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BACHELOR'S THESIS

Literature studies on the Life Cycle Assessment of CO_2 Capture, Storage and Utilization Technologies

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- Tobias

Abstract

In recent years, the awareness of climate change creates concern for the international community. Human activities are the main factors that contribute to the natural greenhouse effect of the earth. The burning of fossil fuels (Coal, Lignite, Natural gas) increases the emission of carbon dioxide into the atmosphere.

The CO_2 capture, and storage (CCS) technology is the best solution to mitigate the greenhouse effect. There are several capture technologies that separate CO_2 out of the fuel gas through absorption, adsorption, or membrane gas separation methods. The capture technologies are post-combustion, pre-combustion, and oxy-fuel capture. Among others, absorption, or carbon scrubbing with amines is currently the dominant capture technology.

The life cycle environmental impact assessment case studies have shown that implementation of carbon capture technology on the fuel driven power plant reduced the greenhouse gas by about 90%. However, the non-greenhouse gas released due to amine degradation have shown negative impacts on the environment such as Acidification potential (AP), Eutrophication potential (EP), and Human toxicity potential (HTP). It is therefore important to perform life cycle environmental impact assessment when implementing CCS and Carbon Capture Utilization (CCU) technologies.

According to the Paris agreement signed by about 192 countries, the ambitious plan is to reduce the CO_2 emission by 50% in 2050 as compared to the level of 1990 (United Nations Treaty Collection, 2016). For this,

- More research should be conducted to develop novel materials and technologies, which have higher CO_2 capture efficiency, reduced environmental impacts, lower energy consumption and cost effectiveness as well.
- All nations should be responsible to fulfill their nationally determined contribution commitments.

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List of Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification potential
BOM	Bill of material
CC	Carbon capture
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization, and storage
CED	Cumulative energy demand
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalents
EOR	Enhanced oil recovery
EP	Eutrophication potential
EPFL	Swiss Federal Institute of Technology – Lausanne
FAETP	Fresh water aquatic ecotoxicity potential
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Gigajoules
GWP	Global warming potential
HHV	High heat value
HSE	Health, safety and environmental
HTP	Human toxicity potential
H_2	Hydrogen

IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IPCC	International Panel on Climate change
ISO	International Organization for Standardization
kWh	Kilo watt hour
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
MEA	Monoethanolamine
MDEA	Methyldietanolamine
MPa	Megapascal
MWh	Megawatt hour
NDC	Nationally determine contributions
NGHG	Non-greenhouse gas
NO_X	Nitrogen oxide
O_2	Oxygen
POCP	Photochemical oxidation potential
SO_X	Sulphur dioxide
TETP	Terrestrial ecotoxicity
tkm	ton-kilometer
TWh	Tera watt hour
ULS	Ultra-low Sulphur

1 Introduction

Global warming is the main concern for the world today. Due to population growth and industrial activities, energy demand is increasing. Including the natural factors, the human activities due to the burning of fossil fuels (Coal, Lignite, Natural gas) rises the emission of carbon dioxide into the atmosphere resulting in the earth's natural greenhouse effect. Figure 1.1 clearly shows the recorded and simulated global temperature incremental (Arias et al., 2021). The vertical axis is the surface annual average change in temperature.

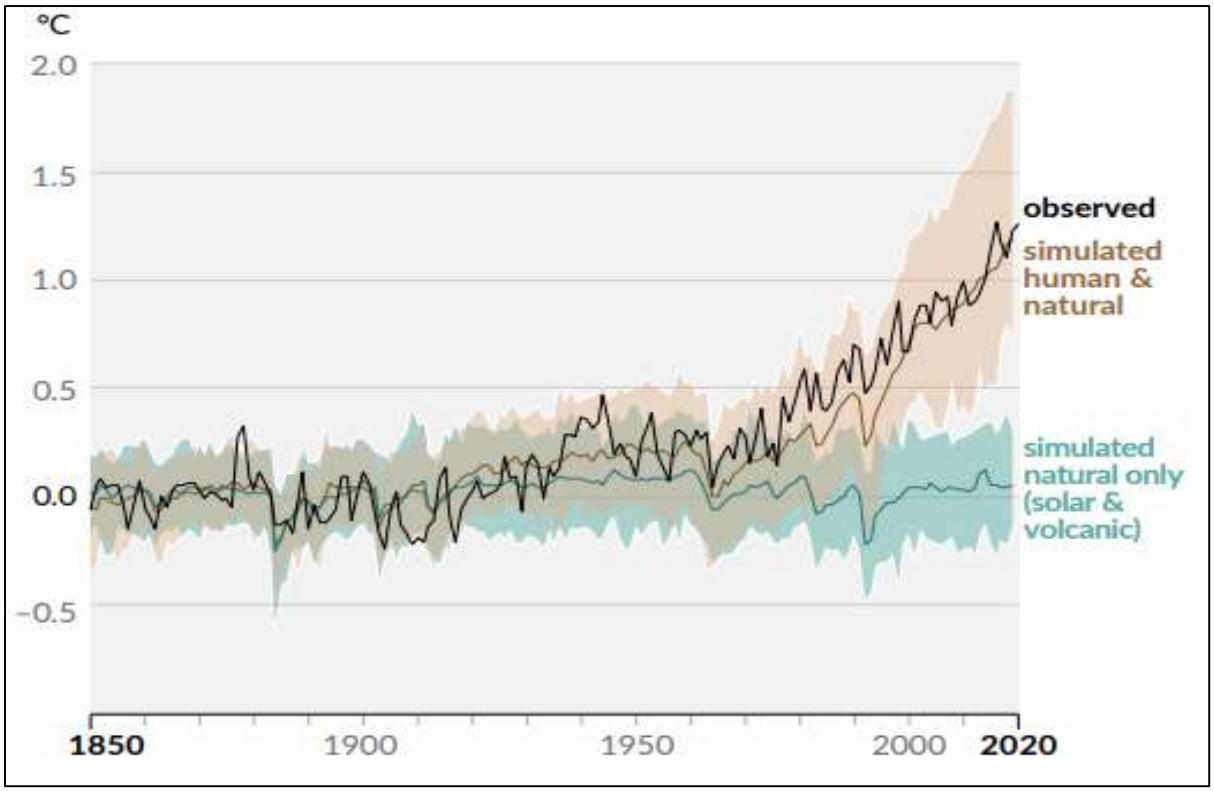


Figure 1.1: Global surface temperature change (annual average) with different factors (Masson-Delmotte et al., 2021).

Due to the rise of global surface temperature, the Paris agreement was adopted on the 12th of December 2015 to reduce climate change (United Nations, 2015). About 192 international communities including European Union entered legally binding treaty on 4th of November 2016 (United Nations Treaty Collection, 2016).

To comply the Paris CO_2 emission reduction agreement, the Norwegian Parliament adopted the Climate Change Act in June 2017 (Climate Change Act, 2017). The Climate Change Act commits the Norwegian government by law was targeting the reduction of the greenhouse gas

emission for 2030 and 2050. For this, the strategy approved by the Norwegian Parliament in October 2019 was further updated and enhanced in Feb 2020 (Norway, 2020a). Norway, in the updated strategy, submitted its nationally determined contributions (NDC) target plan to reduce CO_2 emissions by at least 50 percent and towards 55 percent compared to 1990 levels by 2030 and becoming a low-emission society by 2050 (Norway, 2020b).

The current best method to mitigate the greenhouse gas CO_2 from being released into the atmosphere is by capturing and storing it in geological formations. Additionally, the CO_2 utilization chain value as energy resource and to produce other useful products before being stored indirectly, has a potential of reducing CO_2 emissions and add value to economy as well.

Figure 1.2 shows the structure of the thesis that covers two main issues. The first part will briefly describe the technologies associated with carbon capture, storage (CCS) and utilization chain value (CCU) and storage (CCUS). For instance, the CO_2 contained in the hydrocarbon will be separated, compressed, and transported to the storage location through pipeline, ship for further utilization or storage purposes. The second part deals with the application of the life cycle assessment (LCA) tool to evaluate the impact of greenhouse gas (GHG) and non-greenhouse gas (NGHG) on the environment when using CCS and CCUS technologies.

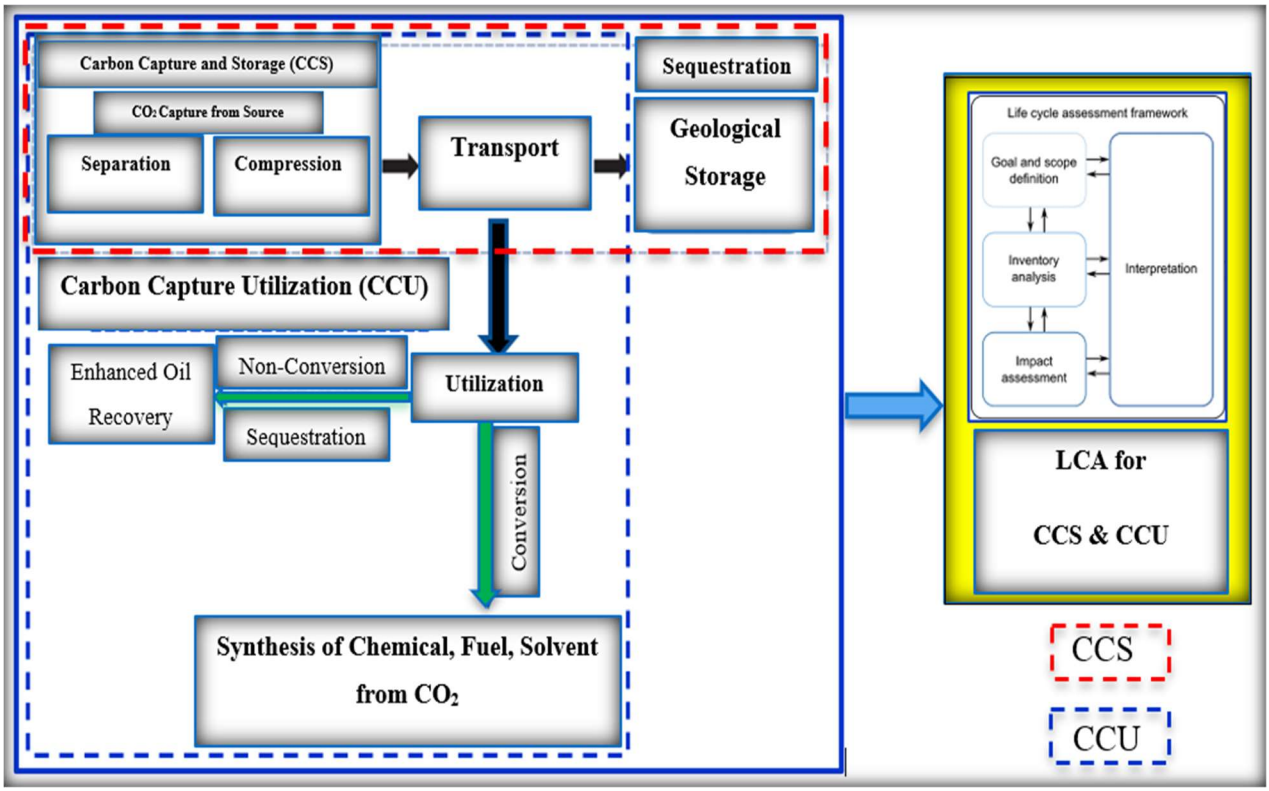


Figure 1.2: Structure of the thesis illustrating CCS and CCUS with LCA of CCS and CCU.

1.1 Background

As mentioned earlier, due to the global population growth and industrial activities, the energy demands will also increase. For instance, the international energy agency (IEA) report indicated that as of 2021, the energy demand increased by 4.6% as compared with that of the. On the other hand, as shown in Figure 1.3, the comparison with the reference of 2019, the energy demand in 2020 was reduced by 4%, which might be associated with the covid-19 crises. Due to the re-opening of the covid-19 restrictions, the increases in energy demand in 2021 shows the continuous trend. It is interesting to observe the correlation between the global GDP and the energy demands as well as the CO_2 emission level. This clearly shows the global activities correlation with the CO_2 emission. Here again as shown in the figure, with respect to the 2019, the CO_2 global emissions in 2020 fell by about 5.8%, which is nearly estimated by 2 Gt CO_2 (International Energy Agency, 2021).

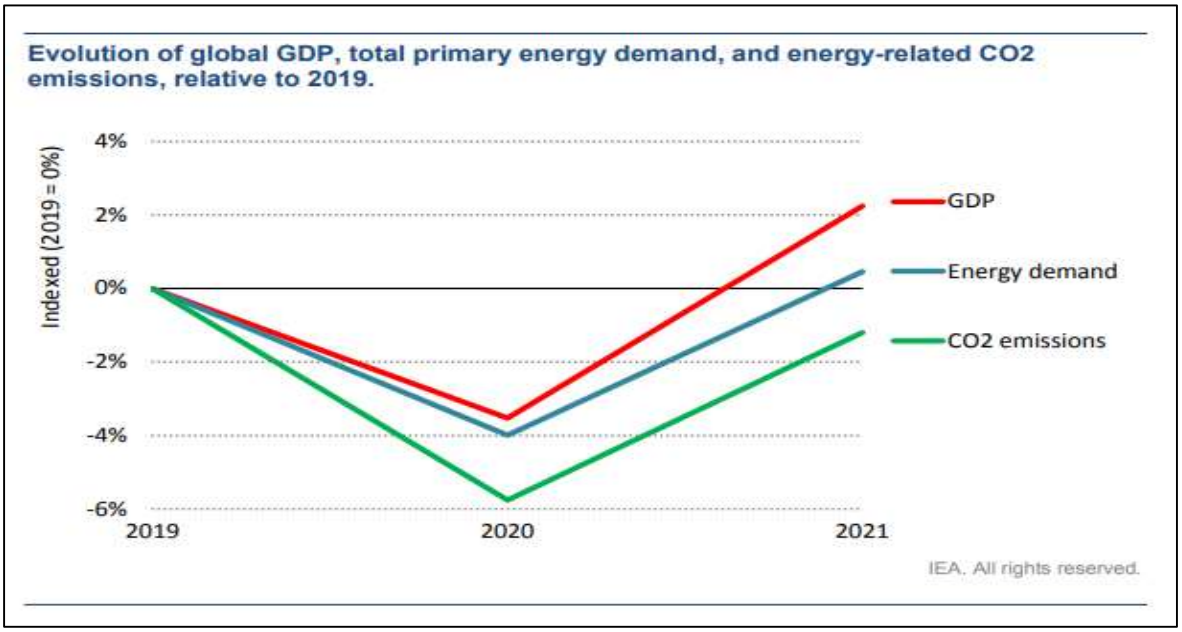


Figure 1.3: Correlation among the Global GDP, energy demand and CO_2 emission (International Energy Agency, 2021).

Figure 1.4 shows the global energy related CO_2 emission during the period of 1990-2021 and the change in CO_2 emission by fuel. As shown in the figure, the CO_2 emissions in 2021 are predicted to increase by 4.8% in similar manner as the energy-demand. However, despite the decline of CO_2 in the year 2020, global energy-related CO_2 emissions is still about at 31.5 Gt. The main reason for the reduction of CO_2 in the year 2020 was due to the decline of the fuel energy resources (coal, gas, and oil) and the use of renewable energy resources.

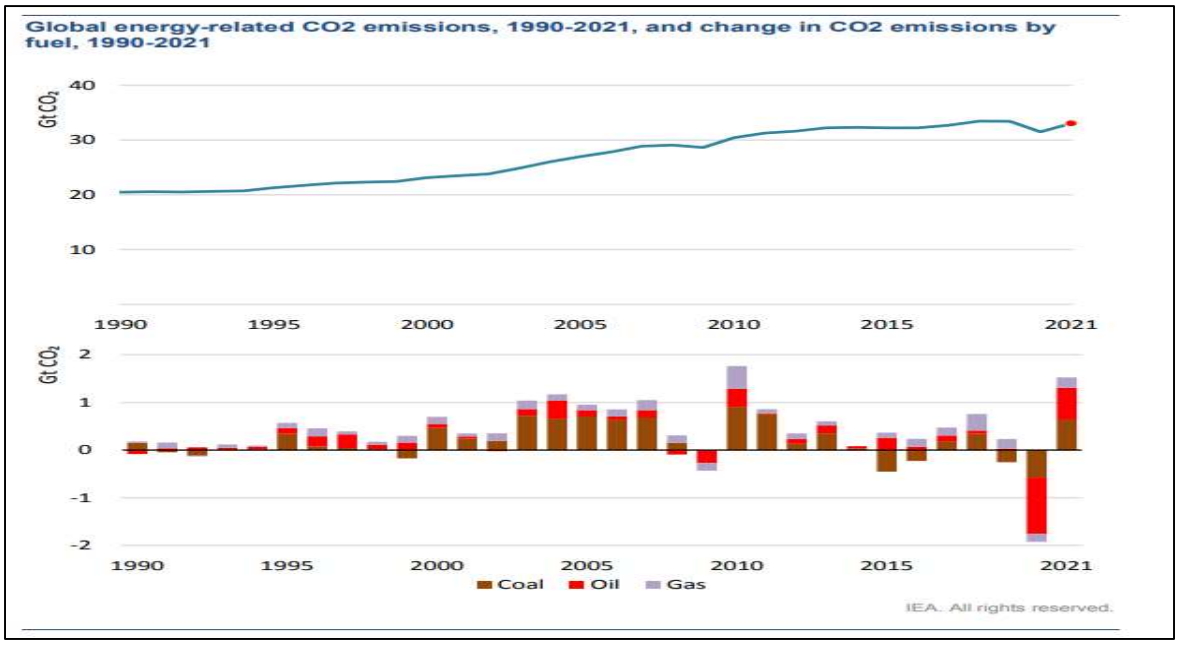


Figure 1.4: Global energy related CO_2 emission by fuel (International Energy Agency, 2021).

The greenhouse gas released in the atmosphere is the main contributor for the increase in annual temperature. Figure 1.5 shows the correlation between CO_2 increase to the atmosphere over time vs the temperature increase. The figure clearly illustrates the global warming associated with greenhouse, CO_2 emission (Lab-aids, n.d.).

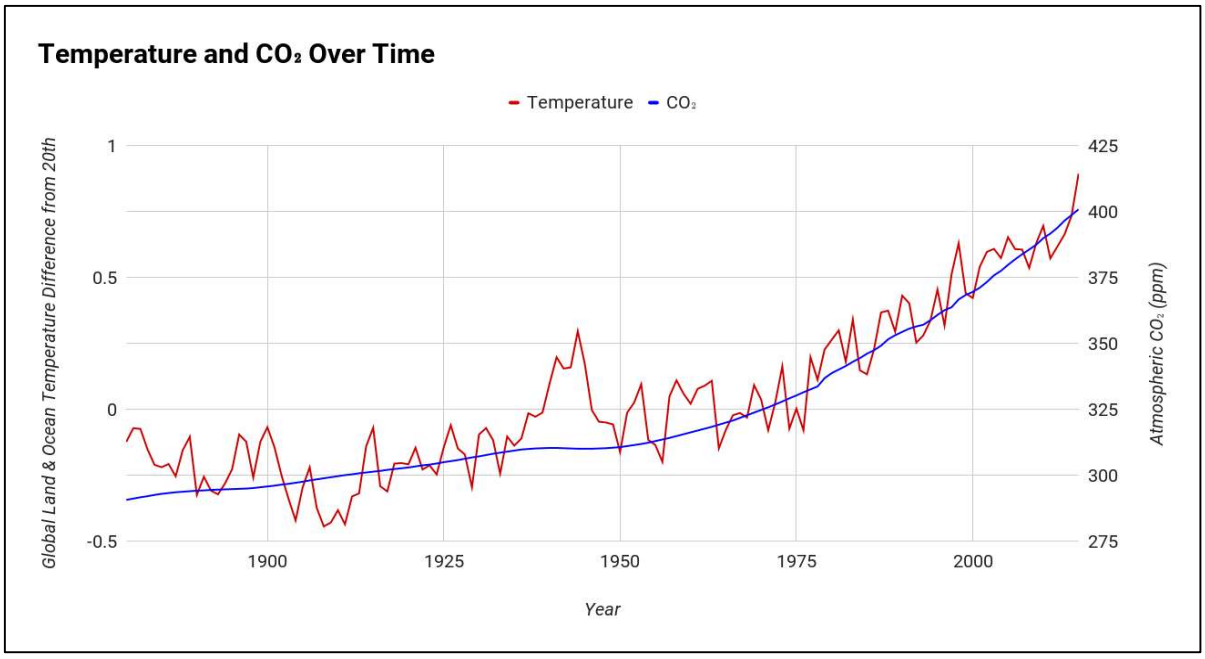


Figure 1.5: Correlation between CO_2 emission and temperature increment overtime (Lab-aids, n.d.).

As mentioned in the introduction part, the currently best solution for reducing the CO_2 emission into the atmosphere is carbon capture, and storage (CCS). Moreover, to convert the CO_2 into useful energy resources as utilization chain value, and then store the CO_2 (CCUS).

For effective CCS and CCUS operations, the selection of the right technology and materials associated with it are the key elements to achieve the climate change and energy utilization related goals.

Therefore, this thesis will investigate the carbon capture, utilization technologies and their lifetime assessment (LCA) impact on the environments.

1.2 Objective and Scope of the thesis

The main objective and scope of this work is to present the literature review and evaluation of:

- ✓ The Carbon Capture Technologies
- ✓ The Carbon Capture and Utilization Technologies
- ✓ Present the Life Cycle Assessment (LCA) methodology
- ✓ Case studies of the Life Cycle Assessment (LCA) of the CC and CCU
- ✓ Finally, to indicate the main findings to meet the target of the Paris Agreement.

2 Literature study

This chapter briefly presents the review of different types of carbon capture and storage as well as the utilization technologies. In chapter 4, the life cycle assessment of these technologies will be evaluated through the LCA methodologies outlined in Chapter 3.

2.1 Overview of CCS and CCU technologies

Figure 2.1 shows the different carbon capture, storage, and utilization options. The first level shows the industries that produces CO_2. These are fossil fuels, oil refineries, cement industries, iron- and steel industry, biogas sweetening and chemical sectors. The CO_2 released from the industries increase the CO_2 concentrations in the atmosphere unless mitigation methods are implemented. The second level shows the CO_2 capture technologies, namely, post-conversion, pre-conversion, and the oxy-fuel combustion captures. The capture methods each have their pros and cons. The third level shows the utilization and storage options (CCUS). As the name implies the CCUS technologies have several advantages such as producing energy and useful products, for then to store CO_2 from being released to the atmosphere.

