COMPARING ALTERNATIVE WAYS OF QUANTIFYING CLIMATE IMPACTS OF POWER-TO-X PRODUCTS VIA CARBON CAPTURE AND UTILIZATION

Carbon footprint calculations for power-to-methanol and power-to-HDPE

Lappeenranta–Lahti University of Technology LUT

Circular Economy Master's Thesis

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ABSTRACT

Lappeenranta–Lahti University of Technology LUT

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Keywords: carbon capture and utilization, CCU, power-to-x, carbon dioxide, LCA, carbon footprint, avoided emissions, European Union, RFNBO, system expansion

This master's thesis was conducted for St1 Oy as part of a wider collaboration with two other companies, Metsä Group and Afry, and their respective thesis workers. The master's thesis examines power-to-X via carbon capture and utilization (CCU) from the perspective of climate impacts and studies how different methods of quantifying climate impacts suit power-to-X products, and how do the methods differ.

The literature part of the Master's thesis examines CCU from a carbon neutrality perspective, the current regulatory field at the European Union (EU) level as well as the life cycle stages and technologies of power-to-X systems. The work also covers life cycle assessment (LCA) guidelines and their suitability for CCU.

The emission calculations of the thesis were conducted for two products made of carbon dioxide: methanol and HDPE plastic. The calculations were made for both products using both fossil and biogenic carbon dioxide. In addition to calculating the cradle-to-grave carbon footprint, system expansions were conducted in order to determine the overall emission reduction and avoided emissions of the CCU system.

The thesis found that CCU products can achieve emission reductions and help to avoid emissions regardless of the source of carbon dioxide. The method of quantifying emissions should always be chosen to be the one that is best suited for the purpose of the calculation. From a decision-making point of view, omittance of life cycle stages can lead to misleading results and system expansion should be used to determine the emission reductions and avoided emissions achieved because of the CCU system.

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ILMASTOVAIKUTUSTEN LASKENTATAPOJEN VERTAILU HIILIDIOKSIDIN TALTEENOTTOA JA HYÖDYNTÄMISTÄ KÄYTTÄVILLE POWER-TO-X TUOTTEILLE

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Tämä diplomityö tehtiin St1 Oy:lle osana yhteistyötä kahden muun yrityksen, Metsä Groupin ja Afryn, ja heidän diplomityöntekijöidensä kanssa. Diplomityö käsittelee power-to-X teknologioita, joissa käytetään hiilidioksidin talteenottoa ja hyödyntämistä (CCU) ilmastovaikutusten näkökulmasta. Työssä tutkitaan miten erilaiset ilmastovaikutusten kvantifiointitavat soveltuvat CCU tuotteille, ja miten nämä eroavat toisistaan.

Diplomityön kirjallisuusosuus tutkii CCU:ta hiilineutraalius näkökulmasta, nykyistä sääntelykenttää Euroopan Unionin (EU) tasolla, sekä power-to-X systeemien elinkaaren vaiheita ja näiden teknologioita. Työssä käydään läpi myös elinkaarimallinnuksen (LCA) ohjeistuksia ja näiden soveltuvuutta CCU tuotteille

Diplomityössä on laskettu päästöjä kahdelle hiilidioksidista valmistetulle tuotteelle: metanolille sekä HDPE-muoville. Laskennat tehtiin molemmille tuotteille sekä hyödyntämällä fossiilista, että biogeenistä hiilidioksidia. Kehdosta hautaan rajatun hiilijalanjäljen laskennan lisäksi tuotteille suoritettiin systeemin laajennukset, päästövähennyksen sekä vältettyjen päästöjen arvioimiseksi.

Työssä havaittiin, että CCU-tuotteet voivat saavuttaa päästövähennyksiä sekä auttaa välttämään päästöjä hiilidioksidin lähteestä riippumatta. Päästöjen kvantifiointitavan tulisi aina soveltua laskennan tarkoitukseen. Päätöksenteon näkökulmasta elinkaaren vaiheiden jättäminen ulos voi johtaa harhaanjohtaviin tuloksiin. Systeemin laajennuksella pystytään selvittämään CCU-systeemin ansiosta saavutetut päästövähennykset ja vältetyt päästöt.

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Writing this thesis was a challenging project but also very insightful especially thanks to the collaborative workshops we had during the writing of this thesis with our project group. I would like to thank the whole project group from St1, Metsä and Afry as well as the professors from three different universities who all put aside their time to discuss the subject of our theses in depth. Also, a big thanks to the project's other thesis writers Emilia Tognetty and Ira Wallén with who we had great sparring sessions during the work. I would especially like to thank my instructors Riitta Silvennoinen and Kirsi Tiusanen as well as Professor Risto Soukka for their valuable help and insight. I would also like to say thanks to my colleagues at St1 who helped and supported my work in writing this thesis.

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In Helsinki February 22, 2024.

Ville Varpula

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1. Introduction

Urgent greenhouse gas (GHG) emission reductions are required to limit human-caused global warming to the safe level of 1.5°C of warming defined by the Intergovernmental Panel on Climate Change (IPCC). Global warming has already reached nearly 1.2°C and current worldwide emissions will very likely cause the warming to exceed the threshold of 1.5°C. Higher levels of global warming will result in greater climate-related risks for humans, as well as different ecosystems. The likelihood of irreversible changes also increases with warmer global average temperatures. Reaching net neutral global greenhouse gas emissions as soon as possible is required to avoid greater climate change related risks. (IPCC, 2023a, 4-6, 14, 26-27).

Reaching net neutral carbon emissions, or carbon neutrality, requires a major shift away from fossil fuels in the energy sector. According to International Energy Agency (IEA) the global energy-related carbon dioxide (CO_2) emissions were a record-high 36.8 $GtCO_2$ in 2022 (IEA, 2023a). IPCC has estimated that in order to limit global warming to 1.5°C, the remaining carbon budget is around 500 $GtCO_2$ (IPCC, 2023a, 82). With global emissions being record high and increasing the remaining carbon budget is currently being used up. IPCC also states that: *"Projected CO_2 emissions from existing fossil fuel infrastructure without additional abatement would exceed the remaining carbon budget for 1.5°C*". (IPCC, 2023b).

Power-to-X technologies can allow a decoupling of energy and fossil fuels by turning electricity produced by renewable sources into different energy carriers (Palys & Daoutidis, 2022a). Power-to-X pathways are estimated to have an impactful role in the energy transition away from fossil fuels and in the quest to close carbon cycles. (Daggash et al., 2018). Power-to-X is not a singular process but rather a term used to describe many different multi-stage processes that all have the same basic underlying principle of turning (renewable) electricity into some other form. The term power-to-X is derived from:

- Power = surplus electricity, renewable electricity or grid mix

- To = different conversion pathways and required conversion infrastructure
- X = end-product or product group

Power-to-X pathways often include processes of turning water into hydrogen (H_2), capturing CO_2 as well as combining hydrogen with CO_2 to create different hydrocarbons (Buffi et al., 2022, 4-6). Examples of different power-to-X pathways used to create products include for instance power-to-hydrogen, power-to-methanol, and power-to-methane. Broader terms that describe the product group as a whole are for instance power-to-gas, power-to-chemicals, and power-to-liquids. (Koj, Wulf & Zapp, 2019).

Utilizing CO_2 in manufacturing of different products is also referred to as carbon capture and utilization (CCU). These methods refer to a wide range of technologies capturing CO_2 from different sources such as industrial flue gases and either utilizing them directly or using CO_2 as a feedstock to manufacture products. CCU methods are viewed as way of achieving emission abatement especially when capturing CO_2 from sources that are hard to avoid such as process industries and by producing new fuels and products from the captured CO_2 that substitute conventional fossil products. The captured CO_2 can also be stored away for instance into geological deposits by carbon capture and storage (CCS). (Ramirez Ramirez et al., 2020, 1, 10-11).

The climate change mitigation potential of a CCU technology is dependent on multiple variables. Emissions can be reduced with CCU but to get an accurate picture of the overall environmental impacts and the GHG emissions of the entire value chain, a lifecycle assessment (LCA) should be conducted. Variables affecting the overall carbon balance of a CCU product are for instance the source of the CO_2 feedstock and the retention time of the carbon before its released to the atmosphere. If the CO_2 is captured directly from the air or from biogenic sources and stored away for a long time, for instance made into construction material, the carbon footprint of the product can even be carbon negative. (IEA, 2019, 9-10). Figure 1 illustrates the carbon balance of CCU and CCS in a simplified manner.

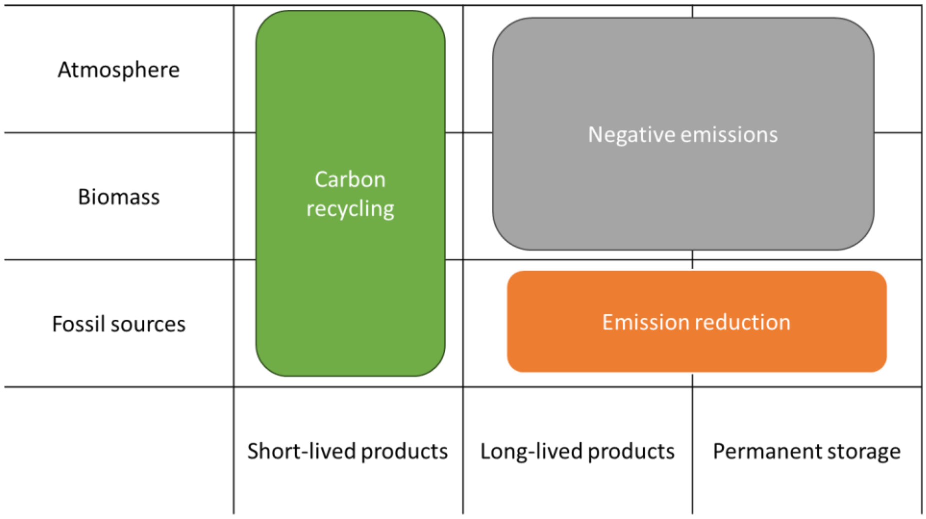

Figure 1. Simplified carbon balance of a CCU process adapted from Kujanpää et al. 2023 and Tynkkynen & Landström 2023. (Kujanpää et al., 2023)(Tynkkynen & Landström, 2023).

