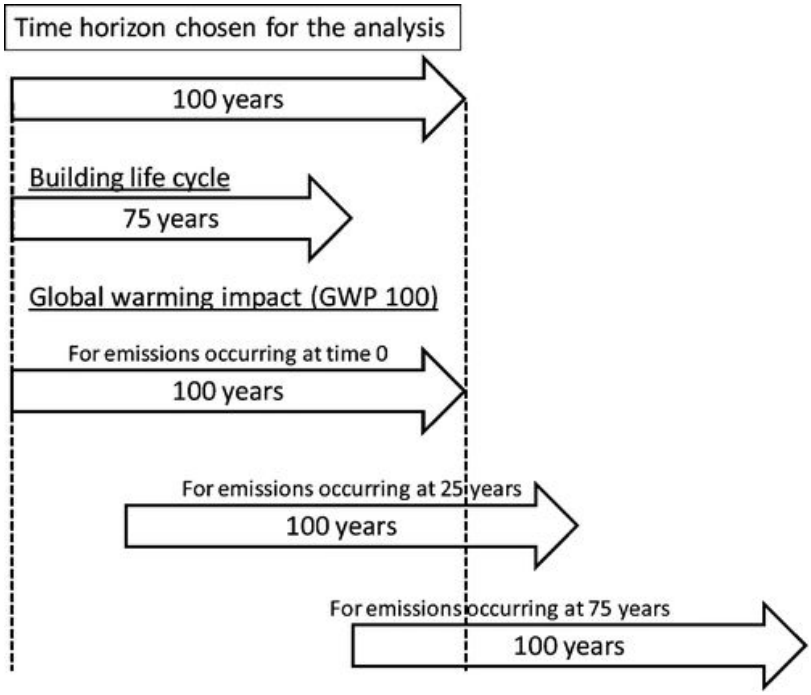


Figure 5-12: Illustration of the inconsistency in time frames for global warming LCIA with the example of a 75-year lifetime building

This limitation is well understood in LCA circles. However, if LCA is used for yearly carbon footprinting; it may raise some methodological issues.

To account for time, dynamic LCA was introduced. In a dynamic LCA, the temporal emission profiles are considered so that LCI results are provided as a function of time (i.e. kg emitted for a year) rather than a single number. Once a dynamic inventory is calculated, the LCIA characterization model can be solved dynamically, i.e. without using steady-state assumptions, to obtain time-dependent characterization factors according to the moment when the emission occurs.

Therefore, the system boundaries of dynamic LCA's are the same as for attributional LCA; only the emissions of each process are put back in their proper timeframe rather than aggregated into a single emission.

For more information, please refer to SCORE LCA's study N° 2020-01 ("Greenhouse gas emissions LCA indicator, definition, and application: temporal challenges").

5.2.10 Defining the system boundaries of CCS/CCU of prospective LCA studies

The challenge of prospective LCA studies is inherent to "predicting" how the future evolves. This challenge is twofold:

- How will the investigated technology/process change?
- What is the anticipated background emissions evolution (from the life cycle inputs of a product)?

As previously mentioned, CCS and CCU are technologies that are still evolving and therefore, will most likely change with time. However, anticipation always comes with a level of uncertainty. A set of conclusions obtained today may be changed with a rapid or unanticipated technological evolution tomorrow. Such modifications are difficult to consider except by trying to anticipate where the most likely changes will occur and then account for these changes via sensitivity analysis or scenario variations. In

that respect, the following figure presents some of the current research focus for some of the solvent that is currently used for carbon capture.

Table 5-7 : CO_2 capture solvent benefits, disadvantages, and future work

Table 4 Solvent summary

Type	Company	Solvents	Benefit	Disadvantage	Future work	Ref.
Advanced amine	Hitachi; Dow; KEPCO; MHI; Fluor; Shell	H3-1; UCARSOL™ FGC 3000; RS-1, RS-2, RS-3; Cansolv; CASTOR 1 & 2; KS-1, KS-2, KS-3; Fluor Econamines FG Plus℠	Extensive operational/design experience available; An extra degree of freedom determining the compositions of amine mixtures to optimise its performance	Corrosion; Solvent degradation; Form heat stable salts with SO_2 and NO; Amine emission; Viscous	Develop novel amine based solvents to lower regeneration energy required, oxidative degradation, corrosion, and increase reaction kinetics and absorption capacity; Heat integration; Equipment innovation such as intercooling system	[22,119–121]
Amino acid salt	Siemens; BASF	PostCap; Puratreat	Low vapour pressure; Low oxidative degradation and emission; Reactive towards CO_2; Low environmental impact; Similar rate constants to MEA	Forms heat stable salts with SO_2 and NO; High heat of regeneration	Performance should be examined on a larger scale and in a real industrial situation	[22,122–125]
Carbonate system	UNOTechnology	UNO MK3	Low vapour pressure; Non-volatile; No oxidative degradation; Low toxicity; Low regeneration energy; Low environmental life-cycle impact; Multi-impurity capture; FGD unnecessary; Low manufacture cost	Reduced kinetics	Scale up of plant based trials; Process of design of large scale systems; Examine new promoter systems; Slurry handling system design and simulation	[22,80,126]
Aqueous ammonia	Alstom; CSIRO; PowerSpan	CAP	Does not decompose, high capacity, high purity product, competitive heat of regeneration	High ammonia vapour pressure; Slower kinetics than MEA; Solid ammonium bicarbonate formation; Ammonia emission; Harsh conditions duo to operating temperature	Additives to enhance CO_2 absorption rate and suppress ammonia vapour, re-engineering industrial ammonium bicarbonate fertilizer production and combined capture of CO_2 and SO_2	[22,69,127–131]
Immiscible liquid	3H Company	Self-concentrating absorbent CO_2 capture process	Low regeneration energy; Non-aqueous environment to mitigate corrosion, degradation and formation of stable salts	Mechanism and chemistry unsure; Low maturity	Develop new system using different liquids; More testing and research on bench scale should be conducted	[22]
Ionic liquid	Notre Dame; Georgia Tech.	NDIL0046; NDIL0157; RevILs	High thermal stability, no water evaporation in regeneration, no vapour pressure, tailorable	Expensive; High viscosity; High selectivity to water	Improve operating performance of ILs; Improve process chemistry; Integration of capture with manufacturing saleable goods, i.e., organic carbonates, formic acid	[22,132–134]

Furthermore, the world in which carbon capture technology will be deployed is itself in motion; what holds now may change tomorrow. Indeed, with an increased carbon (taxation) cost, some cost-prohibitive low-carbon projects might not be so unattractive.

To help account for a world that is changing, scenario modeling in LCA has been deemed a powerful approach capable of capturing effects of technology changes in a product system, evaluate the performance of a product/material/service in a decarbonized economy and improve modeling of the system with a long lifespan.

To account for these changes, climate specialist often refers to the Shared Socioeconomic Pathways (SSP) scenarios which are a "*scenario framework used by the climate change research community in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation*" (Riahi et al., 2017). The SSPs are based on five narratives describing alternative socio-economic developments (O'Neill et al., 2017) and use a set of Integrated Assessment Models (IAMs) to calculate the elaboration of the energy, land-use, and emissions trajectories of SSP-based scenarios (Riahi et al., 2017). SSPs narratives describe plausible future challenges for mitigation and adaptation to climate change and serve as the foundation of the IPCC Sixth Assessment report.

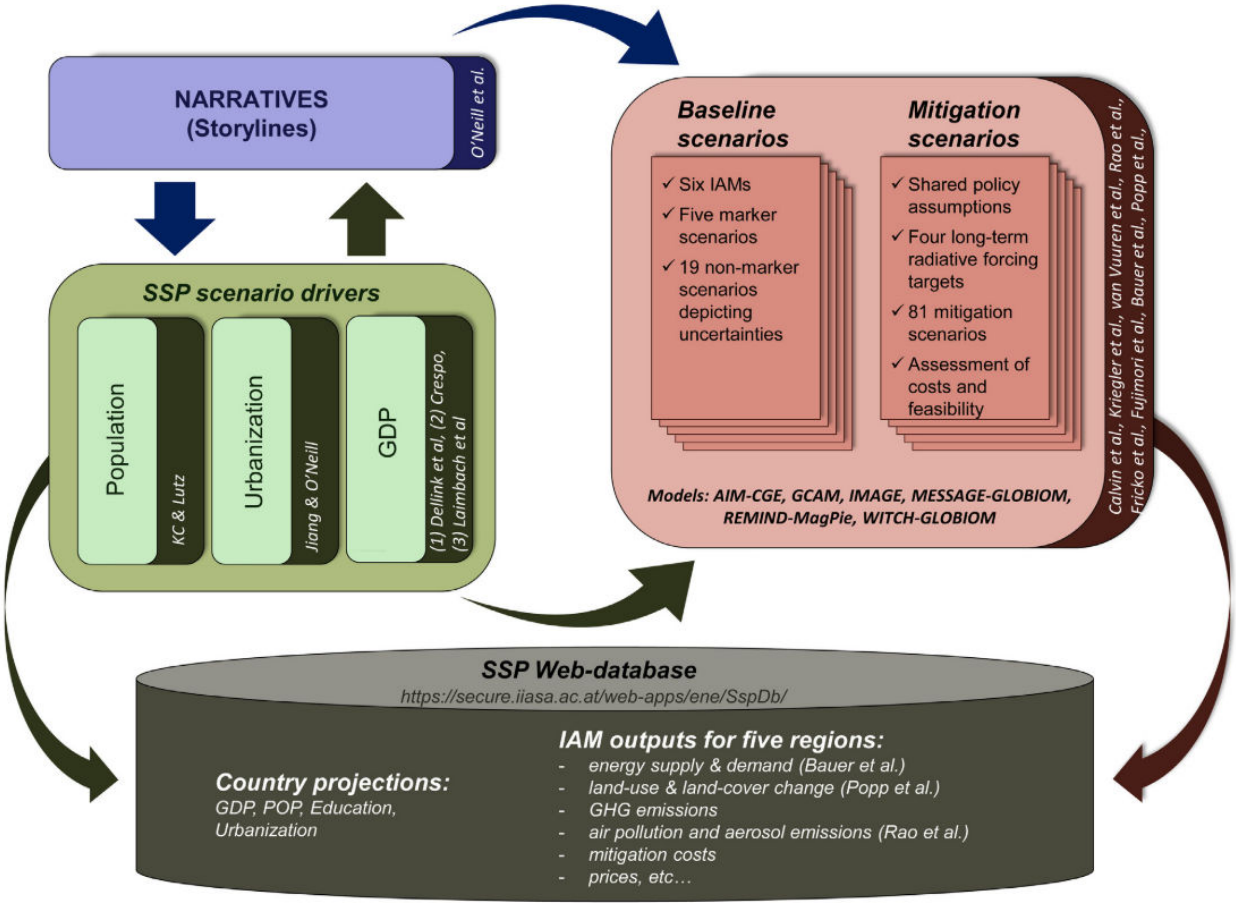


Figure 5-13: Shared Socioeconomic Pathways (SSP) overview

SSPs framework, narratives, and results are an acceptable cornerstone for scenario modeling in LCA because it ensures consistency within scenarios and makes it easier to link with the broader scientific community (Pedneault et al., 2020).

The SSPs framework narratives are illustrated in the following figure and described in the following paragraph:

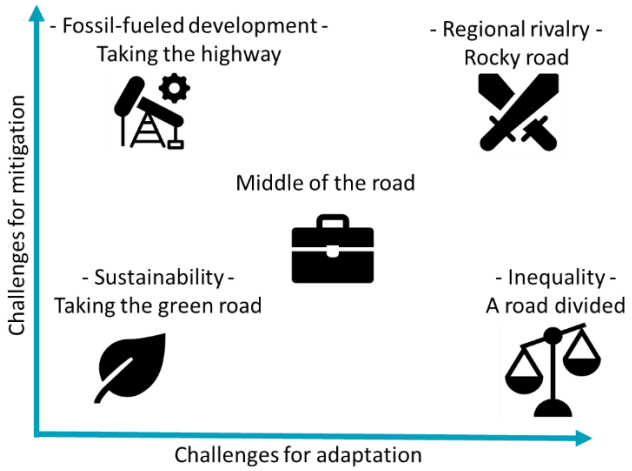


Figure 5-14: Shared Socioeconomic Pathways (SSP) narratives. Adapted from (O'Neill et al., 2017)

- *SSP1 - Taking the Green road* - describes a world "*shifting gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries"*. This implies a reduction in resource and energy intensity. High-income countries support developing countries in their development goals by providing access to human and financial resources and new technologies. This narrative describes a world with low challenges of mitigation and adaptation.
- *SSP2 - Middle of the road* - is an evolution of the societies with no marked shift from historical trends. This narrative describes a world facing moderate challenges to mitigation and adaptation.
- *SSP3 - A rocky road* - is characterized by regional rivalry and international fragmentation. This leads to little international cooperation and low investments in education and technology for development. Environmental concerns are not prioritized, and consumption remains material intensive, causing high challenges to mitigation and adaptation.
- *SSP4 - A road divided* - represents a world with "*highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, leading to increasing inequalities and stratification both across and within countries*". Technology development is rapid in high-tech economies while technology diffusion is slow in other regions. SSP4 represents a world with high adaptation challenges combined with low mitigation challenges.
- *SSP5 - Taking the highway* - is "*driven by the economic success of industrialized and emerging economies, this world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development*". This techno-optimistic pathway leads to high energy and resource consumption, which in turn results in a high challenge in mitigation but the low challenge of adaptation.

Every SSP has a baseline scenario and mitigation scenarios based on the Representative Concentration Pathways (RCPs)[24,25] representing radiative forcing levels of 1.9, 2.6, 3.4, 4.5, and 6.0 W/m^2 by 2100. Some combinations of SSPs and RCPs are not possible due to socio-economic conditions. For example, the lowest radiative forcing level that can be reached from SSP3 is 3.4 W/m^2.

The SSP regional aggregation is made into 5 regions: Asia, Latin America (LAM), Middle East and Africa (MAF), Organisation for Economic Co-operation and Development (OECD) in 1990 and EU member states and candidates, and reforming economies of eastern Europe and the former Soviet Union (REF). See (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10#regiondefs) for the exact regional definitions.

To end this section on an open question, we can foresee that - apart from the evolving world in which carbon capture will be deployed – methodological assumptions could change with time – especially for CCU systems. For example, what happens if/when a cement plant with carbon capture becomes the most widespread way of making business?

- **Can one still claim that system expansion should still be carried out by relying on a cement plant that doesn't exist anymore? (for attributional LCA)**
- **Can one still claim that they are avoiding individual production of both cement plant AND methanol? (for prospective consequential LCA).**

These questions are currently inconsequential but could become very important in the future and affect the system boundaries definition.

5.2.11 Solving CCS multifunctionality

With CCS, CO_2 is considered a waste to be disposed of and does not have any "value". Therefore, the system has only one function and doesn't need to solve multifunctionality issues.

5.2.12 Solving CCU multifunctionality: system expansion

With CCU, CO_2 is now a valuable input to a product. The system then becomes multifunctional: the function fulfilled by the process in which the carbon capture occurred and the product which will use the captured CO_2.

As such, the guidelines states that solving CCU multifunctionality can be tackled with existing methodological approaches – no new developments are required.

Existing standards (BSI, 2011; AFNOR, 2016; European Committee for Standardisation, 2017, 2018) and guidelines (European Commission - Joint Research Center, 2010, 2012; World Resources Institute and World Business Council for Sustainable Development, 2011) rank approaches for solving multifunctionality in a hierarchy which should be consistent with the stated goal. The following decision tree presents this hierarchy, which complies with ISO standards and guidelines.

- Check if multifunctionality can be solved by gathering individual process data. If so, apply sub-division. If not,
    - depending on the goal of the study, if not product-specific,
        - apply system expansion. Note that results obtained via system expansion are associated with the production of more than one product and thus, are not specific to a single product of the CCU technology.
    - depending on the goal of the study, if product-specific,
        - apply substitution;
            - If the substitution is impossible, apply allocation, first using underlying physical relationships, and if impossible, then another relationship, such as economic value.

All investigated guidelines recommend system expansion to deal with CCU multifunctionality even leading Müller et al. (2020) to state that "***results obtained via system expansion shall always be computed to assess the overall effect of introducing the CCU technology***".