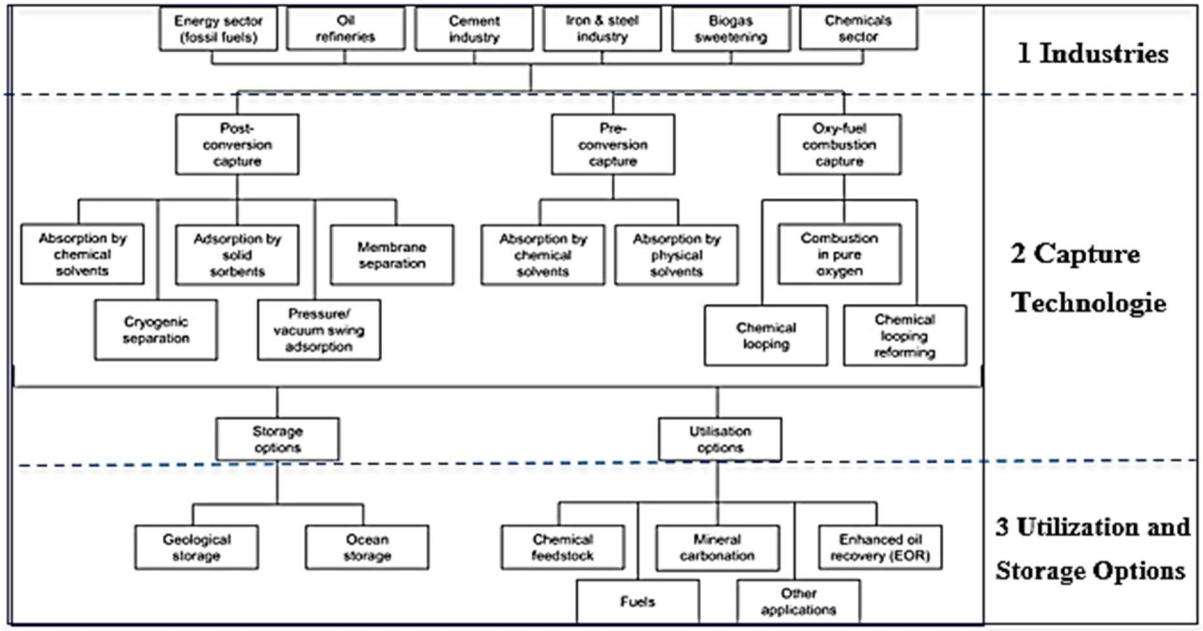


Figure 2.1. Different carbon capture, storage, and utilization options (Cuéllar-Franca & Azapagic, 2015).

2.1.1 Carbon Capture (CC)

The continuous rise of greenhouse gas emission has resulted in increased frequency of extreme weather around the world. Utilization and carbon capture and storage (CCS) technologies will offer significant potential to reduce CO_2 emissions (Creamer & Gao, 2016).

Even though renewable energy has become far more effective throughout the past decade, the world still needs fossil-based fuel (coal, natural gas, and oil). While waiting for renewable energies to meet the global energy demand and replace fossil-based fuels, CCS is vital as a transitional stage between the two energy types (Osman et al., 2021).

Figure 2.2 shows the three major carbon capture (CC) technologies, namely, pre-combustion, post-combustion, and oxy-fuel combustion.

As shown in the figure, the capture process involves the separation of CO_2, H_2 or O_2 from a fuel gas stream. The separation methods are by physical or chemical solvents, membranes, solid sorbents, and cryogenic means. Currently, the efficiency of the post-combustion and pre-combustion technology could capture the net amount of approximately 80–90% of the produced CO_2. On the other hand, oxy-fuel combustion systems captured slightly more than 90% (Metz & Intergovernmental Panel on Climate Change Working, 2005).

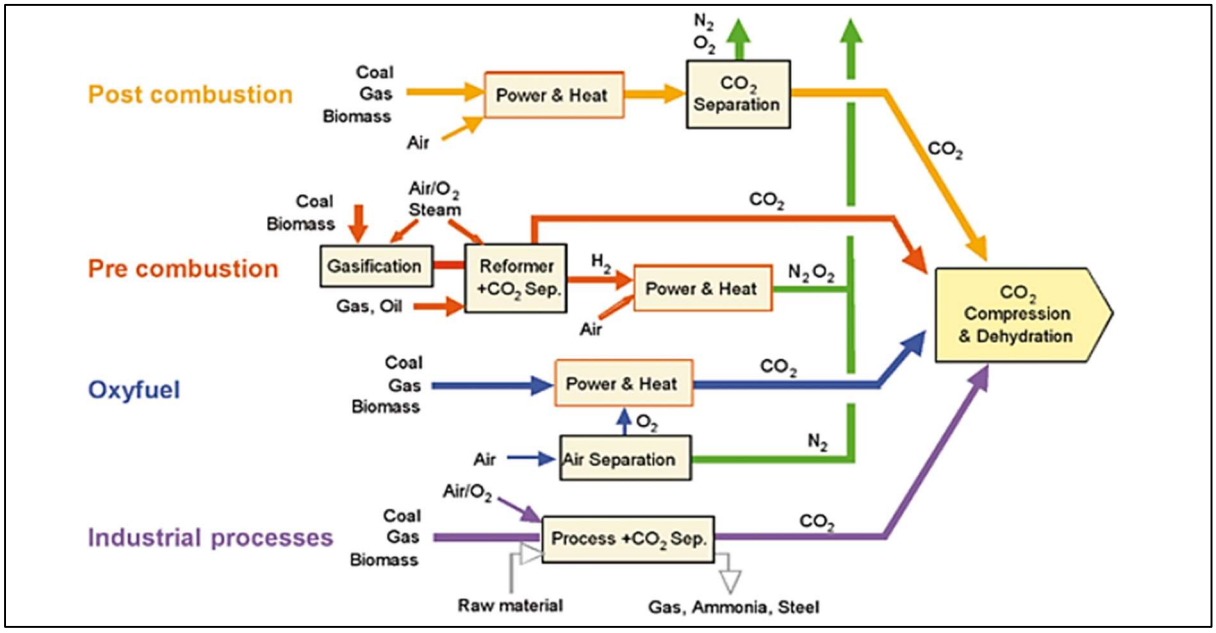


Figure 2.2: Different technologies for CO_2 capture
(Metz & Intergovernmental Panel on Climate Change Working, 2005).

2.1.1.1 Pre-combustion Capture

Figure 2.3 shows the pre-conversion capture option. As illustrated in the figure, the carbon products obtained from fuel driven plants will be partially converted and produces the intermediate product (CO_2) for further separation/capture and conversion process. In the presence of separation and capture technologies, such as solvents, the CO_2 will be converted into useful energies and ammonia. The residual CO_2 will be compressed for transportation, storage, or utilization purposes.

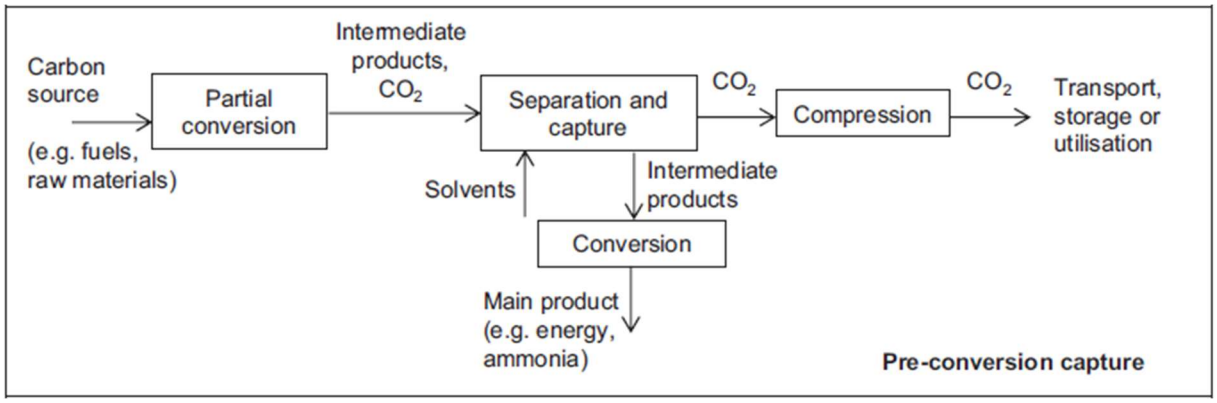


Figure 2.3: Illustration of pre-conversion capture for CCS and CCSU process (Cuéllar-Franca & Azapagic, 2015).

Table 2-1 shows some of the materials used for pre-conversion process. For instance, the solvents (physical adsorption, chemical absorptions) and porous organic frame works are used for ammonia production and gas separation purposes.

Table 2-1: Examples for pre-conversion capture methods, application and materials used (Cuéllar-Franca & Azapagic, 2015).

Capture option	Separation technology	Method	Applications
Pre-conversion	Absorption by physical solvents	• Selexol, rectisol	Power plants (IGCC)
	Absorption by chemical solvents	• Amine-based solvent, e.g., monoethanolamine (MEA)	Ammonia production
	Adsorption by porous organic frameworks	• Porous organic frameworks membranes	Gas separations

2.1.1.2 Post-combustion capture

Figure 2.4 shows the post-conversion capture process that converts fuel into energy and other useful products such as fertilizer and ethylene. Further, the process involves separation and capture of CO_2 from co-product waste with CO_2 (i.e., flue gas, biogas, emissions).

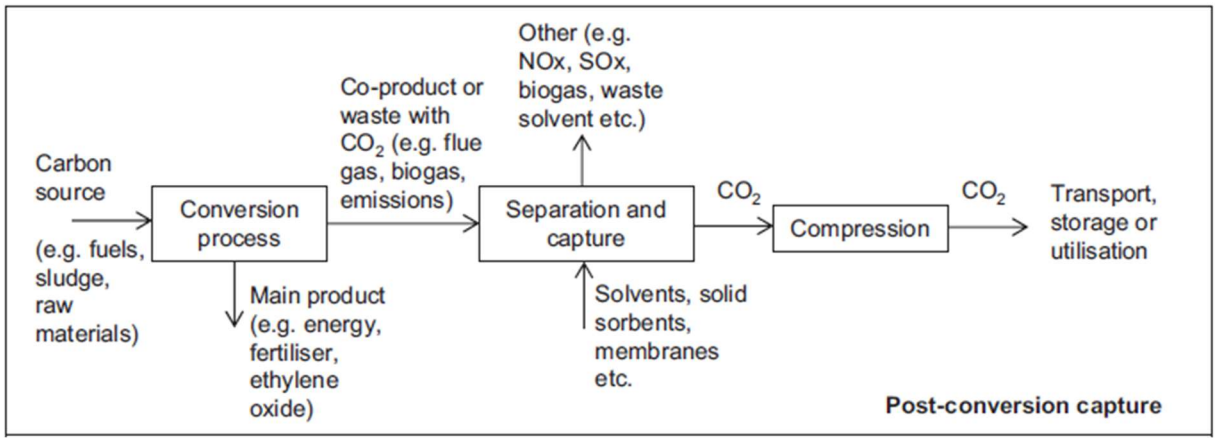


Figure 2.4: Process of post-conversion capture (Cuéllar-Franca & Azapagic, 2015).

Figure 2.5 shows the separation technologies used during the post-capture. As shown in the figure, the separation mechanisms are by absorption (i.e., in solvents), adsorption (i.e., on solid sorbents), membranes, cryogenic separation, pressure swing and temperature swing.

As shown in the figure, monoethanolamine (MEA) is the most commonly used absorption. Chemical absorbents undergo a reaction with CO_2 to create a weakly bonded intermediate compound that can be regenerated when heat is introduced to produce the original solvent and a separate CO_2 stream. During the separation and capture process, the acid gases (NO_2 and SO_2), waste solvents as well as biogas must be removed as it affects the system and its performance (Wang et al., 2011). The captured CO_2 will then be compressed and transported to the storage or its utilizations purposes.

Monoethanolamine absorption is the most common used method in post-combustion. Amine solutions have high CO_2 absorption capacity and selectivity to acidic gases. However, amine solutions have drawbacks such as high energy footprint during regeneration, the high corrosivity of amines, degradation and therefor solvent loss and evaporation. To reduce the cost associated with post-combustion, technology such as membrane separation can be used as it has low energy requirements, carbon footprint, operational cost and easy to modify into existing power plants (Osman et al., 2021).

Then again, membrane separation has its flaws, such as condensation on the membrane during cooling and emissions (NO_X and SO_X) passing through the membrane. Some membranes also suffer from difficulty in temperature adjustments and alteration in humidity which cause severe changes in the membranes ability to be transported (Pfister et al., 2017).

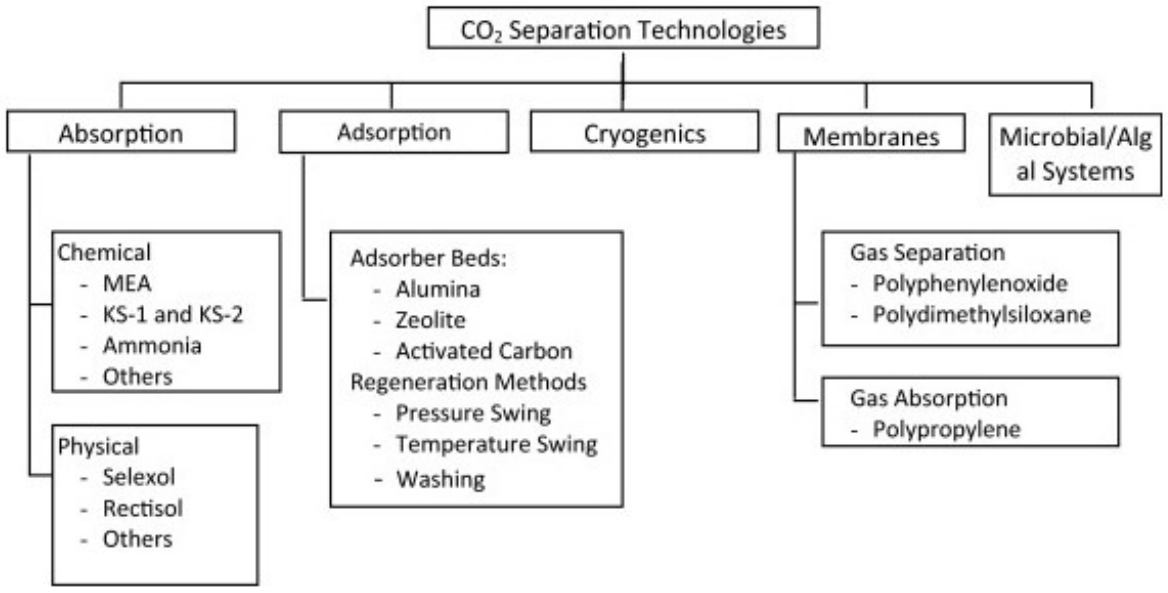


Figure 2.5: Types of post-combustion CO_2 capture technologies (Rao & Rubin, 2002).

Chemical blends were created to combine the positive features of different absorbents and simultaneously counteract their negative features. An example of solvents used are methyldietanolamine (MDEA), where the usual MEA reacts quicker with CO_2 than MDEA, but MDEA has a higher CO_2 absorption capacity and requires less energy to regenerate CO_2 (Wang et al., 2011). This suggests the need to create novel materials with the objective of improving the capture efficiency and reduce the negative environmental impacts.

2.1.1.3 Oxy-fuel combustion capture

Oxy-fuel combustion is also one of the technologies for capturing CO_2 from fuel plants (e.g., cement production and the iron and steel industry) with CCS. As the name implies, oxy-fuel uses oxygen for the fuel burning process. As illustrated in the figure 2.6, burning the fuel with O_2, resulting in energy and the residual CO_2. The CO_2 is then to be compressed for the transportation or unitization value (Cuéllar-Franca & Azapagic, 2015; Stanger et al., 2015).

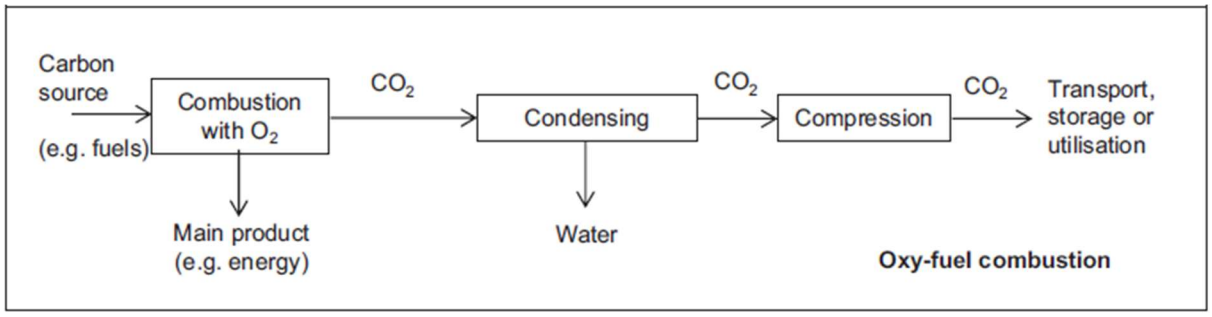


Figure 2.6: Illustration of Oxy-fuel combustion (Cuéllar-Franca & Azapagic, 2015).

Table 2-2 shows the separation technology, the method and application for various power plants. The methods are oxy-fuel, chemical looping combustion and chemical looping reforming.

Table 2-2: Examples for oxy-fuel capture methods, application and materials used (Cuéllar-Franca & Azapagic, 2015).

Capture option	Separation technology	Method	Applications
Oxy-fuel combustion	Separation of oxygen from air	• Oxy-fuel process	Power plants; iron and steel industry; cement industry
		• Chemical looping combustion	Power plants
		• Chemical looping reforming	Power plants; syngas production and upgrading

2.1.2 Transport

Except when power plants are located directly above geological formations with capabilities of storage, captured CO_2 must be transported from location of capture to a location of storage. Pipelines are today the most mature and common market technology for transportation of CO_2. Gaseous CO_2 is usually compressed to above 8 MPa to avoid two-phase flow and to increase the density of the gas. Thereby making it cheaper and easier to transport. It can also be transported by rail, road or ship tankers that can carry CO_2 in insulated tanks at low temperatures and much lower pressures (Metz & Intergovernmental Panel on Climate Change Working, 2005).

2.1.3 Storage

There are several options of storing CO_2. The geological options are in depleted oil and gas reservoirs, storage in association with CO_2 enhanced oil recovery (EOR) projects, deep saline aquifer formations and deep coalbed formations (Metz & Intergovernmental Panel on Climate Change Working, 2005).

The most common way of storing CO_2 after capture is known as geological storage as it uses many of the same technologies that have been developed in the oil and gas industry. It involves injecting CO_2 into geological formations such as depleted oil and gas reservoirs, coal bed formations and saline aquifers, at 800 to 1000 meters depth. The CO_2 cannot be stored in just any type of geological formation though, it requires impermeable layers known as “caprock” (e.g., clays, mudstones, and shales) which then trap the CO_2 underneath (Metz & Intergovernmental Panel on Climate Change Working, 2005).

There are several field scale CCS projects around the world. Among these, the Sleipner gas field can be mentioned as a successful CCS project. The field is situated in the North Sea, where the CO_2 captured from produced natural gas is re-injected to be stored in the Utsira sandstone formation. Utsira is located at about 1000 m below the seabed and the thickness is about 200m. The CO_2 injection started in 1996 (Torp & Gale, 2004). Figure 2.7 shows the Sleipner CO_2 storage in the Utsira formation. As illustrated in the figure, the CO_2 plume after being injected and the storage formation moves to the caprock due to gravity. For safe long-term CO_2 storage in the reservoir, the structural integrity of the caprock should be studied during the planning phase to make sure that the CO_2 will not leak through the possible existing fractures in the caprock as illustrated in Figure 2.8 (Viktoriya M. Yarushina, 2018).

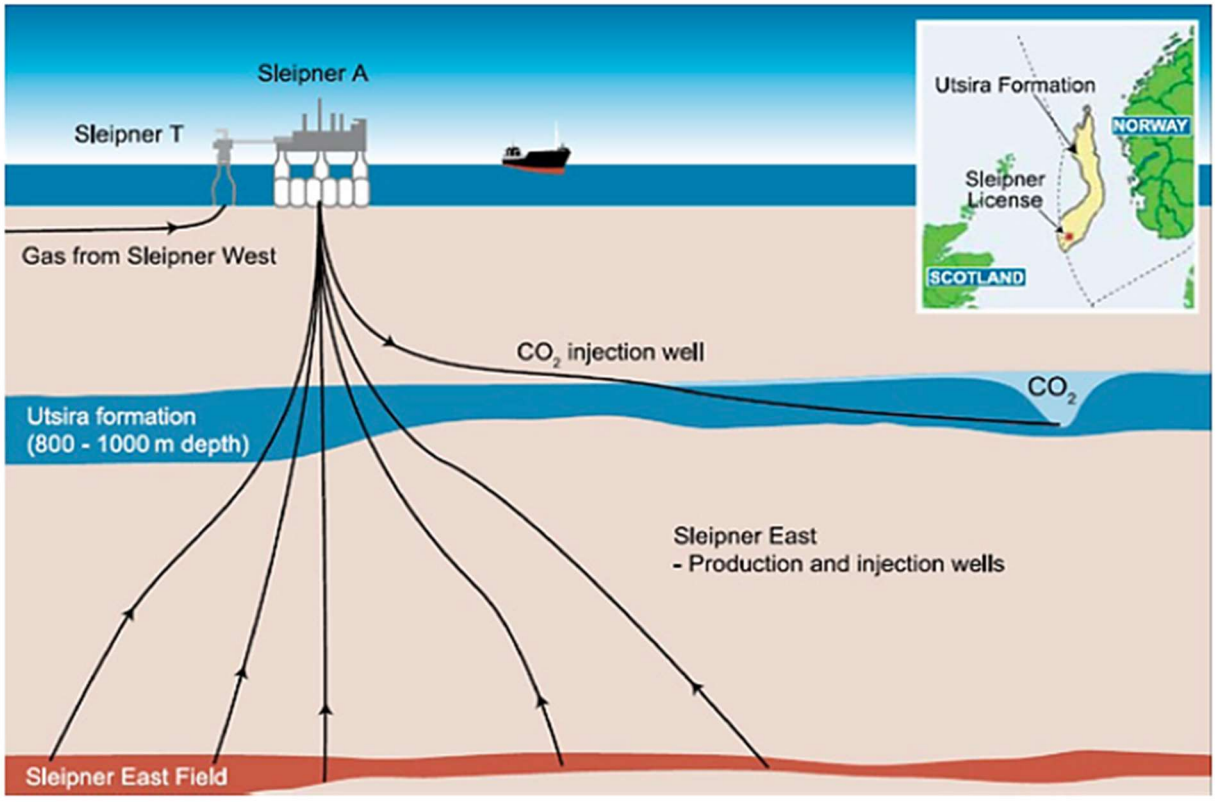


Figure 2.7: Simplified sketch of the Sleipner gas field CO_2 storage project (Torp & Gale, 2004).