Despite the gaining interest towards power-to-X and CCU, there is variation in ways of accounting for the different technologies' carbon emissions and removals. More knowledge and consensus are required regarding methodologies for quantifying carbon emissions of CCU technologies. Also, currently there is not a lot of policy frameworks supporting CCU. (IEA, 2019, 3-5, 67). In the European Union (EU) some discrepancies exist within policy framework regarding CO_2 utilization and accounting for its emissions. It is paramount to understand the full comprehensive lifecycle emissions of CCU, in order to determine the technologies' climate impact. Hence, clarification on the frameworks and methodologies for quantification of CCU systems' emissions is required. (European Commission: Directorate General for Climate Action, 2019, 21-25).

1.1. Background

The subject of this master's thesis was assigned by St1 Oy. It is a part of a wider co-operation with two other companies Metsä Group and Afry both of which also appointed a master's thesis worker to examine the field of CCU. The three companies involved in this co-operation have all identified the need for clarification in the carbon capture field. The current legislative framework and quantification of emissions for CCU technologies is viewed as complex and the three companies sought clarification on the topic by commencing this project and conducting three master's theses. The three master's theses all cover industrial carbon capture and utilization from different perspectives: legislative, economic, and environmental. This master's thesis aims to cover the subject from an environmental angle. Further information on the other topics can be found from the other two master's thesis by Tognetty (2023) and Wallén (2024).

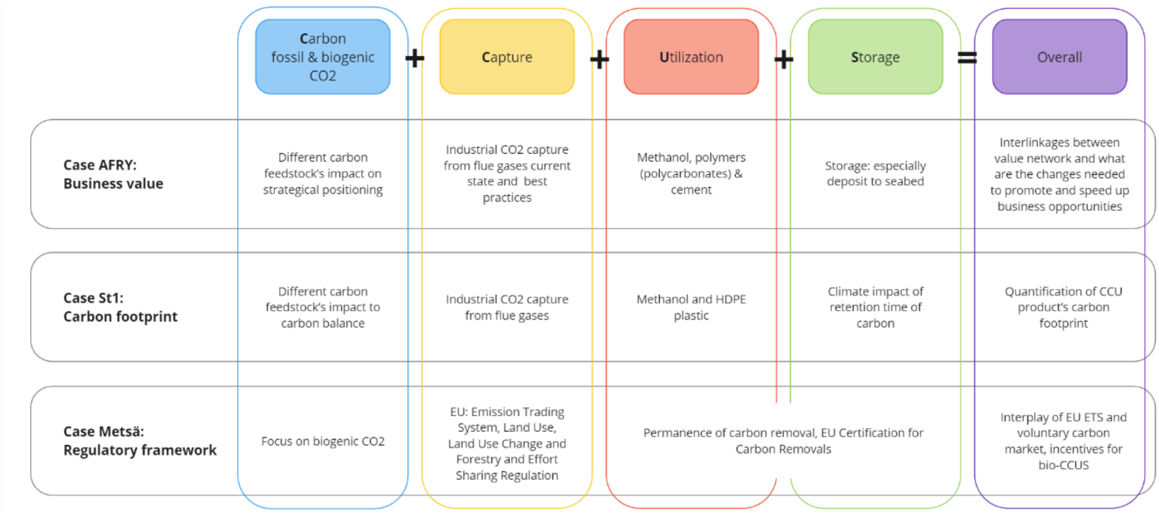

Figure 2. Overview of the entire CCU thesis project

1.2. Scope and assumptions

The purpose of this thesis is to present the current context for power-to-X via CCU from a climate impact perspective, as well as to compare different methods for quantification of carbon footprint for CCU products and examine the difference in using fossil and biogenic CO_2 to manufacture CCU products. The different methods for carbon footprinting are interpreted from the perspective of a company's decision-making. The theory part of this thesis covers carbon neutrality and CCU, policy framework for CCU, and lifecycle and technology of power-to-X systems. This theory will be then used to assess the carbon footprint for two different products made using captured CO_2: methanol, and HDPE plastic. The carbon footprint will be calculated by using fossil CO_2 as a feedstock and by using biogenic CO_2 as a feedstock in order to examine the logic behind the different accounting.

The carbon footprints are calculated roughly using the relevant ISO standards as well as considering CCU-specific suggestions in literature regarding LCA. The data used for the calculations is gathered from literature. The main purpose of the calculations is to demonstrate different methodologies as presented in standards, guidelines, and policies, as well as to compare the impact of using different sources of captured CO_2 feedstocks. The results of the calculations are interpreted, and methodologies compared from the perspective of how they affect decision-making and whether they provide an accurate enough picture of the climate impacts. The results of the calculations are intended to be used solely for the purposes of this thesis and its academic value and should not be used in any real-life decision-making. Full LCA study of a CCU product would be needed to fully understand all the effects on the environment and the climate but this is beyond the scope of this thesis. Further assumptions, boundaries, possible limitations as well as other relevant information regarding the goal and scope of the calculation part of this thesis is explained in chapter five.

The scope of this thesis focuses more on the CCU phase of power-to-X. Although both terms are used, the production of hydrogen required to produce power-to-X products is not at the forefront of this thesis. Hydrogen production is discussed in some depth but omitted from many parts such as for instance policy chapter. Other omittances that could provide relevant knowledge related to CCU include transportation of CO_2, waste legislation, circular economy aspects of CCU as well as information related to renewable energy production required for wide scale implementation of power-to-X.

The research questions of this thesis are:

- How do different methodological choices and assumptions influence the quantification of emissions for CCU products?
- What is the difference between using fossil and biogenic carbon dioxide as a feedstock for a CCU product and how does it affect the product's carbon footprint?
- What is the current state of knowledge and EU policies regarding the climate impacts of CCU?

2. Carbon neutrality and CCU

Carbon neutrality is defined by the IPCC as being the same as net zero carbon emissions. In the IPCC glossary it is defined as: *"Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.* (IPCC, 2018) . Carbon neutrality or net zero is widely defined by science and literature. Currently the consensus around the world is that by achieving real long-term net-zero emissions, the amount of CO_2 in the atmosphere would stop climbing and the climate would eventually stabilize. Global warming would halt in the timeframe of decades and would thus require long-term net zero emissions. Net-zero emissions are currently widely regarded as the goal of global climate policies and emission reduction targets. Pledges are set in both the private and public sector, from companies and organizations of different sizes to cities and regions. (Fankhauser et al., 2022).

2.1. Variables affecting the carbon balance of power-to-X and CCU

Even though interest towards CCU pathways has increased due to the growing need for emission reductions, the climate impacts of CCU depend on many different aspects. CCU technologies can reduce emissions either directly, avoid emissions that would've otherwise been released to the atmosphere or even achieve negative emissions. Variables effecting the climate change mitigation and emissions reduction potential of a CCU product and/or process include:

- the source of the CO_2 feedstock
- the amount and type of energy used to create the CCU product
- the retention time of carbon sequestered in the product
- the potential of the CCU product on large-scale
- the alternative product that the CCU product is replacing

Because of these and other variables affecting a single CCU product, accounting the carbon emissions and reductions can become complex. (IEA, 2019, 25-26). In addition to the forementioned variables, other variables include the emissions caused by the CCU process and carbon emissions leaked during the CCU process (de Kleijne et al., 2022).

In theory CCU technologies offer a possibility of manufacturing two product with just one carbon emission. This offers emission reduction possibilities, as well as positive impacts to resource depletion. However, the real-life carbon balance of a CCU product may still end up unfavorable compared to a reference system for instance because of high energy demand of the CCU system. (Garcia-Garcia et al., 2021).

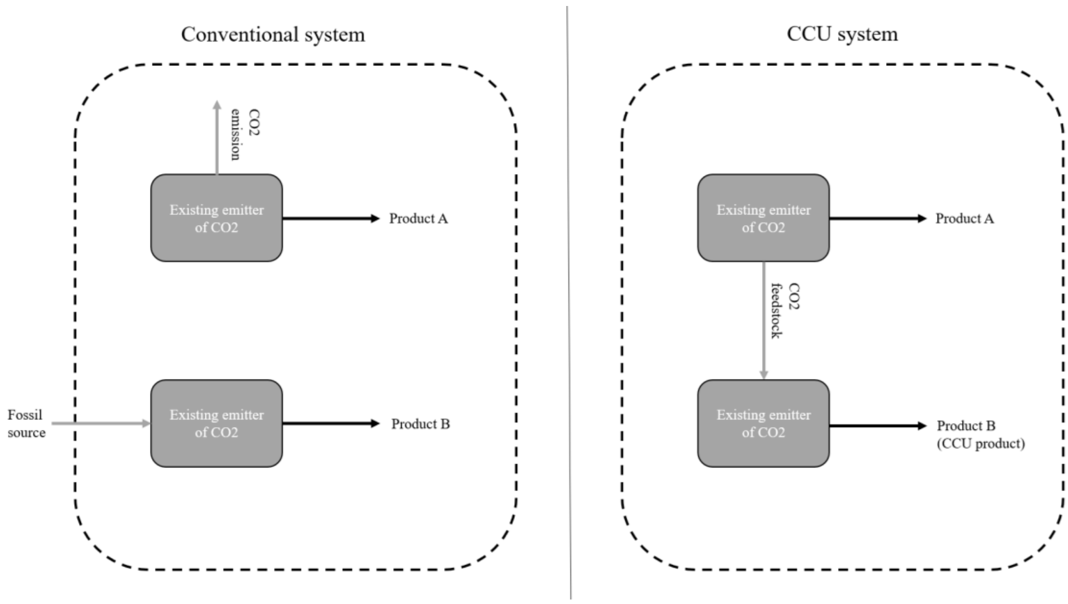

Figure. 3. Simplified emissions of a CCU system in relation to conventional system (adapted from (Garcia-Garcia et al., 2021)

2.1.1. Carbon source

The earth's carbon cycle is a vital biochemical cycle that upholds life on earth. Naturally carbon circulates slowly in different forms between carbon pools. Carbon pools include the atmosphere, vegetation, animals, soils, sediments, oceans, rocks, and minerals. Natural carbon cycle has been disrupted by human activities, primarily burning of fossil fuels and land use change (e.g. deforestation and agriculture). Fossil fuel use has caused the carbon stored in the earth's geological carbon stocks to be released into the atmosphere as CO_2 in much greater quantities than would be naturally possible and land use change has altered the biosphere's carbon stock. These anthropogenic changes have caused an imbalance to the global carbon equilibrium. (Farmer & Cook, 2013, 199-215). Figure below illustrates the global carbon cycle.