The following figure illustrates a generic example for solving multifunctionality with system expansion. **The idea behind system expansion is to subtract from the multifunctional system an alternative system that only provides a single function. Therefore, subtracting the unwanted function from the multifunctional one allows isolating the targeted function**.

- **System expansion**

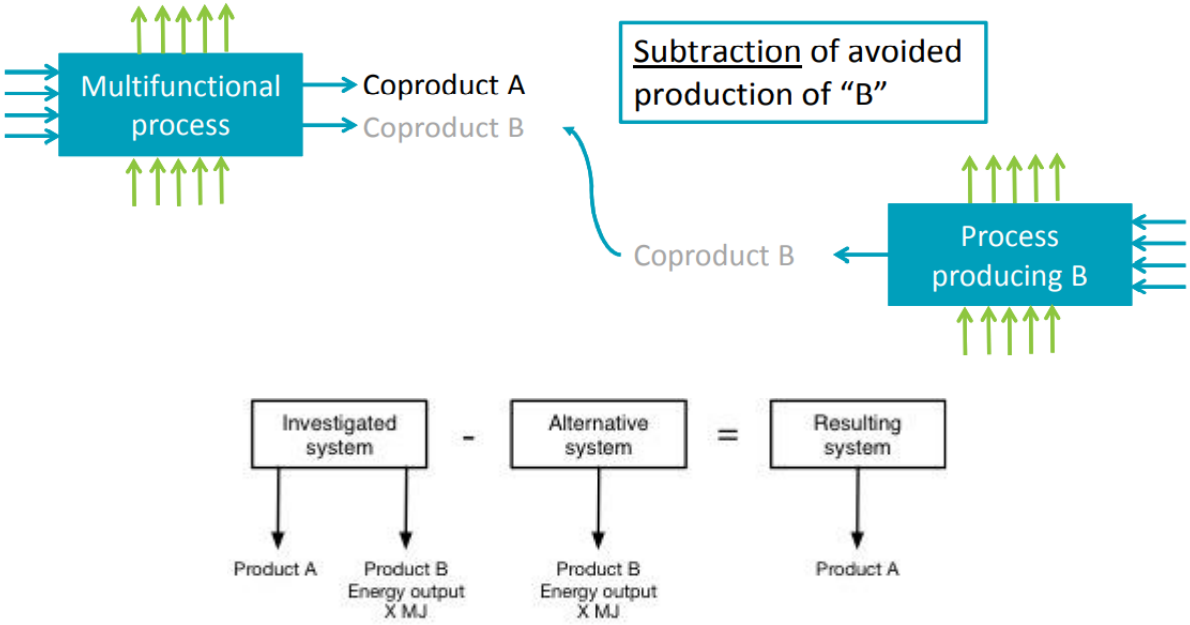


Figure 5-15: System expansion generic calculation[54][55]

The challenge of system expansion then becomes the identification of the alternative system to subtract the unwanted function. This alternative system is typically an unwanted product from the direct mainstream competing process.

Müller et al. (2020) does provide a caveat to this "competing with conventional processes" approach. Indeed, they state that CCU "*does not compete with current technologies, since their market launch lies in the future. Instead, these CCU processes compete with the technologies established in the future. Thus, comparing CCU technologies in stages of early development to currently used processes does not reflect reality. Therefore, the time dimension is crucial for assessing the ecological benefits of CCU. For this purpose, future development techniques, e.g., learning curves, may be applied to both the CCU technology and the reference process, as both processes underlie development".* They, however, concluded that this would be a best-case scenario and one that "*is potentially beyond the scope and experience of many LCA*

[54] https://www.ciraig.org/pdf/4a-CIRAIG_PERF_P_Lesage-LifeCycleInventory.pdf

[55] https://lca-net.com/blog/iso-system-expansion-substitution/

practitioner". Without any reliable predictions on future developments for both the reference and CCU processes, "*the current best available technology should be used as the reference technology*".

Therefore, in a pragmatic approach, the conventional production processes should be used for system expansion.

Figure 5-16 illustrates system expansion for methanol and cement production. In Figure 5-16b) example, a cement plant is equipped with carbon capture. This carbon is feeding a methanol plant. The overall system is therefore multifunctional as it produces both cement AND methanol. The competing mono-functional systems (illustrated in Figure 5-16a)) are a cement plant without carbon capture and methanol production from steam methane reforming (SMR).

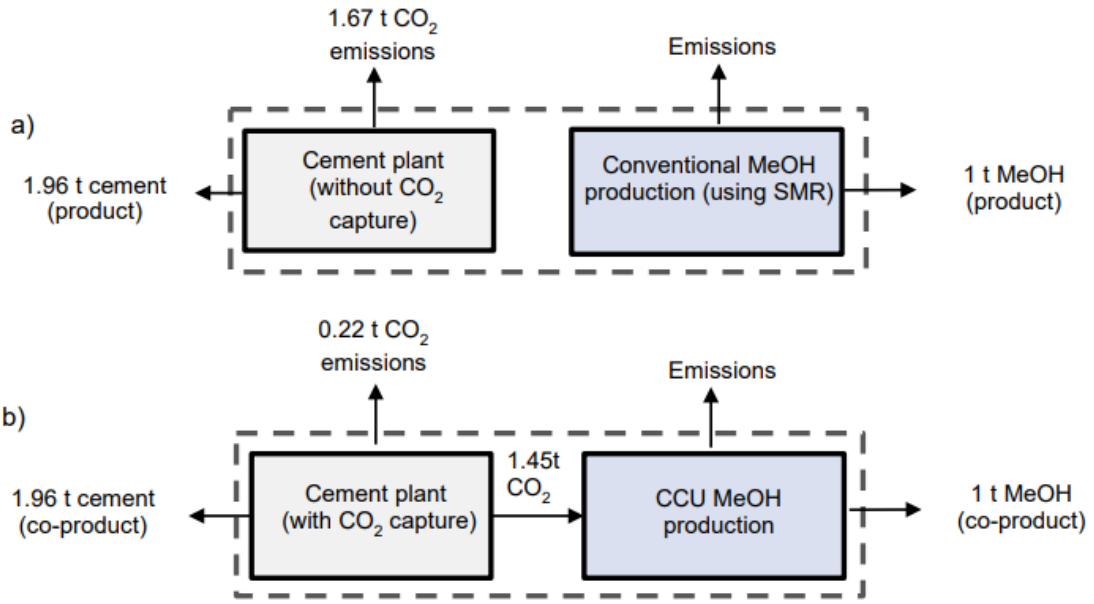


Figure 5-16: Accounting for the multifunctionality of CCU systems; an example for comparing methanol production in a system without capture (a) and with capture (b) from a cement plant with system expansion.

- If the study's objective is the production of methanol, with a functional unit defined as the "*production of 1 tonne of methanol in country X in 20YY*" than the system expansion calculation should be:

$$(1.96\ t\ Cement\ from\ plant\ with\ CO2\ capture + 1\ t\ MeOH\ production\ from\ captured\ CO2) - 1.96\ t\ from\ Cement\ plant\ without\ CO2\ capture = 1\ t\ MeOH\ production\ from\ captured\ CO2$$

- Alternatively, if the study's objective is the production of cement, with a functional unit defined as the "*production of 1.96 tonnes of cement in country X in 20YY*" than the system expansion calculation should be:

$$(1.96\ t\ Cement\ from\ plant\ with\ CO2\ capture + 1\ t\ MeOH\ production\ from\ captured\ CO2) - 1\ t\ from\ MeOH\ from\ SMR = 1.96\ t\ Cement\ from\ plant\ with\ CO2\ capture$$

Figure 5-17 provides another example of system expansion treatment. In Figure 5-17 (right side) example, a municipal solid waste energy from waste (EfW) plant is equipped with carbon capture. This carbon is feeding a concrete block plant. The overall system is therefore multifunctional as it produces both waste treatment AND concrete blocks. The competing mono-functional systems (illustrated in Figure 5-17b))

are municipal solid waste energy from waste without carbon capture and concrete blocks from conventional methods.

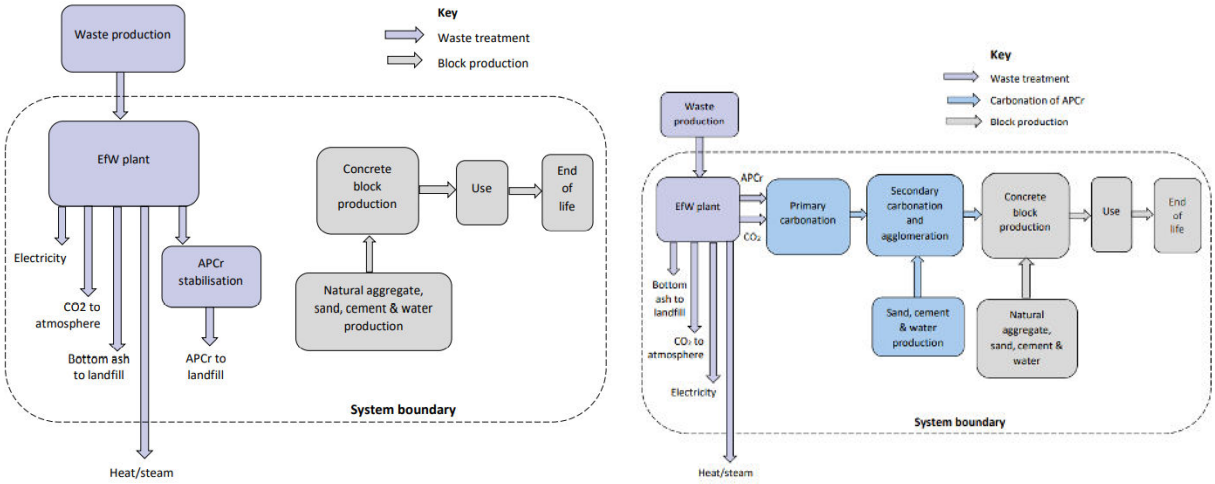


Figure 5-17: Accounting for the multifunctionality of CCU systems; an example for comparing cement production in a system without capture (left) and with capture (right) from a municipal solid waste energy from waste (EfW) plant with system expansion.

- If the study's objective is the production of concrete blocks, with a functional unit defined as the production of 1 tonne of concrete blocks than the system expansion calculation should be:

$$(X\ Waste\ management\ with\ CO2\ capture + 1\ ton\ concrete\ block\ production\ from\ CCU) \\ - X\ Waste\ management\ without\ CO2\ capture = 1\ ton\ concrete\ block\ production\ from\ CCU$$

- Alternatively, if the study's objective is waste management, with a functional unit defined as the "*production of X waste managed in country X in 20YY*" than the system expansion calculation should be:

$$(X\ Waste\ management\ with\ CO2\ capture + 1\ ton\ concrete\ block\ production\ from\ CCU) \\ - 1\ ton\ concrete\ block\ production\ from\ conventional\ methods \\ = X\ Waste\ management\ with\ CO2\ capture$$

From the previous examples, it could be surmised that the same product made from captured CO2 would be different depending on the process from which the CO2 originated. The following example aims to illustrate this. In this example, we investigate the production of 1 kg of methanol in Germany in 2020. We compare the production of methanol from steam reforming, syngas (from coal gasification), from CCU where CO2 has been captured at a coal power plant and CCU where CO2 has been captured at a steel mill.

The example relied on the following data and assumptions:

- The methanol steam reforming process was taken from the ecoinvent database and adapted for Germany
- The methanol syngas process was taken from the ecoinvent database and adapted for Germany.
- The German coal-generated electricity was taken from ecoinvent (plant efficiency was modified to be 38%). The dataset states that the process emits 0.627 kg CO2 eq./kWh (without capture).
- The steel production ("*1 kg Steel, chromium steel 18/8 {RER}| steel production, converter, chromium steel 18/8*") was taken from ecoinvent database and adapted for Germany. The dataset states that the process emits 0.0756 kg CO2 eq./kg steel (without capture).

- Carbon capture, compression, and pipeline transport were modeled according to the life cycle inventory presented in section 5.3.1.
- The CO2 capture efficiency for coal-generated electricity and steel production was set at 90%.
- Methanol production from captured CO2 was modeled according to Perez-Fortez et al. (2016) (i.e., 1 kg of CO2 is used to produce 0.68 kg of methanol).

The CCU systems are multifunctional. The first CCU produces both electricity AND methanol. The second CCU system produces both steel AND methanol.

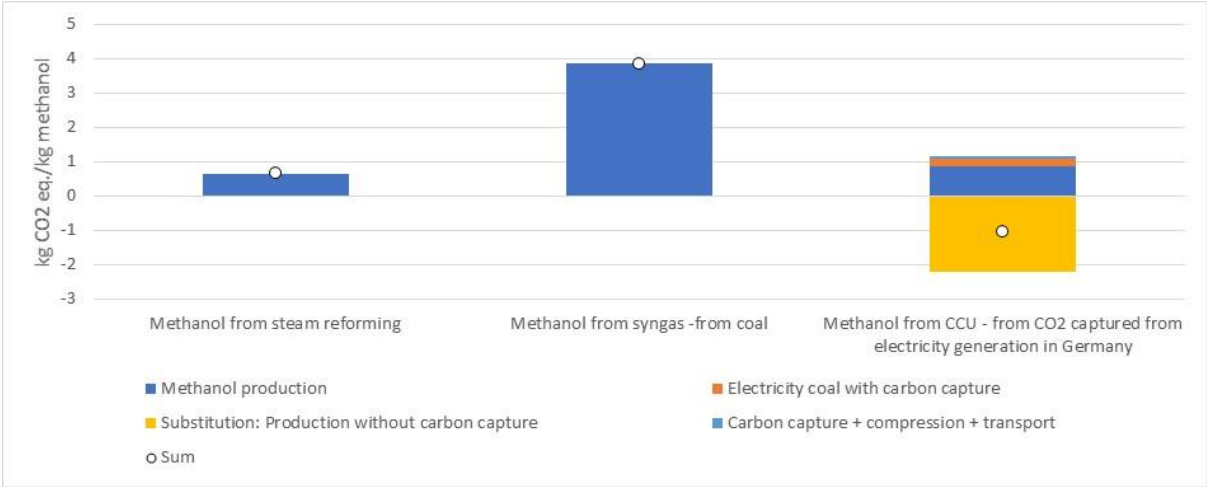
The system expansion is therefore obtained with the following equation:

- CCU system #1 (from coal generated electricity):

$$(2.6\ kWh\ from\ coal\ power\ plant\ with\ CO2\ capture + 1\ kg\ MeOH\ production\ from\ captured\ CO2) - 2.6\ kWh\ from\ coal\ power\ plant\ without\ CO2\ capture = 1\ kg\ MeOH\ production\ from\ captured\ CO2$$

- CCU system #2 (from steel production):

$$(21.6\ kg\ steel\ with\ CO2\ capture + 1\ kg\ MeOH\ production\ from\ captured\ CO2) - 21.6\ kg\ steel\ without\ CO2\ capture = 1\ kg\ MeOH\ production\ from\ captured\ CO2$$



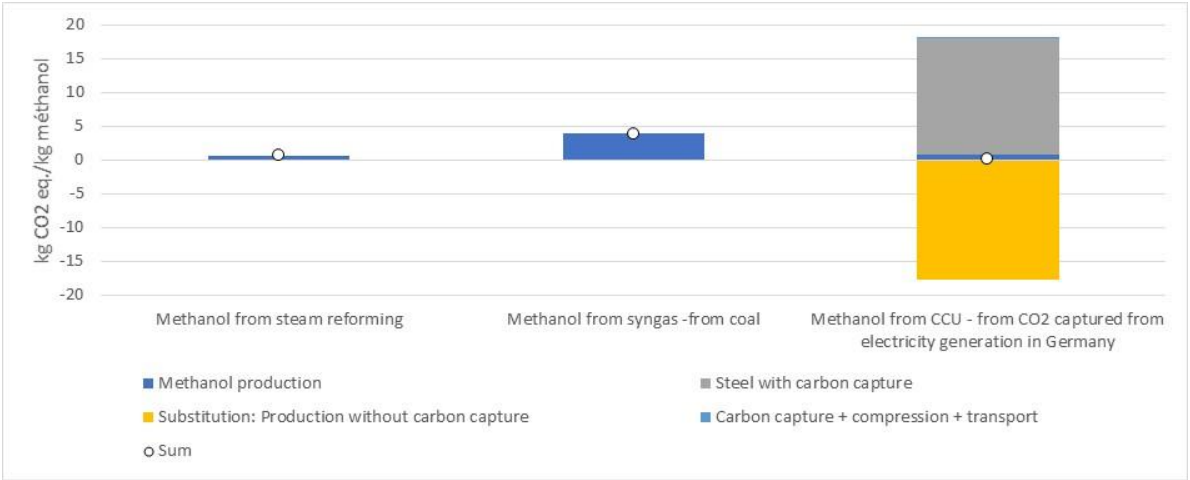


Figure 5-18: Illustration of the importance of the process from which captured CO2 originated. (UP) Focus on methanol produced from CO2 captured from a coal power plant and (DOWN) Focus on methanol produced from CO2 captured from a steel mill

Methanol produced from captured CO2 from a coal power plant amounts to -0.83 kg CO2 eq/kg methanol. Methanol produced from captured CO2 from a steel mill amounts to -0.55 kg CO2 eq/kg methanol. A difference of 33% between both systems.