Site screening, ranking and selection

For the selection of geological storage, it is important to perform appropriate screening processes based on geological, environmental, economic, and logistical considerations. The main geological selection criteria are provided in Table 2-3, that includes the depth and thickness of the reservoir, the petrophysical parameter such as porosity, permeability as well as the seal integrity and salinity (Chadwick et al., 2008).

Table 2-3: Key geological indicators for storage site suitability (Chadwick et al., 2008).

	Positive indicators	Cautionary indicators
RESERVOIR EFFICACY		
Static storage capacity	Estimated effective storage capacity much larger than total amount of CO_2 to be injected	Estimated effective storage capacity similar to total amount of CO_2 to be injected
Dynamic storage capacity	Predicted injection-induced pressures well below levels likely to induce geomechanical damage to reservoir or caprock	Injection-induced pressures approach geomechanical instability limits
Reservoir properties		
Depth	>1000 m <2500m	< 800 m > 2500 m
Reservoir thickness (net)	> 50 m	< 20 m
Porosity	> 20%	< 10%
Permability	> 500 mD	< 200 mD
Salinity	> 100 gl^{-1}	< 30 gl^{-1}
Stratigraphy	Uniform	Complex lateral variation and complex connectivity of reservoir facies
CAPROCK EFFICACY		
Lateral continuity	Stratigraphically uniform, small or no faults	Lateral variations, medium to large faults
Thickness	> 100 m	< 20 m
Capillary entry pressure	Much greater than maximum predicted injection-induced pressure increase	Similar to maximum predicted injection-induced pressure increase

Carbon Dioxide Leakage and Potential Leakage Pathways

Once the CO_2 is stored, the desire is for the CO_2 to be stored safely over several years. A reservoir is considered as adequate to ensure long terms effective CO_2 storage, if the leak rates is 0.01% per year. This means that over 100 years, the retention of CO_2 being stored in the reservoir is 99% (Chadwick et al., 2008; Hepple & Benson, 2003; Metz & Intergovernmental Panel on Climate Change Working, 2005).

Figure 2.8 shows the carbon dioxide leakage and potential leakage pathways which includes

- Through geological faults that intersecting the storage formation(s) and surrounding zone.
- Through permeable zones existing in the caprock.
- Through the annulus of the casing and the formation of the abandoned well (Viktoriya M. Yarushina, 2018).

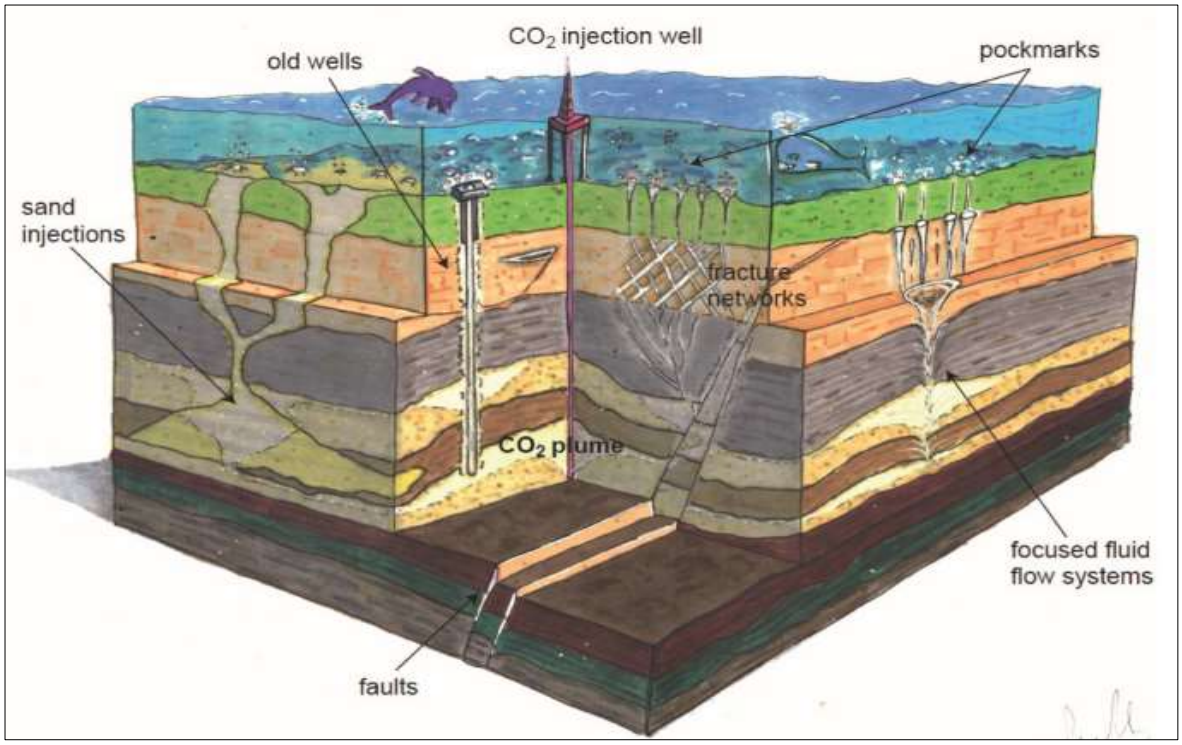


Figure 2.8: Outline of potential CO_2 leakage pathways (Viktoriya M. Yarushina, 2018).

Potential Environmental Impacts of Carbon Dioxide Leakage and Risk analysis

The CO_2 leakage has impact on environments that include global warming, human health and safety, effect on ecosystems, groundwater contamination can be mentioned as examples. It is important to perform the health, safety and environmental (HSE) risk assessment associated with the CO_2 storage sites. A risk is defined as a function of the probability of an event that causes harm/hazard and its consequence. The detail is beyond the scope of this thesis work.

2.2 Utilization Values

Utilization of CO_2 is based on the use and recycling of CO_2 contrary to CO_2 storage where it is simply stored to be kept away from the atmosphere. According to the IPCC 2005 Special Report on Carbon Dioxide Capture and Storage - the term "CO_2 – utilization" refers to use of CO_2 at concentrations above atmospheric levels, directly or as feedstock in industrial or chemical processes to produce valuable carbonaceous products (Hepburn et al., 2019).

The ten CO_2 utilization methods are Chemicals from CO_2; Fuels from CO_2; Products from microalgae; Concrete building materials; CO_2-EOR; Bioenergy with carbon capture and storage; Enhanced weathering; Forestry techniques; Soil carbon sequestration techniques; Biochar. In the following, the selected CO_2 utilizations are presented. Figure 2.9 shows a clear picture of the stages and processed in CCUS technologies. At first, CO_2 is captured with either of the three capture technologies described in section §2.1.1 and then transported through different means for storage and or utilization (Imteyaz et al., 2021).

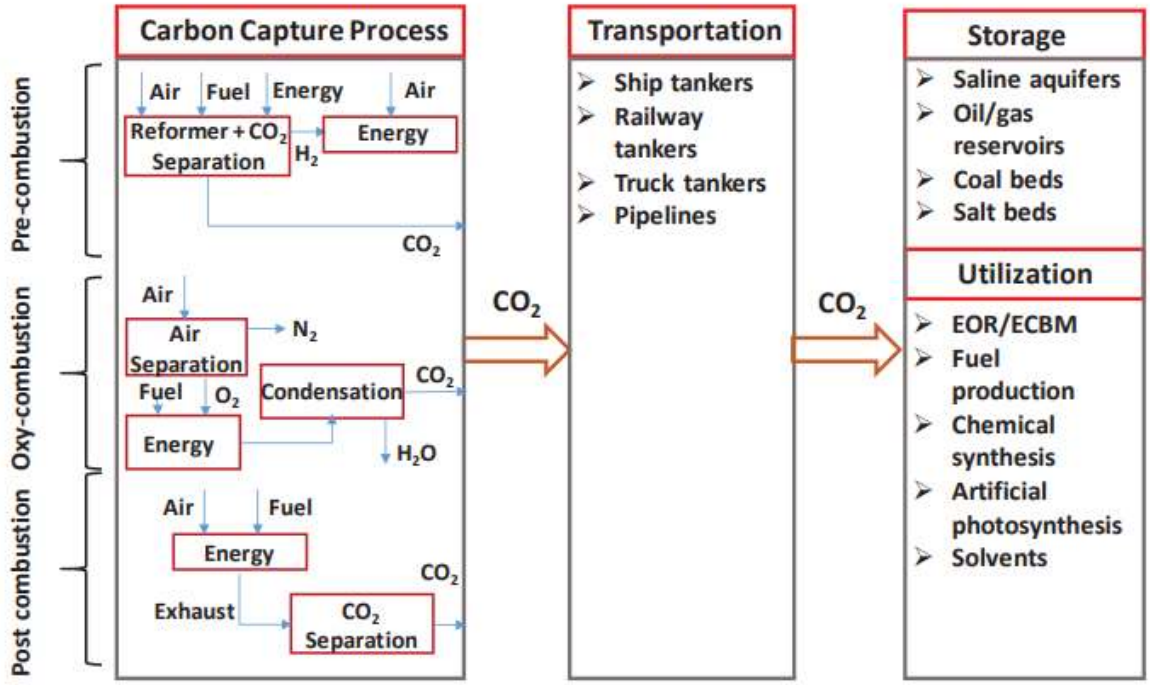


Figure 2.9: Illustration of stages and processes during the application of CCUS technologies (Imteyaz et al., 2021).

Further the capture utilization technologies along with the details of conversion/utilization and non-conversion/utilization methods are presented in Figure 2.10.

Among the outlined carbon capture utilization technologies, in this thesis only two examples will be presented. The methods are non-conversion/utilization (i.e., CO_2-EOR) and conversion/utilization (i.e., Fuels from CO_2, Biofuel from microalgae)

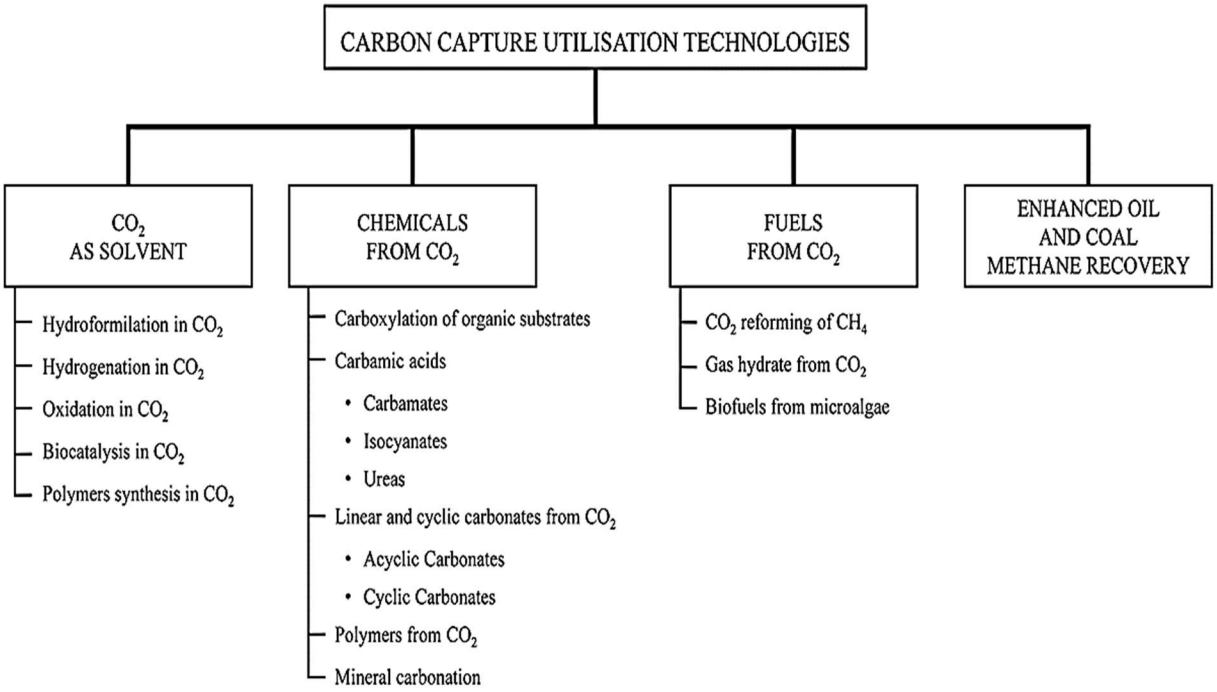


Figure 2.10: Examples of CCU technologies (Baena-Moreno et al., 2019).

2.2.1 CO_2-EOR

Before the reservoir is getting mature, the oil and gas is produced with the reservoirs natural pressure. During years of production, the reservoir pressure is reduced to a level where it is no longer enough to move oil to the surface. Depending on the rock formation a significant amount of oil may be left behind (up to 60 % and more) as residual oil. As illustrated in Figure 2.11, in order to boost the reservoir pressure, the alternate water – CO_2 injected at the injection well enhance the oil recovery (EOR). Figure 2.12 shows the primary (oil production), the secondary water injection as well as water production, where the productivity showed declining. However, during tertiary, the injection of CO_2 along with water enhanced the oil recovery by the amount under the green shaded area (National Energy Technology Laboratory (NETL), 2010).

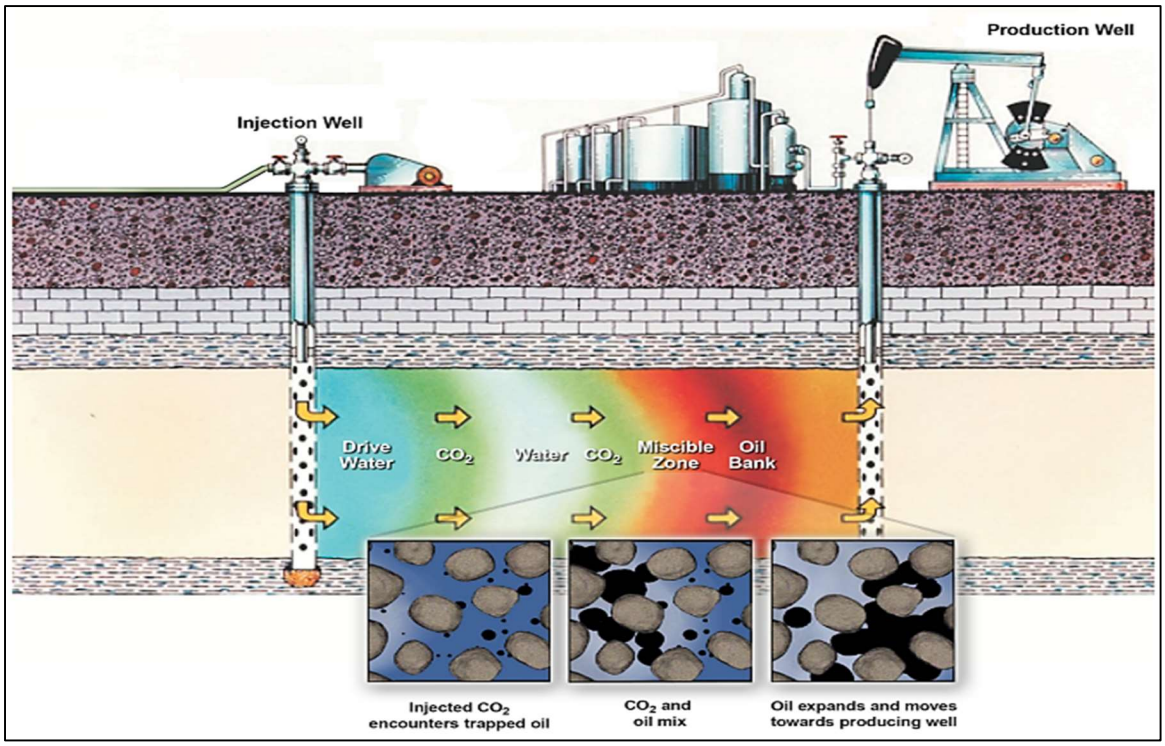


Figure 2.11: Illustration of carbon dioxide and water alternating injections is used to move residual oil from a rock formation between wells (National Energy Technology Laboratory (NETL), 2010).

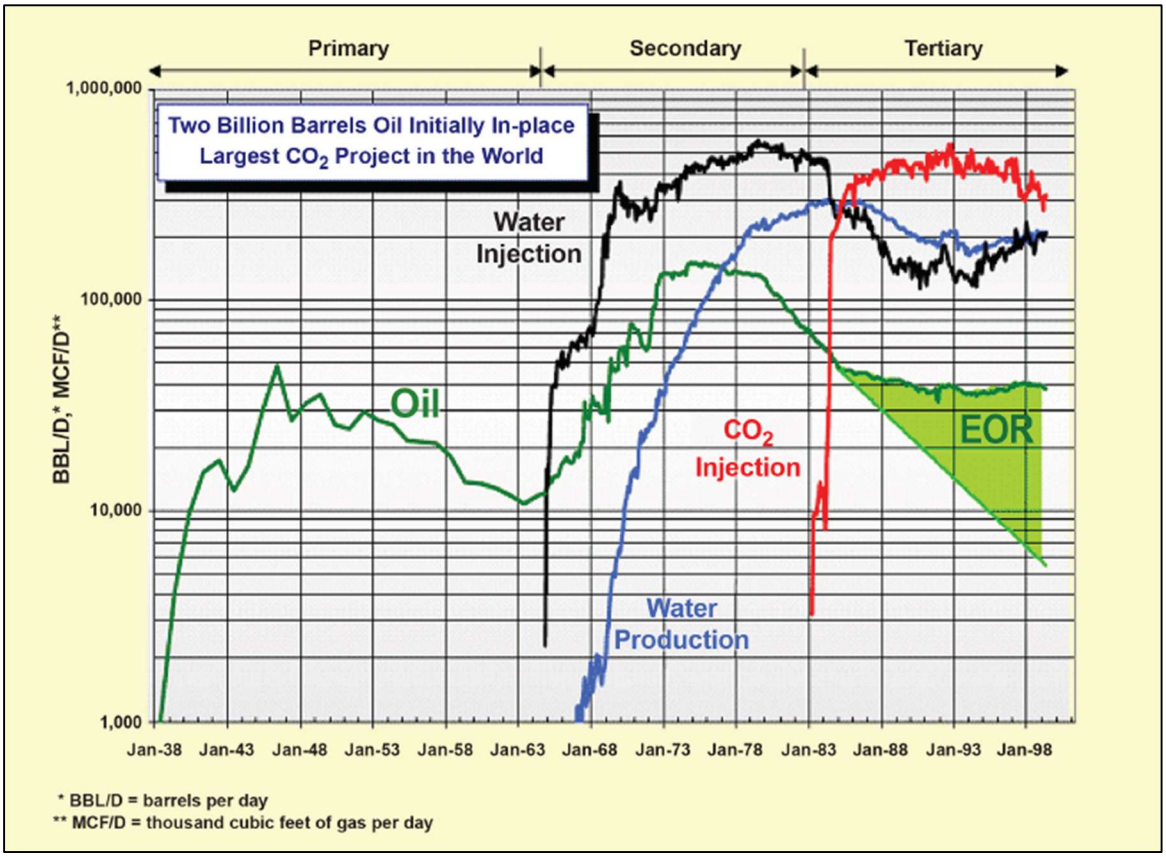


Figure 2.12: Oil production versus time for primary, secondary(waterflood) and tertiary (CO_2-EOR) oil production periods (National Energy Technology Laboratory (NETL), 2010).

2.2.2 Biofuels from microalgae

Baena-Moreno et al. (2019) have reviewed the conversion of Biofuels from microalgae. The sources of CO_2 for microalgae are from atmosphere, industrial emission, and soluble carbonates. The two possible ways of microalgae cultivation are in open channel ponds or photo-bioreactors. In terms of cost the bioreactors are more expensive than open-bond systems (Baena-Moreno et al., 2019).

Figure 2.13 outlines the processes required to convert microalgae to biofuels. As shown in the figure, following the conversion of carbon source in a flue gas, a microalgae cultivation stage resulted in obtaining a wastewater biomass. After the biomass is dried by the applied heating system, and wastewater is separated, the resulting biomass produces biofuels. In addition to the final biofuel production, the cultivation of algal biomass itself uses a large amount of CO_2 and hence reduces the emission of greenhouse gases. This indirectly mitigate the negative environmental impact (Baena-Moreno et al., 2019).

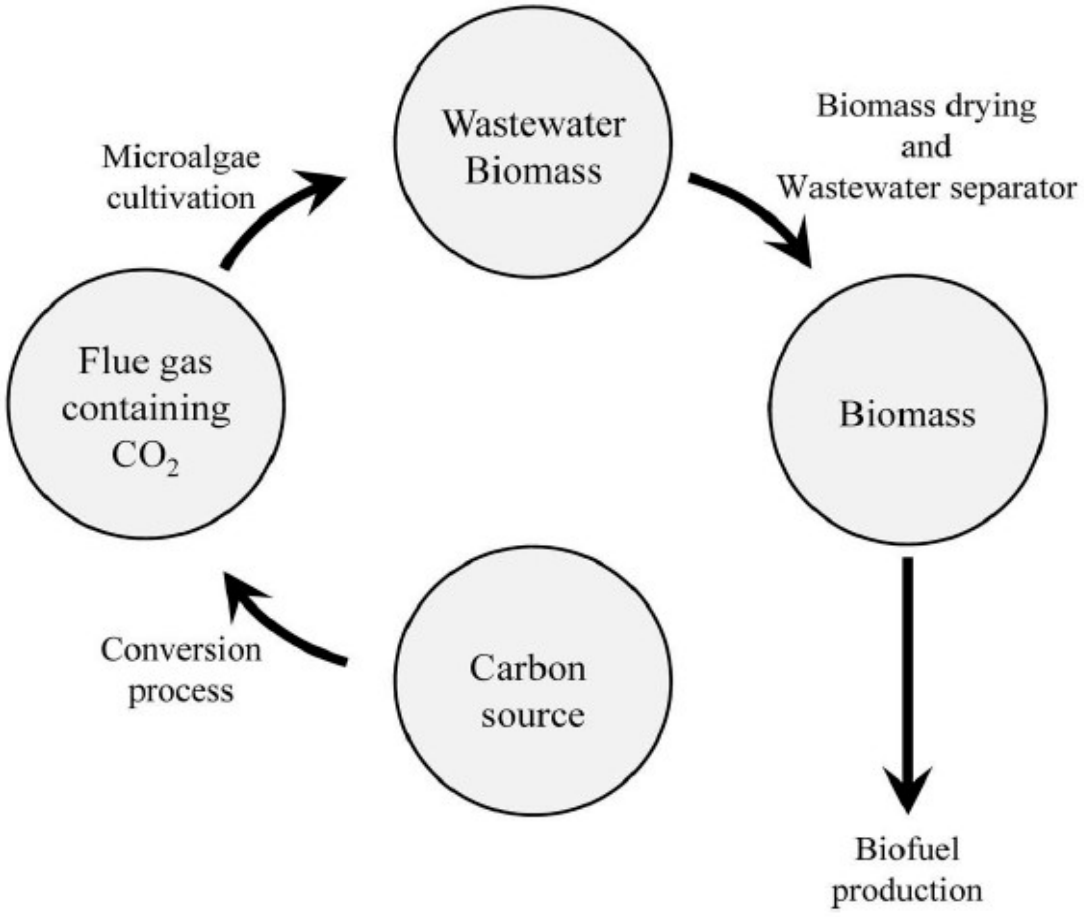


Figure 2.13: Process of biofuels formation from microalgae process (Baena-Moreno et al., 2019).