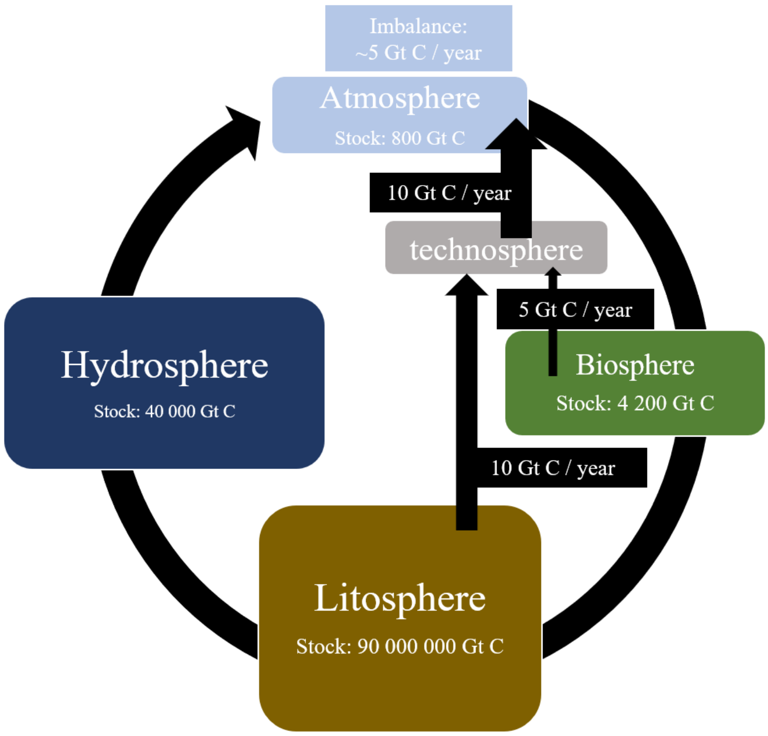

Figure 4. Global carbon cycle. Values from: (Commission & Directorate-General for Research, 2021, 29)

Origin of the CO_2 feedstock used to manufacture a CCU product has great impact on the overall carbon footprint of the product. In this context the source of CO_2 refers to the categorization of the CO_2 feedstock between the different carbon pools which are mainly categorized to:

- biogenic CO_2,
- fossil CO_2, or
- atmospheric CO_2.

Biogenic CO_2 is released by combustion or decomposition of biomass and products that are manufactured from biogenic materials (IPCC et al., 2022). Fossil CO_2 refers to the carbon released from the burning of fossil fuels which adds CO_2 into the atmosphere from the earth's lithosphere. Atmospheric CO_2 refers to the CO_2 that is currently in the atmosphere and could be removed by direct air capture (DAC) or photosynthesis.

CO_2 flows of a power-to-X system between different carbon pools, mainly atmospheric, biogenic, and below ground fossil carbon pools, determine the overall climate impact. From the climate change perspective, it is imperative to learn the overall carbon flow to (and from) the atmospheric carbon pool caused by the CCU process because adding carbon to the atmosphere causes global warming. (Ramirez Ramirez et al., 2020, 16-17, 33-36).

As presented in figure 2, regardless of the source of CO_2 CCU process can achieve emission reduction due to the simplified logic of the same emission being "used twice". When the emission is originally from a fossil source for instance an energy plant that burns fossil fuels to produce energy and is used to manufacture a product that eventually releases the carbon feedstock into the atmosphere at the end of its lifetime, net emissions are released from the earth's geological carbon stock into the atmosphere. Compared to a conventional reference system the utilization of fossil CO_2 can achieve a theoretical 50% reduction in total overall system emissions. (IEA, 2019, 34-35).

Achieving net neutral carbon emissions would require closing of carbon cycles. Carbon cycles can be closed by using non-fossil carbon feedstocks in power-to-X processes. Non-fossil sources of CO_2 refer to biogenic as well as atmospheric CO_2. (Daggash et al., 2018). CO_2 emissions from biogenic sources are presumed to be zero due to the assumption that the carbon released into the atmosphere will eventually be stored back into the biogenic carbon stock via photosynthesis. When biogenic CO_2 is presumed carbon neutral, the use of biogenic CO_2 can achieve closed carbon cycles. Global carbon accounting guidelines have also widely accepted this assumption. However, it may be an oversimplification of a complex system of different biogenic carbon fluxes and in reality the zero-value of biogenic CO_2 does not accurately describe the reality of current situation. (Liu et al., 2019).

In many countries industrial sources of biogenic CO_2 from flue gases are quite scarce (Koj, Wulf & Zapp, 2019) This is not the case however in Finland where biomass combustion and pulp and paper industry are common. Roughly 60% of the CO_2 emissions coming from large industrial point sources (over 50 MW) were classified as being of biogenic origin in 2020 in Finland. Majority of the biogenic CO_2 emissions in Finland arise from forest industry. Thermal energy plants are the second most prominent emitters of biogenic CO_2. (Kujanpää et al., 2023, 37-38).

2.1.2. Energy demand

Power-to-X systems have high energy demand. These systems usually have multiple energy intensive phases, such as hydrogen electrolysis, carbon capture, as well as further processing of CO_2 and H_2 to higher chemical. Because of the high overall energy demand of the system, it is imperative from a climate point of view that renewable energy is used. If energy for the processes is provided from fossil sources or grid mix, the climate change impact of CCU products can become even greater than that of their fossil counterparts. Meaningful emission reductions with power-to-X systems can only be achieved if they are powered by renewable energy. (Garcia-Garcia et al., 2021).

Capturing of carbon from flue gases causes losses in energy efficiency, also called energy penalty. The energy penalty is higher when capturing CO_2 from a source with a low CO_2 concentration. Typical energy penalty related to the capture of CO_2 from flue gases of a power plant is around 9 % (Capocelli & De Falco, 2022). However, the energy penalty can even be around 20 % in flue gases with low CO_2 concentration (Vasudevan et al., 2016).

Review by Garcia-Garcia et al. of LCA-studies published in literature on different power-to-X systems noted that majority of climate impacts happen during the production of hydrogen due to the high energy demand of electrolysis (Garcia-Garcia et al., 2021). Power-to-X systems encompass multiple phases in which energy in converted to a different form. All of these stages cause some energy efficiency losses. When all the efficiencies of the different processes are combined from the electricity provided in the start to the end use of the energy, the overall efficiency can be significantly lower than compared to for instance direct use of electricity. A study by Ueckert et al. (2021) found the overall efficiency to be around 40 % when producing e-fuel from electricity and only 10 % when using the e-fuel in an internal combustion engine to produce mechanical energy. The study used typical efficiencies for each process phase, not particular efficiencies of a certain process. (Ueckerdt et al., 2021).

CCU could provide a way of decoupling of production from fossil carbon sources on some sectors such as in production of high value chemicals. The energy requirements to fulfil the wide-scale potential of CCU chemical production are however vast. Kätelhön et al. (2019) estimated that it would require 55% of the entire world's estimated electricity production in 2030 to decouple the chemical industry from fossil carbon and move to power-to-X production. (Kätelhön et al., 2019). Although just an estimate on the current knowledge on the TRL of CCU, it shows the scale of power-to-X systems' energy demand.

2.1.3. Scalability

When assessing the potential of power-to-X via CCU to deliver climate change mitigation measures worldwide the scalability of CCU products has great influence. This means the scale of potential for emission reductions and CO_2 utilization in products. This differs between different product groups. The amount of CO_2 that can be utilized is estimated through the market size of the product group. For instance, fuels have vast estimated CO_2 utilization potential because of the great amount of fuel usage that exists worldwide. Another variable affecting the scalability of products in regard to the climate change mitigation potential is the retention time of the carbon within the product as well as the direct emissions of the power-to-X system. (IEA, 2019, 29).

2.1.4. Retention time

The retention time of the carbon in the product defines a lot of the climate change impact of the CCU product, but the timeframe varies between different product groups. Products such as fuels only store the carbon for short periods of time before releasing the CO_2 into the atmosphere when combusted as delayed emissions. Chemicals also store the carbon for a relatively short time but possibly for longer than fuels. Products such as plastics on the other hand can store carbon for years or up to multiple decades. Even longer carbon retention can be achieved in building materials. The ultimate release of carbon into the atmosphere also depends on the end-of-life treatment of the product. (IEA, 2019, 36).

Temporary carbon sequestration's climate impact is especially difficult to quantify. LCA does not take into account any time elements, so temporary storage of carbon is not intrinsically accounted for in LCAs. There is also no clear consensus on accounting of delayed emissions from temporary storage albeit solutions exist. (IEA, 2019, 36). Delaying emissions with temporary storage could however provide benefits from a climate perspective. The benefits of temporary storage are based on the logic that radiative forcing is lower for the duration of the retention period of the carbon which is the products lifetime. (de Kleijne et al., 2022). This is however dependent on the source of the carbon. If carbon is from atmospheric or biogenic carbon pool, the radiative forcing is lowered for the duration of carbon retention. If the carbon is however from fossil carbon pool, the overall net radiative forcing will increase when the carbon is emitted to the atmosphere. Albeit some benefit could also come from delaying the warming impact of the fossil carbon. (Brandão et al., 2013).

One method of quantifying the temporary carbon storage of CCU products is to calculate dynamic global warming potentials (GWP). GWP describes the aggregate radiative forcing of a GHG over a time period, with the timeframe usually defined as 100 years. GWPs are relative to the radiative forcing of CO_2, meaning that GWP for CO_2 is set at 1 and usually higher for other GHGs as they have higher radiative forcings. GWPs also change with different time horizons as the lifetimes of GHGs in the atmosphere vary. For instance, methane has a lifetime of roughly a decade whereas CO_2 can remain in the atmosphere for centuries.