Thus, different indicator results can be obtained depending on the process from which capture CO2 originated – putting more emphasis on the necessity of considering the entire cradle-to-grave system and stating that CO2 doesn't come without an environmental burden.

5.2.13 Solving CCU multifunctionality: allocation

This section does not apply to CCS systems – only CCU systems.

With CCS, CO_2 is considered a waste to be disposed of and does not have any "value". Solving CCU multifunctionality can be tackled with existing methodological approaches – no new developments are required. All guidelines are adamant: **CCU multifunctionality should be dealt with system expansion**.

However, system expansion can only be applied if the goal of the study is not product-specific.

If the goal of the study is to be product-specific then "*apply substitution and if impossible, apply allocation, first using underlying physical relationships, and if impossible, then another relationship, such as economic value*".

It should be noted that Brander et al. (2012)[56] stated that "*substitution is not appropriate for attributional LCA*" since "*the substitution method is unique in creating negative results for an LCA even when the physical removals associated with the product's life cycle are not greater than physical emissions. The reason for this difference is that substitution involves credit for emissions that have not happened. Because the substitution method includes a credit for emissions that have not happened, the results from an LCA that uses the substitution method will not equal total physical emissions.*".

Therefore, if a product-specific approach is taken, the allocation should be performed. The selection of an allocation basis will lead to important variations of results when allocating the impacts of a product and captured CO2. Indeed, CO2 is characterized as:

- Low mass (due to its gaseous nature);
- High volume (due to its gaseous nature);
- Doesn't have an energy content;
- Varying economic value depending on the location may or may not attribute an economic value to CO2 (such as a form of a carbon tax – which should also vary in time).
- From a philosophical point of view, CO2 is considered by many as waste and therefore should be unburdened with impacts – this was shown, however, to be untrue with a system expansion approach.

To illustrate the challenges of allocation with carbon capture, let's compare two different simplified examples with a coal power plant that captures its CO2 and then sell it to produce methanol and the same at a steel plant.

[56] https://ecometrica.com/assets/substitution_problem_with_current_LCA_standards.pdf

- At the German coal power plant:

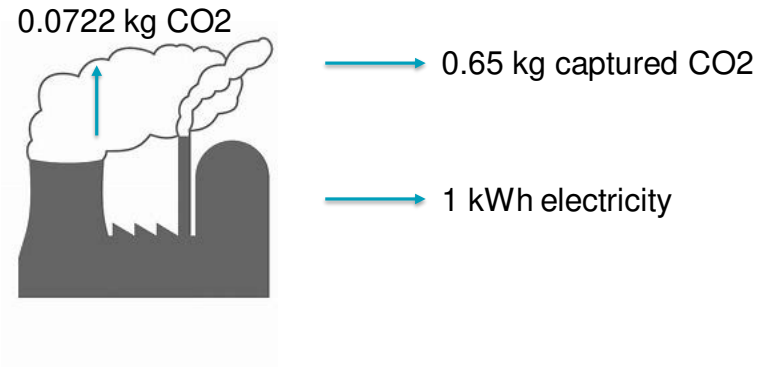


Figure 5-19: Illustration of a German coal power plant multifunctionality

In this instance:

- An energy allocation basis would be the most logical physical property to use (since the function for generating electricity is "to generate energy"). However, with this allocation basis, the electricity generation process wouldn't share the entire environmental impact burden since CO2 has no energy content;
- On an economic value, with an LCOE for coal power plant around 0.05$US/kWh and a carbon tax around 20$US/ton (0.02$/kg). If 0.650 kg CO2/kWh are removed, the impact split would be 80% for the electricity generation and 20% for the CO2 production.
- If CO2 is unburdened with impacts, 100% of the impact assessment should be allocated to electricity generation.

For the steel plant, assuming that 0.068 kg CO2/kg steel is captured (according to ecoinvent's "*1 kg Steel, unalloyed {RER}| steel production, converter, unalloyed*":

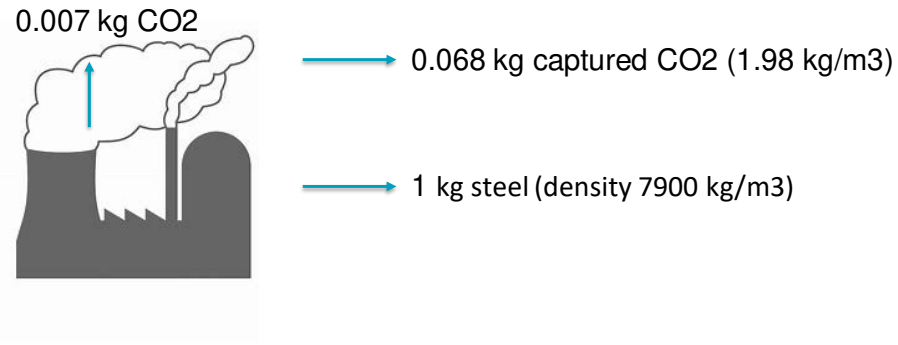


Figure 5-20: Illustration of a European steel mill multifunctionality; according to ecoinvent's "*1 kg Steel, unalloyed {RER}| steel production, converter, unalloyed*

In this instance:

- A mass allocation would split the impact indicators with 94% for the steel production and 6% for the CO2
- A volume allocation would split the impact indicators with nearly 100% for the steel production (considering a density of 7900 kg/m3)

- An economic allocation would split the impact indicator with 97% for the steel production (with a steel cost of 650$US/ton) and 3% for the CO2 (around 20$US/ton).
- If CO2 is unburdened with impacts, 100% of the impact assessment should be allocated to steel production.

Considering the observed variability in both examples, good LCA practices should always include a sensitivity analysis of several bases of allocation to assess the variations in indicators results following the allocation choice.

5.2.14 Data sources and assumptions, the included and excluded processes (and the reason for their exclusion if applicable), life cycle impact assessment method description, and subsequent analysis to ensure the robustness of the obtained conclusions.

While in an LCA report the data sources and assumptions, the included and excluded processes (and the reason for their exclusion if applicable), the life cycle impact assessment method description, and the subsequent analysis to ensure the robustness of the obtained conclusions, are presented in the Goal and Scope of the study, each of these topics is rather discussed in details in the following sub-sections.

5.3 Life cycle inventory

In an LCA, this second phase is akin to an accounting exercise during which the material and energy inputs and outputs (including waste), the emissions to air, water, and soil, are computed for each process in the life of a product/process/service.

During this phase, primary and secondary data are collected with questionnaires, from the literature and/or from life cycle inventory databases. The data is then typically entered into LCA software.

5.3.1 Data availability for attributional LCA

Data availability is often the main challenge in providing a reliable life cycle assessment as inventory data need to describe a given process with the right technological level, representative of the on-location practice of a specified geographical context at a given time (i.e. the functional unit).

From the literature review (from Section 4), two different approaches have been considered for data acquisition: relying on past studies from the literature and process modeling.

1) **Find data in the literature from previous works**
   - 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.
2) **Process modeling**
   - 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 datasets.

The following tables provide some LCI data taken from the literature for the readers' convenience for MEA-based post-conversion capture, carbonate-based post-conversion capture, CO_2 compression, CO_2 transport, and CO_2 injection (specific to CCS).

Table 5-8 : MEA and carbonate post-conversion - based carbon capture

Process	Data	Data source	Comment
MEA/Carbonate capture efficiency			
CO_2 (% removal from flue gas)	90% (85-96%)	Literature	Kornneef et al. 2008
H_2O (% removal from flue gas)	5%		
SO_2 (% removal from flue gas)	90% (40%-99.5%)		
NO_X (% removal from flue gas)	1.25% (0.8-1.25%)		
HCl (% removal from flue gas)	95%		
HF (% removal from flue gas)	90%		
PM (% removal from flue gas)	50%		
NH_3 (kg /t CO_2)	0.21		
Carbon capture – MEA			
Input MEA [kg /kg CO_2]	0.002143	Literature	Average of values from Korre et al. (2010), Kornneef et al. (2008), and Grant et al. (2014)
Input NaOH [kg /kg CO_2]	0.000107		
Input Energy (steam in elec eq): coal systems [kWh /kg CO_2]	0.273 (0.11-0.37)		
Input Energy (steam in elec eq): natural gas systems [kWh /kg CO_2]	0.17 (0.08-0.19)		
Input Electricity [kWh /kg CO_2]	0.0265		
Input Cooling water [kg /kg CO_2]	1.914		
Input $CaCO_3$	0.0027		
Output Reclaimer waste	0.005999		
Output Filter waste	7.88E-05		
Output Emission to water	Several		Grant et al. (2014)
Output Emission to air	Several		
Carbon capture - carbonate			
Potassium carbonate [kg /kg CO_2]	0.00012	Literature	Grant et al. (2014)
Rate promoter [kg /kg CO_2]	0.00048		
Potassium hydroxide [kg /kg CO_2]	0.0045		
IX resin [kg /kg CO_2]	3.8E-6		
Water [L /kg CO_2]	1.009		
Input Energy (steam in elec eq): natural gas systems [kWh /kg CO_2]	0.12		
Input Electricity [kWh /kg CO_2]	0.017		
Carbon capture - infrastructure			
Steel (t)	317	Literature	Kornneef et al. 2008
Concrete (m^3)	1		
Total CO_2 capture over lifetime (Mt)	94		

Table 5-9 : life cycle inventory data for CO_2 compression

Process	Data	Data source	Comment
Compression - operation			
Compression energy (kWh/t CO_2)	111	Literature	Kornneef et al. 2008
Fugitive CO_2 emission compressor (t CO_2 /MW /yr)	23.2 (7.0-116.1)		
Compression - infrastructures			
Concrete (m^3)	65	Literature	Kornneef et al. 2008
Diesel (GJ)	1978		
Electricity (MWh)	61		
Steel (t)	65		
Copper (t)	7		
Polyethylene (t)	20		
Total CO_2 compressed over lifetime (Mt)	62		

Table 5-10 : Life cycle inventory data for CO_2 transport - pipeline

Process	Data	Data source	Comment
Transmission – operation			
Pipeline length (km)	50	Literature	Kornneef et al. 2008
Fugitive CO_2 emission pipeline (t CO_2 /(km year))	2.32 (0.2-23.2)		
Transmission – infrastructures			
Sand (t)	97500	Literature	Kornneef et al. 2008
Diesel (GJ)	165500		
Steel (t)	12000		
Bitumen (t)	116		
Polyethylene (t)	232		
Total CO_2 transported over lifetime (Mt)	94		

Table 5-11 : Life cycle inventory data for CO_2 injection

Process	Data	Data source	Comment
Injection – operation			
Injection – compression energy (kWh /t CO_2)	7	Literature	Kornneef et al. 2008
Injection – infrastructure			
Sand (t)	712000	Literature	Kornneef et al. 2008
Steel (un-alloyed) (t)	3800		
Steel (high alloyed steel) (t)	8100		
Concrete (m^3)	10463		
Copper (t)	425		
Total injection capacity over lifetime (Mt)	219		

The main challenge of data acquisition from the literature is a risk that technology hasn't been documented, such as with technologies at low TRL. 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.

5.3.2 Data availability for consequential LCA

The data for the CO2 capture, compression, transport, injection or use are the same as with attributional LCA. Additional information needs to be gathered, however, to assess both the market evolution for the affected activities from the availability of CO_2-based products and the life cycle inventory data of those affected activities.

5.3.3 Data availability for dynamic LCA

The data is the same as the attributional LCA. Additional information needs to be provided, however, such as the moment in time in which the emission will occur. The data is now not only technology and geographically dependant, but also time dependant. Unfortunately, the timing of the emission is not currently documented in available LCI databases. Therefore, work is needed to put the inventory emissions in their proper timeframe.

5.3.4 Data availability for prospective LCA

The data will be somewhat like attributional LCA. The data in the entire life cycle database will need to be modified to ensure the representativity of the prospective scenarios.

5.3.5 Data variability

When data is available from multiple sources, it is possible that for the same given process, gathered data vary widely as it represents different on-location practices or accounts for an intrinsic variation (e.g. the composition of extracted natural gas varies from well to well and from region to region altering the treatment process).

The only way to tackle this issue is first to select the most credible and appropriate value (or if impossible, select an average value of the varied data), then to perform sensitivity and/or uncertainty analyses and, depending on the life cycle impact assessment indicators results, provide mitigated overall conclusions.

5.3.6 Included/excluded processes

As with all LCA, one should include as many processes as possible. If for any reason, a process is excluded, reasons for the exclusion and potential effects on the overall conclusion of said exclusion need to be provided in all transparency.

5.3.7 Regionalization

Depending on the geographical location, different practices and inventory data may be available – especially for the electricity consumed by different processes. It is good LCA practices to attempt to represent, as best as possible, the operating conditions.

The figure below illustrates the potential variation of GHG emissions associated with the adaptation of LCI data to different geographical contexts.

Note: in these examples, except for electricity consumption and water consumption, data could not be regionalized for lack of correct market identification.

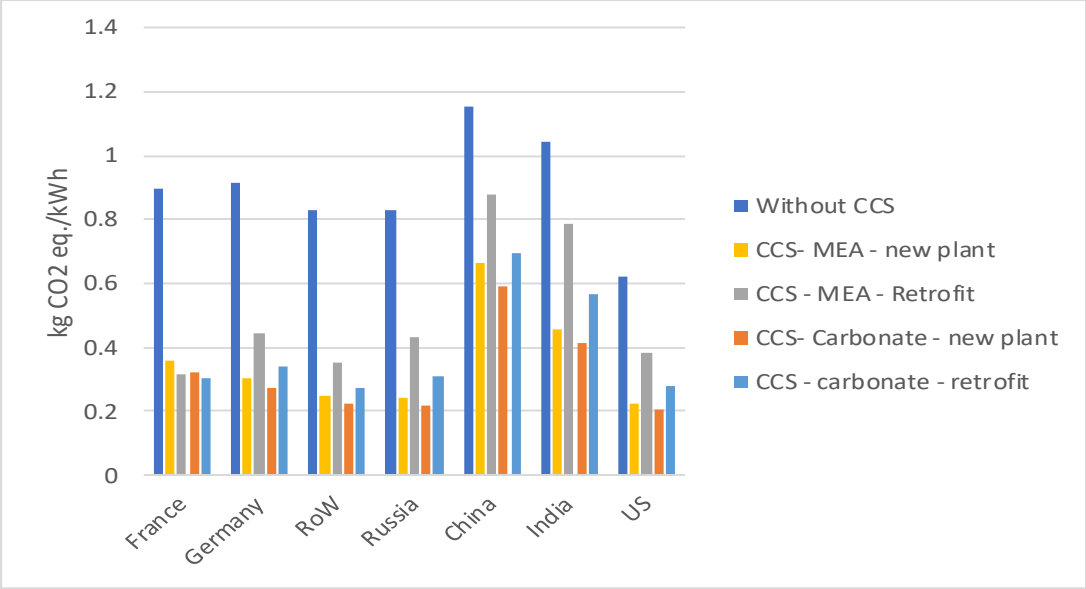


Figure 5-21: GHG emissions from electricity generation from a coal conventional power plant with and without carbon capture adapted to different countries

Note: new plants generate 1 kWh of electricity while retrofitted plants provide 0.7 kWh from the plant and require compensation of 0.3 kWh of electricity from the grid.