3 LCA Analysis for Carbon Capture and Utilization

As reviewed, CO_2 is one of the greenhouse gases. It is therefore imperative to carbon capture (CC) CO_2 from the industry, store (CCS) and convert CO_2 into valuable products. This process is known as Carbon Capture and Storage (CCS) and also utilize (CCUS) (Baena-Moreno et al., 2019). The conversion of CO_2 into valuable products has benefits both on economy and to reduce negative environmental impacts such as on climate change. In general, the CCS and CCUS technologies with regards to environmental impacts is assessed with a broadly accepted method among academic and industrial practitioners called Life Cycle Assessment (LCA).

Life Cycle Assessment (LCA) is a technique for assessing the potential benefit assessment as well as multiple environmental impacts during the life cycle of products or services. The LCA is based on a standardized method outlined in ISO 14040/14044 (European Commission, 2010). The LCA analysis described in the standard is based on selecting the functional unit, system boundaries, background processes, or environmental impact assessment as well.

In Chapter 3, the LCA methodologies will be summarized. Then, the application of LCA on CCU and CCS case studies will be presented in Chapter 4.

3.1 Phases of Life Cycle Assessment

During the life cycle of a product, the Life cycle assessment methodology assess the environmental impacts of a product or service including stages from raw material extraction, manufacturing & processing, transportation, usage and retail, and recycling to final disposal (Muthu, 2020). During each stage, the LCA quantitatively describes the impact on the environment due to the applied resources (input) and the resulting emission pollutants (output).

Inputs:

- raw materials
- water
- energy
- chemicals and other auxiliaries.

Outputs:

- product
- co-product
- solid waste
- air emissions
- water emissions
- emissions to land.

Figure. 3.1 depicts the various phases involved in the life cycle of a product considered for the quantification of LCA.

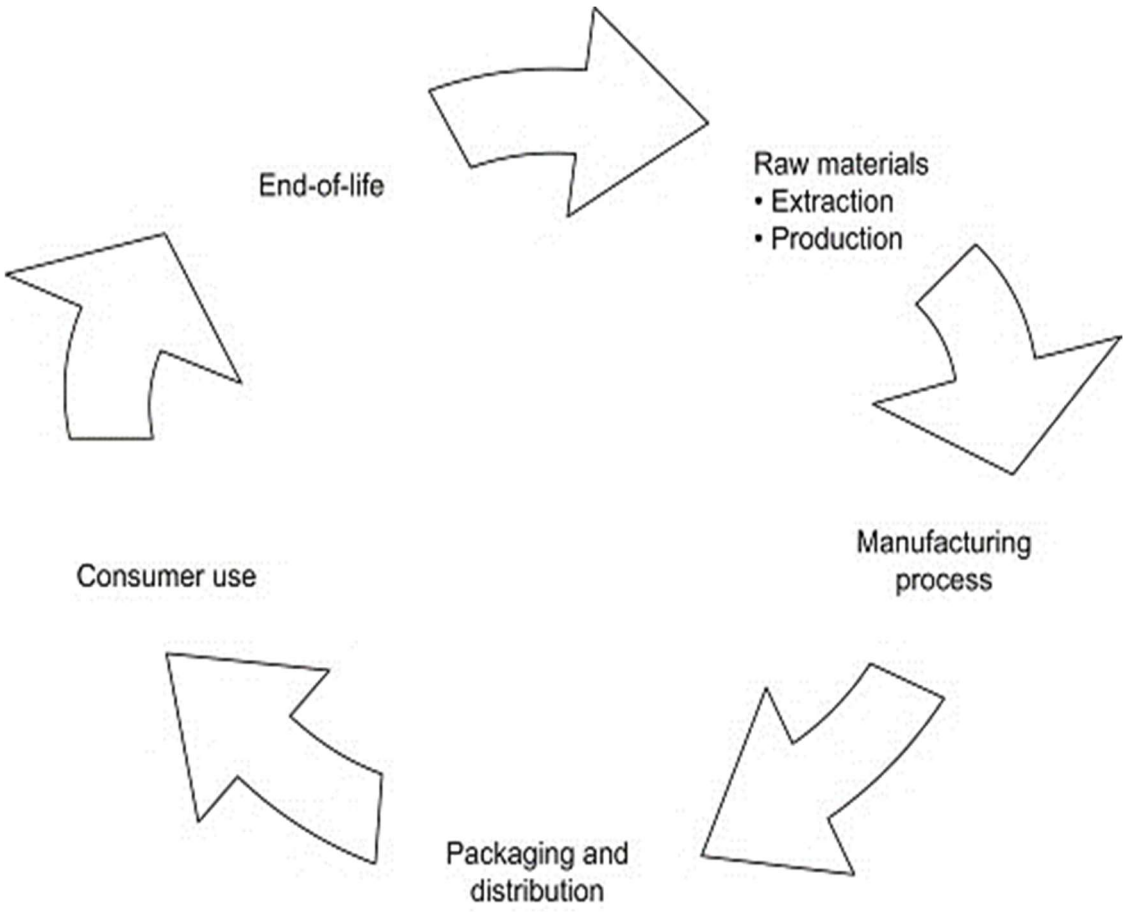


Figure 3.1: Various life cycle phases of a product (Muthu, 2020).

Figure 3.2 shows the LCS assessment framework. According to ISO standard, the four phases of LCA study are:

1. Goal and Scope definition
2. Life cycle inventory analysis
3. Life cycle impact assessment
4. Interpretation.

As shown in the figure, the phases are interdependent. For instance, with respect to time and space, the life cycle inventories should fit with the goal and scope.

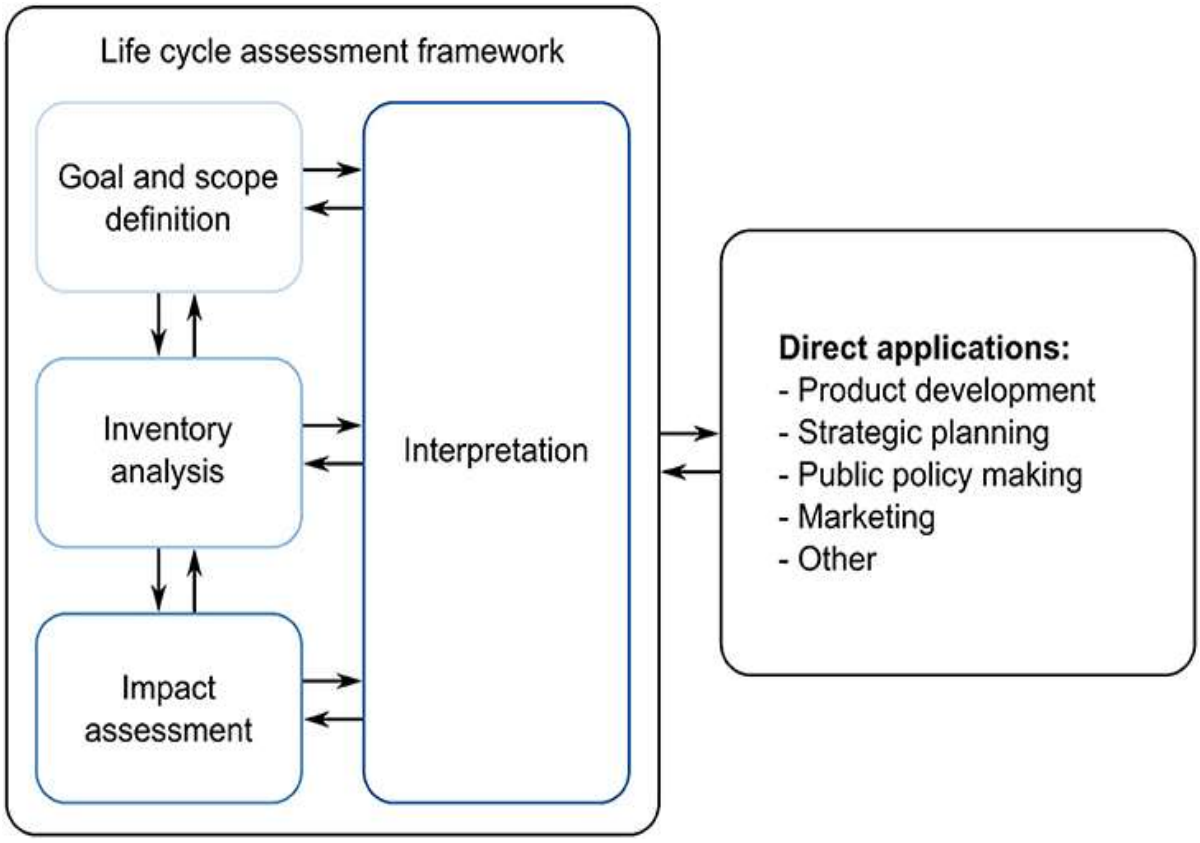


Figure 3.2: General framework for life cycle assessment (European Commission, 2010).

With the ISO standard 14044 there are different weighing methods used in LCA. Weighing is based on value choices and the methods are based on principles such as distance to target and damage values. For instance, among the weighting methods described in section §3.3, the purpose of the ReCiPe's method is to consistently combine midpoint and endpoint methodologies.

3.1.1 Stage 1: Goal and Scope definition

The minimum requirement to include in the LCAs goal and scope is:

The goal should state the objective of performing the LCA study, what the application areas of the results are and who the potential audience is.

The scope should have a distinct description of the product system, the product system boundaries, the function of the product system and the data category (Lee & Inaba, 2004).

3.1.2 Stage 2: Inventory Analysis

Life cycle inventory analysis (LCI) deals with the description of materials and the calculation of energy flows within a product system, as well as interacting with the environment and emissions to the environments.

Figure 3.3 shows ISO 14041 common procedures for the application of LCI (Lee & Inaba, 2004). The process flow chart shows the interrelationship between unit processes in the product system. The detailed description of the process is beyond the scope of this thesis. Interested readers can be referred to reference (Lee & Inaba, 2004).

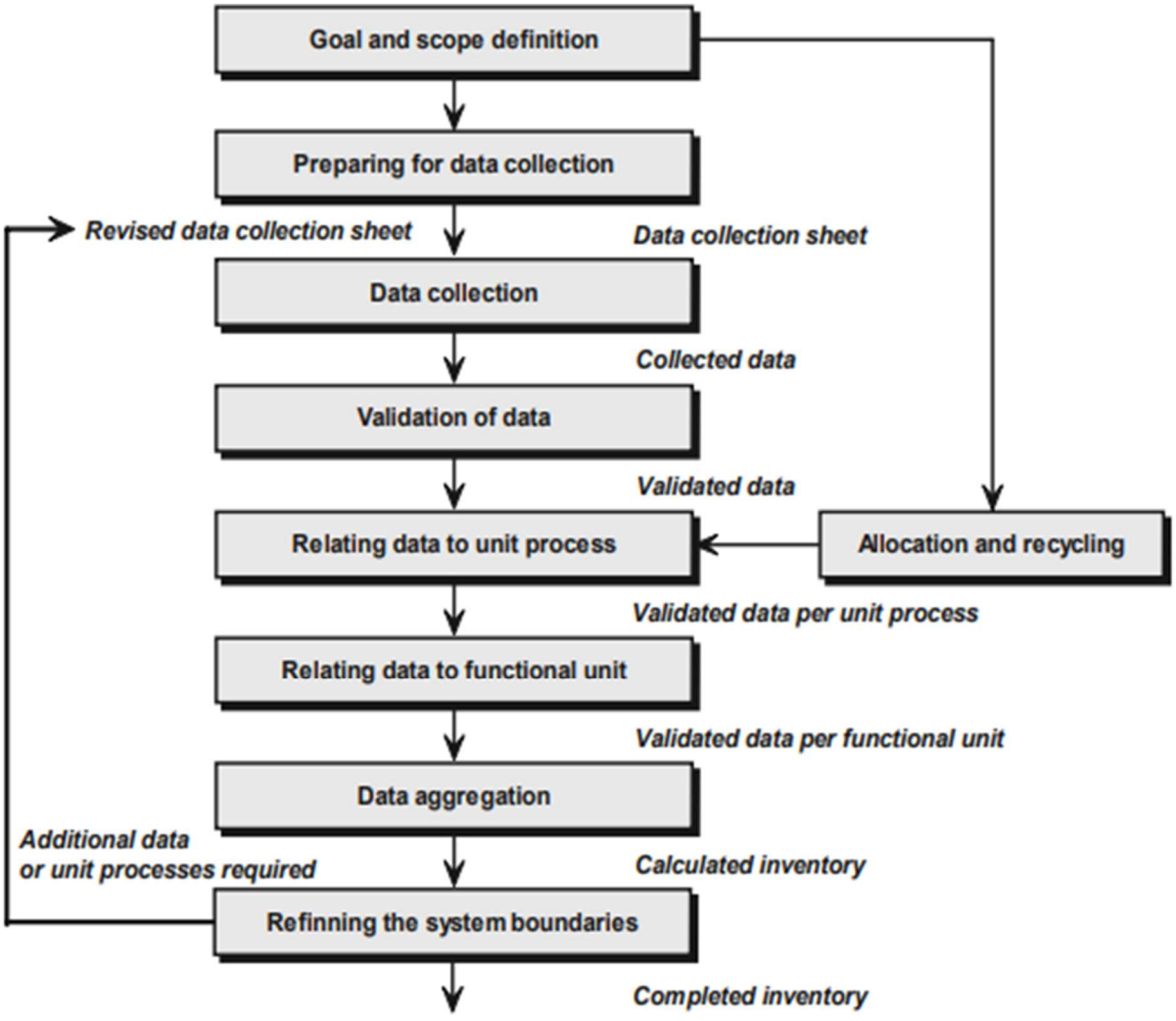


Figure 3.3: ISO 14041 LCI operational procedures (Lee & Inaba, 2004).

3.1.3 Stage 3: Impact assessment

Life cycle impact assessment (LCIA) is used to figure out the significance of potential environmental impact of a product system based on life cycle inventory.

As shown in Figure 3.4, the LCIA process consists of different elements within the inventory elements, where the importance of impact categories is assessed by classification, characterization, normalization, and weighting. However, out of the four only classification and characterization is mandatory, while weighting and normalization is optional (Lee & Inaba, 2004). The figure also shows the elements and their relationships in LCIA.

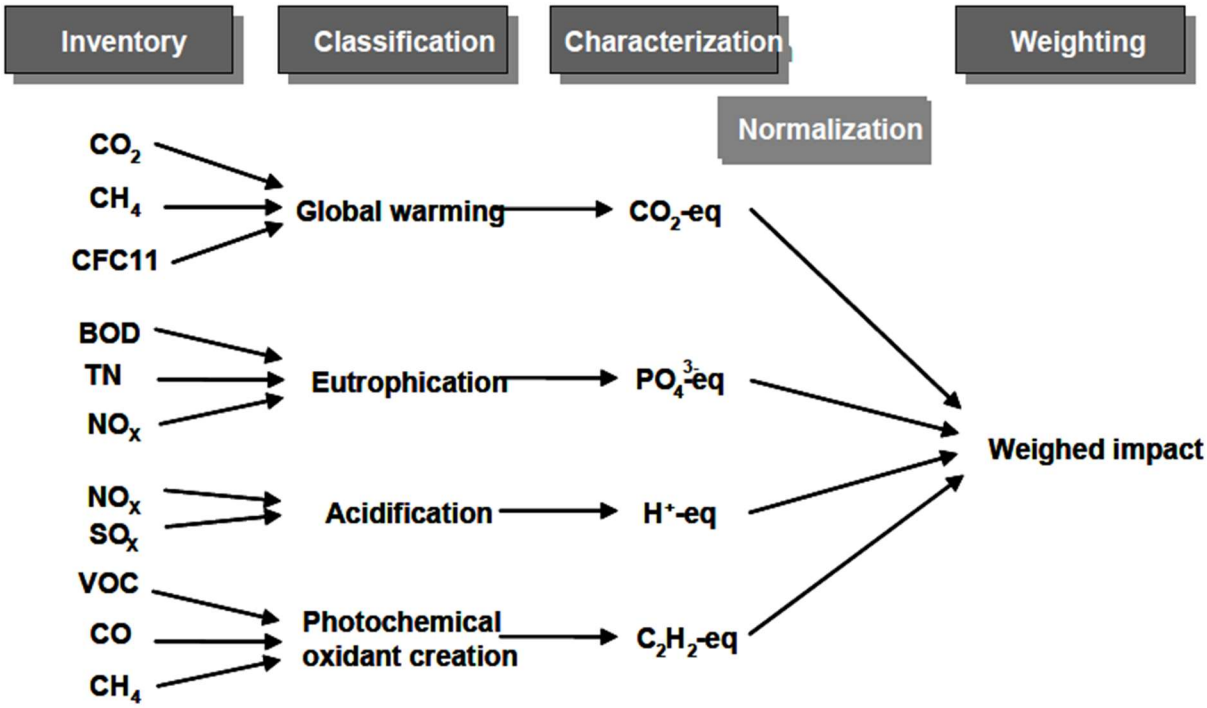


Figure 3.4: Elements and relationship among the elements of LCIA (Lee & Inaba, 2004).

3.1.3.1 Classification

The classification part of life cycle impact assessment deals with classifying the LCIA results into different impact categories, which are listed in section §3.2, Table 3-1. The categories can in general be grouped into greenhouse gas effects resulting in global warming and non-greenhouse gas effects resulting in increased environmental impacts, which occur at both global and local scales.

3.1.3.2 Characterization

After classifying the impact categories, the environmental impacts associated with the given impact category is quantified by the characterization factor or equivalency factor. For illustration, the greenhouse gases, CO_2 and CH_4 have different chemical formulas and have a different degree of impact on global warming. In terms of global warming impacts, the contribution of 1 g of CH_4 is equivalent to 23 g of CO_2.

In other words, if 1 g CO_2 is defined as unit global warming, then 1 g of CH_4 can be expressed as a 23 g CO_2 equivalent that contribute to the global warming. Consequently, the equivalency factor or characterization factor of CH_4 is 23 g CO_2 equivalent (eq). This value is recognized as the global warming potential (GWP) of CH_4. The detail is beyond the scope of this thesis except for outlining the LCI process. Interested readers can be referred to (Lee & Inaba, 2004).

3.1.3.3 Normalization

The normalization part of the LCIA splits up a characterization value of an impact category by the normalization reference of the same impact category. Unlike characterization, the normalization reference considers geographical (global, local, regional) and temporal system boundaries (typically one year). Whereas the characterization considers the product system (Lee & Inaba, 2004).

However, according to reference (Lee & Inaba, 2004), ISO 14042 does not recommend doing normalization. Although, performing the normalization step in an LCA study allows to check for error of inventory data and characterization values. Moreover, it allows a better interpretation of the characterized impact values and provides information for the subsequent weighting step. The detail is beyond the scope of this thesis except for outlining as part of the LCI process. Interested readers can be referred to (Lee & Inaba, 2004).

3.1.3.4 Weighting

As shown in figure 3.4, following the normalization step, weighting is the last part of the LCIA process. The weighting assign weight to the impact categories (Lee & Inaba, 2004). The two different weighting methods are the broader perspective (i.e., qualitative) and the narrower perspective (i.e., quantitative). These weighting methods are used for comparing systems and processes as well as materials. Here again, the detail is beyond the scope of this thesis except

for outlining as part of the LCIA process. Interested readers can be referred to (Lee & Inaba, 2004). However, the basic elements of the two commonly weighing methods for the LCIA analysis are described in section §3.3.

3.1.4 Stage 4: Interpretation

According to the ISO 14043, the three main fundamentals in life cycle interpretation are a) key issues identification (i.e., as materials, components, and processes) b) evaluation (i.e., checking completeness, checking sensitivity and checking consistency), and c) draw conclusions along with recommendations (Lee & Inaba, 2004). Figure 3.5 illustrates the process of LCI and LCIA results (Laurent et al., 2020). As shown in the figure, authors have proposed five steps on the checking and identifying the significant issues as well as conclusion/limitations and recommendation. The black dotted arrow shows the inputs information flow from the goal and scope definition phase to the interpretation process. The red-dashed arrow clearly indicates that the nature of interpretation is an iterative process. The detail is beyond the scope of the thesis and interested readers can be referred to the (Laurent et al., 2020).

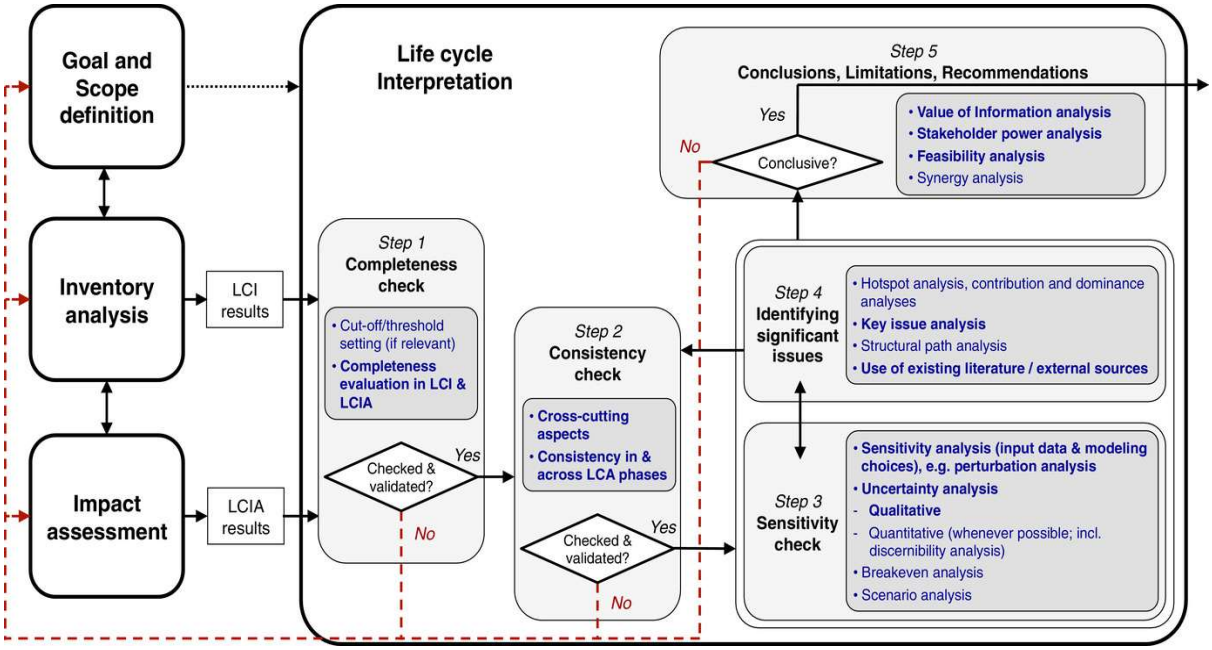


Figure 3.5: Illustration of LCI and LCIA framework to perform life cycle interpretation (Laurent et al., 2020).