This leads to methane having much higher GWP with a time horizon of 20 years compared to 100 or 500 years. (Levasseur et al., 2010). If the storage time is accounted for in the GWP values, it changes the numbers quite a lot. In an article by de Kleijne et al. (2022) GWP factors were calculated for temporary storage with a time horizon of 100 years. These dynamic GWPs are presented in the table below. (de Kleijne et al., 2022).

Table 1. GWP storage factors from de Kleijne et al. (2022).

Lifetime	**0-6 months**	**0.5-1 year**	**1 year**	**5 years**	**10 years**	**25 years**	**50 years**	**100+ years**
$GWP_{storage}$-100	1	0.99	0.98	0.92	0.85	0.67	0.42	0

The climate benefits of delaying emissions are however not clear. Argument can be made that the dynamic GWP methods do not take into account the future of climate systems. For example, emissions that are delayed for decades could be released at a time where the global climate is much more unstable than it is at the moment. Releasing emissions to a more chaotic climate could cause greater implications. Concerns also exist of incentivizing storage of carbon for a medium time horizon which from a climate point of view is roughly 100 years. This could cause emissions to be release a hundred years from now at a time much worse for the climate systems resilience than now. (Ramirez Ramirez et al., 2020, 58-59).

2.1.5. Comparison to conventional product

Comparison to the conventional production (also called reference system) of a product can define the overall emission reduction caused by the power-to-X system. This is based on the assumption that the power-to-X system replaces some conventional fossil production method. The conventional production method is not necessarily straightforward to determine, but for instance, in some cases where chemicals are conventionally produced from fossil fuels and would be superseded by power-to-X systems the comparison is somewhat ease to draw. This is the case for instance in methanol, where the conventional natural gas reforming is replaced by power-to-methanol. (IEA, 2019).

CCU can help avoid emissions by replacing conventional production. However, an article by Tanzer & Ramirez (2019) found the use of the term negative emissions to be inconsistent in literature and often mixed with avoided emissions. Avoided emissions are an estimate derived from the emissions of the CCU product compared to the conventional product that the CCU process is replacing. As pointed out in the article, avoided emissions are sometimes subtracted from the life-cycle emissions caused by the CCU process resulting in a negative emission. Avoided emissions are not physical but rather an estimated emission reduction potential. In some cases, it can also be difficult to precisely know what is the conventional product that the CCU process is replacing leading to in some cases an exaggeration of the emission reduction potential if the CCU process is compared to high-polluting fossil fuels for instance. (Tanzer & Ramirez 2019).

2.1.6. Other effects on carbon balance

One relevant risk associated to CCU and carbon capture in general is the phenomenon called carbon lock-in. This refers to a state in which large investments are made and infrastructure built that relies heavily on carbon and releases emissions which are in a sense “locked” to emit for tens of years into the future. The already deeply integrated built-in inertia of the fossil carbon-based energy system is feared to possibly become even more deep with the implementation of carbon capture to existing emitters. This is because the building of large infrastructure designed to capture carbon will cause the activities causing emitting of carbon to remain at use for the lifecycle of the building rather than switching to a non-emitting technology. (Asayama, 2021).

2.2. The role of CCU in carbon neutrality

Energy and climate models from wide range of organizations and academia deem carbon capture, utilization, and storage a vital role in achieving net zero emissions. A wide deployment of carbon capture is needed to reduce emissions as well as to remove carbon from the atmosphere. Pathways that limit global warming to 1.5℃ modelled by the European Commission, IEA, IPCC and other organizations and academia all include carbon capture in the scale of hundreds of megatons of CO_2 captured annually within the EU. The numbers range from around 300 $MtCO_2$ to 600 $MtCO_2$ captured annually by 2050 in Europe. (CCUS Vision Working Group, 2023, 2-4, 9).

The variables effecting CCU's carbon balance also affects the technologies' relevance in achieving carbon neutrality. The variables presented earlier are of major relevance, but other factors also exist. One factor affecting especially the relevance for carbon neutrality is whether the technology is technologically mature enough in time to achieve climate change mitigation on a relevant scale. Considering the carbon neutrality target of 2050 set in the Paris agreement and other relevant targets for 2030, the technologies that reduce emissions are only relevant until 2030 and by 2050 only CCU technologies achieving CO_2 removal are of relevance to carbon neutrality. (de Kleijne et al., 2022).

Modern societies however require a lot of different chemicals, products, and materials, some of which are very hard or impossible to decarbonize feasibly. Many chemicals and materials contain carbon, and industries producing the products need a supply for the carbon also in the foreseeable future. Albeit, CCU routes' carbon emissions and emission reduction potential may vary, they are still very likely needed in net-zero future to manufacture valuable carbon-containing products. (vom Berg & Carus, 2023, 6-9).

3. Feasibility of CCU under current EU policies

Carbon dioxide is regulated through number of policies in the EU. The relevant policies regarding CO_2 emissions, carbon capture, CO_2 utilization, and emission accounting within the EU are presented in this chapter. The possible barriers or policies hindering the deployment of CCU are also examined. Overall, the regulatory environment around CCU in the EU can be considered scattered with mentions on CCU coming from multiple different sources of European policies but lacking consistency on the role of CCU technologies in EU's energy transition and carbon neutrality (vom Berg & Carus, 2023, pp 33).

The EU aims to achieve net-zero GHG emissions by 2050. By 2030 the aim is to cut emissions by 55% compared to 1990 as well as achieve increase in renewable energy and improve energy-efficiency. This target is implemented by a wide set of legislation, policies and proposals named "Fit for 55" package. Emission reduction targets are defined in different sectors in many different policies including the Emission Trading System Directive (ETS), the Effort Sharing Regulation (ESR), the Land use, land use change and forestry regulation (LULUCF) as well as the Member states' own reduction targets for GHG emissions. (European Commission official website, 2024).

the EU has identified the need for carbon capture and carbon recycling. In a 2021 communication to the European Parliament and the Council about sustainable carbon cycles, the European Commission stated that carbon from sustainable biogenic sources and atmospheric sources should be utilized to manufacture non-fossil-based carbon products to replace fossil-based carbon products in certain sectors that are reliant on fossil sources. In order to achieve greater implementation of CCU within the EU, the European Commission set forth the following "aspirational objectives" in its 2021 communication:

- *"By 2028, any ton of CO_2 captured, transported, used and stored by industries should be reported and accounted by its fossil, biogenic or atmospheric origin;*
- *At least 20% of the carbon used in the chemical and plastic products should be from sustainable non-fossil sources by 2030, in full consideration of the EU's biodiversity*

and circular economy objectives and of the upcoming policy framework for bio-based, biodegradable and compostable plastics.

- *5Mt of CO_2 should be annually removed from the atmosphere and permanently stored through frontrunner projects by 2030"*

(European Commission, 2021, 1-2, 16).

Current EU legislation has some roadblocks from the CCU perspective. Geological CO_2 storage has been regulated with its own CCS directive since 2009. CO_2 storage is also enforced by the ETS directive, in which capturing and storing CO_2 permanently instead of emitting it allows the emitter to avoid surrendering ETS allowances (CCUS Vision Working Group, 2023, 12-13). However, such policies do not exist regarding carbon utilization. An analysis initiated by the European Commission Directorate-General for Climate Action (2019) identified that regarding the climate and energy related policy framework "*CCU processes introduce a logic which differs from the one intended by the different legislative mechanisms*". The problem in logic arises from at least the accounting of flows of carbon for instance when CO_2 is captured under some sector and used to manufacture products in another sector which is regulated differently. In the analysis the accounting of GHG emissions from CCU technologies was deemed "*not entirely feasible"* under current legislation such as Monitoring and Reporting Regulation (MRR) which is the regulatory framework for accounting of emissions under the ETS (601/2012). (European Commission: Directorate General for Climate Action, 2019, 170-171).

The barriers that CCU faces in current EU policy environment hinders the wide implementation of CCU. The possible environmental benefits of CCU are not well enough accounted in the policies. CCU would need support from policies to compete with cheaper fossil fuels and other conventional products. (European Commission: Directorate-General for Climate Action 2019, 19). Currently The EU has not given clear signal on the role of CCUS technologies for its net-zero target, nor has it driven forward a plan to implement CCUS. Also, the infrastructure around CCU, such as CO_2 transport and storage systems, is currently non-existent and unlikely to change without a clear signal and policy support from the EU. With current policies, ETS sectors that could otherwise benefit from CCU may be forced to emit

CO_2 and pay hefty ETS allowances instead of capturing their emissions, due to a lack of transport and other accommodating infrastructure and policy (CCUS Vision Working Group, 2023, 2-6).

At the time of writing this thesis some upcoming developments that could alter the CCU context are at works. One of the main points of interest could be the EU's climate goal for 2040, which can be expected to be proposed by the Commission in the first quarter of 2024. The goal can be expected to be in the region of -90% reduction compared to the 1990 level. (EURACTIV.com, 2024a). Likely very relevant policy to CCU is also the EU's "Industrial carbon management – carbon capture, utilisation and storage deployment". This strategy proposed by the Commission will likely introduce real targets for carbon capture amounts within the EU and some strategies related to CO_2 management, storage and transport. The strategy will be published early 2024. It is believed that the strategy will also consider ETS and a vision on how to integrate CCU better to ETS. (EURACTIV.com, 2024b).

3.1.1. Emission trading scheme

EU ETS does not entirely accommodate CCU. As mentioned previously, exemptions from emission allowances are given only to CCS, although there is some leeway for CCU technologies that store carbon permanently. More specifically the directive refers to technologies that can store the carbon chemically in a way that keeps the carbon permanently from releasing under normal use. The directive also mentions a possibility to adopt delegated acts regarding this. (Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the European Union, §16).

A recital of the ETS in 2018 acknowledges CCU as a *"a breakthrough innovation in low-carbon technologies and processes*". These breakthrough innovations are said to be given exemption from having to surrender ETS allowances for the avoided or permanently stored CO_2 emissions that the innovations enable. This recital, however, is not well equipped to give exemptions to incentivize CCU technologies because the ETS's scope for accounting emissions only covers the specific installation's emissions and thus cannot consider the possible CO_2 savings that happen upstream in the life cycle of a CCU technology. The ETS also does not have instruments to account for the emission reduction that can happen when CCU products are used to replace conventional carbon products. This means that CCU provides the sectors regulated under ETS no exemptions from having to surrender ETS allowances. (European Commission: Directorate-General for Climate Action 2019, 175-176, 179-182).