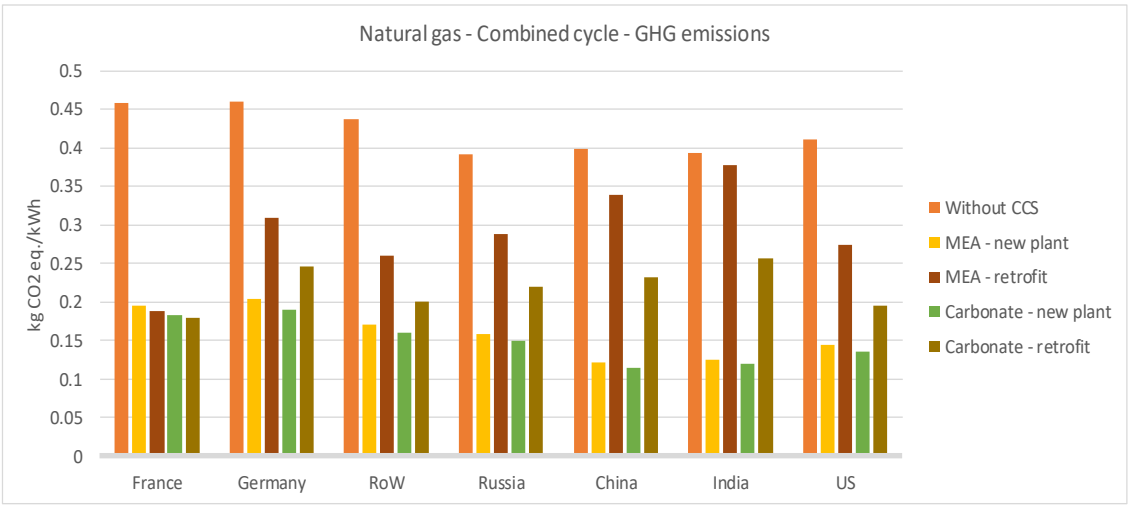


Figure 5-22: GHG emissions from electricity generation from natural gas in a combined cycle power plant with and without carbon capture adapted to different countries

Note: new plants generate 1 kWh of electricity while retrofitted plants provide 0.7 kWh from the plant and require compensation of 0.3 kWh of electricity from the grid.

5.4 Life cycle impact assessment

During this third phase of an LCA, the life cycle impact assessment method converts the life cycle inventory data into different environmental impact indicator results which assess in a single numerical value a complex environmental cause-effect chain from emission to potential damages to areas of protection (i.e.

Human health, *Ecosystem quality*). This conversion from quantity (i.e. life cycle inventory) into impact indicators is carried out with the so-called characterization factors which translate, for each impact category, the cause-effect chain which has been modeled through a series of environmental models.

Even if CO_2 is the main focus of CCS/CCU, i**t is extremely important to state that *Climate change* is not the only impact category that should be considered within an LCA of CCS and/or CCU**

To follow the ISO 14040: 44 standards, "*all relevant impact categories **should** be considered*". As the development of CCS/CCU technologies affects a variety of environmental impact categories (see Figure 4-2 to Figure 4-8), to identify the transfer of impacts, impact categories **should not** be omitted from LCA studies and impact assessment should be carried out using reliable existing impact assessment methods.

5.4.1 Indicator results

CO_2 is captured from fossil or biogenic emission point sources or directly from the atmosphere via direct air capture. Fossil point sources release carbon previously stored in underground reservoirs, while biogenic point sources release carbon previously removed from the atmosphere (i.e. plant uptake). The capture process will use different types of solvents and energy to isolate CO_2. The compression, transport, injection, or use will also use energy.

Therefore, one can expect that CCS indicator results will always be positive

For CCU, due, in part, to the system expansion calculations, indicator results can either be positive, negative, or neutral. Specifically, for *Climate change*, Müller et al. (2020) describe the instances when each situation occurs for CCU technologies:

- Neutral:
  - CCU technologies can theoretically be carbon neutral over their entire life cycle (i.e. not zero) if CO_2 is captured from the atmosphere (via biogenic point sources or direct air capture) and is released at the end-of-life, or if CO_2 is captured from fossil point sources and is sequestered or permanently stored in the product and if there are no other GHG emissions over the life cycle.
- Negative:
  - CCU technologies can have net negative emissions if CO_2 is captured from the atmosphere (via biogenic point sources or direct air capture) and is sequestered or permanently stored in the product and if other life cycle GHG emissions are lower than the amount of CO_2 captured. If the amount of atmospheric CO_2 captured and sequestered is equal to the amount of other life cycle GHG emissions, the process is carbon neutral.
- Positive :
  - In all other cases, CCU technologies have a net positive life cycle GHG emissions.

5.4.2 Impact assessment applied to CLCA of CCU

As previously mentioned, CLCA has been sparingly applied to CCU. The paper entitled *Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry*[57] compared different carbon capture use according to a "net substitution" approach which is akin to system expansion in attributional LCA. In this paper, no modeling with partial and general equilibrium models has been used. The obtained results are shown in the following figure.

[57] https://pubs.rsc.org/en/content/articlepdf/2019/ee/c9ee00914k

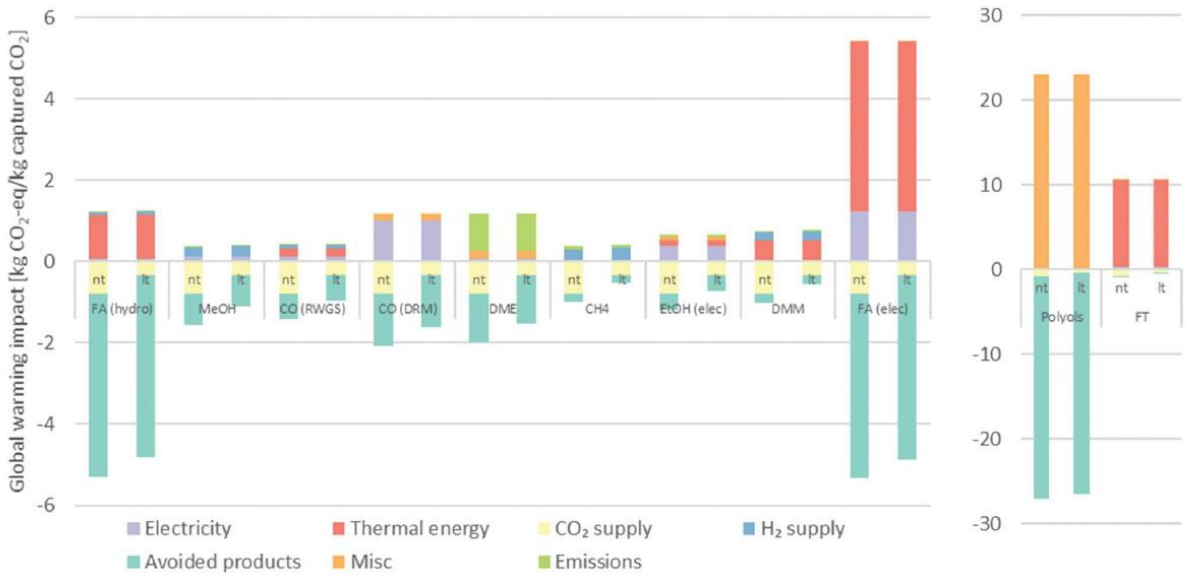


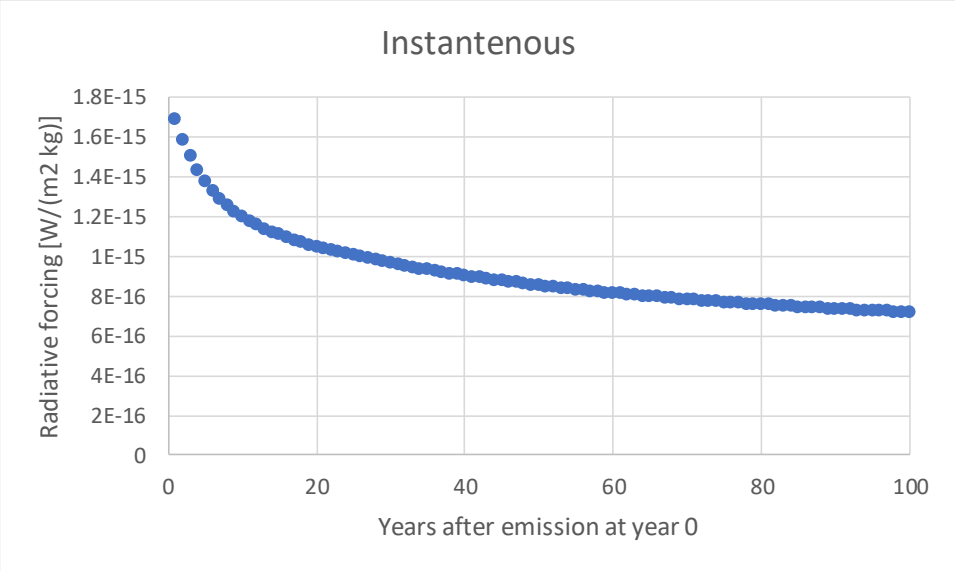
Figure 5-23: Consequential "net substitution" LCA results obtained by Thonemann et Pizzol (2019)

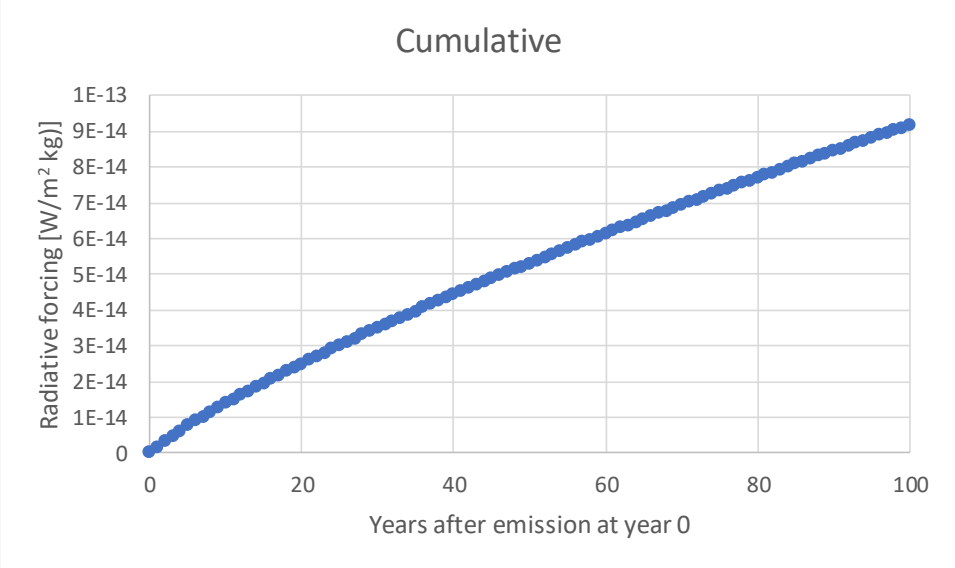
As seen, **results vary significantly depending on the avoided displaced production**.

5.4.3 CCS/CCU dynamic impact assessment

To obtain a dynamic impact assessment, one needs to not only apply a time-dependent life cycle inventory but also dynamic characterization factors. **Currently, the dynamic characterization factors are limited to the *Climate change* impact category**. Additional methodological developments are required to obtain dynamic characterization factors for other impact categories.

The following figure illustrates the instantaneous (i.e. yearly) and the cumulative (i.e. the sum of all previous instantaneous effects) of radiative forcing of 1 kg of CO2 at year 0. The known GWP is the ratio between the cumulative radiative forcing of a GHG and the cumulative radiative forcing of CO2 for a given time horizon.





The following examples illustrate the potential importance of dynamic LCA to CCS and CCU.

For CCS, as previously mentioned, stored CO_2 is still expected to leak: the NETL estimates a leakage rate between 0 and 1% (with an average of 0.5% over a 100-yr horizon) (Cooney et al. 2015)[58]. The following figure presents the effects of applying dynamic LCA calculations, over a 100 years time frame, to the life cycle GHG emissions considering that the coal electricity generation in Germany, carbon capture, transport, and injection occur at year 0 and that the leaks will occur following:

[58] NETL states that this remains an assumption until measurements from operating storage sites can validate the leakage rate. They also state that geologic formations with a potential leakage rate greater than 1% would be discarded for CO_2 storage.

- 0.5% of the sequestered carbon will leak uniformly for 100 years starting at year 20 and leaking up to 120 years after injection;
- 0.5% of the sequestered carbon will leak uniformly for 100 years starting at year 50 and leaking up to 150 years after injection;
- 0.5% of the sequestered carbon will leak uniformly for 100 years starting at year 80 and leaking up to 180 years after injection;

In this example, the GHG contributors from the attributional LCA (considering a GWP_{100}) is as follow:

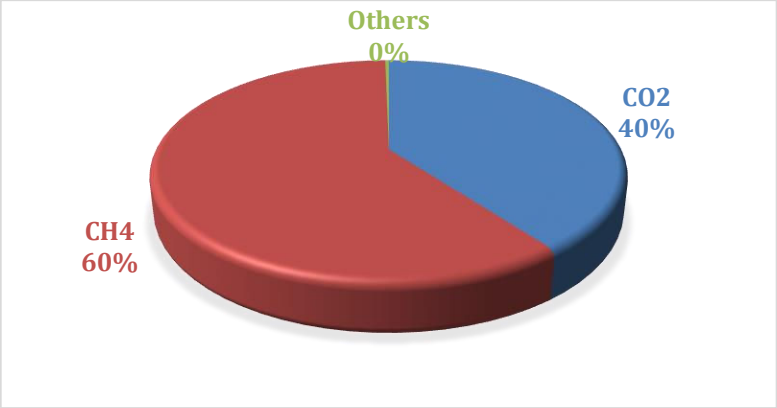


Figure 5-24: Attributional LCA GHG inventory breakdown of coal-generated electricity in Germany with CCS.

Therefore, this example will only target the dynamic effects of CO2 and CH4 to the instantaneous radiative forcing.