3.2 Impact categories

The potential environmental effects caused by CCS and CCU are divided into impact categories. This includes

1. Global warming potential (GWP),
2. Acidification potential (AP),
3. Eutrophication potential (EP),
4. Photochemical oxidation potential (POCP),
5. Human toxicity potential (HTP),
6. Fresh water aquatic ecotoxicity potential (FAETP) and
7. Terrestrial ecotoxicity potential (TETP).

Table 3-1 shows an overview of LCA impact categories (Zapp et al., 2012). Global warming potential (GWP) is the impact of human emission on radiative forcing of atmosphere, causing a temperature rise. Acidification potential (AP) are emissions caused by acid-forming substances. Eutrophication potential (EP) are excessive supply of nutrients. Photochemical oxidation potential (POCP) is the phenomenon of Smog, formation of reactive chemical compounds by the action of sunlight on primary pollutants. Human toxicity potential (HTP) are the impacts on human health of toxic substances. Fresh water aquatic ecotoxicity potential (FAETP) are the effects of toxic substances on fresh water. Terrestrial ecotoxicity potential (TETP) are effects of toxic substances on soil (Zapp et al., 2012).

Table 3-1: Overview of LCA impact categories (Zapp et al., 2012).

Impact Category	Abbreviation	Scale	Examples of relevant LCI data	Characterization factor
Global Warming Potential	GWP	Global	Carbon Dioxide, CO_2 Nitrous Oxide N_2O Methane CH_4 Sulphur hexafluoride, SF_6 Chloroform $CHCL_3$ Chlorofluorocarbons CFSs Hydrochlorofluorocarbons HCFCs Methyl Bromide, CH_3Br	kg CO_2 –equivalents
Acidification Potential	AP	Regional Local	Sulphur oxides SOx Nitrogen Oxides NOx Hydrochloric acid HCl Hydrofluoric acid, HF Ammonia NHs Nitric acid, HNO_3 Sulphuric acid, H_2SO_4	kg SO_2 –equivalents
Eutrophication Potential	EP	Local	Phosphate PO_4^{3-} Nitrogen Nitrogen dioxide NO_2 Nitric acid HNO_3 Ammonia NH_3 Phosphoric acid H3PO_4 Chemical Oxygen demand COD	kg PO_4^{3-} –equivalents
Photochemical Oxidation Potential	POCP	Local	Alkanes Alkenes Alkyne Aromatic hydrocarbons	Kg ethylene-equivalents
Stratospheric Ozone Depletion Potential	ODP	Global	CFCs HCFCs Halons Methyl Bromide Methyl chloride, CH_3CL	Kg CFC-equivalents
Human Toxicity Potential	HTP	Regional Local	Arsenic Benzene Chromium IV Hexachlorobenzene	Kg 1,4-DCB equivalents
Fresh water Aquatic Ecotoxicity Potential	FAETP	Local	Arsenic Chromium IV	Kg 1,4-DCB equivalents
Marine Aquatic Ecotoxicity Potential	MAET P	Local	Arsenic Chromium IV	Kg 1,4-DCB equivalents
Terrestrial Ecotoxicity Potential	TEP	Local	Arsenic Chromium IV	Kg 1,4-DCB equivalents
Cumulative energy Demand/Abiotic Depletion Potential	CED/ADP	Global Regional Local	Quantity of energy used/ Quantity of minerals used Quantity of fossil fuels used	MJ/kg-antimony equivalent

Based on several studies obtaining worldwide emissions associated with all impact categories for the year 2000, Sleeswijk et al., 2008 have calculated global normalization values. Table 3-2 provides the global values for various impact categories.

Table 3-2: Normalized Equivalent CO_2 factors (Sleeswijk et al., 2008).

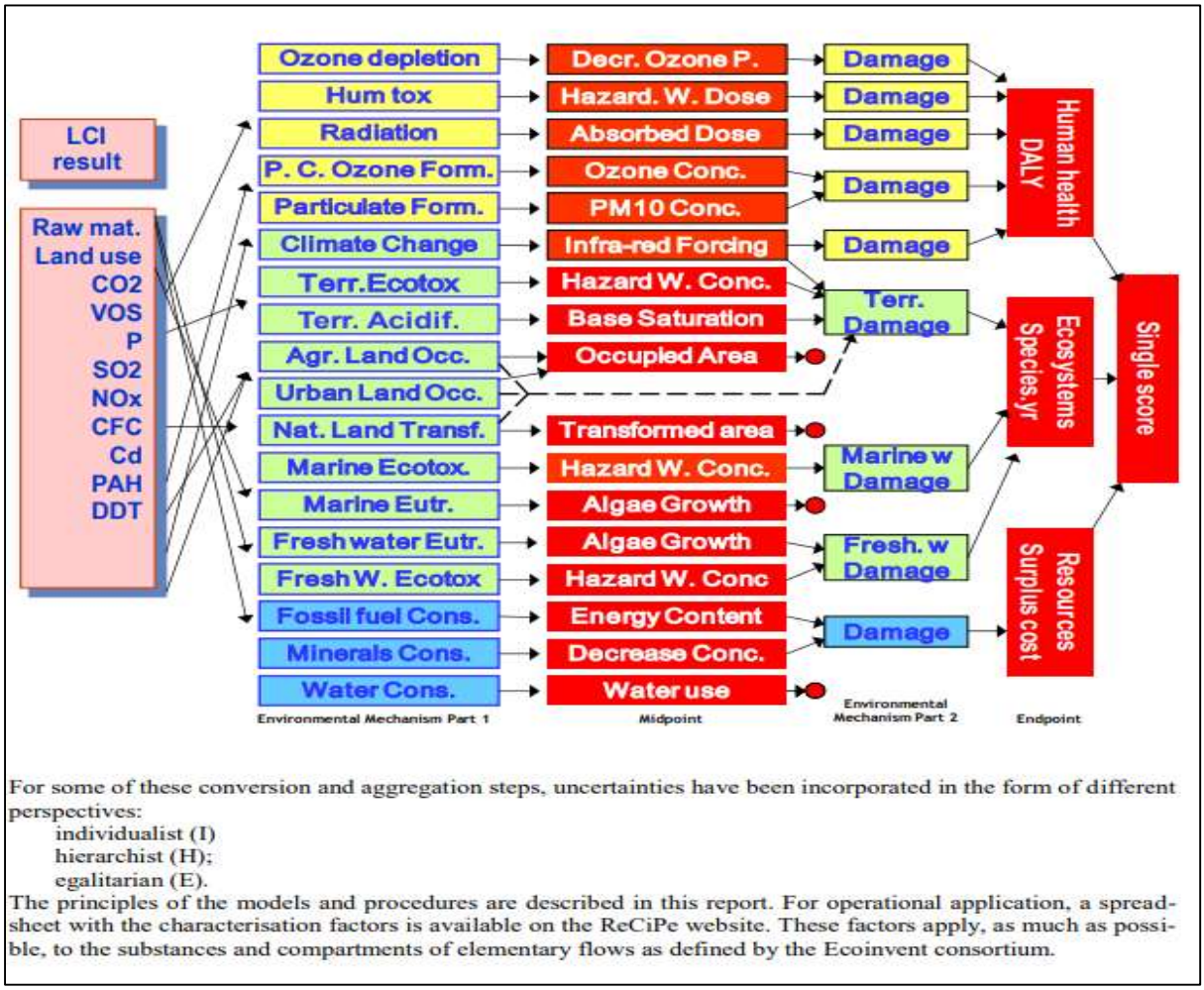
Impact category	World 2000
Global warming potential (GWP 100 years)	4.18E+13 kg CO_2 equiv.
Acidification potential (AP)	2.39E+11 kg SO_2 equiv.
Eutrophication potential (EP)	1.58E+11 kg phosphate equiv.
Photochemical oxidation potential (POCP)	2.90E+10 kg ethane equiv.
Human toxicity potential (HTP)	3.63E+12 kg DCB equiv.
Fresh water aquatic ecotoxicity potential (FAETP)	3.47E+12 kg DCB equiv.
Terrestrial ecotoxicity potential (TETP)	1.09E+12 kg DCB equiv.

3.3 Weighting methods

3.3.1 ReCiPe

The Ecoinvent is an international Life Cycle Inventory (LCI) database, which is used for several life cycle assessment projects. The database comprises of among others in the areas of energy supply, agriculture, transport, biofuels and biomaterials and others (Weidema et al., 2013).

Using the Ecoinvent v2.2 database/inventory data, the LCA calculate the assessment results with ReCiPe. Figure 3.6 illustrates the ReCiPe 2008 framework showing relationship between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) (Goedkoop et al., 2009). The ReCiPe framework is a method for LCIA, which provides a recipe to calculate life cycle impact category indicators (Goedkoop et al., 2009). As shown in the figure, the framework comprises of about eighteen impact categories at midpoint level and the environmental impact mechanisms are further grouped into three categories at endpoint level. In order to make these combinations, some uncertainties have been incorporated in the form of the perspectives; individualist (I), hierarchist (H) and egalitarian (E).



For some of these conversion and aggregation steps, uncertainties have been incorporated in the form of different perspectives:

individualist (I)
hierarchist (H);
egalitarian (E).

The principles of the models and procedures are described in this report. For operational application, a spreadsheet with the characterisation factors is available on the ReCiPe website. These factors apply, as much as possible, to the substances and compartments of elementary flows as defined by the Ecoinvent consortium.

Figure 3.6: ReCiPe 2008 framework showing relationship between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe 2008 (Goedkoop et al., 2009).

3.3.2 IMPACT 2002+

The Impact 2002's is acronym for the Impact Assessment of Chemical Toxics. The impact assessment methodology originally developed at the Swiss Federal Institute of Technology - Lausanne (EPFL). The methodology combines midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories (human health, ecosystem quality, climate change and resources) as illustrated in figure 3.7. The weighting unit in this model is also damage costs, as in ReCiPe.

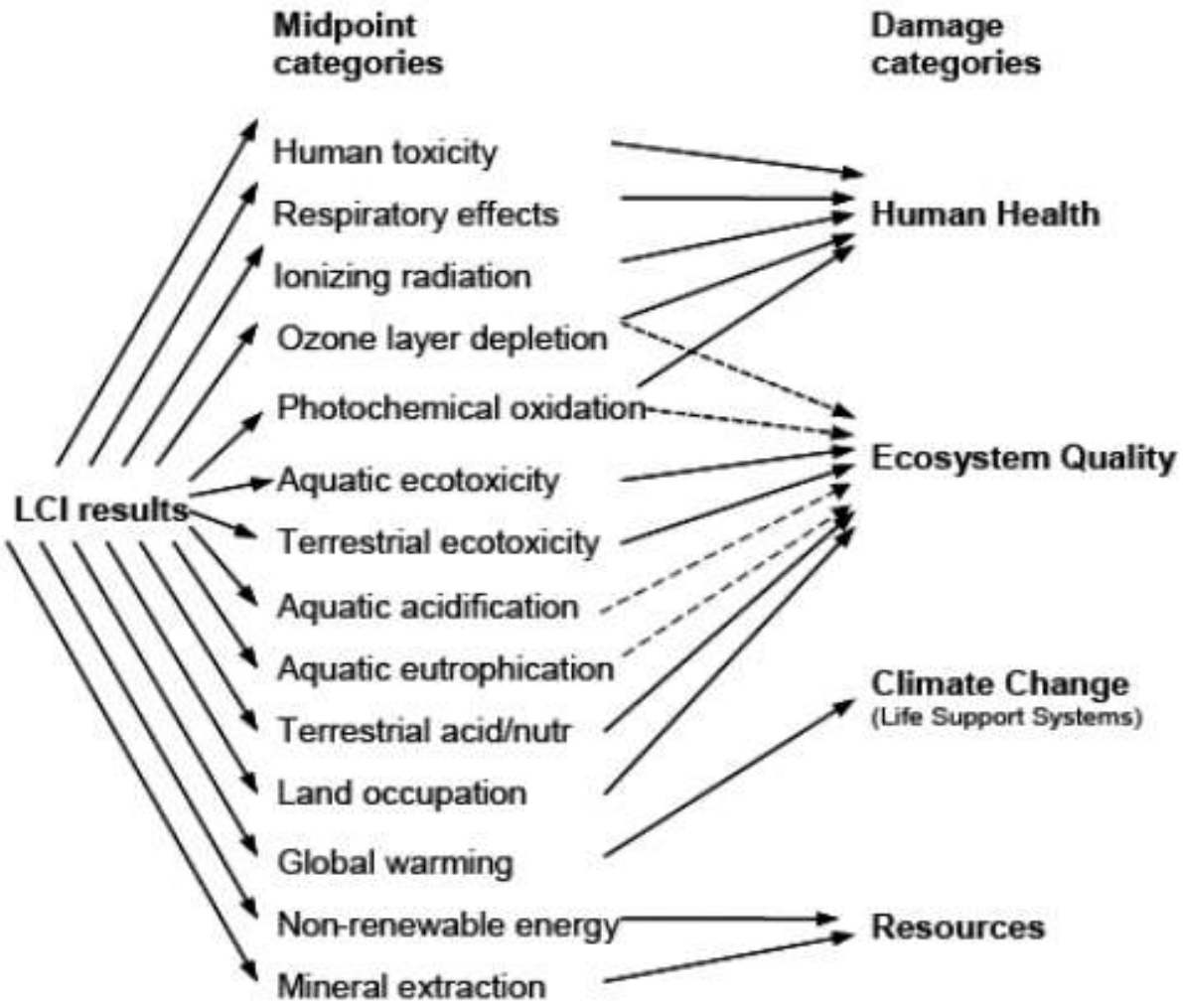


Figure 3.7: Scheme of the IMPACT 2002+ framework that links LCI results via the midpoint categories to damage categories. Based on (Jolliet et al., 2003).

4 Life Cycle Assessment (LCA) of CCS and CCU Technologies

This chapter presents a total of four LCA case studies to show the role of LCA in identifying the environmental impacts associated with the CCS and CCU technologies. The impact categories are on greenhouse gas (GHG) reduction and non-greenhouse gas (NGHG) effects on environment. Figure 4.1 illustrates how carbon capture and utilization impacts the environment by use of the LCA process.

Due to the unavailability of LCA analysis tools (SimaPro software) and power plants databases at UiS, the author of this thesis chose to perform LCA through case studies since the results also are informative.

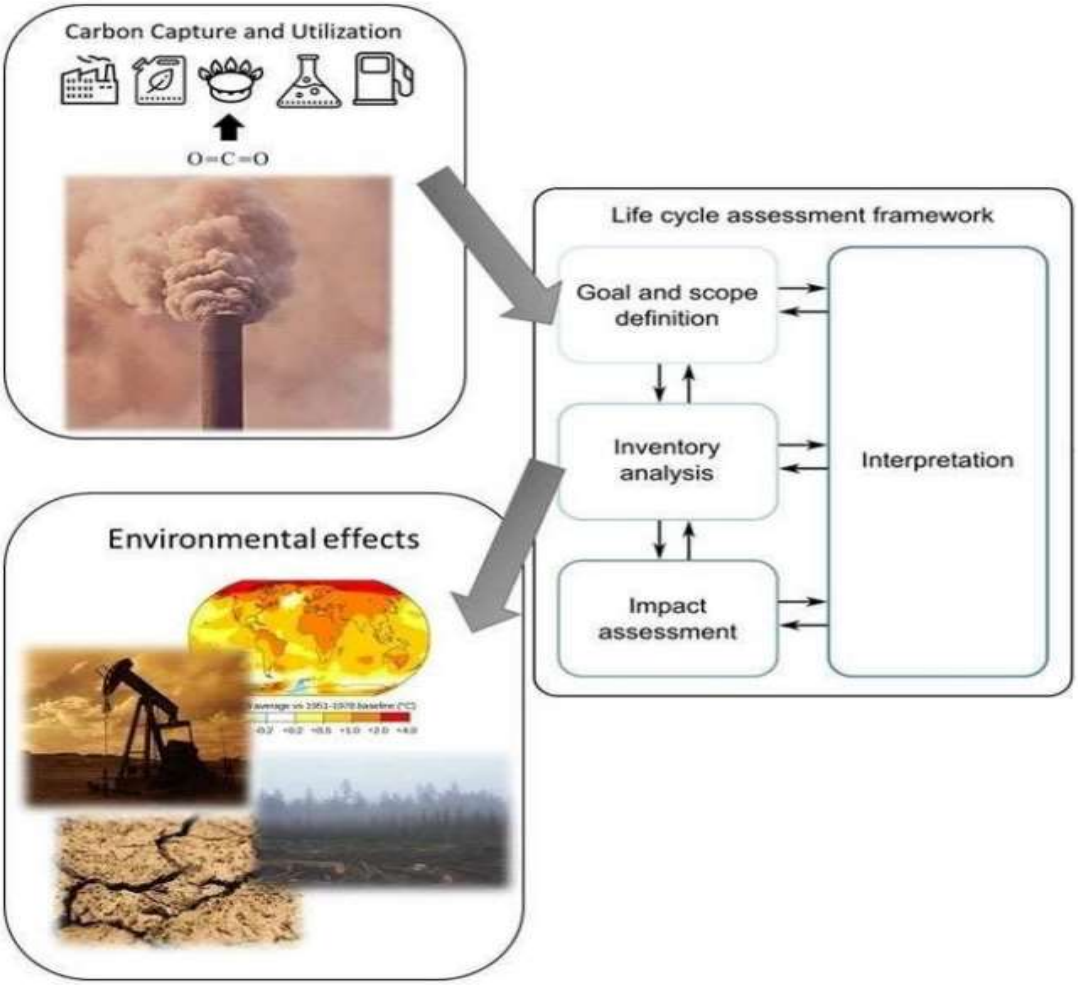


Figure 4.1: Illustration of the process of LCA of CCU technologies (Garcia-Garcia et al., 2021).

4.1 Case study #1 LCA of power plant with and without CCS

Sathre et al., (2011) have conducted critical review and analysis LCA studies of CCS systems comparing without CCS. For the study, they considered a total of 11 studies documented in literatures. The objective of the study was to investigate the fuel driven electric power plants impact on the environmental impacts.

The study considered:

- **23 power plants**, which comprise of 13 hard coal fuel, 6 lignite fuel, and 4 natural gas power plant.
- **Two capture technologies**, which are amine-based solvent (18 primarily MEA) and (5 plant used primarily physical solvents such as Rectisol and Selexol).

Figure 4.2 shows the averaged 23 power plants with and without CCS energy and GHG flows with respect to producing 1 MWh of electricity.

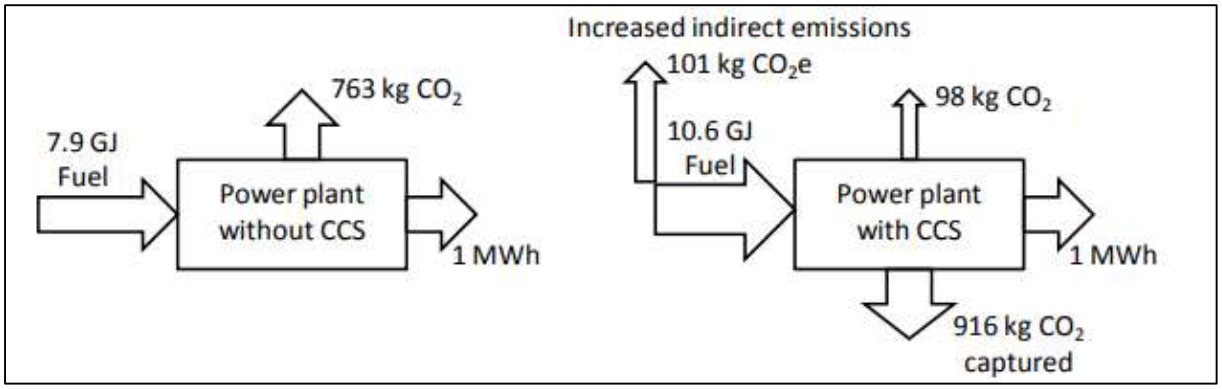


Figure 4.2: Energy and GHG flows associated with 1 MWh electricity production (Sathre et al., 2011).

Energy and GHG analysis

As shown in Figure 4.2, to produce unit electricity, the CCS system requires 2.7 GJ (i.e., 34%) more fuel than the System without CCS. This is because of the need for extra energy for capture and sequestration. However, in terms of the net CO_2 emission reduction, the power plant without CCS emitted all the CO_2 in the fuel (i.e., 763 kgCO_2) into the atmosphere. On the other hand, in the plants with CCS, about 916 kg CO_2 was captured and sequestrated (i.e., 90% of the carbon in the fuel), and only 98 kgCO_2 emitted to the atmosphere (i.e., and 10% of the carbon in the fuel). This shows that the CCS system allows the net reduction in CO_2 emission is less than 90%.

As can be seen in the process flow chart, the 101 kgCO_2-e increased indirect CO_2 emission is arise from the processes such as CCS infrastructure, mining and transporting. Therefore, the net total CO_2 emission therefore is reduced by 82%.

It is important to note that the emission also contains non-CO_2 GHGs such as methane, which are produced from coal mining and natural gas and other indirect sources. Therefore, due to the total 101 kg CO_2-e indirect GHG emissions per MWh of electricity, further reduced the overall GHG emission to 74%. Table 4-1 shows the summary of the CO_2 emission reduction and the net GHG emission reduction of the three power plants. As shown, the capture technologies employed in the power plants efficiency is about 90%.

Table 4-1: Percent fuel carbon capture, CO_2 emission reduction, and GHG reduction, by fuel type (Sathre et al., 2011).

	All plants	Lignite	Hard coal	Natural gas
Fuel carbon captured	90%	90%	91%	90%
Net CO_2 emission reduction	82%	84%	83%	74%
Net GHG emission reduction	74%	81%	74%	65%

Non-climate impacts analysis (Environmental impacts)

The authors have studied the LCA analysis on the environmental impacts of non-GHG emissions due to the CCS system. The emission also contains non-CO_2 flue gases such as NO_X due to degradation of monoethanolamine (MEA) capture solvent, which has impact on the ecological and human health.