The revision of the ETS also describes the Innovation fund which aims to fund project that can considerably help climate change mitigation. Innovation Fund is aimed to accelerate deployment of new technologies that can help decarbonizing the EU and it is financed by the auctioning of EU ETS allowances. CCU is acknowledged by the ETS revision to be eligible for Innovation Fund as long as the project "*shall deliver a net reduction in emissions and ensure avoidance or permanent storage of* CO_2". CCU is mentioned to be especially important to industries that may have process emissions deemed unavoidable. (Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the European Union, 2023, § 8). Innovation fund also has specific guidance on how to quantify the emission reduction of a CCU project (European Commission, 2023a). Innovation fund has already provided funding for a dozen of large-scale CCUS projects. (European Commission, 2023b).

Sectors that fall under the ETS are mentioned in ETS directive (2003/87/EC) in Annex I. These include a wide range of industries related to at least energy production, manufacturing processes, maritime and aviation. ETS secludes installation used for research and development, small-scale installations of under 3MW and emissions from combustion of biomass. ETS sectors that could be seen as relevant for supplying CO_2 feedstock to power-to-X processes include energy production (with fossil fuels) and energy-intensive industry such as production of steel, cement, aluminum, paper, pulp, cardboard, and different chemicals. Waste incineration plants are also of interest to supply the CO_2 feedstock for CCU (Fortum, 2024). Waste incineration is currently not included in the EU ETS, but the EU will assess the feasibility of addition to the ETS by 2026. If decided to be included, waste incineration will be regulated under ETS (Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the European Union, 2023 § 97 & 98).

3.1.2. Renewable energy directive and other legislation related to renewable energy

The recast of Renewable Energy Directive (2018/2001/EC) (RED II) introduced new targets for renewable energy consumption. The overall target is now 42.5% of all energy consumption coming from renewable sources by 2030. The renewable energy consumption target was increased three times within five years with different revisions, which is depicting of the rapid movement of the policy environment around net-zero targets. (European Commission, 2023c). The target in RED II regarding the transport sector is 14.5 % reduction in GHG intensity and achieving 29 % share of renewable energy in final energy consumption. RED II also has a sub-target of 5.5 % of transport sector's energy consumption achieved via combined use of advanced biofuels and renewable fuels of non-biological origin (RFNBO) with a minimum of 1 % achieved by RFNBO use. (European Commission, 2023d). These RFNBO fuels cover hydrogen produced with renewable sources as well as fuels using CO_2 as a feedstock, i.e., power-to-X fuels made with CCU. These are also called e-fuels. (Buffi et al., 2022, 7). RFNBOs are defined in RED II as "*liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass*". The revision of RED II also introduced recycled carbon fuels (RCF) which are defined as "*liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin (...), or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations*" (Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (recast), 2023, Art. 2. § 35).

To further implement RFNBO's policy environment, two Delegated Acts were published by the EU to supplement RED II's legislation namely on articles 27 and 28 which cover renewable energy in transportation. These delegated acts for instance determine rules for production and GHG accounting of RFNBOs. The delegated acts also clarify the meaning of the

70% GHG reduction requirement for RCFs and RFNBOs which is mentioned in RED II. RFNBOs produced according to the Delegated Acts are in line with climate goals as well as EU's other legislation. (Scheyl, 2022).

The EU Council and the Parliament have agreed to promote e-fuel use also in aviation with the ReFuel EU aviation initiative. The initiative has an obligation for aviation fuel suppliers to supply certain minimum amounts of sustainable aviation fuel (SAF) at EU airports from 2025 onwards. The minimum share of SAF required by the suppliers to supply at the airports will rise over the years. The initiative also calls for a minimum distribution of synthetic fuel (or e-fuels), to be supplied at airports from 2030 onwards. Synthetic fuels can be used to reach the minimum requirement of SAF already also in 2025 along with compliant biofuels and hydrogen. (Council of the European Union, 2023).

Similarly, to aviation and transportation, legislation has been put in place also in maritime transportation. The FuelEU Maritime initiative has targets for lowering GHG intensity as well as to promote the use of RFNBO in shipping. The GHG intensity reduction target on-board will start at a 2 % reduction in 2025 and increase to 6 % from 2030. It will then gradually reach an 80% reduction in GHG intensity by 2050. RFNBO use is promoted by allowing a use of multiplier when RFNBO is utilized. The energy content of RFNBO use can be counted twice thus enabling reaching the GHG intensity reduction target quicker by using RFNBOs. The use of the multiplier will stop in 2034 when the 2% RFNBO sub-target will be set to commence. The sub-target is preliminary and subject to increase if RFNBO use is widely adopted sooner than. (Council of the European Union, 2023).

3.1.3. Delegated acts on RFNBOs

E-fuels or RNBOs must adhere to the criteria presented in RED II and the related Delegated Acts to be classified as renewable energy. RFNBOs must have a **minimum of 70% reduction in GHG emissions** compared to fossil fuels. The criteria also obligate the power-to-X processes to be powered by renewable energy in order to be classified as renewable energy and be eligible for the minimum distribution obligation targets for SAF and RFNBO. The Delegated Act on RED II specifies that the RFNBOs must be:

a.) connected directly to renewable electricity production,

b.) connected to a grid mix that had at least 90% renewable electricity in the previous calendar year,

c.) or connected to a grid mix which is balanced to match renewable electricity via power purchase agreements (*with added requirements regarding inter alia additionality).

(Commission Delegated Regulation on RFNBO production, 2023; Scheyl, 2022).

The two delegated acts of RED II revision on the *"minimum threshold for GHG savings of recycled carbon fuels*" contain guidance on the quantification of carbon footprint especially for RFNBOs. The second Delegated Act defines the exact formula for the carbon footprint calculation of recycled carbon fuels. The formula from the delegated act is presented below:

$$E = e_i + e_p + e_{td} + e_u + e_{ccs}$$

where:

E = total emissions from the use of the fuel (gCO2eq / MJ fuel)

e i = e i elastic + e i rigid - e ex-use: emissions from supply of inputs (gCO2eq / MJ fuel)

e i elastic = emissions from elastic inputs (gCO2eq / MJ fuel)

e i rigid = emissions from rigid inputs (gCO2eq / MJ fuel)

e ex-use = emissions from inputs' existing use or fate (gCO2eq / MJ fuel)

e p = emissions from processing (gCO2eq / MJ fuel)

e td = emissions from transport and distribution (gCO2eq / MJ fuel)

e u = emissions from combusting the fuel in its end-use (gCO2eq / MJ fuel) e ccs = emission savings from carbon capture and geological storage (gCO2eq / MJ fuel)

(Commission Delegated Regulation on RFNBO GHG methodology, 2023).

In order to qualify as RFNBO, the -70% reduction (among other qualifications mentioned in the delegated acts) must be reached. This threshold is harder to reach with fossil CO_2 (albeit not impossible) because the emissions arising from the fuel's combustion must then be accounted for. Furthermore, the threshold becomes easier to reach with utilization of CO_2 that fulfills the qualification requirements for the existing use or fate (e ex use) variable in the equation above. This variable determines the avoided emissions from capturing and utilizing CO_2 in an RFNBO. It is defined as being the same amount of carbon that is incorporated into the product, and which would have otherwise been emitted directly into the atmosphere without the carbon capture. (Commission Delegated Regulation on RFNBO GHG methodology, 2023).

Considerations on the source of the CO_2 feedstocks that can be considered avoided are mentioned in the Commission Delegated Regulation on RFNBO production. At the moment the viewpoint is that because there are numerous emission sources, and capturing any one of them would avoid emissions, all sources can be used for RFNBOs. However, the delegated act defines two different deadlines for the utilization of CO_2 from non-sustainable sources by defining that "*combustion of non-sustainable fuels for the production of electricity should be considered avoided emissions up to 2035, as most should be abated by that date, while emissions from other uses of non-sustainable fuels should be considered avoided emissions up to 2040, as these emissions will remain longer*". CO_2 emissions arising from activities that are deliberately set up just to produce carbon emissions are naturally not qualified in the RFNBO framework. (Commission Delegated Regulation on RFNBO production, 2023; European Commission, 2023e).

3.2. Policies on the source of CO_2

This chapter aims to clarify the legislative differences between different sources of CO_2 as well as policies and legislation regarding the use of different CO_2 sources. Differences between different carbon pools and sources from a natural science perspective were presented in chapter 2.1.1 However, many choices have been made in policies and regulations as to how these different sources of carbon are treated.

Biogenic CO_2 released from biomass is regulated as being zero. This is mentioned in numerous different pieces of legislation. EU ETS Annex IIIa states that "*The emission factor for biomass that complies with the sustainability criteria and greenhouse gas emission-saving criteria – shall be zero".* (Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the European Union, 2023). RED II mentions in its Annexes V and VI that the emission factor for the use of biofuels, bioliquids and biomass fuels is zero. RED II however also considers other factors than just the emissions from the use of fuel. These include factors considering the land use and indirect land use change caused by the production of biofuels. RED II also regulates biomass-based waste streams such as biodiesel from waste cooking oil as having life-cycle emissions of zero in the disaggregated default values for GHG-emissions from biofuels presented in Annex V of RED II. (Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (recast), 2023).

The EU regulation establishing certification framework for carbon removals also mentions that only biogenic and atmospheric CO_2 can be accepted to be called `carbon removal´ (European Commission, 2022). Regarding CCU the policies establishing real differences to biogenic and fossil CO_2 are still quite scarce. Commission's "*Communication in Sustainable Carbon Cycles*" stated that biogenic and atmospheric carbon should be favored over fossil sources as stated earlier in the beginning of chapter four. The meaning of fossil CO_2 is also not explicitly determined in EU legislation, rather just all emissions are fossil or non-sustainable CO_2 unless proven otherwise.