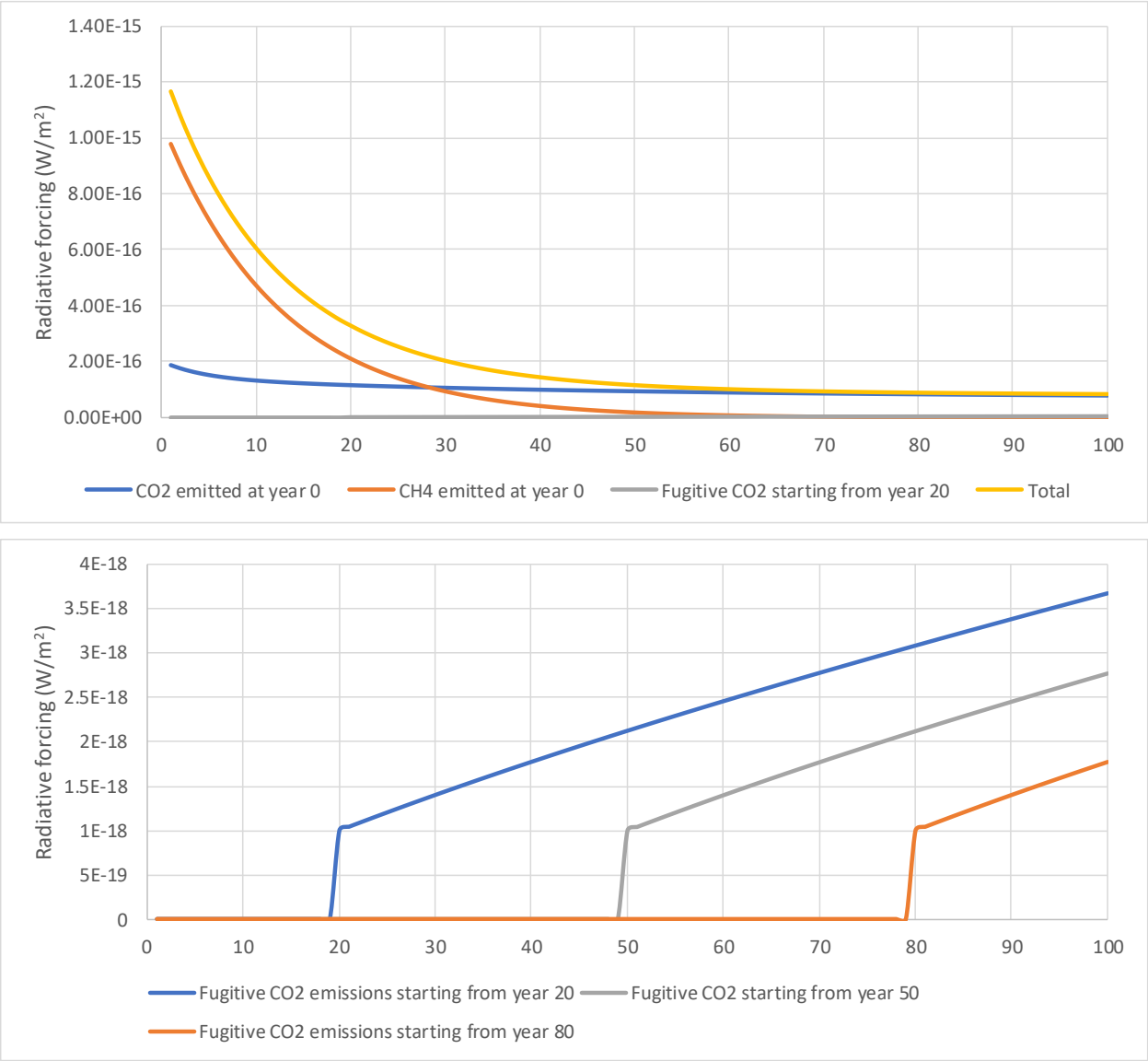


Figure 5-25: Dynamic LCA framework over a 100 years' time frame starting from CO_2capture of a coal power plant in Germany – CCS framework:

(up) CCS's CO2 and CH4 related radiative forcing without the fugitive CO2 emissions after storage, (down) focus on the fugitive CO2 emissions after storage.

As seen, from this example, the yearly CO2 fugitive emissions escaping the long-term storage are gaining importance with each passing year but are nowhere near the impact of the rest of the system whose emissions occurred at year 0. It is also shown that most of the "total" radiative forcing of the entire system is related to methane – a short-lived GHG - until CO2 becomes the main contributor. Starting from year 50, the instantaneous radiative forcing of the "total" is indistinguishable from the "CO2" curve.

CCU products offer temporary carbon storage. Due to temporary carbon storage, CO_2 emissions can be delayed and thus, do not contribute to climate change during the storage period. The relevance of temporary storage depends on the class of CO_2-based products or fuel considered. Müller et al. (2020) propose a decision tree to identify if temporary carbon storage is relevant, depending on different uses, and will need to be accounted for in dynamic LCA.

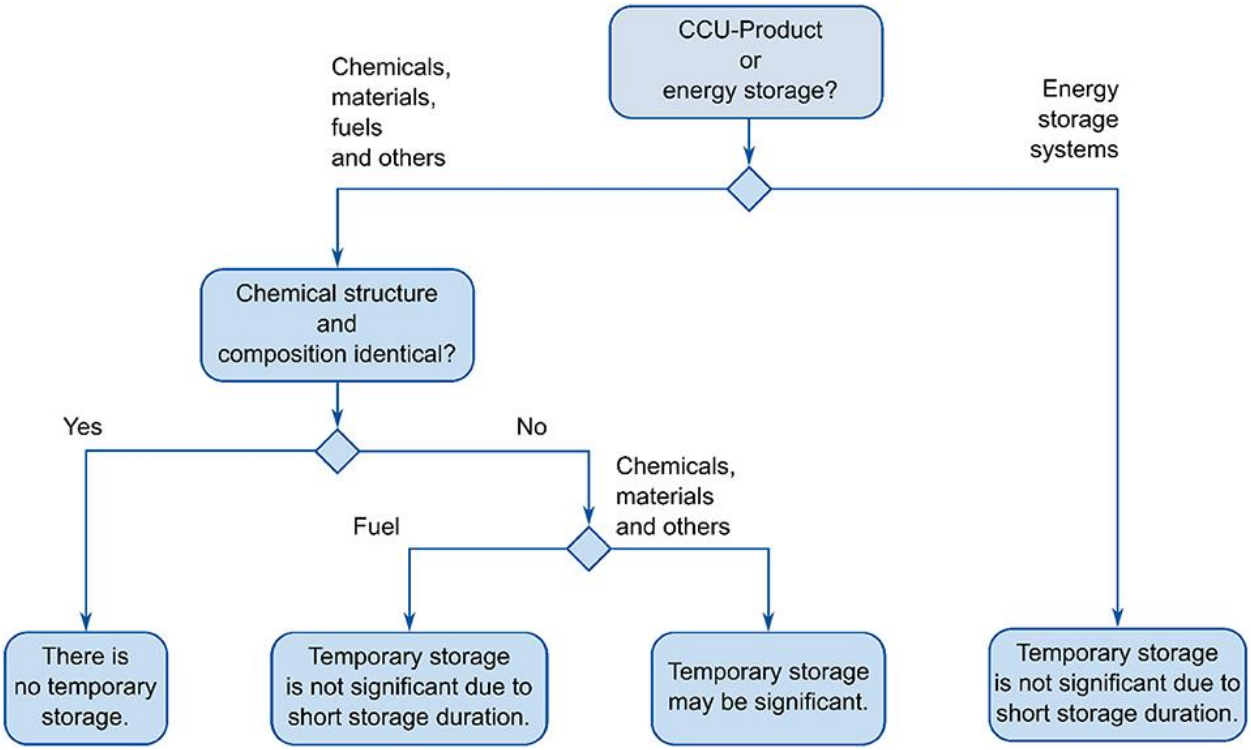


Figure 5-26: Temporary storage relevance for dynamic LCA of CCU-based products (Muller et al., 2020)

Note: the figure was taken directly from Muller et al. (2020) which defines the "identical chemical structure and composition" as the same chemical structure and composition to their conventional counterparts; meaning that in a comparison with their counter-part, captured CO2-based chemical, materials, fuels, and others wouldn't be differentiated from their counterpart. Without differentiation, the products downstream would be identical and therefore could be excluded from the comparison.

As seen, only for *Chemicals, materials, and others* with different chemical structures and compositions, **can** the temporary storage be key.

The temporary storage of chemicals, materials, and others need to be checked as not all captured CO_2-based products will allow significant sequestration. As an example, in the next figure, 98% of the carbon from the urea is shown to be reemitted back to the atmosphere within 8 days.

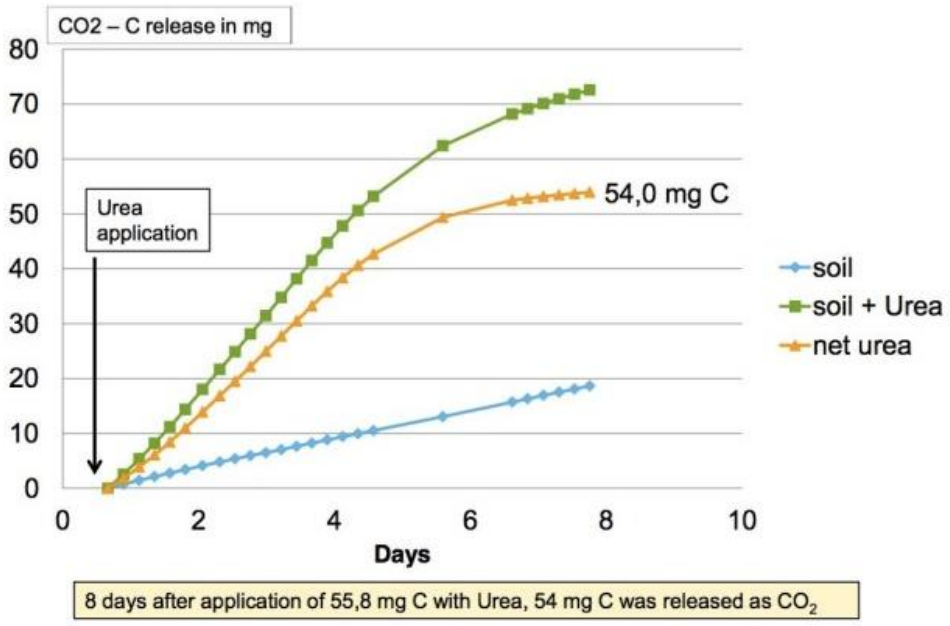


Figure 5-27: CO_2 emissions from urea hydrolysis (Brown, 2016)

As such, in most cases, the use of CO_2 is not a permanent solution to CO_2 emissions – it helps limit additional ones by recycling CO_2 from other processes.

The following example highlights an example of a dynamic assessment approach to CO_2 use through methanol production. For this example, the system generated 1 kWh of electricity in a coal power plant equipped with post-conversion MEA capture technology in Germany. The captured CO2 is then used to produce methanol (1 kg of used CO_2 to produce 0.68 kg of methanol according to Perez-Fortez et al. (2016)). For the sake of this example, the methanol is then used a year later. There was a temporary storage of the captured CO2 for a year. The given dynamic assessment is shown in the following figure.

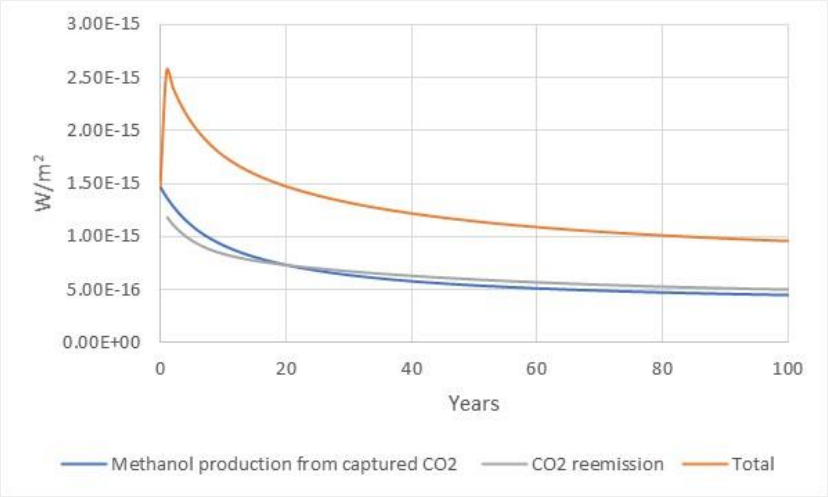


Figure 5-28: Potential effects of temporary storage of CO2 in methanol over a year – CCU framework

As seen, in the previous example, the temporary storage allowed to decrease about 50% the overall GHG emissions of the use of CO_2 in methanol for a single year after its capture in a coal power plant.

5.4.4 Changes in conclusions depending on the impact assessment method

Not all life cycle impact assessment methods evaluate the same cause-effect chain or use the same environmental model for a given impact category. Therefore, different conclusions can be obtained depending on the impact assessment method.

This issue is not specific to CCS/CCU LCA studies and, as with all ISO compliant LCA studies, a sensitivity analysis should be carried out with another impact assessment method to assess the robustness of the conclusions.

5.4.5 Regionalization

Depending on the impact category, indicator results may vary depending on sets of factors that would detail a more specific reality.

This issue is not specific to CCS/CCU LCA studies.

The *Climate change* impact category is not affected by regionalization as effects are modeled at a global; not regional, scale.

The following table summarizes the impact categories that may be affected by regionalization and those that are not.

Global impact categories (unaffected by regionalization)	Regional impact categories (affected by regionalization)
Climate change	*Smog*
Fossil and nuclear energy depletion	*Ecotoxicity*
Mineral resource depletion	*Toxicity*
Ozone layer depletion	*Acidification*
Ionizing radiations	*Eutrophication*
	Water scarcity
	Land use
	Land transformation
	Particulate matter

5.5 Interpretation

The fourth and final phase of an LCA, interpretation, ensures the robustness of the conclusions through different contributions, sensitivity, and uncertainty analyses, data quality assessment, etc. Recommendations on how to improve the robustness of the study are also enumerated.

Each of those is discussed in the following sub-section.

5.5.1 Contribution analysis: CCS systems

Figure 5-29 and Figure 5-30 present contribution analyses for coal conventional and natural gas combined cycle power plants with CCS in Germany. They show, for the *Climate change* impact category the contribution of each life cycle stage. The analysis could also be made at the substance level, or for other impact categories.

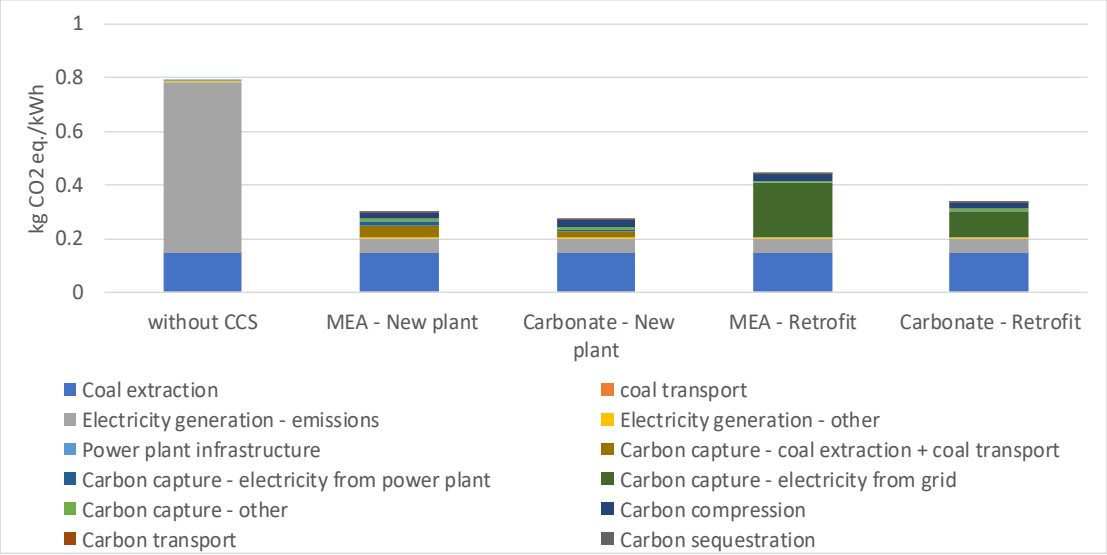


Figure 5-29: Contribution analysis for electricity generation from coal with and without CCS in Germany

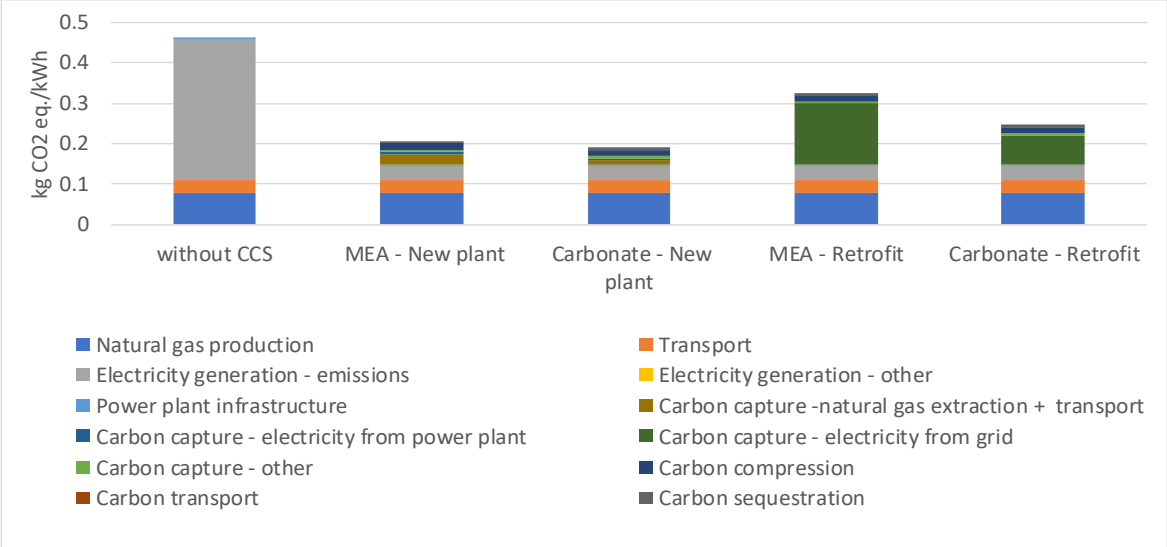


Figure 5-30: Contribution analysis for electricity generation from natural gas in a combined cycle power plant with and without CCS in Germany

Based on these examples, the focus should be on the electricity generation process and the coal/natural gas extraction/production since these stages show the highest contributions to the overall life cycle GHG emissions.