Analysis results shown in table 4-2 summarizes the percentile changes in CCS equipped power plants. Authors have reported based on the selected studies that the NO_X emissions in general showed an increasing trend when implementing CCS system. The main reason is due to the increased fuel quantity and indirect emissions. On the other hand, the emissions of SO_X and particulate matter decrease. One of the reasons could be according to the authors due to the removal of particles. However, the authors have pointed out that due to the considered few numbers of studies, and the large variation in observation restrict them from making a tangible conclusion regarding non-GHG emission quantities.

Table 4-2: Changes in quantities of non-GHG emissions due to implementation of CCS in case-study power plants (Sathre et al., 2011).

	NO_X	SO_X	Particulate matter
Mean change	+17%	-61%	-19%
Standard deviation	36%	48%	49%
Number of plants	12	12	6

Environmental impacts

Table 4-3 shows the impact category associated with the of CCS in power plants. The authors have also reported combined impacts of the non-GHG emissions on the environment. Even though the SO_X level shows a decreasing trend, the acidification Potential is found out to be increasing due to the increases of NO_X, which has an acidifying effect.

Moreover, as shown in the Table, the Eutrophication and Human Toxicity Potential associated with the CCS are higher. The toxicity impacts largely caused by the uses and disposal of MEA capture solvent. This is also reported in section 2.1.1.2 as the negative impact of MAE capture technology. However, here as well, the authors indicated that due to the limited number of studies, and variation, it restricts them from making a tangible conclusion regarding non-GHG emission climate impacts.

Table 4-3: Changes in non-climate impact category scores due to implementation of CCS in case-study power plants (Sathre et al., 2011).

	Acidification Potential	Eutrophication Potential	Human Toxicity Potential
Mean change	+28%	+80%	+215%
Standard deviation	25%	56%	273%
Number of plants	14	14	13

Summary

From the of LCA studies of CCS systems, it is observed the net GHG emission reduction varies from 59% to 83%. The non-climate impacts analysis such as toxicity and acidification results show the possible increases with CCS system. However, improving the capture technology (i.e., usage and disposal impacts), one may reduce the indirect non-GHG impacts on the environments.

4.2 Case study #2 - LCA of Post-combustion in Norway

Modahl et al., (2012) have studied the LCA of post-combustion of the gas power plant at Tjeldbergodden (Norway) impact on the environment using LCA methodology. The main idea was the possibility of including post-combustion CCS. For the study they considered four case scenarios. Figure 4.3 shows the simplified design of the Tjeldbergodden gas power plant case with CO_2 capture, transport, and storage (four scenarios)

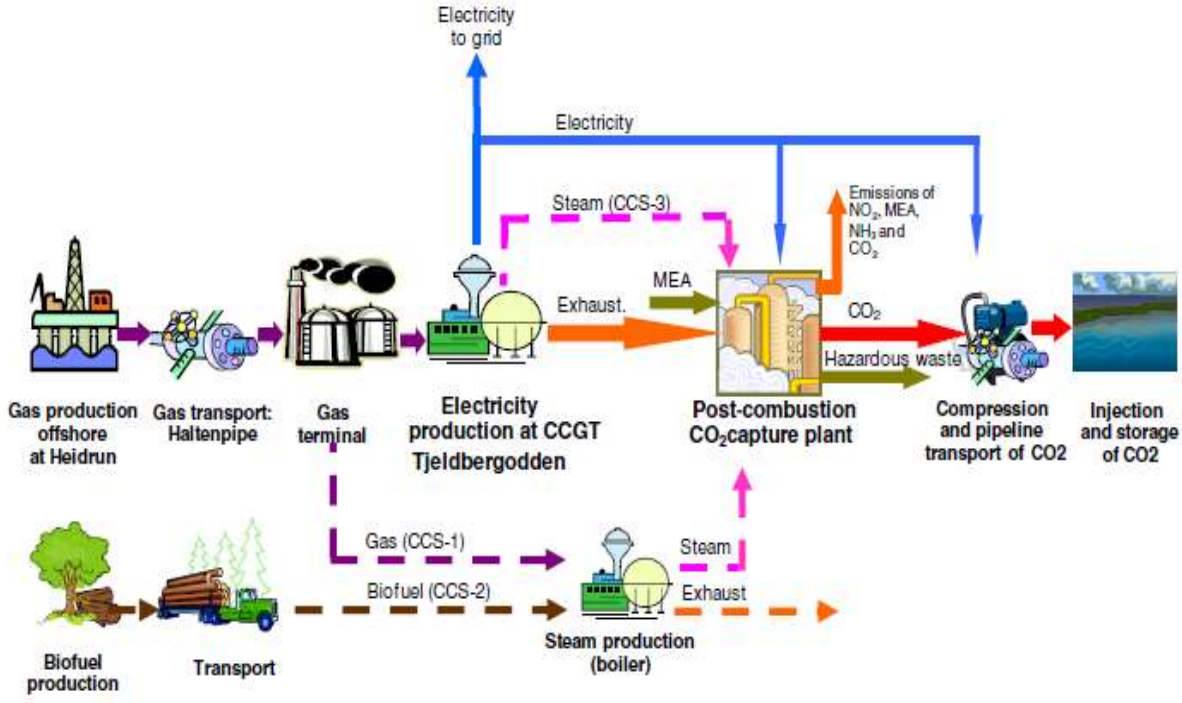


Figure 4.3: Simplified flow sheet of the gas power plant with CCS (Modahl et al., 2012).

Four scenarios were analyzed:

1. **Reference**: Gas power plant without CCS
2. **CCS-1:** Gas power plant with CCS, with a separate gas fueled steam boiler for amine regeneration
3. **CCS-2:** Gas power plant with CCS, with a separate biomass (wood)-fueled steam boiler for amine regeneration that shows different transport means
4. **CCS-3:** Gas power plant with CCS. Steam for amine regeneration is delivered from the low-pressure steam turbine in the power plant (process integration).

Authors have used three weighting methods. Except for EPS 2000, the methods are described in section §3.3, these are:

1. ReCiPe
2. EPS 2000
3. IMPACT 2002+

The impact assessment result categories as provided in Table 4-4, which include GWP, AP, EP, POPC and CED. As shown, the study indicates that the implementation of CCS only reduces the GWP category. The total GWP for the reference case scenario is 395,220 tons CO_2. On the other hand, comparing with the references case, the total reduction in CO_2 emissions is 47% for CCS-1 scenario, between 71-76% for the CCS-2 scenarios and 77% for the CCS-3 scenario. One can observe from Table 4.4 that all the other impact categories of CCS scenarios are higher than in the reference scenario. Figure 4.4 also shows the relative impacts of the CCS scenarios in relation to the reference scenario.

Table 4-4: Impact assessment results for the analyzed power plant scenarios (Modahl et al., 2012).

Scenarios	Global warming potential (tonne CO_2 eqv./TWh, g CO_2 eqv./MWh)	Acidification potential (tonne SO_2 eqv./TWh, g SO_2 eqv./MWh)	Eutrophication potential (tonne PO_4^{3-} eqv./TWh, g PO_4^{3-} eqv./MWh)	Photochemical ozone creation potential (tonne C_2O_4 eqv./TWh, g C_2O_4 eqv./MWh)	Cumulative energy demand (TWh LHV/TWh, kWh LHV/kWh)
Reference scenario	395,220	148	28.1	54.0	1.84
Scenario CCS-1 (gas boiler)	208,220	275	68.0	101.4	2.57
Scenario CCS-2a (biofuel boiler)	94,573	378	104.2	114.7	2.46
Scenario CCS-2b (biofuel boiler)	108,216	453	123.7	131.6	2.53
Scenario CCS-2c (biofuel boiler)	100,251	542	120.1	125.0	2.49
Scenario CCS-2d (biofuel boiler)	114,219	806	151.1	146.8	2.55
Scenario CCS-3 (process integration)	90,666	239	62.1	101.5	2.20

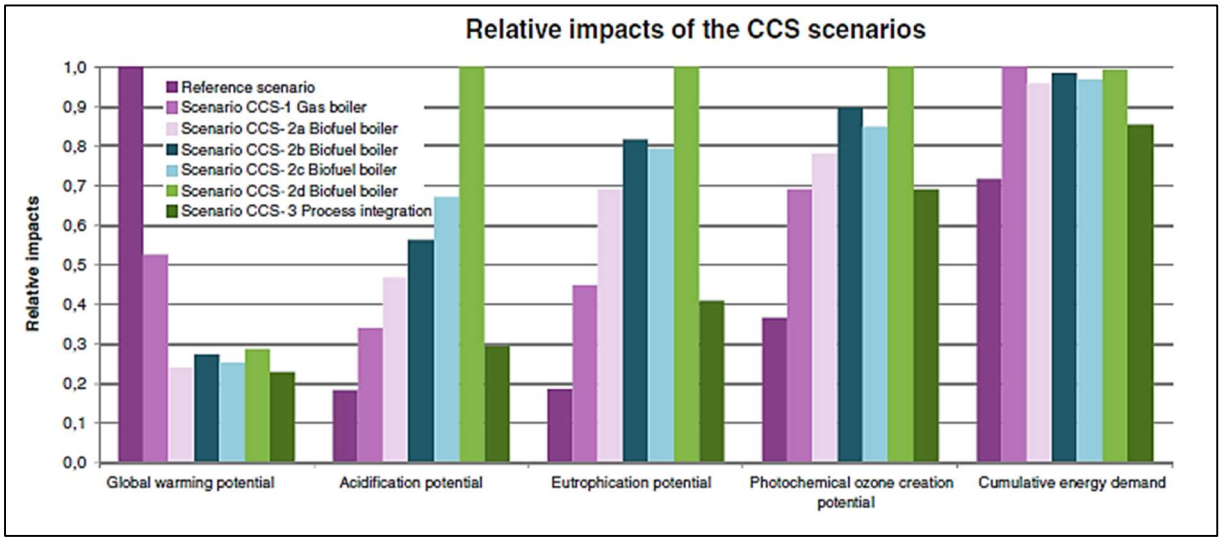


Figure 4.4 Relative impacts of the CCS scenarios in relation to the reference scenario (Modahl et al., 2012).

The authors have indicated from the LCA study of weighting environmental trade-offs is that even though it is not possible to currently draw a conclusion if production with or without CCS is more favorable. Both the characterization and weighting results show that the CCS-3 process is the better CCS option with separate steam boilers. From the study, we can also see that the issues of human health are possibly an important aspect of CCS. Figures 4.5, 4.6 and 4.7 shows the weighting results obtained from the ReCiPe, EPS2000 and IMPACT 2002+ models, respectively.

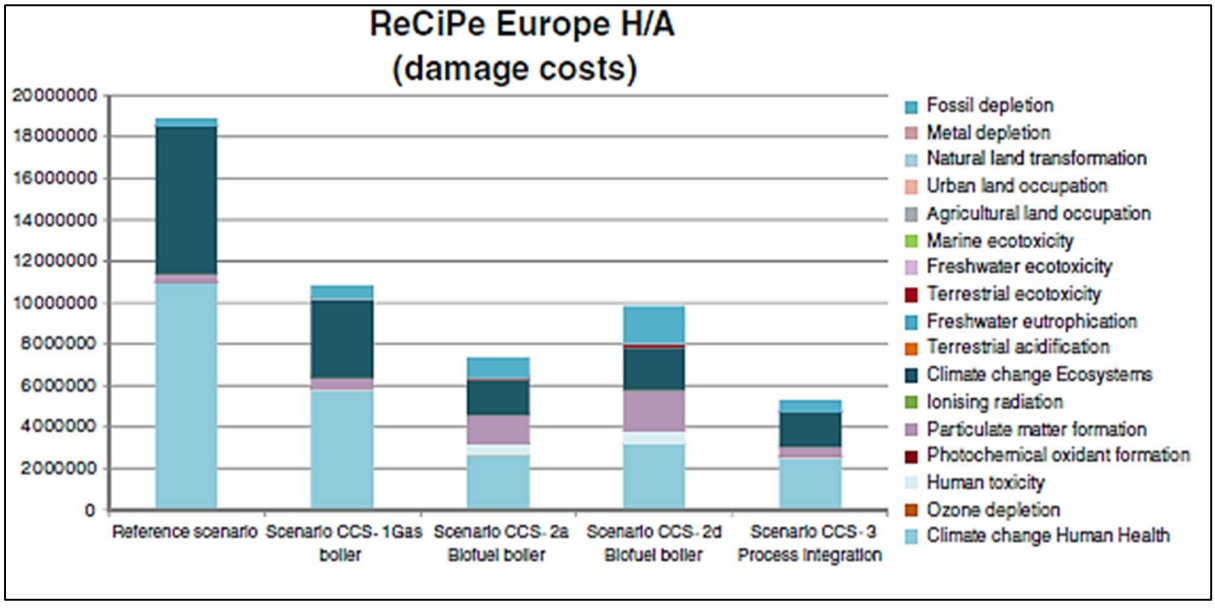


Figure 4.5: Weighting results for the ReCiPe model (Modahl et al., 2012).

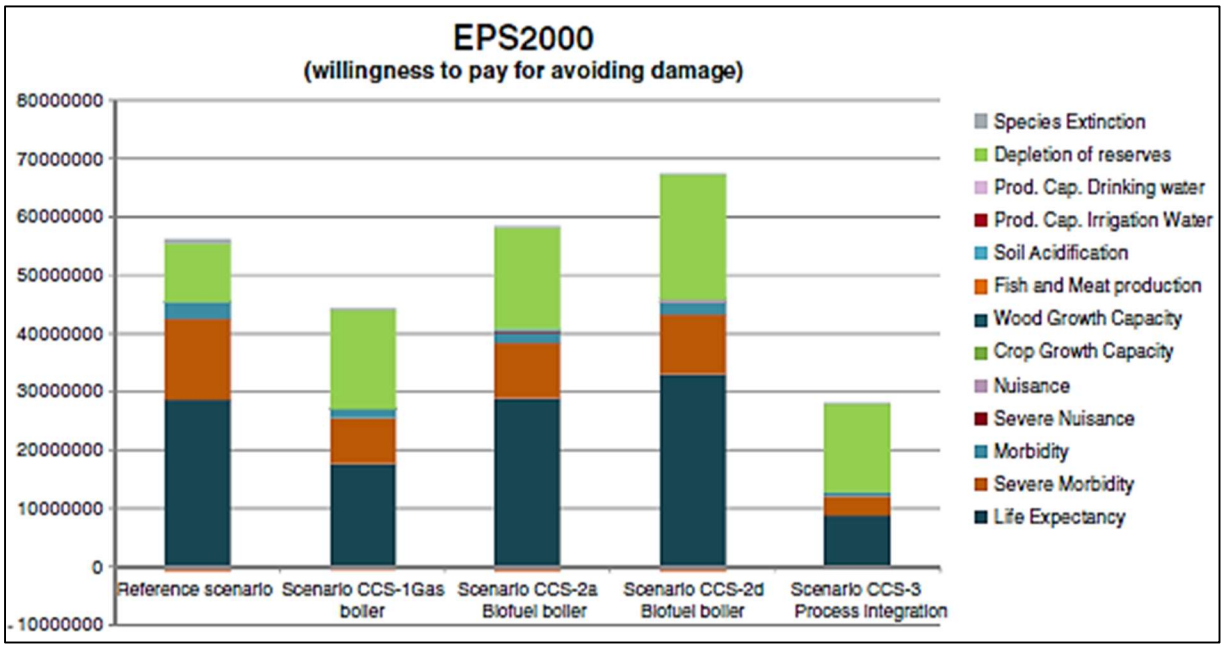


Figure 4.6: Weighting results for the EPS2000 model (Modahl et al., 2012).

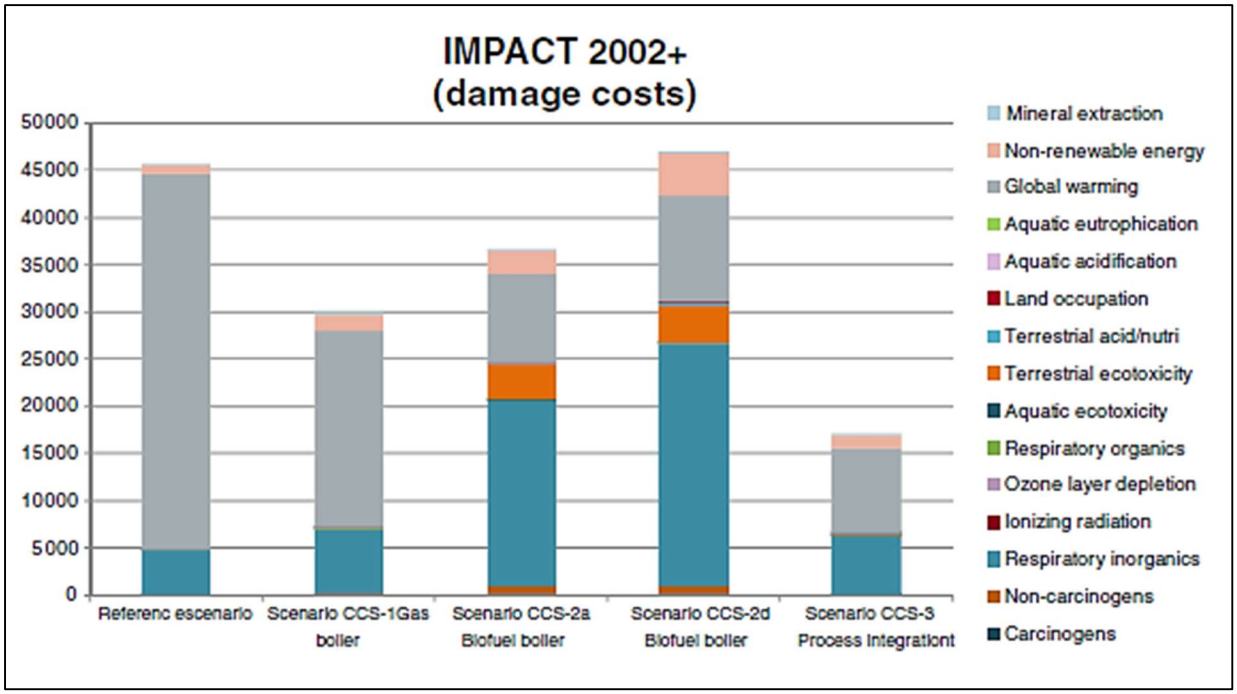


Figure 4.7: Weighting results for the IMPACT 2002+ model (Modahl et al., 2012).

Evaluations of CCS technologies based on Weighting methods

Considering all the impact assessment scenarios, the three weighting methods show that CCS-3 is the better option of CCS for this case. Comparing with the best scenario (CCS-3), results obtained from the three weight methods are summarized as follows:

- The ReCiPe weighting result show CCS-3 as the best option with CCS-2 39-84 % higher, CCS-1 at 104 % and the reference scenario at more than 250 % increase from the best scenario.
- The EPS 2000 weighting model also shows that CCS-3 achieved the best result, followed by CCS-1 at 58% higher, reference scenario at 99 % higher and CCS-2a and 2d at 108 and 140 % higher.
- Similarly, the IMPACT 2002+ model indicates that CCS-3 achieves the best result with CCS-1 at 75 % higher, CCS-2a at 115 % higher, and CCS-2d and reference scenario at almost the same with 168 and 176 %.

Summary

Comparing the different scenarios and based on the characterization and weighting, results show that CCS-3 is the better choice of CCS, regardless of fuel used in the boiler. The weighting also show that human health issues are possibly an important part of CCS.

4.3 Case study #3 LCA of CCS technologies

Zapp et al., (2012) have conducted LCA approach for the evaluation of the overall environmental impacts of CCS technologies. For the impact investigation associated with the different technologies, authors have used the functional unit of 1 kWh of electricity generation.

The capture technologies are post-combustion, oxy-fuel, and pre-combustion. Authors have used three power plants (Hard coal, Lignite and Natural gas), which are employed in the mentioned capture technologies. For the performance evaluation the net energy and energy penalty parameters were used.

Results as shown in Figure 4.8 indicate that the efficiency values of the hard coal post-combustion are between 29.6% and 49%. For the lignite, the net efficiency is between 26.3% and 49%. On the other hand, for the oxy-fuel, the process requires a higher energy, which is due to the need for oxygen production.

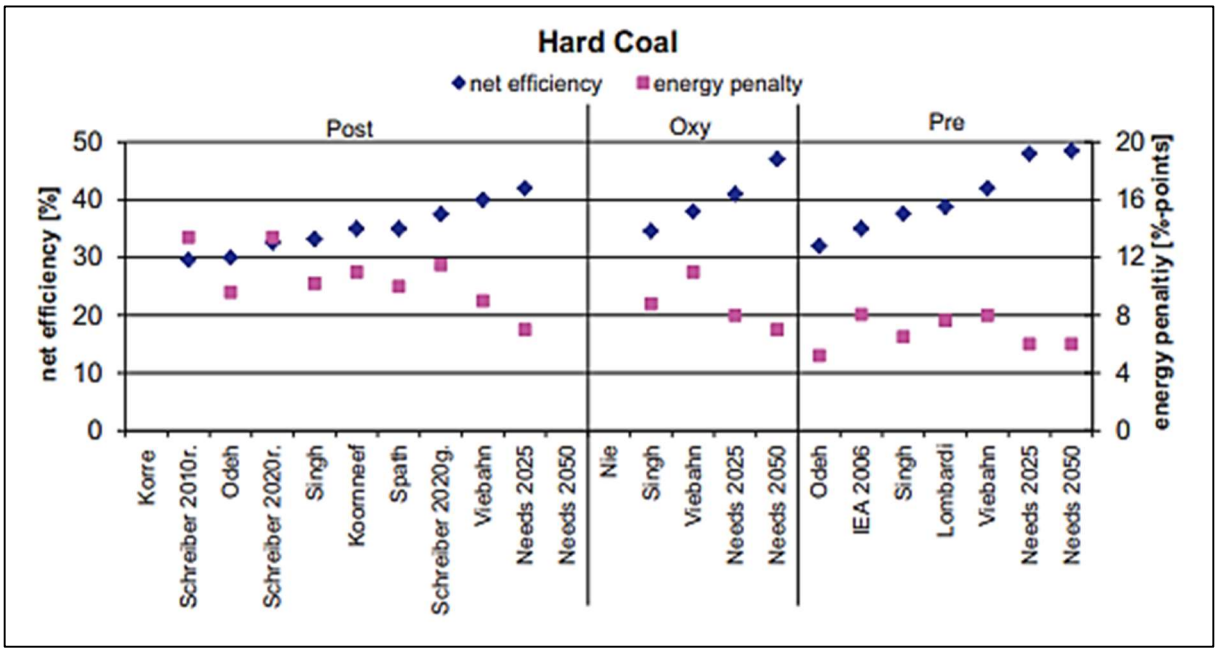


Figure 4.8: Net efficiency and energy penalty for hard coal (Zapp et al., 2012).