3.3. Life-cycle assessment and carbon footprint guidelines of CCU products

Life cycle assessment (LCA) is a framework developed to quantify the inputs, outputs and the environmental impacts of a system (e.g., a product or a service) throughout its life cycle, from acquiring of materials to the end-of-life. The methodology for LCA is defined by international standards, set by International Organization for Standardization (ISO). The main standards defining LCA are ISO 14040 and ISO 14044. These standards explain thoroughly the framework, terms, and steps of an LCA study. (European Commission: Joint Research Centre, 2010, iv-v).

LCA is separated into four main stages:

1) goal and scope definition, in which the goal and reasons behind the study are clarified and important criteria such as system boundary and functional unit are chosen on well justified decisions based on the goal of the study.

2) life cycle inventory (LCI), in which an inventory of relevant inputs and outputs is compiled,

3) life cycle impact assessment (LCIA), in which the impacts of the system's inputs and outputs to the environment are quantified in line with the chosen impact categories justified by the goal and scope of the study,

and finally

4) life cycle interpretation, in which the results and their implications are interpreted, and possible limitations and uncertainties are discussed.

These stages are examined in an iterative manner. LCA is mainly focused on environmental impacts and other tools should be used to focus on for instance the social or economic side of a life cycle. LCA is relative and all inputs and outputs of the system are quantified relatively to a specific functional unit that is chosen accordingly in the early phases of an LCA study. The functional unit defines the subject of study and its function. (ISO 14040:2006, 1-2, 7-9).

When conducting a carbon footprint calculation, also standard ISO 14067:2018 should be applied. This standard is consistent with ISO 14040 and ISO 14044, but focuses only on carbon footprints, not other impact categories. Carbon footprint is defined in the standard as "*sum of GHG emissions and GHG removals in a product system, expressed as* CO_2 *equivalents and based on a life cycle assessment using the single impact category of climate change.*". (ISO 14067:2018, 9).

Thorough guidance for conducting LCAs in line with ISO standards are presented in ILCD Handbook (International Reference Life Cycle Data System). The handbook was produced by the European Commission in order to develop LCA. The handbook expands from the standards and explains more thoroughly all the steps required in an LCA as well as introduces the terminology and best practices for conducting LCA. The handbook also considers issues related to LCA and how to deal with them, which is something that the standards don't really mention. (European Commission: Joint Research Centre, 2010). Among the mentioned issues is multifunctionality which is a prominent issue in power-to-X.

The existing standards ISO 14044 and ISO 14040 should be followed in every LCA as the principles of an LCA are the same regardless of the product or system in question. LCA methodology defined in the standards is designed to be holistic and versatile and suit all products, goods, and services. However, power-to-X systems' life cycles can be complex and have its own specific life cycle steps that are of particular interest such as carbon capture and retention time of carbon. These may need some extra attention to interpret as LCA guidance is broad and versatile and may leave some major decisions related to the specifics of the assessment up to the LCA practitioner. Power-to-X products that fall under CCU category may also differ from conventional linear manufacturing and have questions related to the multifunctionality of the systems, as well as have higher uncertainties than conventional production because of the low TRL of some process technologies. Because of these and other reasons some CCU-specific LCA-guidelines have been drafted in literature. These guidelines give suggestions for instance to the choice of goal and scope, functional unit and other decisions included within an LCA study. Guidelines that have been drafted regarding LCA of CCU include at least Ramirez-Ramirez et al. 2022 report "*LCA4CCU*" which was prepared for the European Commission, Directorate-General for Energy as well as Langhorst et al. 2022 "*Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO2*

Utilization (Version 2)" which was prepared by an organization called Global CO_2 initiative. (Langhorst et al., 2022, 14-15, 146-149)(Ramirez Ramirez et al., 2020, 6-7).

First step of an LCA is goal and scope definition. Goal definition phase explains the intended use of the study as well as the reasons behind it and what is hoped to achieve by conducting the LCA. The scope definition of an LCA contains many key decisions such as the definition of the studied system, system boundary, functional unit, assumptions, utilized data and other criteria that is incremental to the implementation of the LCA study. (ISO 14044:2006). The scope definition step of an LCA has great implications to the results and from a CCU perspective there are certain factors that need to be treated with extra care. The choice of the functional unit should be done in accordance with the function of the system in question as well as with consideration to the goal of the study. For instance, CCU products serving as energy carriers should be examined in relation to the energy content of the product (e.g. kgCO_2eq/MJ) and CCU products such as chemicals and materials should be examined in relation to mass (kgCO_2eq/kg). The choice of functional unit should however also represent the goal of the study and thus even energy carriers can be quantified in relation to mass (or other functions) if it's required to achieve the goal. (Ramirez Ramirez et al., 2020, 26-27).

Well defined system boundary that is done in accordance with the goal of the study and based on well justified decisions is paramount for the credibility of the LCA results. No life cycle steps should be omitted from an LCA study unless the omitted steps don't have any significant effect to the conclusions of the study. Omittances should also have clear explanations. (ISO 14044:2006, 8-9). Definition of system boundary is of utmost importance also in LCAs conducted on CCU products. Cradle-to-grave examination of the life cycle should be the default system boundary however omittances can be allowed in certain circumstances. The literature on LCA for CCU has some discrepancies regarding the choice of system boundary for some CCU life cycles. The Ramirez Ramirez et al. (2022) report prepared for EU Commission discourages basically any omissions of life cycle phases. Yet, Langhorst et al. (2022) report guides to choose cradle-to-gate system boundary in many cases. Langhorst et al. argues that cradle-to-gate is sufficient for comparative LCAs of products with identical chemical structure as their conventional counterparts because the life cycle emissions can be assumed to be identical for both products from factory gate onwards (Langhorst et al., 2022, 146). Ramirez Ramirez et al. however does not share this view and argues that life cycle phases from gate onwards should be accounted for and that in order to determine if product could be carbon neutral, the end-of-life phase must be included in the calculations. (Ramirez Ramirez et al., 2020, 27-28).

One of the major pitfalls related to the LCA of CCU products is considered to be the so-called problem of multifunctionality. This refers to the challenge of how to divide the burden of the CO_2 emissions to the different products that are manufactured within the broader system. In LCA terminology the capturing of CO_2 from an existing emitter that is producing some product turns the CO_2 flow from an elementary flow (CO_2 emissions) to a technical flow (CO_2 feedstock) that is used to produce a CCU product. However, when the carbon is in most cases ultimately released from the CCU product (for instance by combustion) the CO_2 is once again an elementary flow and an emission. The choice of how to address the CCU product's end-of-life emission between the original production where the CO_2 is captured from and the production of the CCU product can be a complex decision, but few options have been suggested in literature. (Müller, Kätelhön, Bringezu et al., 2020). Langhorst et al. (2022) suggests that hierarchy of decision-making to solve multifunctionality should be:

1. Sub-division by individual process data.
2. System expansion to examine the impacts of the whole system, not just one product.
3. System expansion by substitution in which the credit for the captured CO_2 is given to the CCU product.
4. Allocation based on physical attribute or some other underlying attribute such as economic value. (Langhorst et al., 2022, 150-155).

The hierarchy is similar to that of ISO standards. ISO standards suggest that allocation of emissions should be avoided if possible and system expansion chosen instead. Allocation cannot be however avoided in some cases, so it is important that the decisions behind the allocation are explained thoroughly. (ISO 14044:2006, 14).

The problem of multifunctionality can be difficult to solve when assessing cradle-to-grave CCU systems. The CO_2 entering the CCU system has been an unwanted another system, and one view is that thanks to the CCU system, the CO_2 is not directly emitted to the atmosphere. According to this view the so-called burden for the ultimate CO_2 emission that is released at the end-of-life of the CCU product should be accounted to the primary emitter of the CO_2 (i.e. the installation of whose emissions are captured) and the credit for avoided emissions given to the CCU plant. This method suggested by Ramirez Ramirez et al. is suitable for so-called consequential LCA modelling since the logic relates to the changes and dividing the credits and burdens according to the consequences of change. (Ramirez Ramirez et al., 2020, 45-46). The third option of solving multifunctionality in Langhorst et al. (2022) presented earlier is system expansion via substitution which presents a similar approach. In system expansion by substitution the credit for avoided emissions is also given to the CCU product. Both options presented solve multifunctionality by dividing the credit of avoided emissions to the CCU product and burden of released emissions to the original plant where the carbon is captured. Both methods may lead to negative carbon footprints because of the credit for the avoided emissions which can alter the interpretation and lead to false conclusions of overstated environmental benefits. (Langhorst et al., 2022, 152).

One recommendation for quantifying CCU products' impacts arising from for example Ramirez Ramirez et al. (2022) is that the LCAs should be consequential LCAs (CLCA) rather than the most commonly used attributional LCA (ALCA). The difference in viewpoint between the two modes of LCA is that essentially ALCA considers what proportion of the global environmental impacts are caused by the products system and CLCA considers how are the global environmental impacts altered by the product system. This subtle seeming difference in viewpoint is however significant since CLCA aims to consider the changes or "consequences" caused by a product system and ALCA considers only the direct impacts caused by the products system. ALCA is at the moment much more common and has much more guidance and established documentation on how to perform the calculation. CLCA can provide very important information on the impacts of certain decisions, but currently it is not as well-established and due to the somewhat speculative nature of defining the consequences it can also be considered more uncertain. (Ekvall, 2019).

4. Power-to-X products' lifecycle

This chapter aims to identify the relevant lifecycle steps that are contained within typical power-to-X chains that utilize CO_2 as a feedstock. Chains that utilize CO_2 to manufacture new products for instance by combining it with hydrogen, also fall under the category of CCU. In order to fully understand carbon balances related to CCU, the whole power-to-X chain must be introduced from literature related to the subject.

4.1. Lifecycle phases of power-to-X

Power-to-X products' lifecycles are often quite complex and contain multiple steps and possible intermediary chemicals. Conversion processes that include inter alia electrochemical and thermochemical conversion routes can be used to manufacture valuable common chemicals from H_2 and CO_2. Using CO_2 as a feedstock for these processes can help replace the need for fossil fuels. Chemicals that can be manufactured from CO_2 and H_2 include gasoline and diesel, methane, methanol, olefins, different alcohols, dimethyl ether and numerous more chemicals, all of which either have utilization on their own or as an intermediary to form other high value products. (Vo, Nguyễn & Nanda, 2022) (IEA Carbon to use, 10).