Note: contribution analysis should be carried out for all impact categories to properly identify all main contributors; not only those for the *Climate change* category

5.5.2 Sensitivity analysis

Sensitivity analyses should be carried out on the most influential parameters – the ones that affect the most the life cycle impact assessment results. Contribution analyses will allow for better identification of these sensitive parameters.

As was said another LCIA method should always be used to test the robustness of the conclusions. Several impact assessment methods are available, and the European Platform on Life Cycle Assessment has made recommendations, the most recent through the Product- and Organisation- Environmental Footprint (PEF and OEF, or more generally EF) initiative[59].

Other sensitivity analyses may consider (but not limited to):

- The CO2 capture efficiency;
- The CO_2 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;
- The leakage rate of the CO_2 storage geological formation;
- Methane fugitive emissions associated with coal or natural gas systems;
- The allocation rules (if applicable) such as mass, energy, or economic;
- The avoided process(es) for CCU systems in consequential LCA (if applicable).

CO2 Capture efficiency

As seen from LCI data, the CO_2 capture process efficiency is variable: between 85% and 96% with an average of 90%. The following figure shows the results of a sensitivity analysis on the capture efficiency for coal electricity generation with CCS across different countries. As seen, the efficiency variability range leads to *Climate change* indicator results that can change by ±50 g CO_2 eq./kWh.

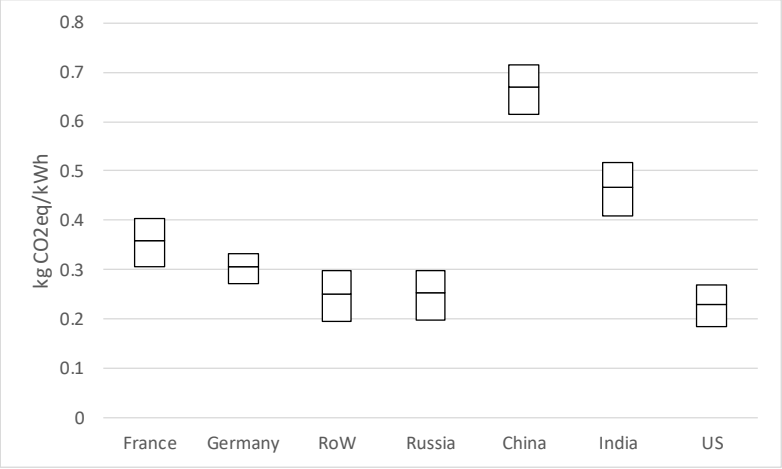


Figure 5-31: Sensitivity analysis results on the CO_2 capture efficiency for the *Climate change* category for coal electricity generation with CCS in different countries

[59] https://eplca.jrc.ec.europa.eu/singleMarket.html

The CO_2 capture process energy consumption

Figure 5-32 presents the GHG emissions for electricity generated from coal and natural gas new and retrofitted power plants with MEA-based carbon capture technology (CCS framework), for Germany according to variation energy consumption ranges found in the literature: 0.11-0.37 kWh/kg CO2 and 0.08-0.19 kWh/kg CO for coal and natural gas power plants, respectively.

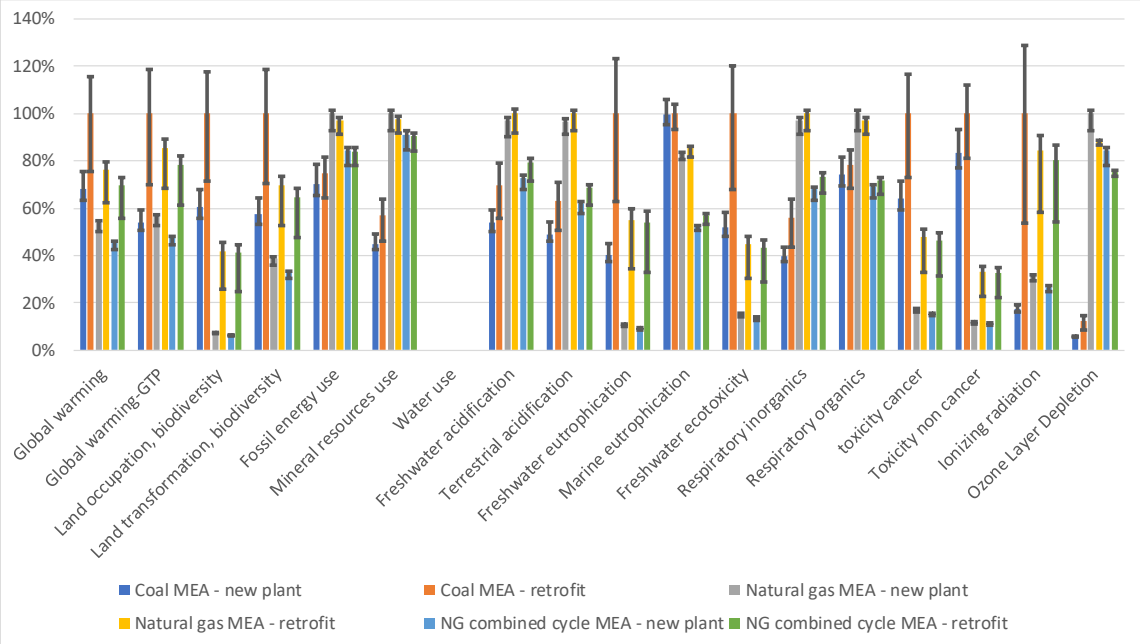


Figure 5-32: Effects on life cycle impact assessment of carbon capture energy requirements variations for coal and natural gas new and retrofitted power plants with MEA-based capture technology, for Germany

The type of capture process (pre-conversion, post-conversion, oxy-fuel combustion, or DAC)

If the goal of the study is to perform a comparison of different capture technology, then this sensitivity analysis wouldn't need to be performed – it should have been assessed in the main analysis. If, however, the goal of the study is to assess, for example, the "environmental impacts related to captured CO2 to generate product X" then it would be recommended to test several capture technologies.

The type of solvent used during the carbon capture

The use of different solvents may lead to a difference in process operations which could influence the overall results of the carbon capture. For example, it is well known that amines have adverse toxicological and ecotoxicological effects. Therefore, if a carbonate-based solution was used instead, then those toxicological and ecotoxicological effects would not occur. Furthermore, it has been shown (see section 5.3.1) that carbonate-based solution requires less energy for the same process. Therefore, we recommend testing different types of solvents if the goal of the study is unspecific to a particular solvent type.

The following figure illustrates the potential changes with either MEA or carbonates for post-conversion capture in a coal power plant.

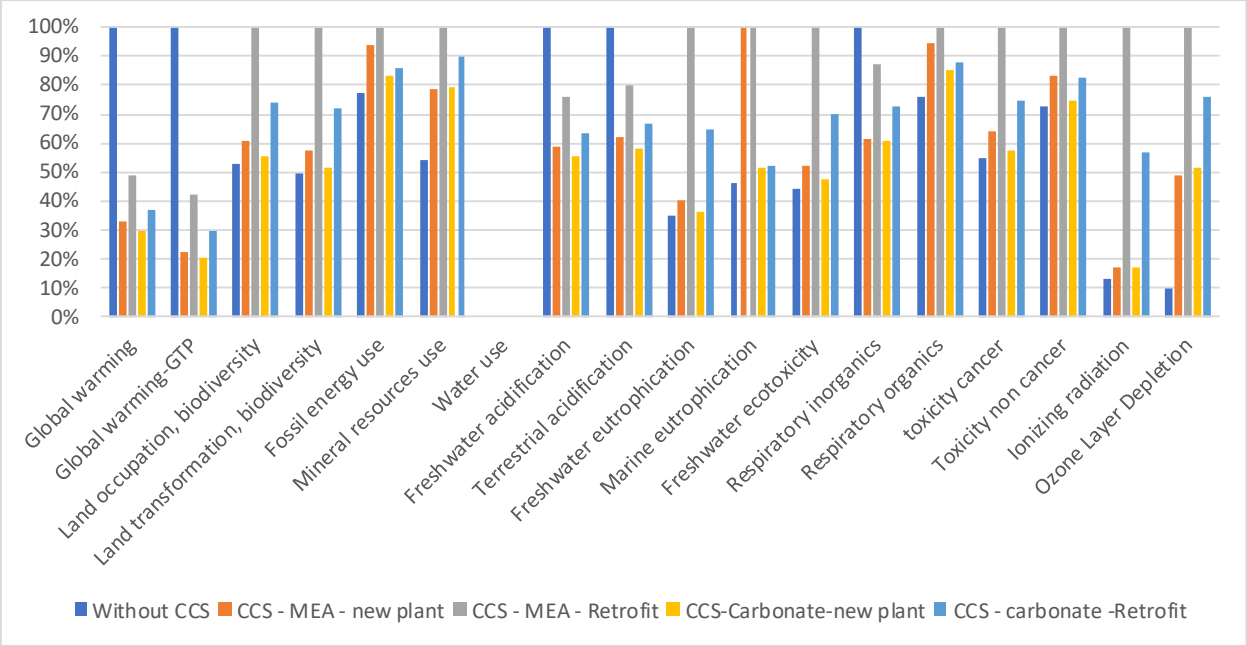


Figure 5-33: Illustration of the potential variations associated with coal-generated electricity without and with CCS (with MEA or carbonates) for the German context [60] - IMPACT World + impact assessment method

Note: the life cycle inventory data used to provide these results were presented in section 5.3.1

Combustion efficiency

This sensitivity analysis is not specific to carbon capture but may change the overall environmental profile of power plants. The following figures illustrate the consequences of varying electricity generation efficiency at the power plant on GHG emissions in different countries around the world.

[60] Note: Water use is listed as an impact category at the midpoint level but doesn't assess the impact of any substances.

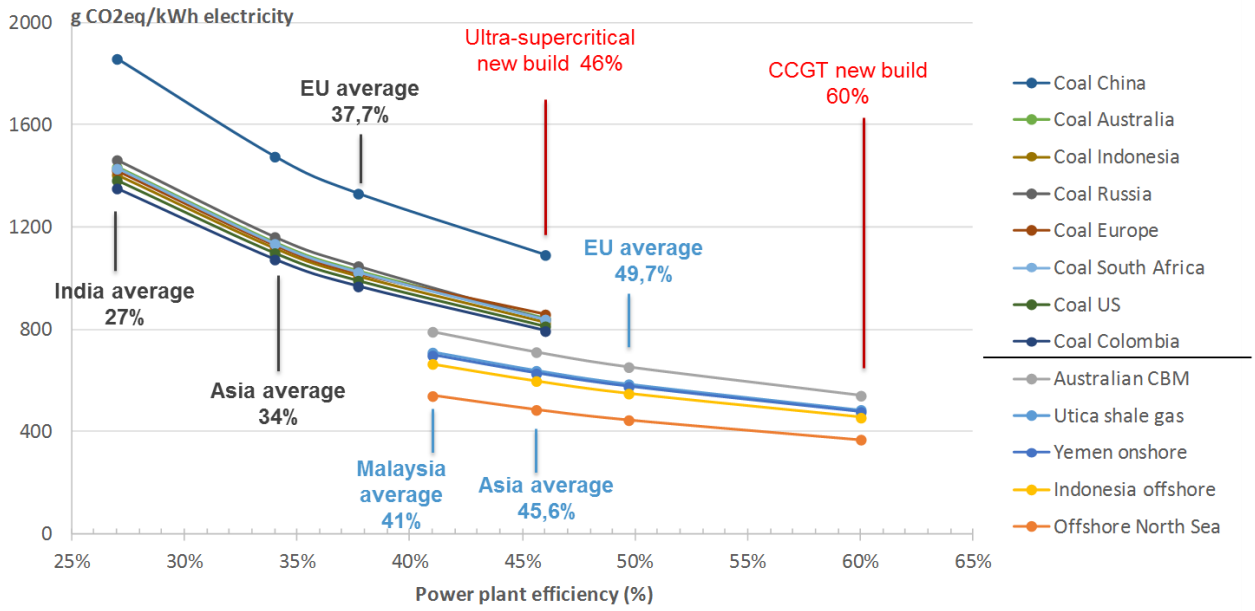


Figure 5-34: Consequences of varying the electricity production efficiency at the power plant on the estimates of the GHG emissions (IPCC 2007's GWP_{100}) (taken from Roy et al., 2016)

Similar trends could be achieved for heat-producing systems also (the efficiency would be in another bracket, but the point still stands).

The CO2 transport options and distances: pipeline or freight transport;

The following figure illustrates the results of a sensitivity analysis related to the transport type and transport distance.

Data for CO2 compression and pipeline travel were presented in section 5.3.1. Data for CO2 liquefaction ("*Carbon dioxide, liquid, production*") and ship transport ("*Transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas*") were taken directly from the *ecoinvent* database.

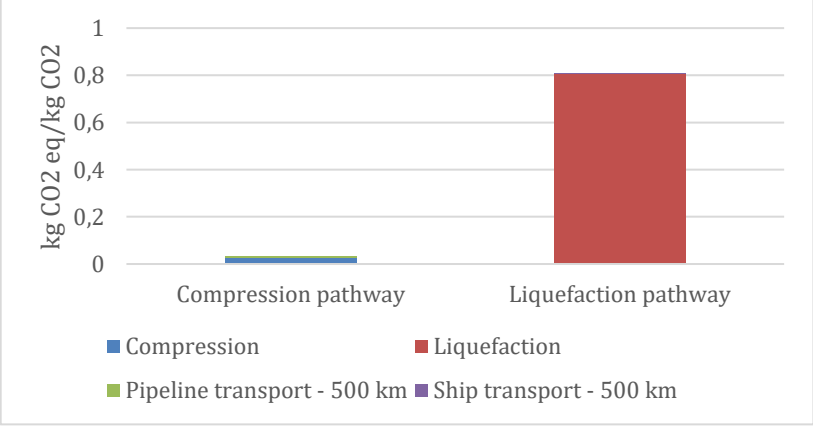


Figure 5-35: Sensitivity analysis of captured CO2 transport types

Note: we believe the ecoinvent's CO2 liquefaction process to be significantly overestimated. CO2 liquefaction data warrants an in-depth review which is out of the scope of this study.

Travel distance between transport type can be obtained from the following equation:

$$Compression\left[\frac{kg\ CO2\ eq}{kg\ captured\ CO2}\right] + Pipeline\left[\frac{kg\ CO2\ eq}{kg\ captured\ CO2\ x\ km}\right] \times distance[km]$$
$$= Liquefaction[\frac{kg\ CO2\ eq}{kg\ captured\ CO2}] + Ship\left[\frac{kg\ CO2\ eq}{kg\ captured\ CO2\ x\ km}\right] \times distance[km]$$

From the previous example, the distance that would allow both systems to be equivalent is equal to 79720 km.

The leakage rate of the CO_2 storage geological formation

The NETL and IPCC state that CO2 may be emitted from the long-term geological storage at a rate between 0 and 1% of the stored CO2 over 100 years. We recommend using the average value of this range for the main scenario but to test the effects of modifying the emission rate on the overall results.