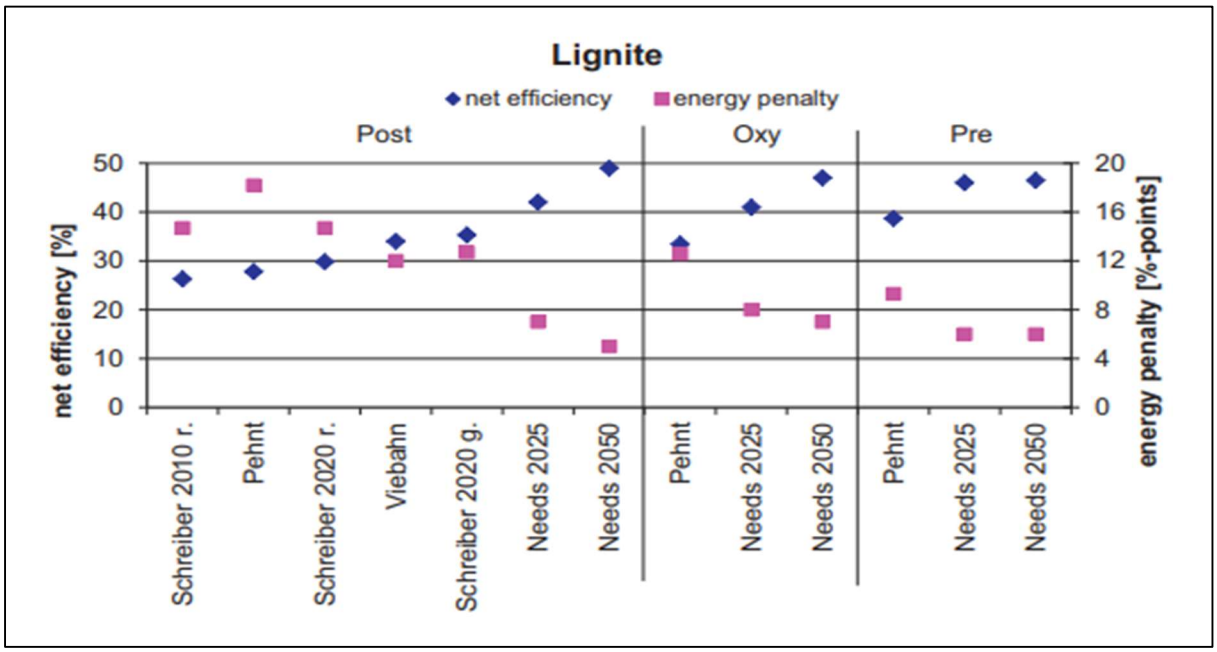


Figure 4.9: Net efficiency and energy penalty for lignite fuel (Zapp et al., 2012).

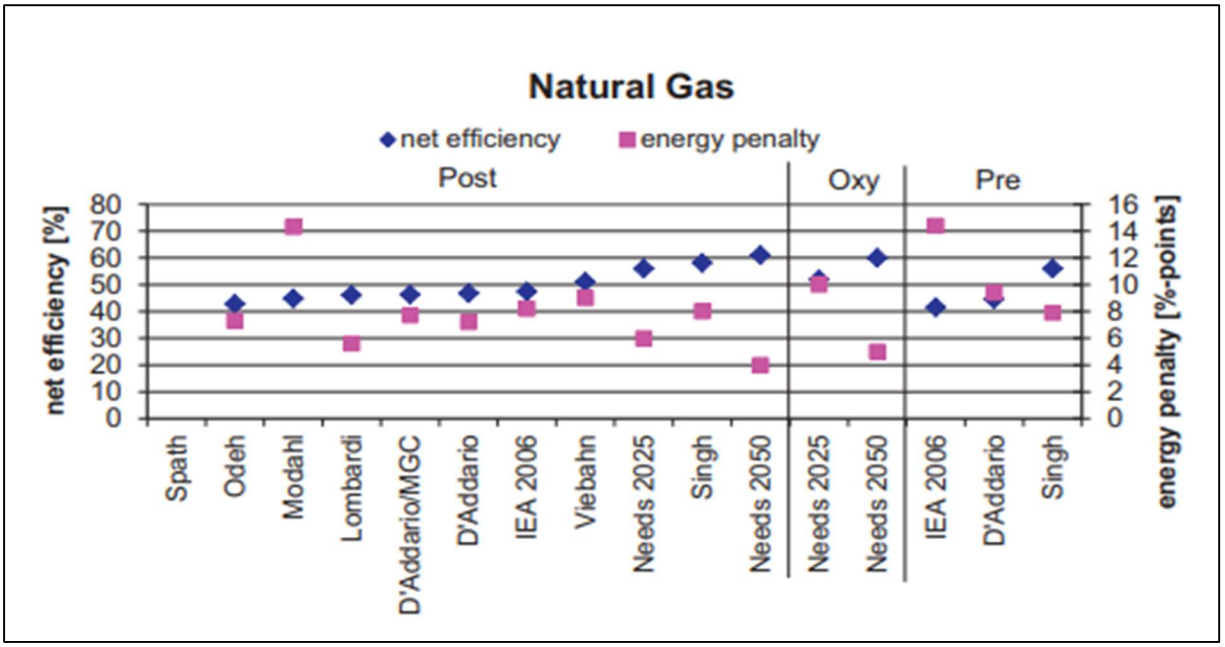


Figure 4.10: Net efficiency and energy penalty for natural gas (Zapp et al., 2012).

The results shown here in figures (Figs. 4.11-4.13) show the comparison of environmental impacts of CCS technologies considering different capture techniques and fuel types. Due to the fact that one can overvalue impact categories with big changes, but small contribution to the environment, the article follows global normalization values set by an extensive study done by (Sleeswijk et al., 2008) for the year 2000, which is provided in Chapter 3, Table § 3-2.

Considering the values in given Table 3.2 (in section §3.2) the electricity generated in year 2000 have been used for consistency, hard coal: 5136 TWh, lignite: 749 TWh and natural gas: 2677 TWh (Zapp et al., 2012).

The results in Figures 4.11-4.13 show that as soon as CCS is implemented to the power plant, the GWP gets reduced significantly, while the other NGHG impact categories increase due to various factors. The AP values are not as homogeneous as GWP. As expected, the GWP for lignite-based plant without CCS is a little higher than hard coal.

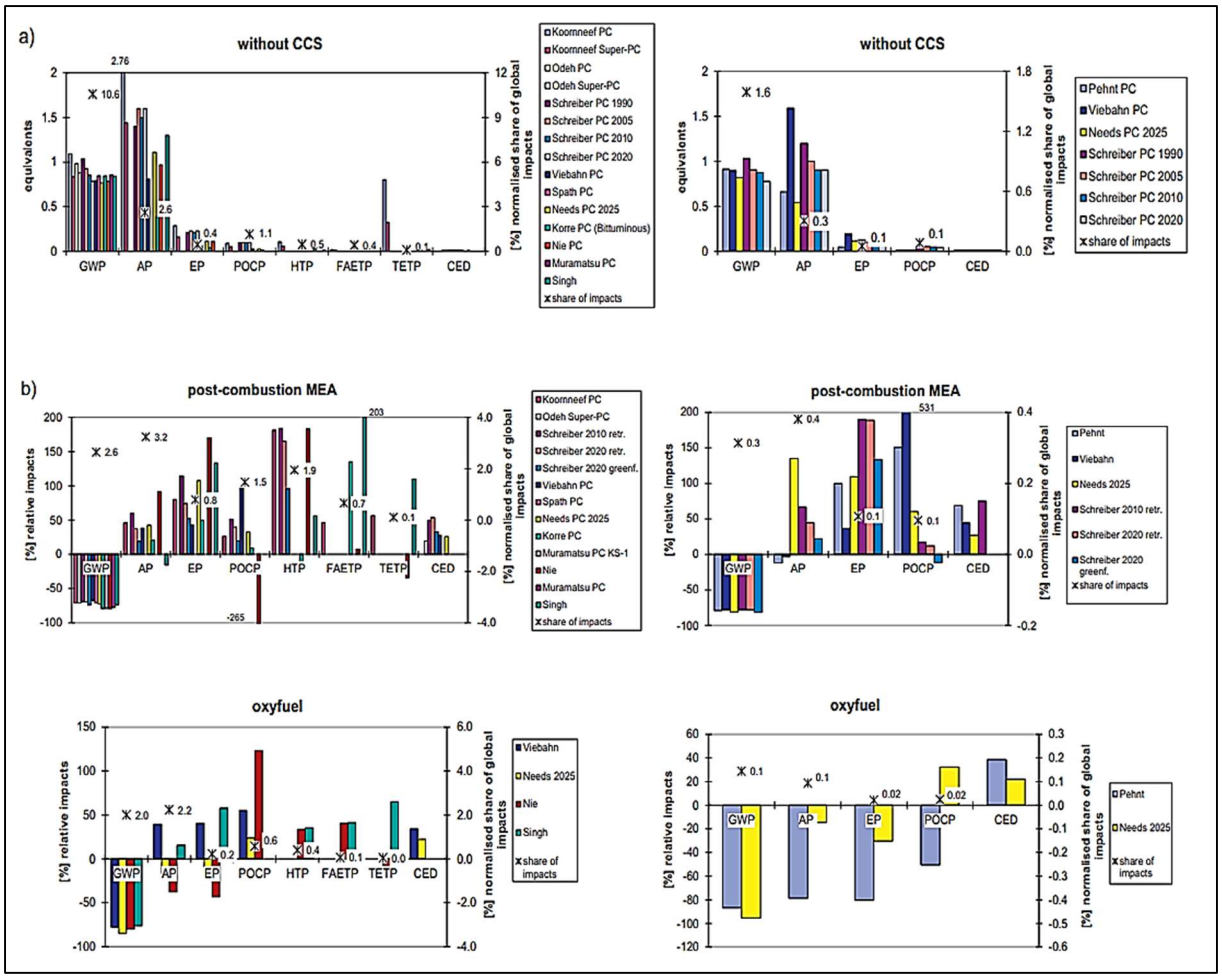


Figure 4.11: Environmental impacts of hard coal (left column) and lignite (right column) fired pulverized coal combustion technology (a) without capture and (b) relative impacts for plants with post-combustion/MEA or oxy-fuel capture and normalized values related to global emissions in 2000 (Zapp et al., 2012).

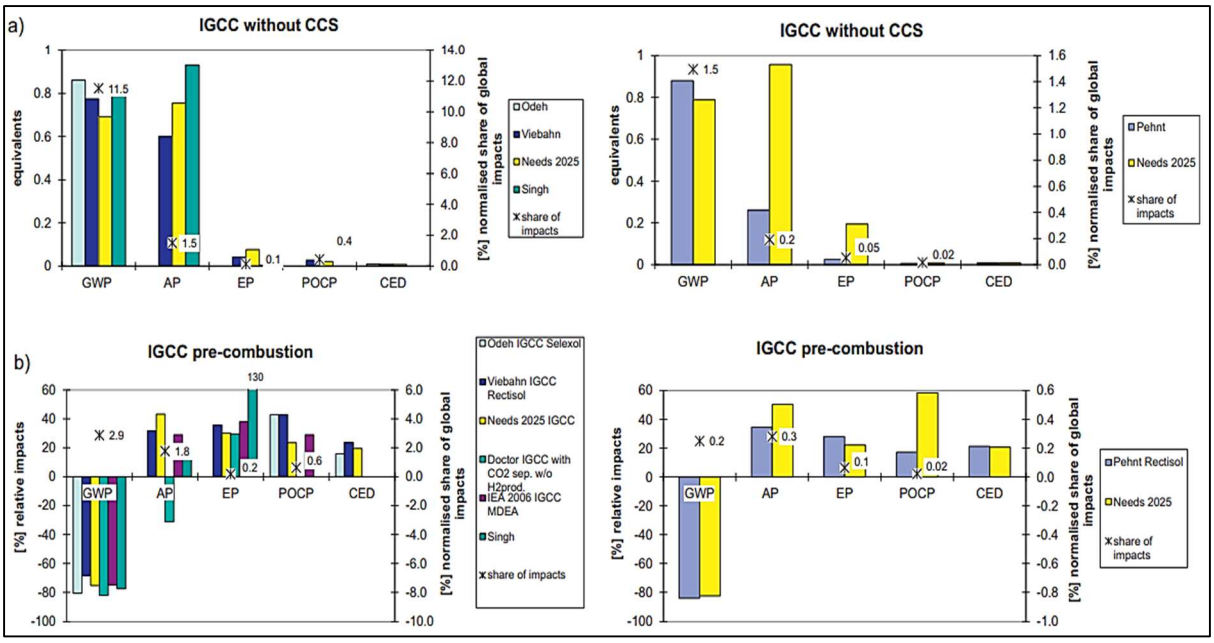


Figure 4.12: Environmental impacts of an integrated coal gasification combined cycle (IGCC) hard coal (left column) and lignite (right column) gasification system (a) without capture and (b) relative impacts of systems with pre-combustion capture and normalized values related to global emissions in 2000 (Zapp et al., 2012).

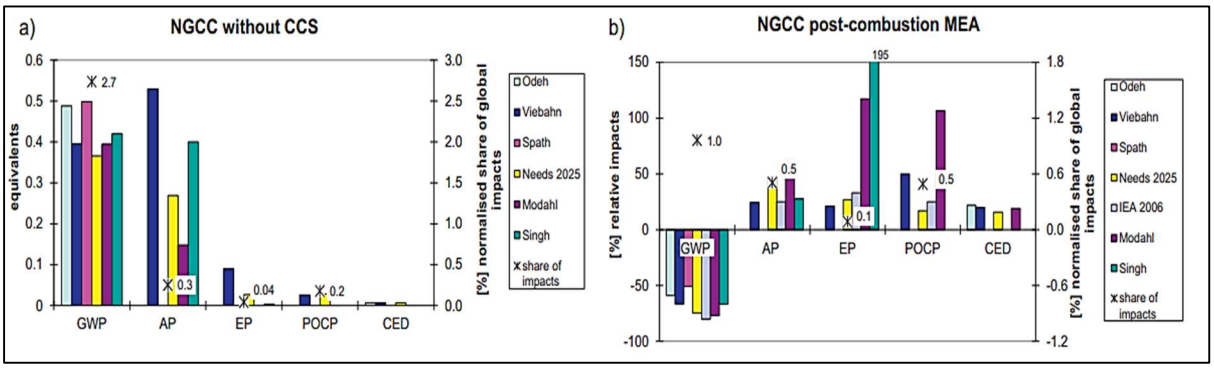


Figure 4.13: Environmental impacts of a natural gas combined cycle (a) without capture and (b) relative impacts of systems with post-combustion MEA-capture and normalized values related to global emissions in 2000. No absolute figures for IEA (2006) available (Zapp et al., 2012).

Results from the hard coal and lignite LCAs clearly show that SO_2 and NO_X decrease at the power plant itself, but the overall value of SO_2 and NO_X are increased during transport and the associated AP and EP effects occur (Zapp et al., 2012). Furthermore, the LCAs show an increase in all other impact categories (AP, EP, POCP, HTP, FAETP, TETP and CED). Except for GWP, due to inconsistent results from the four studies of impact assessment for hard coal oxy-fuel power plants (shown in figure 4.11), Zapp et al., (2012) states that no general conclusion can be drawn for the environmental assessment of oxy-fuel power plants.

For natural gas, mostly post-combustion systems are investigated. It is shown that the absolute GWP is much lower for natural gas as for coal plants without CCS. While power generation is nearly half of the hard coal plants, the GWP is less than a quarter (2.7%), with CCS it comes down to 1.0%. With natural gas as with hard coal and lignite, GWP has the most uniform results. Within the studies, there is no consistent picture concerning the other impact categories that are visible. The increase for AP, EP, POCP and CED is mostly within the range of 15% and 50% and all normalized impacts are well below 1% of world total, even when considering the increase in the different categories.

Generally, the LCA studies showed that GWP is greatly reduced by introduction of CCS and the increase of non-GWP environmental impacts, regardless of fuel or capture method used. The non-GWP impacts are due to efficiency loss, increase in fuel demand, operating materials and increase in waste.

For hard coal plant CCS, the emission of acid gases (i.e., SO_X, NO_X) occurs during transport and resulting in additional AP and EP values. For hard coal and lignite post-combustion, the impacts except GWP can increase by 100% and more. For oxy-fuel and pre-combustion the increase is smaller, but still visible. To relate this to total global emissions, it shows that large impacts tied to power generation are GWP, which decreases by using CCS, and AP which slightly increases. The study indicated that LCA is a useful analysis tool to provide information about the environmental impacts of CCS technology.

Summary

The case study has in general shown that the implementation of CO_2 capture technology resulted in the reduction of GWP (up to – 85% hard coal oxy-fuel, – 95% lignite oxy-fuel, – 80% natural gas post-combustion) along with an increase of negative environmental impacts (Zapp et al., 2012). The results here again indicate the need to develop technologies and methods that reduce the negative environmental impacts and enhance CO_2 capture along with less energy requirement for the process.

4.4 Case study #4 LCA of CCUS technologies

The non-conversion/utilization and the conversion/utilization technologies presented in section §2.2.1 and §2.2.2, respectively have shown that the use of CO_2 enhanced oil recovery and producing biofuel before storage results in added value to the economy.

However, in this section, the LCA of CCU associated with the considered utilization technologies will be presented in order to assess the impacts on the environment.

4.4.1 Case study #4.1 LCA of Non-Conversion Utilization: CO_2-EOR

Jaramillo et al., (2009) have conducted an LCA where they are looking at the overall life cycle emissions associated with sequestration coming from CO_2-EOR under five different projects. Their goal was to find an estimate of GHG emissions linked with the use of CO_2-EOR where the CO_2 is captured from a power plant. They were following the guidelines of the ISO 14040 standard. Within their analysis they have included electricity generated at the power plant their CO_2 got captured, transportation of CO_2 from plant to field, oil extraction, transportation of crude oil produced, crude oil refining and the combustion of products refined.

The five projects they considered for the study are the Northeast Purdy Unit, SACROC Unit, Ford Geraldine Unit, Joffe Viking Unit and Weyburn Unit. The CO_2 emissions shown in Table 4-5 are the total CO_2 emissions during the lifetime of each case. They assumed that the CO_2 captured was produced at an IGCC power plant with eastern U.S. bituminous coal, that captures 90% of the CO_2 emissions.

Table 4-5: Showing CO_2-EOR Project Performance Characteristics (Jaramillo et al., 2009).

CO_2—EOR Project Performance Characteristics

case	Northeast Purdy Unit	SACROC Unit, Kelly Snyder Field	Ford Geraldine Unit	Joffe Viking Unit	Weyburn Unit
reference	*13*	*13*	*13*	*13*	*14*
project lifetime (yrs)	9[a]	21[a]	8	17[a]	15[a]
incremental oil recovered (million STB)	36	402	13	23	130
total CO_2 purchased (million metric tons)	6.2	87.5	2.37	3.6	20

[a] Currently operational.

With a high heat value (HHV) coal power plant efficiency of 32%, it results in 55 kg CO_2-e/MWh for upstream emissions and 975 kg CO_2/MWh overall production. With the assumed 90% capture rate, it will emit 97.5 kg CO_2/MWh and capture 878 kg CO_2/MWh for EOR use.

The investigators first looked at the total CO_2 emissions created by the CO_2-EOR projects. Their intention was trying to figure out the system as a singular project to see if there will be an overall reduction of atmospheric CO_2 from sequestration. Figure 4.14 shows the new GHG emissions for each CO_2-EOR project and including the life cycle of the electricity generated at the coal power plant. Results showed that since the net emissions are in the positive it means that the GHG emissions are larger than what is being injected and stored in the reservoir. As figure 4.14 shows, the SACROC Unit and Weyburn unit have the largest net emissions.

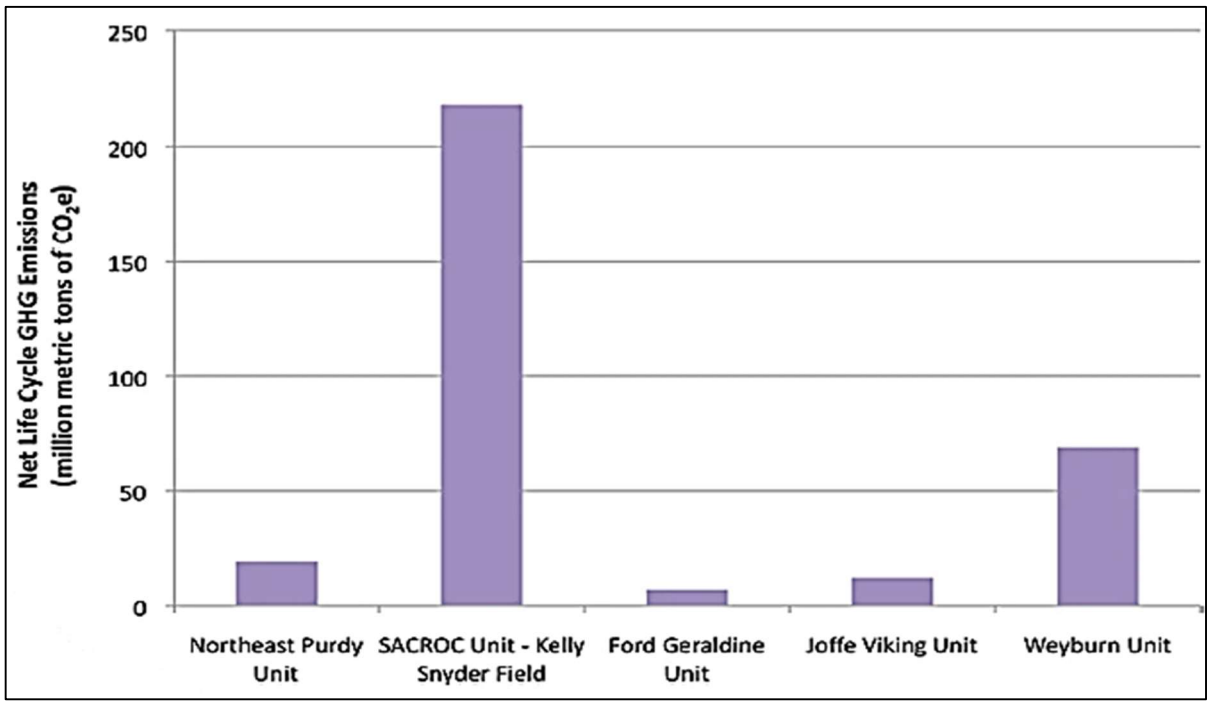


Figure 4.14: Showing net life cycle GHG emissions for each modelled CO_2-EOR (Jaramillo et al., 2009).

Figure 4.15 displays all the sources of emissions in the two largest net emission projects mentioned earlier. The largest source of GHG emissions is related to the combustion of the petroleum product production. By itself, the combustion emissions are larger than emissions from CO_2 sequestration.