4.1.1. Water electrolysis

Hydrogen produced by water electrolysis with renewable energy is at the heart of power-to-X systems. Electrolysis is a process that uses electrical power to separate the oxygen and hydrogen in a water molecule. Water electrolysis technologies utilize anode and a cathode with an electrolyte in-between them to incite oxidation and reduction reactions that separate H_2O molecule into H_2 and O_2:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{1}$$

Storing hydrogen and its energy is a crucial step of power-to-x chains. Storage technologies to store pure hydrogen include pressurized gas, metal hydrides, and cryogenic liquid.

Hydrogen can then be used directly for energy use either in a fuel cell or simply by combustion. However, hydrogen can also be used as a precursor for all kinds of fuels, chemicals and products which can be easier to store and transport. (Palys & Daoutidis, 2022b).

Electrolysis technology is currently most viable using alkaline electrolysis (AEL) technology. AEL technology utilizes two electrode rods that are submerged in alkaline liquid electrolyte. The alkaline liquid solution is usually potassium hydroxide or sodium hydroxide. AEL technology works by decomposing the H_2O molecule to hydrogen by utilizing the two electrodes which make electrons flow from the anode to the cathode. Then H^+ ions consume the electrons thus forming H_2. AEL forms very high purity hydrogen as well as high purity oxygen. (Chisholm & Cronin, 2016, 321-322).

In addition to alkaline electrolysis polymer electrolyte membrane electrolysis (PEM) and solid oxide electrolysis (SOEC) are emerging electrolysis technologies. PEM installations are currently at use only on small scale and SOEC is still at low TRL. (Rego de Vasconcelos & Lavoie, 2019). Different electrolysis technologies have their own specific advantages and disadvantages. AEL's disadvantages are said to be for instance its inability to working on low loads and low pressure, aspects that PEM technology has to its advantage. (Chisholm & Cronin, 2016, 324-326).

4.1.2. Carbon capture

CO_2 capture from industrial point sources can be achieved using multiple different routes with most prominent technologies being, post-combustion, pre-combustion and oxyfuel combustion. Post-combustion carbon capture separates CO_2 from flue gases via chemical solvent such as amine that is used to absorb the CO_2 from the flue gas. After that the CO_2 is separated from the solvent in a stripper. The recovery rate for post-combustion carbon capture is usually 80-90% but depends on e.g., nitrogen oxide, sulphur oxide content and CO_2 content of the flue gas which is determined by the type of fuel used. Pre-combustion carbon capture involves decomposing the fuel's hydrocarbons to CO_2 and H_2 in high temperature.

This leads to the CO_2 emission being released before the combustion and only the H_2 being used as the fuel. CO_2 is then removed by absorption using solvent such as amine. In oxy-fuel combustion carbon capture pure oxygen is used in the combustion of the fuel. This leads to the flue gases containing only CO_2 and water vapor because there are no impurities such as nitrogen oxide caused by the addition of nitrogen to the combustion process via air. Thus, the CO_2 is easily separated by only refrigerating the flue gas which causes the water vapor to condense and only the CO_2 remains as a gas. Oxy-fuel combustion leads to almost all the CO_2 being captured. All of the forementioned capture processes cause some efficiency penalty to the overall combustion process caused by for instance compression and heating. (Rahimpour et al. 2020, 54-57).

The composition of the flue gas from which the CO_2 is captured impacts the energy requirements of carbon capture. The defining factor is namely the CO_2 concentration of the flue gas. The lower the CO_2 concentration of the flue gas, the higher the energy demand. Other chemical composition aspects as well as the temperature of the flue gas also impacts the efficiency of carbon capture. The costs of carbon capture also increase with lower CO_2 concentration. (Gür, 2022).

In addition to the capture from flue gases, CO_2 can also be captured directly from ambient air using direct air capture (DAC). The CO_2 concentration of air is record-high from a climate perspective; however, it is very low compared to industrial flue gases. The low CO_2 concentration makes DAC's energy requirements substantial and large volumes of air is needed to process to capture any sensible amount of CO_2. DAC also requires land area because the low CO_2 concentration leads to a need for a large contact surface for the absorption of CO_2 from the air. (Gür, 2022).

The separation of CO_2 can be achieved in multiple ways. Absorption using amines is a developed and viable technology. Absorption happens by utilizing liquid or solid sorbents like amines such as monoethanolamine and diethanolamine. These sorbents react quickly to acid gases such as CO_2 and absorb them. Other sorbents beside amines include for instance potassium carbonate. Adsorption of CO_2 is another separation technology in which the pressure of a system is increased that leads to the CO_2 getting absorbed into the surface of a solid adsorbent. (Khurana et al. 2021, 11-31).

4.1.3. Utilization phase

CO_2 is already a common feedstock in different industries such as fertilizer manufacturing, enhanced oil recovery (EOR), metal fabrication and use in foods and beverages. CO_2 can be used directly without any conversion processes in numerous uses but the current rise in interest towards CO_2 use though is mainly to do with products that require conversion processes. CO_2-based products that require conversion pathways include fuels, chemicals, and building materials. CO_2-derived fuels are often called electro fuels, e-fuels or power-to-X fuels (Kujanpää et al., 2023, 25-31). Global interest in the use of captured CO_2 to create new carbon-based products has risen due to the threat of climate change. The use of captured CO_2 to create carbon-containing chemicals and fuels without the need for fossil sources could also be one of the only viable options for certain industries to switch away from fossil fuels. (IEA, 2019, 5-6).

CO_2 molecule is non-reactive, stable and has a low energy state and thus the conversion pathways to different fuels require the addition of external energy. Most viable technologies that exist to date involve using hydrogen as the energy-carrier. By adding hydrogen and external energy to CO_2, it can also be processed into different chemicals that are commonly used in number of industrial processes and or converted further. There are also CCU pathways that do not necessarily require lots of added external energy, such as using CO_2 to replace a portion of the fossil-based part of polymer production and using CO_2 in concrete production by process called CO_2 curing. (IEA 2019, 18-19).

Common conversion pathway to produce high value chemicals from CO_2 includes a first step of producing synthesis gas, or syngas, from CO_2. Syngas is a mixture of carbon monoxide (CO) and hydrogen, and it can be produced from CO_2 for instance by reverse water-gas-shift. The reaction to produce syngas from CO_2 also requires water, hydrogen, catalysts, as well as high thermal energy (>800°C). The reaction for reverse water-gas-shift is presented below. (Hannula, Kaisalo & Simell, 2020).

Hydrocarbons can be manufactured from syngas using Fischer-Tropsch synthesis. This reaction is widely studied and has been developed for a long time. Different hydrocarbons manufactured using FT process include gasoline, diesel, olefins, alcohols as well as other higher hydrocarbons. (Nanda, Vo & Nguyen, 2022).

$$CO + 2H_2 \rightarrow CH_2 + H_2O \tag{2}$$

Chemicals from CO_2 can also be manufactured directly without the need to produce syngas, via hydrogenation. Hydrogenation requires the use of catalysts and external energy to produce valuable chemicals directly from CO_2 and H_2. Chemicals that can be manufactured via hydrogenation include methanol, alcohols, olefins, formic acid as well as other hydrocarbons. These chemicals can be utilized in many ways directly or as intermediate feedstocks to manufacture for instance polymers or fuels. (Nanda, Vo & Nguyen, 2022).

Technological readiness level (TRL) varies widely among CCUS technologies and processes ranging from being only concepts to proven to be technologically stable. TRL is a scale (usually a number between 1-9) used to assess the readiness of certain technology, with 1 being just on an idea scale and 9 being fully operational. Within a CCU product's manufacturing system there is often multiple processes with differing TRLs. Generally, when assessing TRL of a whole system, the TRL is defined according to the lowest TRL process within the system. (Langhorst et al., 2022, 20-22). International energy Agency (IEA) has assessed multiple different CCUS systems and processes, and some selected processes related to CCU are presented in the table below. IEA uses a scale of 1-11 to assess TRL of different technologies. (IEA, 2023b).

Table 2. TRL of various CCU processes assessed by IEA (IEA, 2023b)

Technology	TRL
Production of synthetic hydrocarbon fuels with Fischer Tropsch synthesis	6
Production of synthetic methane via chemical methanation of CO and CO_2	7
Bioenergy with post-combustion capture using chemical absorption	6–7
Bioenergy with pre-combustion capture using physical absorption	3
Natural gas with post-combustion capture using chemical absorption	8
Coal post-combustion capture using chemical absorption	8–9
Chemical absorption of CO_2 in ammonia production	11
Oxyfuel CO_2 capture in cement kilns	6
Methanol production from chemically absorbed CO_2	9
Direct air capture	6–7

4.2. Power-to-methanol

The details of the power-to-methanol route is presented in this chapter. Power-to-methanol was selected to be of interest in the scope of this thesis because of the wide range of uses that exists for methanol. Methanol can be used as an intermediate to manufacture a wide range of valuable chemicals such as acetic acid and olefins. Methanol can also be used as a fuel either directly or blended into for instance gasoline. (Methanol Institute, n.d.). Interest towards methanol has also emerged more because of the technologies converting H_2 and CO_2 into methanol. Methanol is also seen as an energy carrier that is easier and more efficient to store and transport than hydrogen. (Rego de Vasconcelos & Lavoie, 2019).

Currently the conventional way to manufacture methanol consists of synthesis gas production, synthesis gas conversion to methanol and distillation. Synthesis gas is a mixture gas that contains CO_2, H_2 and CO and its production is a crucial step of conventional methanol production. The manufacturing of synthesis gas has variations, but the most usual route is by steam reforming of natural gas i.e. methane. Other routes include reforming or partial oxidation of other carbon-based substances such as coal, biogas or petroleum coke. The reactions that happen during the methanol production are brought forward by the use of catalysts. Most common catalysts in methanol production are copper (Cu), zinc (Zn), and aluminum oxide (Al_2O_3). Methane steam reforming has a co-reaction of water gas shift that produces the CO_2 in synthesis gas:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (3)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (4)$$

Methanol is the synthesized by the following reactions:

$$CO + 2H_2 \leftrightarrow CH_3OH \quad (5)$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad (6)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (7)$$

(Bozzano & Manenti, 2016).