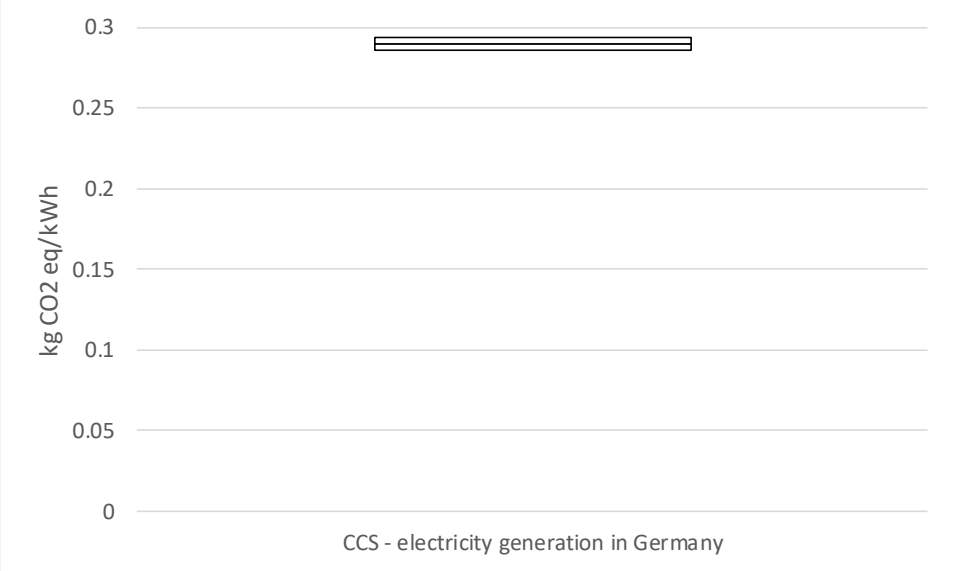


Figure 5-36: Variations in GHG emissions associated with the potential fugitive CO2 emissions (between 0 and 1% of the sequestered CO2) from the long-term storage location

Methane fugitive emissions associated with coal or natural gas systems/ use of GWP_{20} vs GWP_{100}

We only recommend performing this sensitivity analysis if natural gas is the focus or used in the foreground processes of a system. However, this sensitivity analysis is not specific to carbon capture and is related to methane emissions that may change the background GHG emissions.

The allocation rules (if applicable) such as mass, energy, or economic.

We have discussed the particulars of this analysis in section 5.2.13

The avoided process(es) for CCU systems in consequential LCA (if applicable).

The goal of consequential LCA is to assess the impacts of introducing a new product into a market. If this new product can substitute existing products, then the production of these products is avoided. This sensitivity analysis doesn't apply if the new product is used additionally to existing products.

While accounting for the process which captures the CO2 is relatively easy to identify (the process with and without carbon capture), the process which is "displaced" by the captured CO2-based product may regionally differ or differ in time, potentially altering the overall environmental profile.

The following example illustrates the net substitution of methanol from natural gas steam reforming and methanol from syngas from coal gasification by methanol produced from captured CO2.

According to Perez-Fortez et al. (2016), it takes every 1 kg of used CO2 to produce 0.68 kg of methanol. According to the ecoinvent database, with a 90% capture efficiency, 0.7 kg CO2/kWh can be captured.

The following figure details the positive GHG emissions from the produced methanol related to the post-conversion capture of a coal power plant in Germany. It also details the avoided generated electricity from a coal power plant without carbon capture as well as either 1 kg of methanol from natural gas steam reforming or from syngas obtained from coal gasification.

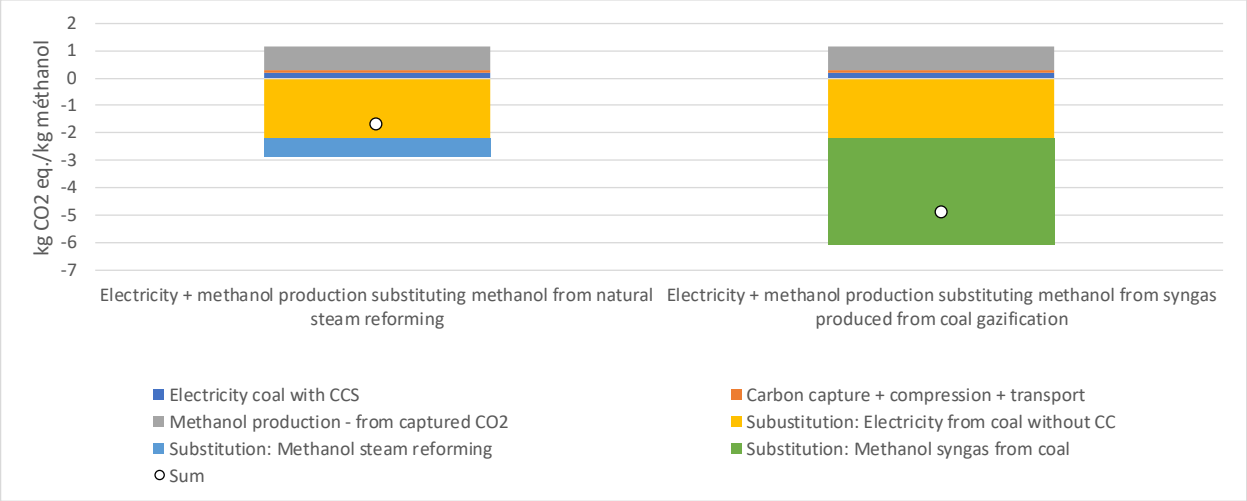


Figure 5-37: Climate change indicator overall results after system expansion with different reference scenarios

As shown, the selection of the reference scenarios which is avoided/substituted will provide variable indicator results.

5.5.3 Uncertainty analysis

Uncertainty analysis is the most efficient way to assess all the LCI data variability and/or uncertainty. Data variability of the different parameters has been somewhat reported in the life cycle inventory section of this report.

Uncertainty analysis in an LCA software uses Monte Carlo simulations for which, at each of a minimum of 1000 iterations, data is randomly selected for each data point (i.e. individual input or output of the included processes) following the defined variability and/or uncertainty and the overall impact indicator results are calculated. The following figure presents the uncertainty analysis results for coal and natural gas (conventional and combined cycle) power plants with and without CCS.

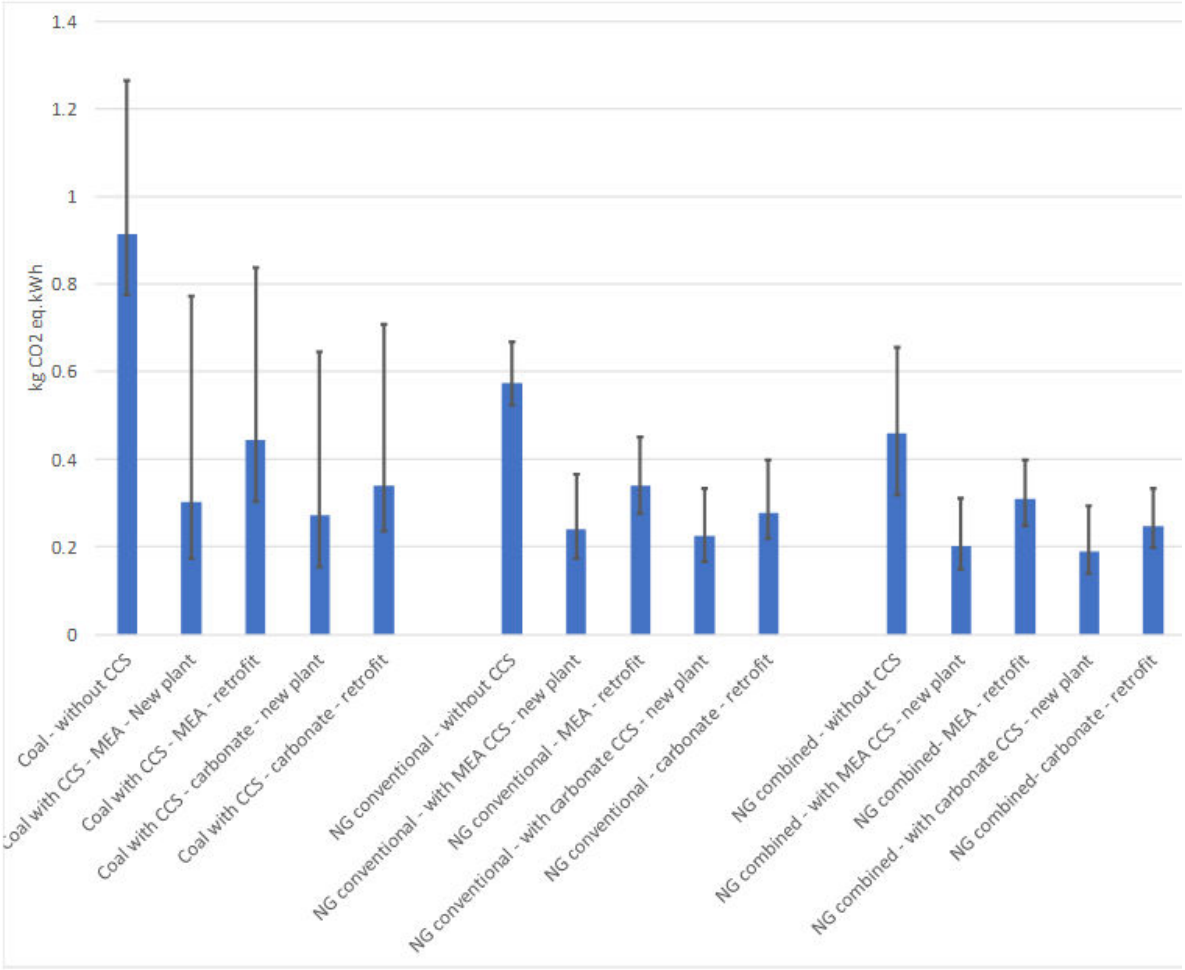


Figure 5-38: Uncertainty analysis results for the *Climate change* category for coal and natural gas electricity generation without and with CCS in Germany

As seen, the parameter's variability of individual system brings the interpretation into a greyer area. Indeed, one cannot conclude on the system preferability if the uncertainty brackets overlaps. In this example, it isn't possible to differentiate between coal power plant with carbon capture systems and natural gas systems.

5.6 Data quality

The reliability of the results and conclusions of a life cycle assessment depends on the inventory data quality. It is important to ensure that the information meets certain requirements that are in line with the goals of the study.

Though ISO does not propose a method for such inventory data quality assessment, the Pedigree matrix[61] approach, as employed in the *ecoinvent* life cycle inventory database, is one of the most recognized, systematic, approaches to describe data quality. It provides five criteria, each with five quality levels:

Reliability

1) Verified data based on measurements
2) Verified data based on assumption or non-verified data based on measurements
3) Non-verified data partly based on qualified estimates
4) Qualified estimate (e.g. by an industrial expert)
5) Non-qualified estimate

Completeness

1) Representative data from all site for the market considered, over an adequate period of time
2) Representative data from >50% of the sites relevant to the considered market, over an adequate period of time
3) Representative data from some sites (<<50%) relevant for the for the market considered
4) Representative data from only one site relevant for the for the market considered
5) Representativeness unknown

Temporal correlation

1) Less than 3 years
2) Less than 6 years
3) Less than 10 years
4) Less than 15 years
5) Age unknown or more than 15 years

Geographic correlation

1) Data from the area under study
2) Average data from the larger area in which area under study is included
3) Data from an area with similar production conditions
4) Data from an area with slightly similar production conditions
5) Data from unknown or distinctly different area

Further technological correlation

1) Data from enterprises, processes, and materials under study
2) Data from processes and material under study but from different enterprises
3) Data from processes and material under study but from different technology
4) Data on related processes or materials
5) Data on related processes on a laboratory scale or from different technology

Highest quality data would score only “1” for all criteria while lowest quality data would score only “5”.

Lower quality data may be very appropriate in the case of a process whose contribution to the overall indicator results is minimal. On the contrary, higher quality data should be collected for processes having a great influence on the conclusions of the study.

[61] Empirically based uncertainty factors for the pedigree matrix in ecoinvent | SpringerLink (https://link.springer.com/article/10.1007/s11367-013-0670-5)

6 Recommendations

This section highlights the main recommendations for the identified methodological challenges.

The following table summarizes all recommendations when conduction LCA's for CCS or CCU. Details are provided in the following sub-sections.

Table 6-1 : CCS/CCU LCA studies methodological recommendations summary

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	the most common research questions for **attributional CCS** LCA studies are: ▪ 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? 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 **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) **PLCA** should be used if one needs to ascertain a specific technology that would be employed in the mid to long-term.		the most common research questions for **attributional CCU** LCA studies are: ▪ 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)? **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 **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) **PLCA** should be used if one needs to ascertain a specific technology that would be employed in the mid to long-term.	
	Defining the functional unit	• Functionally equivalent • Quantifies the function and defines both geographical and temporal contexts		• 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 case, the quantity of captured carbon should be the focus.	Varies according to the study's context	
	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	• 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	• 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	• 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	• Assessment of all possible futures improvements of CCS • One should consider the use of the Shared Socioeconomic Pathways (SSP)	• 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. CO2 is a waste that must be eliminated (akin to "waste sent to a landfill")	System expansion should always be considered. **Captured CO2 doesn't come unburdened. Indicator depends on the process in which CO2 was captured.** If product-specific, allocation according to several bases (mass, volume, energy, economic) should be considered to ascertain the potential variations from selecting one basis over the other	

Life cycle inventory	Obtaining life cycle inventory data for attributional LCA	• Data should be representative of geographical and temporal context • Data quality should be assessed • Life cycle inventory data are taken from the literature ▪ 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.	• Data should be representative of geographical and temporal context • Data quality should be assessed • Life cycle inventory data are obtained from process modeling ▪ 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 datasets.	See CCS	
	Obtaining data for CLCA	• Attributional LCA comments apply • Additional data needs to be gathered for all processes affected by the captured carbon.			
	Obtaining data for DLCA	• Attributional LCA data needs to be assigned by hand to their respective timeframe.	• Build a dynamic LCA database	See CCS	
	Obtaining data for PLCA	Assumptions need to be made about technological	Build an uncertainty assessment that would	Assumptions need to be made about technological	Build an uncertainty assessment that would

		improvements. If history is any indication, those assumptions are likely to be wrong	allow assessment for "all possible futures" – the answer being one of the "possible futures"	improvements. If history is any indication, those assumptions are likely to be wrong	allow assessment for "all possible futures" – the answer being one of the "possible futures"
Life cycle impact assessment	Attributional LCA impact assessment/regionalization	• 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.	• Apply existing LCIA methods as is • Regionalization capabilities are limited now • When applying system expansion, indicator results can be: ▪ Negative: the process used to subtract the unwanted function, indicator results are higher than the indicator 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	Apply worldwide regionalized impact assessment methods that provide an overall coherent framework all the while accounting for a regionalized life cycle inventory database.
	CLCA impact assessment/regionalization	See Attributional LCA impact assessment/regionalization			
	DLCA impact assessment/regionalization	Dynamic characterization factors are only available for the *Climate change* 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	See CCS	

			coherent) characterization factors	
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
	Sensitivity analysis	The following sensitivity analysis should be considered as best practices: • Impact assessment method • The CO2 capture efficiency; • The CO_2 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 CO_2 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	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.		
	Data quality assessment	Though ISO does not propose a method for such inventory data quality assessment, the Pedigree matrix approach, as employed in the *ecoinvent* 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.		
Regulatory purposes	Who gets the credit?	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.		
	LCA recommendations for regulatory purposes	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.		

6.1 Defining the goal of the study

The question one wants to answer will motivate the use of an LCA approach. If one is interested in knowing:

- The environmental profile of CCS/CCU
- The contribution to the life cycle of CCS/CCU
- The potential environmental trade-offs from CCS/CCU
- The environmental footprints of products or services used as a basis for consumer decisions

Then an attributional LCA should be carried out.

If, however, one is more interested in assessing the expected environmental consequences occurring following a change in production, consumption, and/or disposal of a product, then, one should select a consequential LCA approach.

If one is more interested in differentiating the timing of the individual emissions occurring during the life cycle of a product (i.e. the effects of capture vs long-term storage), then one should opt for a dynamic LCA approach.

Finally, if one is more interested in ascertaining the environmental impacts of a specific technology in the mid to long-term, then one would probably be best served with a prospective LCA.

The question one wants to answer will then define the rest of the CCS/CCU study.

6.2 Defining the functional unit

As with all LCA, the compared products must be functionally equivalent. A functional unit needs to 1) quantify the function, 2) define the geographical context, and 3) define the temporal context.

With CCS, the functional unit is defined according to the "original product".