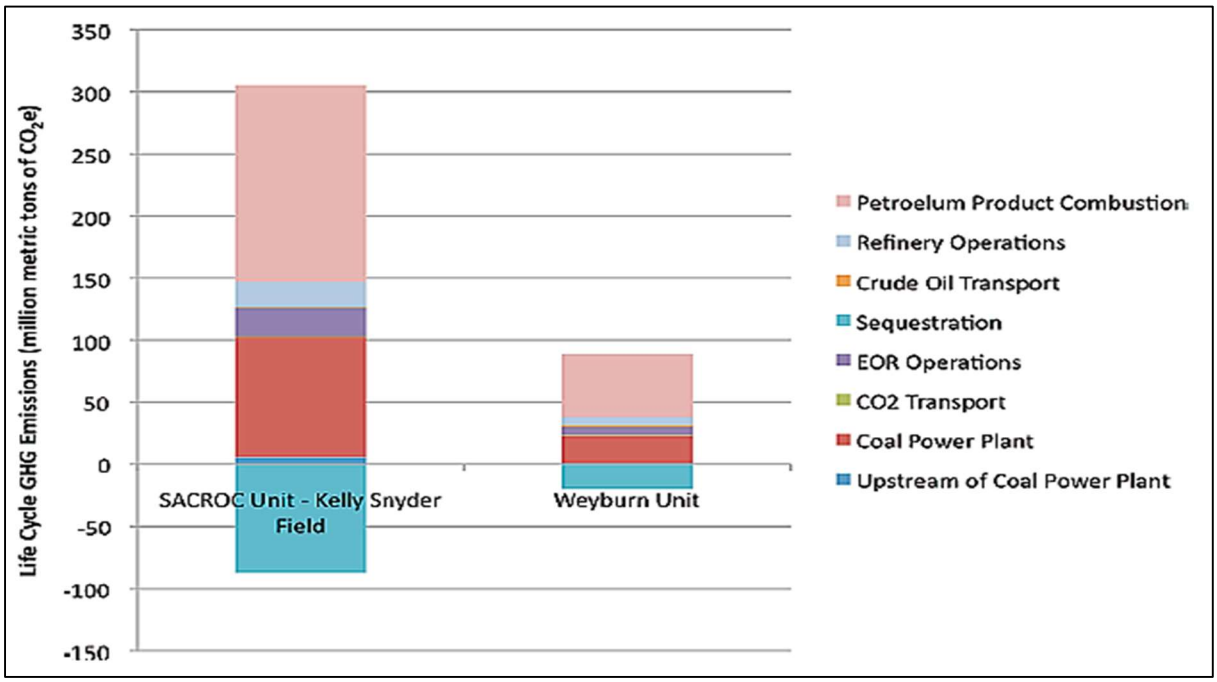


Figure 4.15: Showing source of GHG emissions from the two largest projects, SACROC Unit and Weyburn Unit (Jaramillo et al., 2009).

Summary

According to the authors calculated results, it showed that between 3.7 and 4.7 metric tons CO_2 are released into the atmosphere for every metric ton CO_2 injected. The fields currently inject, and store less than 0.2 metric tons CO_2 per bbl. oil produced. In order to have a net CO_2 emission equal to zero, 0.62 metric tons of CO_2 has to be injected and permanently stored for every bbl. of oil produced. The only way to reach numbers this high would be to instead of recycling produced CO_2 as in typical CO_2-EOR, produced CO_2 from the project could be reinjected into the water leg of the formation or into a nearby geological formation capable of storing it permanently.

4.4.2 Case study #4.2 LCA of Conversion Utilization: Biofuel

Campbell et al., (2011) analyzed the potential environmental impacts and how viable production of biodiesel from microalgae grown in pons is economically. An LCA study was conducted to find an estimated production design for Australian conditions and to compare biodiesel production from algae with canola and ultra-low Sulphur (ULS) diesel. They reviewed three different scenarios for CO_2 supplementation and two different production rates, comparisons of GHG emissions and costs. However, in this section, the LCA result focus only on GHG emissions as an environmental impact.

The investigators have compared the LCA results obtained from the algae production rate of 15gm^{-2} d^{-1} and 30g m^{-2} d^{-1}. Additionally, they tested three different CO_2 supplies, namely, a) pure form from adjacent ammonia plant via pipe, b) Pipe delivery of 15 % concentration flue gas from adjacent fossil-fuel power plant, and c) delivery by truck and liquefied(compressed) form.

The main GHG emissions focused on in this paper are carbon dioxide, methane, and nitrous oxide. The GWP factors are from the Kyoto Protocol with a 100-year timespan. Table 4-6 and Table 4-7 show GHG emissions produced from 1 tkm fuel use assuming the production rate of algae at 30g m^{-2} d^{-1} and 15g m^{-2} d^{-1}, respectively. The tables list the total various GHG emissions, separating fossil and non-fossil emissions as well as upstream and tailpipe emissions. The fossil emissions are the result from combustion of fossil fuels, and it contributes to the increase of GHG to the atmosphere, while the non-fossil does not contribute to extra GHG emissions as it is recycling of biomass.

Table 4-6: GHG emissions for 1 tkm connected truck fuel use, with the facilities having a production of 30 g m^{-2} d^{-1} (Campbell et al., 2011).

Impact category	Biodiesel, algal, 100% CO_2 (ammonia plant)	Biodiesel, algal, 15% CO_2 (flue gas) – power station	Biodiesel, algal, 100% CO_2 (truck delivered)	Biodiesel, canola	ULS diesel
Greenhouse Gas (total fossil)	−27.560	−23.019	8.298	35.856	81.239
GHG (total fossil upstream)	−28.030	−23.489	7.828	35.386	19.213
GHG (total fossil tailpipe)	0.470	0.470	0.470	0.470	62.026
GHG (total upstream)	−27.949	−23.408	7.852	35.465	19.241
GHG (total tailpipe)	62.028	62.028	62.028	62.028	62.026
GHG-CO_2 (fossil upstream)	−28.563	−23.797	6.861	33.437	18.040
GHG-CO_2 (fossil tailpipe)	0.001	0.001	0.001	0.001	61.557
GHG-CH_4 (total)	0.030	−0.181	0.250	0.984	1.156
GHG-N_2O (total)	0.971	0.957	1.117	1.431	0.486
GHG-CO_2 (total upstream)	−28.547	−23.987	6.657	33.659	18.047
GHG-CO_2 (total tailpipe)	61.559	61.559	61.559	61.559	61.557
GHG-other (total)	0.001	0.001	0.068	0.004	0.000

Table 4-7 shows the same data as table 4-6 but assumes a production rate of 15g m^{-2} d^{-1}.

Table 4-7: GHG emissions for 1 tkm connected truck fuel use, with the facilities having a production of 15 g m^{-2} d^{-1} (Campbell et al., 2011).

Impact category	Biodiesel, algal, 100% CO_2 (ammonia plant)	Biodiesel, algal, 15% CO_2 (flue gas) - power station	Biodiesel, algal, 100% CO_2 (truck delivered)	Biodiesel, canola	ULS diesel
Greenhouse Gas (total fossil)	−15.648	−10.524	18.164	35.856	81.239
GHG (total fossil upstream)	−16.118	−10.994	17.695	35.386	19.213
GHG (total fossil tailpipe)	0.470	0.470	0.470	0.470	62.026
GHG (total upstream)	−16.037	−10.913	17.719	35.465	19.241
GHG (total tailpipe)	62.028	62.028	62.028	62.028	62.026
GHG-CO_2 (fossil upstream)	−16.742	−11.477	16.594	33.437	18.040
GHG-CO_2 (fossil tailpipe)	0.001	0.001	0.001	0.001	61.557
GHG-CH_4 (total)	0.102	−0.033	0.364	0.984	1.156
GHG-N_2O (total)	0.990	0.984	1.138	1.431	0.486
GHG-CO_2 (total upstream)	−16.689	−11.562	16.470	33.659	18.047
GHG-CO_2 (total tailpipe)	61.559	61.559	61.559	61.559	61.557
GHG-other (total)	0.001	0.001	0.068	0.004	0.000

Summary

Based on the results, authors concluding remarks indicate that with favorable soil conditions, present day technology and high yearly growth rates, it is a viable option to reduce GHG emissions in the Australian transport industry economically. It will make it even more worthwhile economically and environmentally considering the rate of which technological advancements are made within the ethanol biofuel industry. Overall, the Algae GHG emissions are between -27.6 to 18.2 g CO_2-e depending on factors like production rate. These numbers compare very favorably to canola (35.9g CO_2-e) and ULS diesel (81.2gCO_2-e).

5 Summary and Discussion

Climate change due to global warming is the main concern for the world today. In this thesis work, the issues associated with greenhouse effects and the methods to mitigate the emission as well as the lifetime assessment impact on the environment when implementing the CCS and CCUS technologies are evaluated. In this chapter, the main work presented in the thesis will be summarized and discussed.

5.1 Greenhouse gases (GHG) and Impacts

The report from IEA shows the correlation between the global energy demand and the CO_2 greenhouse emission rate. Due to population growth and the increased human activity along with the natural factors, the greenhouse gases are increasing over the years. Measured and simulated data have also shown the correlation between the increasing of CO_2 concentration in the atmosphere and the climate change, resulting in the rise of global warming. The impact of global warming is observed as the increased frequency of extreme weather globally. Since the climate change is becoming a critical issue internationally, the United nation adopted the legally binding Paris agreement such that all countries should partake and contribute to control the climate change with the objective of saving the planate earth.

5.2 CCS and CCUS-Solution methods to mitigate GHG impacts

While working on meeting the global energy demand with renewable energies, the best solution associated with non-renewable energies impact on the GHG effect is by capturing the CO_2 and to either utilize or store it.

The conventional post-combustion capture technology focuses on most of the same method's pre-combustion does, with addition of membrane separation as the most common ones. One of the main problems with this method is within chemical absorption and the degrading of amines, where the release of the degraded products has negative potential effects on the environment. To mitigate the drawbacks associated with post-combustion, membrane separation was developed. Unlike the chemical absorption method, membrane separation has a lower energy requirement, carbon footprint, and easy to retrofit, but then again it offers its own flaws with condensation on membrane during cooling.

Oxy-fuel combustion capture uses oxygen for fuel burning. The fuel is burned with nearly pure oxygen to make a flue gas free of compounds like NO and NO_2. The benefit of this method is that there is no need for chemical separation of CO_2 from the flue gas. The drawbacks of this method are the fact that oxygen is very expensive as well as CO_2 emissions from the highly energy demanding air-separation process.

From the reviewed research materials, we can observe that the drawbacks associated with the current capture technologies suggest the need to develop more improved novel technologies in terms of efficiency of and cost effectiveness.

Moreover, the future green energy transition will also definitely add values in the reduction of greenhouse gas effects. However, until the world fully utilizes green energy, the implementation of the Paris agreement and the countries contribution to the CO_2 emissions reduction reduce the greenhouse gas effect and hence, reduces the global warming.

5.3 LCA of CCS Technologies

From case studies of LCA applied to a CCS system, results show the reduction of net greenhouse gas emissions significantly. However, the LCA showed that non-GHG impacts such as acidification and human toxicity increase with the use of CCS. The emissions from a power plant with CCS systems also contain non-CO_2 flue gases such as NO_X and SO_2, which is due to degradation of the amine capture solvents (i.e., monoethanolamine (MEA)) and results in a negative impact on human health and the ecology.

From the reviewed LCA of CCS coupled power plants, investigators analysis results showed that there is an increase in environmental effects once CCS is put to use regardless of fuel or capture method. This increase does not only come from amine degrading, but also from an increased need of fuel to produce the same amount of energy. Comparing the impact categories of the three methods, the post-combustion records a higher impact category. Although oxy-fuel and pre-combustion have increase in their impact categories as well, but less than post-combustion.

Studies also showed that for any hard coal power plant regardless of capture method, acid gases, SO_X and NO_X emissions during transport results in additional AP and EP impacts.

From the LCA case studies, it is clear that the application of CCS contributes for the GHG effect reduction. On the other hand, the CCS technologies increase the non-GHG related impacts on environment. This suggests the need to develop improved novel materials like for example the application of nanoparticle coupling with the current conventional technologies. This will open the door for more research activities.

5.4 LCA of CCU Technologies

The CO_2-utilizations considered in this thesis, namely, non-conversion utilization (CO_2-EOR) and conversion utilization (i.e., biofuel) add values economically both by utilizing energy and producing useful products as well. Moreover, the LCA environmental impacts during these operations have also been studied.

The LCA of the non-conversion CO_2-EOR utilization case study estimates the GHG emissions linked with the use of CO_2-EOR where the CO_2 was supplied from a power plant. The study showed that during CO_2-EOR operation, for every metric ton injection, the net greenhouse gas emission rate in all the projects was high. However, to mitigate the CO_2 emissions, for every bbl. of oil produced the produced CO_2 can be re-injected for permanent storage.

The LCA of conversion utilization, analyzed the production of biodiesel from microalgae grown in pons, and its potential environmental impacts. The study showed that following the design of the algae ponds there is an estimated uptake of 95% of used CO_2 gas. During the final biofuel production, the cultivation of algal biomass itself uses a large amount of CO_2 and does not add extra GHG to the atmosphere.

6 Conclusion

The continuous rise of global warming over the years creates an awareness internationally. In order to reduce the CO_2 emission by 50% in 2050 (United Nations, 2015) as compared to the level of 1990, the International Panel on Climate change (IPCC) adopted an agreement in 2015 and then nations entered the legally binding agreement in 2016, which is called the Paris agreement.

Based on the studied CCS and CCU technologies and the LCA of these technologies, the summary and conclusion of the main results are:

- LCA case studies showed that the application of CCS technologies reduced the GHG by about 90%, which is positive in reducing global warming/climate change. However, the NGHG released have shown negative environmental impacts due to the degradation of amine-capture technology.

- LCA case studies showed that the application of non-conversion CCU technology reduced the GHG by storing CO_2 in reservoirs as well as enhancing hydrocarbon production. Moreover, the utilization allows the conversion of CO_2 into useful energy and products as well. This as a result reduced the release of GHG into the atmosphere and mitigated the negative environmental impacts.

- Finally, to meet the Paris agreement's 2050 emission reduction target (United Nations, 2015), this thesis work concludes that:
    - More research should be conducted to develop novel materials and technologies, which have higher CO_2 capture efficiency, reduced environmental impacts, require lower energy consumption, and cost effectiveness as well.
    - All nations should fulfill their nationally determined contribution commitments.

7 References

Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.-K., & Rogelj, J. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group14 I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Technical Summary.

Baena-Moreno, F. M., Rodríguez-Galán, M., Vega, F., Alonso-Fariñas, B., Vilches Arenas, L. F., & Navarrete, B. (2019). Carbon capture and utilization technologies: a literature review and recent advances. *Energy sources. Part A, Recovery, utilization, and environmental effects*, *41*(12), 1403-1433. https://doi.org/10.1080/15567036.2018.1548518

Campbell, P. K., Beer, T., & Batten, D. (2011). Life cycle assessment of biodiesel production from microalgae in ponds. *Bioresour Technol*, *102*(1), 50-56. https://doi.org/10.1016/j.biortech.2010.06.048

Chadwick, A., Arts, R., Bernstone, C., May, F., Thibeau, S., & Zweigel, P. (2008). *Best practice for the storage of CO2 in saline aquifers-observations and guidelines from the SACS and CO2STORE projects* (Vol. 14). British Geological Survey.

Climate Change Act. (2017). *Act relating to Norway's climate targets* (LOV-2017-06-16-60). Lovdata. https://lovdata.no/NLE/lov/2017-06-16-60

Creamer, A. E., & Gao, B. (2016). Carbon-Based Adsorbents for Postcombustion CO2 Capture: A Critical Review. *Environ. Sci. Technol*, *50*(14), 7276-7289. https://doi.org/10.1021/acs.est.6b00627

Cuéllar-Franca, R. M., & Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO2 utilization*, *9*, 82-102. https://doi.org/10.1016/j.jcou.2014.12.001

European Commission. (2010). *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance.* Publications Office of the European Union. https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf

Garcia-Garcia, G., Fernandez, M. C., Armstrong, K., Woolass, S., & Styring, P. (2021). Analytical Review of Life-Cycle Environmental Impacts of Carbon Capture and Utilization Technologies. *ChemSusChem*, *14*(4), 995-1015. https://doi.org/10.1002/cssc.202002126

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008. *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*, *1*, 1-126.

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P., & Williams, C. K. (2019). The technological and economic prospects for CO2 utilization and removal. *Nature (London)*, *575*(7781), 87-97. https://doi.org/10.1038/s41586-019-1681-6

Hepple, R. P., & Benson, S. M. (2003). Implications of surface seepage on the effectiveness of geologic storage of carbon dioxide as a climate change mitigation strategy. Greenhouse Gas Control Technologies-6th International Conference

Imteyaz, B., Qadir, S. A., & Tahir, F. (2021). Prospects of CO2 utilization after carbon capture process. *Fuel*, *2*, N2.

International Energy Agency. (2021, 2021). *Global Energy Review*. IEA Publications. https://www.iea.org/reports/global-energy-review-2021

Jaramillo, P., Griffin, W. M., & McCoy, S. T. (2009). Life Cycle Inventory of CO2 in an Enhanced Oil Recovery System. *Environ. Sci. Technol*, *43*(21), 8027-8032. https://doi.org/10.1021/es902006h

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: a new life cycle impact assessment methodology. *The international journal of life cycle assessment*, *8*(6), 324-330.

Lab-aids. (n.d.). *Global Warming Interactive - Temperature & CO2*. Retrieved December 7 from https://www.lab-aids.com/global-warming-interactive-temperature-co2

Laurent, A., Weidema, B. P., Bare, J., Liao, X., Maia de Souza, D., Pizzol, M., Sala, S., Schreiber, H., Thonemann, N., & Verones, F. (2020). Methodological review and detailed guidance for the life cycle interpretation phase. *J Ind Ecol*, *24*(5), 986-1003. https://doi.org/10.1111/jiec.13012

Lee, K.-M., & Inaba, A. (2004). *Life cycle assessment: best practices of ISO 14040 series*. Center for Ecodesign and LCA (CEL), Ajou University.

Masson-Delmotte, V. P., Anna, Chen, Y., Matthews, J. B. R., Yelekçi, O., Lonnoy, E., Leitzell, K., Connors, S. L., Goldfarb, L., Berger, S., Yu, R., Maycock, T. K., Zhai, P., Péan, C., Gomis, M. I., Huang, M., Zhou, B., Waterfield, T., & Caud, N. (2021). *Climate Change 2021: The Physical Science Basis* (Summary for Policymakers). Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

Metz, B., & Intergovernmental Panel on Climate Change Working, G., III. (2005). *IPCC special report on carbon dioxide capture and storage*. Published for the Intergovernmental Panel on Climate Change by Cambridge University Press.

Modahl, I. S., Askham, C., Lyng, K.-A., & Brekke, A. (2012). Weighting of environmental trade-offs in CCS—an LCA case study of electricity from a fossil gas power plant with post-combustion CO2 capture, transport and storage. *The international journal of life cycle assessment*, *17*(7), 932-943. https://doi.org/10.1007/s11367-012-0421-z

Muthu, S. S. (2020). *Assessing the environmental impact of textiles and the clothing supply chain*. Woodhead publishing.

National Energy Technology Laboratory (NETL). (2010). Untapped Domestic Energy Supply and Long Term Carbon Storage Solution. *National Energy Technology Laboratory (NETL), US Department of Energy*.

Norway. (2020a). *Norway's long-term low-emission strategy for 2050*. Norway. https://unfccc.int/sites/default/files/resource/LTS1_Norway_Oct2020.pdf

Norway. (2020b). *Update of Norway's nationally determined contribution*. Norway. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Norway%20First/Norway_updatedNDC_2020%20(Updated%20submission).pdf

Osman, A. I., Hefny, M., Abdel Maksoud, M. I. A., Elgarahy, A. M., & Rooney, D. W. (2021). Recent advances in carbon capture storage and utilisation technologies: a review. *Environmental Chemistry Letters*, *19*(2), 797-849. https://doi.org/10.1007/s10311-020-01133-3

Pfister, M., Belaissaoui, B., & Favre, E. (2017). Membrane Gas Separation Processes from Wet Postcombustion Flue Gases for Carbon Capture and Use: A Critical Reassessment. *Ind. Eng. Chem. Res*, *56*(2), 591-602. https://doi.org/10.1021/acs.iecr.6b03969

Rao, A. B., & Rubin, E. S. (2002). A technical, economic, and environmental assessment of amine-based CO2 capture technology for power plant greenhouse gas control. *Environmental science & technology*, *36*(20), 4467-4475.

Sathre, R., Masanet, E., Cain, J., & Chester, M. (2011). *The role of Life Cycle Assessment in identifying and reducing environmental impacts of CCS*.

Sleeswijk, A. W., van Oers, L. F., Guinée, J. B., Struijs, J., & Huijbregts, M. A. (2008). Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. *Science of the total environment*, *390*(1), 227-240.

Stanger, R., Wall, T., Spoerl, R., Paneru, M., Grathwohl, S., Weidmann, M., Schefflmecht, G., McDonald, D., Myohanen, K., Ritvanen, J., Rahiala, S., Hyppanen, T., Mletzko, J., Kather, A., & Santos, S. (2015). Oxyfuel combustion for CO2 capture in power plants. *International journal of greenhouse gas control*, *40*, 55-125. https://doi.org/10.1016/j.ijggc.2015.06.010

Torp, T. A., & Gale, J. (2004). Demonstrating storage of CO2 in geological reservoirs : The Sleipner and SACS projects. *Energy (Oxford)*, *29*(9-10), 1361-1369. https://doi.org/10.1016/j.energy.2004.03.104

United Nations. (2015). *Paris Agreement Under the United Nations Framework Convention on Climate Change*. United Nations. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations Treaty Collection. (2016, 09.12.2021). *Paris Agreement Signatories*. United Nations. https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

Viktoriya M. Yarushina. (2018). *Potential leakage mechanisms and their relevance to CO2 storage site risk assessment and safe operations*. Christian Michelsen Research AS. http://www.fme-success.no/doc/Reports/Vol%202-Potential%20leakage%20mechanisms%20and%20their%20relevance%20to%20CO2%20storage.pdf

Wang, M., Lawal, A., Stephenson, P., Sidders, J., & Ramshaw, C. (2011). Post-combustion CO2 capture with chemical absorption: A state-of-the-art review. *Chemical engineering research & design*, *89*(9), 1609-1624. https://doi.org/10.1016/j.cherd.2010.11.005

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C., & Wernet, G. (2013). Overview and methodology: Data quality guideline for the ecoinvent database version 3.

Zapp, P., Schreiber, A., Marx, J., Haines, M., Hake, J.-F., & Gale, J. (2012). Overall environmental impacts of CCS technologies—A life cycle approach. *International journal of greenhouse gas control*, *8*, 12-21. https://doi.org/10.1016/j.ijggc.2012.01.014