Table 6-2 : CCS recommended functional units

Industrial sector	Functional unit example
Power generation	1 kWh of electricity generation in [year] in [country/continent]
Natural gas processing	1 kg of natural gas produced in [year] in [country/continent]
Steel	1 kg of steel produced in [year] in [country/continent]
Fertilizer	1 kg of fertilizer produced in [year] in [country/continent]
Chemicals	1 kg of [chemical] produced in [year] in [country/continent]
Hydrogen	1 kg of hydrogen produced in [year] in [country/continent]
Oil refining/fuels	1 kg of [fuel] produced in [year] in [country/continent]
Plastics	1 kg of [plastics] produced in [year] in [country/continent]
Cement	1 kg of cement produced in [year] in [country/continent]
Different sectors	1 kg of CO2 captured in [year] in [country/continent]

Note: terms in "[]" needs to be specified according to the study's context.

With CCU, the functional unit is to be defined differently according to the goal of the study.

Table 6-3 : LCA4CCU functional unit recommendations for CCU LCA studies

	Recommended FU
Product: Energy carrier - Transportation fuel	1 vehicle km (or 1 tonne km) using a specified means of transport
Product: Energy carrier - Other	Define FU quantifying the energy service
Product: Chemical/material - chemically identical	1 kg of product
Product: Chemical/material - chemically different	Define FU based on equal technical performance
Energy storage system	Define FU quantifying the storage characteristics
Comparison of various CCU processes	1 kg of CO_2 input

6.3 Defining the system boundaries of an attributional LCA

For both CCS and CCU, we recommend that the system boundaries be cradle-to-grave to ensure that no activity be missed and to provide the proper contribution to the overall life cycle indicators.

6.4 Defining the system boundaries of consequential life cycle assessment

For both CCS and CCU, we recommend that the system boundaries be cradle-to-grave.

For CCS, there is a limited application to carry out a CLCA. Indeed, the displaced technology is assuredly the same technology without carbon capture. An attributional LCA often compares the two. To assess the implementation of carbon capture with CLCA, one would simply need to take the indicator result for the product with capture, the capture, compression, transport, and injection of the CCS system and subtract the attributional indicator results of the process without carbon capture, to obtain a CLCA result.

For CCU, identification of the consequences of introducing two paths can be selected:

- Using different scenarios
  - Pros: easily applied; CO2-based product, alternatively, is added to the market, completely substitutes an existing product, or substitute an existing product locally only to see that product used somewhere else in the world.
  - Cons: most likely will not assess all the potential repercussions of the introduction of a CO2-based product on the economy.
  - Challenge: the conclusion of such an assessment lacks credibility and can be heavily criticized.
- Relying on partial or general equilibrium models to identify the ripple effects of introducing a CO2-based product into the market
  - Pros: if production is significant to alter the market, this approach is more reliable
  - Cons: computationally heavy, dependant on partial or general equilibrium models which are most likely proprietary and have their assumptions/data which may introduce a bias into the assessment.

- Challenge: The National Academy of sciences, engineering, and medicine (2019)[62] stated that consequential LCA had been sparingly applied to carbon utilization because i) the production volumes were not disruptive to current markets to provide valuable information, ii) the partial and general equilibrium models lacked the level of details to track the influence of captured carbon-derived products, fuels, and materials on existing supply chains and markets; requiring the development of more detailed models, iii) market information are often outdated, and uncertainty assessment of consequential LCA is a field of research on its own.

The first approach could be considered as easily accessible for practitioners while the second approach requires additional research-focused and will require more time to implement in studies.

6.5 Defining the system boundaries of dynamic life cycle assessment

For both CCS and CCU, we recommend that the system boundaries be cradle-to-grave.

The system boundaries for dynamic LCA are the same as with attributional LCA. The dynamic assessment interest is to assess the emissions of a system – occurring at different times – into their rightful perspective. For CCS or CCU, two situations could warrant a dynamic assessment:

- To assess the effects of fugitive CO2 emissions from long-term storage for CCS;
- To assess the effects of CO_2 use for systems that include medium to long-term storage solutions comparatively to systems that use CO_2 for a short time.

6.6 Defining the system boundaries of prospective life cycle assessment

For both CCS and CCU, we recommend that the system boundaries be cradle-to-grave.

What these system boundaries look like is more uncertain. Both CCS and CCU are emerging technologies and, therefore, are still evolving. In other words, capture today is likely not how to capture will be achieved in the future. Predicting how these technologies will evolve is a challenge that is hard to address in any other way than testing different potential improvements to the existing technologies or decrease the consumption of inputs and increase the capture efficiency to improve the efficiency of existing technologies. Therefore, the system boundaries could be like the one from attributional LCA or modified according to technological changes.

Furthermore, while the CCS/CCU system boundaries shouldn't be affected by the surrounding world, it is important to note that the background processes are likely to change. For example, if the process requires electricity, the CCS/CCU system boundary will include the input of electricity. The generation of electricity is likely to change according to the Shared Socioeconomic Pathways (SSP) narratives.

6.7 Solving multi-functionality

CSS is not multi-functional. CCU on the other is multifunctional.

[62] https://www.nap.edu/read/25232/chapter/10

Multi-functionality should always be dealt with through system expansion. The challenge with the system boundaries with system expansion is to identify the most likely "substituted" production process which subtracts the unwanted function.

If a product-specific approach is necessary, then allocation should be used by accounting first for underlying physical relationships, and if impossible, then another relationship, such as economic value. As it is expected that the selection of an allocation basis will lead to important variations of results; **a sensitivity analysis based on different allocation bases should always be carried to avoid potential results manipulation.**

6.8 Life cycle inventory: data acquisition for attributional LCA

Data acquisition for attributional, consequential, dynamic, or prospective LCA's is always challenging. Data should always be representative of the assessed technology as well as the geographical and temporal context. As always, the focus should be put on collecting primary data. If one must rely on secondary data, then two pathways are available.

- **Find data in the literature from previous works**
  - 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.
- **Process modeling**
  - 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 datasets.

Finding data in the literature from previous works is more suited for LCA practitioners as results can be obtained rather easily. The second approach is more research-oriented as in-depth knowledge of the process is required and will take time to build the process simulation.

6.9 Life cycle inventory: data acquisition for consequential LCA

Reminder: consequential LCA is mostly for CCU.

All the comments from the attributional LCA for CCU applies. Additional data needs to be collected for all processes or activities whose market share would be modified by the introduction of a new CO_2-based product.

6.10 Life cycle inventory: data acquisition for dynamic LCA

Conventional Life cycle inventory databases are not time-dependant. To answer this challenge, two approaches are available. The first one is to investigate the attributional LCA database and assign by hand the respective timeframe of all activities. For example, all processes related to the infrastructures will occur some years before operations and operations occur at t=0. Capture, compression, transport, and injection (if applicable) are likely to also occur at t=0. Fugitive CO2 emissions for CCS will occur at different rates and at a different time (t). For CCU, CO2 (re)emission will depend on the use; some uses have no-to-short sequestration time while others have medium-to-high sequestration times.

The other approach is very research-oriented and is to build an entire life cycle database entirely time-dependant To the authors' knowledge, such work hasn't been attempted yet.

6.11 Life cycle inventory: data acquisition for prospective LCA

Data acquisition for prospective CCU/CCS LCA is two-fold:

- Finding how the CCS/CCU technology is likely to evolve
- Modifying the background processes to match the five different Shared Socioeconomic Pathways (SSP) narratives.

For the first one, different data assumptions can be selected from the existing process (e.g. decrease some of the inputs and increase the efficiency) or follow recommendations of potential improvements.

All involved inputs and waste management processes of CCS/CCU need to be analyzed and modified to be representative of the five different Shared Socioeconomic Pathways (SSP) narratives.

6.12 Life cycle inventory: Data variability for attributional, consequential, dynamic, and prospective LCA

When data is available from multiple sources, it is possible that for the same given process, gathered data vary widely as it represents different on-location practices or accounts for an intrinsic variation (e.g. the composition of extracted natural gas varies from well to well and from region to region altering the treatment process).

The only way to tackle this issue is first to select the most credible and appropriate value (or if impossible, select an average value of the varied data), then to perform sensitivity and/or uncertainty analyses and, depending on the life cycle impact assessment indicators results, provide mitigated overall conclusions.

6.13 Life cycle inventory: Regionalization

Depending on the geographical location, different practices and inventory data may be available – especially for the electricity consumed by different processes. It is good LCA practices to attempt to represent, as best as possible, the operating conditions.

6.14 Life cycle impact assessment: attributional LCA

For CCS, indicator results will be positive

For CCU, life cycle indicators can be either be positive, negative, or neutral due, mostly, to the system expansion calculations. For GHG assessments, this is translated as:

- Neutral:
  - CCU technologies can theoretically be carbon neutral over their entire life cycle (i.e. net zero) if CO_2 is captured from the atmosphere (via biogenic point sources or direct air capture) and is released at the end-of-life, or if CO_2 is captured from fossil point sources and is sequestered or permanently stored in the product and if there are no other GHG emissions over the life cycle.
- Negative:
  - CCU technologies can have net negative emissions if CO_2 is captured from the atmosphere (via biogenic point sources or direct air capture) and is sequestered or permanently stored in the product and if other life cycle GHG emissions are lower than the amount of CO_2 captured. If the amount of atmospheric CO_2 captured and sequestered is equal to the amount of other life cycle GHG emissions, the process is carbon neutral.
- Positive :
  - In all other cases, CCU technologies have net positive life cycle GHG emissions

6.15 Life cycle impact assessment: consequential LCA

Reminder: consequential LCA is mostly for CCU.

There are not methodological challenges for the impact assessment of consequential LCA. CLCA can be conducted with the same impact assessment methods as attributional LCA. The indicator results can be positive, neutral, or negative depending on the consequence of introducing a CO2-based product (for CCU) on the market.

6.16 Life cycle impact assessment: dynamic LCA

To the best of the authors' knowledge, dynamic LCA impact assessment can only be carried out for the *Climate change* impact category. The assessment can be carried out with the cumulative radiative forcing models provided by the IPCC.

Other impact categories do not, currently, have characterization factors allowing for the assessment in time of emission, depletion, or land occupation/transformation. Therefore, research is required to create those dynamic characterization factors before their use in full life cycle dynamic assessment.

6.17 Life cycle impact assessment: prospective LCA

For short-term prospective LCA, the current impact assessment methods shouldn't create too much of a bias.

However, for long-term assessment, the underlying assumption in the environmental models is likely to be modified and the representativity of the characterization factors is questionable. For example, the radiative forcing model for CO_2, in the latest AR-5 IPCC report (2013) is based on the current (at the time)

global CO2 concentration (i.e. 391 ppm [63]) which has been updated from the value (i.e. 379 ppm [64]) used in the AR-4 IPCC report (2007).

Several impact categories rely on atmospheric pathways (e.g. marine eutrophication, terrestrial and aquatic acidification, human toxicity, ecotoxicity, particulate matter, photochemical oxidation) whose underlying model relies on temperature, precipitation, wind direction, etc. These factors vary yearly but long-term shows significant variations for all these parameters. There are currently, no long-term characterization factors available. The development of such characterization factors is an area of research.

6.18 Life cycle impact assessment: Regionalization

Regionalized impact assessment methods exist for Europe, North America, and Japan. However, using such impact assessment methods inherently assumes that all emissions from the life cycle will occur within these regions. Using several of these regionalized impact assessment methods will not guarantee coherence in the impact assessment since the underlying environmental models are (most likely) different from one impact assessment to the next. Therefore, one cannot guarantee that the difference between the results from two regionalized methods stem from the potential impact and not from a model discrepancy.

Recently, research has aimed to assess impacts with global models to ensure coherence within the different regions. Such impact assessment methods, such as IMPACT World +, are operational at a world level but not yet fully operational at a regional level. Work to provide a fully operational regionalized impact assessment method is ongoing.

6.19 Interpretation: Contribution analysis

For CCS, contribution analysis should be performed to provide a better understanding of the compared systems.

For CCU, due to the system expansion calculations, results should **only** be presented in a contribution analysis to highlight the contribution of the capture process and the process, used to subtract the unwanted function.

6.20 Interpretation: Defining sensitivity analyses

Sensitivity analysis should target the system's parameters that contribute most to the indicator results or alternative scenarios that could have an impact on the reliability of the obtained conclusions.

Depending on the goal of the study, these sensitivity analyses should be considered:

- Alternative impact assessment method (mandatory)
- The CO2 capture efficiency;
- The CO_2 capture process energy consumption;

[63] Section 8.SM.11.3.1 from WGI_AR5.Chap_.8_SM.pdf (ipcc.ch)

[64] 2.3 Chemically and Radiatively Important Gases - AR4 WGI Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing (ipcc.ch)

- The type of capture process (pre-conversion, post-conversion, oxy-fuel combustion or DAC) (if the goal of the study isn't to investigate different carbon capture technology);
- 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 and distances;
- The leakage rate of the CO_2 storage geological formation (for CCS systems);
- Methane fugitive emissions associated with coal or natural gas systems (if a system requires natural gas);
- The allocation rules (if applicable) such as mass, energy, or economic;
- The avoided process(es) for CCU systems in consequential LCA (if applicable).

6.21 Interpretation: Uncertainty analysis

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.

6.22 Interpretation: Data quality assessment

Though ISO does not propose a method for such inventory data quality assessment, the Pedigree matrix approach, as employed in the *ecoinvent* 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.

6.23 Who gets the credit?

This question is only for those who use LCA for "*Product Carbon footprinting*" for CCU otherwise, the overall LCA doesn't care about who gets the credit.

So who should get the credit?

- The producer who deployed means to capture CO2 and make it available?
- If CO2 is considered a waste, then it comes without an environmental burden
- The CO2 user who uses the CO2 instead of the usual materials?
- A 50-50% split between them?
- A split following system expansion?

This is still an open question, which is more likely to be politically motivated – to promote either capture or the reuse of CO2 or both - rather than a methodological issue.

6.24 LCA use for regulatory purposes

LCA provides a global perspective and allows for an evaluation of potential burden shifting. While a standardized methodology for carbon capture studies can be established, one must not expect to have a single evaluation – in the form of an emission factor for example – of carbon capture as **sources of**

variations limit consistency in obtained results even if a coherent methodology is applied. These variations include (but not limited to):

- Carbon capture technology
- System expansion choice of reference/allocation basis
- Data source: literature (which one is more relevant) vs process modeling (with limited transparency?
- Impact assessment interpretation: negative, neutral, or positive results depending on the investigated system and/or system expansion or allocations calculation.
- Sensitivity analysis provides a wide array of variations according to data found in the literature such as carbon capture efficiency, the energy penalty, the transport type and distances, etc.
- Dynamic, consequential, prospective assessments…

Therefore, CCS/CCU studies are filled with potential exceptions and/or specificities and should be treated on a case-by-case basis.

7 Conclusion

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 modeling and interpretation perspectives.

Given 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 is either carried out with either post-conversion capture (i.e. the separation of CO_2 from the flue gas after the conversion of a carbon source), pré-conversion (i.e. capture CO_2 through a chemical reaction before a conversion/combustion process. CO_2 is then an undesirable co-product of an intermediate reaction), oxyfuel (i.e. the fuel is burned with pure oxygen (instead of air) to produce a combustion gas with high a CO_2 concentration) or direct air capture (i.e. CO_2 (and potentially other greenhouse gases) are removed directly from the atmosphere). Among these carbon capture technologies, post-conversion with amine scrubbing as well as pre-conversion with solvents are more mature while oxyfuel isn't much used, and DAC is mostly theoretical at this point.

Disposition of the capture CO_2 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 CO_2 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 CO_2 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 CO_2 and allow to compensate, in some way, for the capture, compression, and transport costs.

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.

Past LCA CCS studies results typically show that carbon capture will decrease GHG emissions and, perhaps, terrestrial and aquatic acidification, and respiratory inorganics impacts over a system without carbon capture but at the expanse of all other environmental indicators since one is increasing the energy consumptions, the operations, and their related emissions. Past LCA CCU studies show more variability in their results due, in part, to the considered assumptions.

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.

This report analyzes each of these methodological issues, illustrated the challenges, and showed how best to circumvent them with different examples.

From these illustrations, a list of short-term and long-term recommendations was provided.

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