Power-to-methanol processes can be achieved in differing ways, but often the chains involve few steps. Typical steps include water electrolysis to manufacture the hydrogen, carbon capture and separation to prepare the CO_2 feedstock, hydrogenation process to synthesize the methanol, as well as distillation. The front-running process in power-to-methanol is a two-step process which includes H_2O electrolysis and methanol synthesis by CO_2 hydrogenation. Power-to-methanol can also be achieved via three-step process which includes H_2 and CO_2 are co-electrolyzed to produce synthesis gas (a mixture of CO_2, H_2 as well as CO) which is synthesized to methanol. A one-step process of direct electrosynthesis of CO_2 and H_2O to methanol is also viewed as a promising power-to-methanol route but this has significantly lower TRL than the forementioned two-step and three-step routes. (Adnan & Kibria, 2020).

In this thesis the power-to-methanol route of choice is a two-step process of H_2O electrolysis and methanol synthesis by hydrogenation of CO_2. AEL is the most advanced and viable water electrolysis technology currently available. This technology was presented in chapter

2.1. Water electrolysis is energy intensive and requires a lot of external electricity to split the water molecules into hydrogen. (Zhang et al., 2017). Hydrogenation of CO_2 is considered to have a TRL of 8-9 and other less mature technologies for methanol synthesis such as direct synthesis are at TRL of 1-3. (Chauvy et al., 2019). Co-electrolysis of CO_2 and H_2 is also a promising technology and could be more efficient because CO is more effectively synthesized to methanol than CO_2 so the synthesis gas route of power-to-methanol can have some added efficiency compared to the more direct hydrogenation of CO_2. However, direct hydrogenation utilizes more CO_2 and thus is more suitable from carbon abatement perspective. (Mbatha et al., 2021). The hydrogenation of CO_2 happens chemically according to the following reaction equation:

$$CO_2(g) + 3H_2 \rightleftharpoons CH_3OH(g) + H_2O \tag{8}$$

$$CO_2 + H_2 \rightleftharpoons CO + H_2O \tag{9}$$

(Marlin, Sarron & Sigurbjörnsson, 2018).

Methanol synthesis from CO_2 and H_2 is an exothermic reaction though not as exothermic as regular methanol synthesis from synthesis gas. The less exothermic nature of the reaction leads to some benefits in synthesis reactor design with some added efficiency compared to regular methanol synthesis mainly due to the simplicity of the process and better heat distribution. Regular methanol synthesis requires complex boiling water reactors but methanol synthesis by direct hydrogenation can be achieved in more simple reactors such as tube-cooled reactor. The crude-methanol produced by methanol synthesis still contains H_2O, CO_2 and other by-products such as ethanol and dimethyl ether and thus methanol must be separated from water and distilled. By-product formation is however lower in CO_2 hydrogenation than compared to conventional route (Dieterich et al., 2020). The purification and distillation of methanol synthesized by direct CO_2 hydrogenation may be simpler than compared to regular methanol synthesis. Power-to-methanol route also provides the advantage of a possibility to loop the remaining CO_2 left in crude-methanol back into the methanol synthesis reactor. Methanol synthesis from CO_2 hydrogenation can be considered more energy efficient, less polluting and in general to be more advantageous from a process perspective in comparison to conventional methanol synthesis. (Marlin, Sarron & Sigurbjörnsson, 2018).

CO_2 molecule is chemically very inert and has high thermal stability and thus synthesizing it to methanol requires input of external energy and use of a working catalyst. The most promising catalysts for CO_2 hydrogenation are considered to be copper based. Copper alone is not enough though and zinc oxide is often alongside copper as the catalysts in hydrogenation. (Nor Hafizah & Noor Asmawati Mohd, 2022).

The overall efficiency and energy consumption of the power-to-methanol process is dependent on number of variables such as the integration of processes, cooling requirements, heat utilization as well as other details. The electrolysis phase has a substantial impact especially on the electricity demand of the power-to-methanol route with other phases like carbon capture and methanol synthesis contributing to the energy demand more by cooling and heating requirements. (Abad et al., 2021). Electrolysis phase accounts for up to 97% of the overall electricity demand of the power-to-methanol process. The overall efficiency of power-to-methanol (from flue gases) ranges from a low-value of 45% to a high-value of 60% based on literature. (Dieterich et al., 2020). The overall electricity and energy demand for the whole power-to-methanol chain is dependent on numerous factors and different values can be found in literature based on the choices of the study for example regarding the choice of electrolyzer technology.

4.3. Power-to-polymers via methanol

Power-to-polymers is the other route that was selected to be of interest in this thesis and is thus presented with more accuracy. Polymers can be manufactured from methanol; thus, the manufacture of polymers requires few extra steps from the manufacture of power-to-methanol. In this thesis the choice of plastic is high-density polyethylene (HDPE). HDPE is a polyolefin thermoplastic. Polyethylenes are the most popular plastics in the world and can be utilized in countless applications in different industries. HDPE is a tough and rigid plastic which has high tensile strength. HDPE is utilized widely for all kinds of products such as plastic piping, plastic furniture, different industrial fabrics as well as strong plastic packages and products. (Matmatch, 2016). HDPE is also one of the most utilized plastics in buildings and construction (PlasticsEurope, 2014, 8).

When manufacturing polyethylene from methanol, the first step is to manufacture ethylene from methanol in a process called methanol-to-olefins (MTO). Few slightly different processes of MTO are currently viable. The most common of the different MTO technologies is a process called DMTO. MTO technologies work in the same basic principle of utilizing a molecular sieve catalyst to form new carbon bonds. The most common catalyst is a silicon-based porous substance named SAPO-34. (Yang et al., 2019).

MTO process is presented in literature sometimes to have an intermediary chemical of dimethyl ether (DME) (Hoppe, Thonemann & Bringezu, 2018). However, ethylene can also be directly synthesized from methanol with a near 100% methanol synthetization and co-products of propylene and butane. The main chemical reactions of the MTO process are presented below with the reaction to form ethylene presented first, propylene second and butene below that:

$$2CH_3OH \rightarrow C_2H_4 + 2H_2O \tag{10}$$

$$3CH_3OCH_3 \rightarrow C_3H_6 + 3H_2O \tag{11}$$

$$4CH_3OCH_3 \rightarrow C_4H_8 + 4H_2O \tag{12}$$

(Xiang et al., 2014).

Once ethylene is synthesized from methanol, it needs to be polymerized to produce polyethylene. In this thesis the polymerization is assumed to be identical to conventional ethylene polymerization. HDPE can be polymerized in numerous different ways and thus a single common polymerization process is not straightforward to name but the technologies are mainly characterized by low pressure. Slurry suspension polymerization and gas phase polymerization are among the technologies that can be utilized to polymerize HDPE. The specific characteristics of the finished HDPE are impacted by the choice of the catalyst as well as co-monomers. (PlasticsEurope, 2014, 11-13).

Polymers can also be manufactured utilizing CO_2 by co-polymerization. In this process part of the fossil feedstock is replaced by CO_2 (IEA, 2019, 11). Co-polymerization using CO_2 feedstock is already quite common with many installations around the world producing CO_2-based plastics, this however does not eliminate the need for new fossil-based materials. Co-polymerization may offer some benefits for the manufacturer in efficiency and costs. The overall CO_2 content of the finished product is however limited to rough maximum estimate of 50% with rest being still fossil-based. (Inamuddin et al., 2022, 21-22).

5. Carbon capture and utilization pathways and calculations

In the next chapters the carbon footprint calculations are presented and interpreted. This chapter is divided according to the ISO 14040 methodology to scope and goal definition, LCI phase and LCIA phase, all presented separately for the different calculations. The interpretation phase is presented in the next chapter along with discussion and comparison of different calculation methods.

The aim of this thesis is to examine the quantification of carbon footprint for CCU products and compare different methodological choices that these calculations entail. The relevant climate context as well as the EU legal framework around the subject was examined in the literature part. In the calculation part of this thesis the previously introduced knowledge from literature is used to examine and interpret the calculations. To examine the questions properly, the carbon footprint for the selected CCU products (methanol and HDPE plastic) are calculated in different relevant ways. These include a base calculation of cradle-to-grave carbon footprint using both biogenic and fossil CO_2 feedstock, system expansion to calculate the avoided emissions of the two products, calculation using RED II delegated acts' methodology as well as some added examinations regarding the retention time of carbon and the impact of system boundary.

5.1. Methodology

The two products; methanol and HDPE plastic were chosen because of their scalability (i.e., vast existing use) and thus potential for wide range of implementation. The two products also represent different functions and have (potentially) differing life cycles. Methanol has a short expected-life cycle and plastic can become a long-lived product. Both products and their respective lifecycles, and production technologies were presented more thoroughly in the previous chapters. Carbon footprints are quantified according to the relevant standards such as ISO 14067, ISO 14040, and ISO 14044. Because, electricity demand presents large portion of power-to-X life cycles' environmental impact, two scenarios are calculated, using the emission factor for electricity in Finland in 2022 as well as the estimated emission factor in Finland in 2035.

5.2. Goal and scope

Goal of the calculations is to examine the difference in results between using fossil and biogenic CO_2 as a feedstock as well as to examine the differences in methodologies of quantifying the carbon footprint for CCU products. The calculations are part of a master's thesis conducted for the company St1 and the intended audience of the calculations are mainly academia, internal use inside the company as well as people generally interested in CCU. The results of the calculations should not be used to make any real-life decisions per se, but rather to widen the understanding related to quantification of carbon footprint of CCU and power-to-X products. A specific LCA should always be conducted when the goal is to help real-life decision making.

The system boundary of this study is from cradle (referring to the pipe from which CO_2 is captured from) to grave (end-of-life). Production of different materials and machinery required to operate the process is beyond the scope of this study. Transportations are also left out of this study because the calculations do not rely on any real-life process and means of transportation and their distances would only be guesswork. One allocation by mass was conducted in the HDPE case in MTO process. This is explained in the HDPE LCI and can be seen in the system boundary. The system boundaries for the cradle-to-grave calculations for both products, methanol and HDPE are presented below in their own respective process charts.

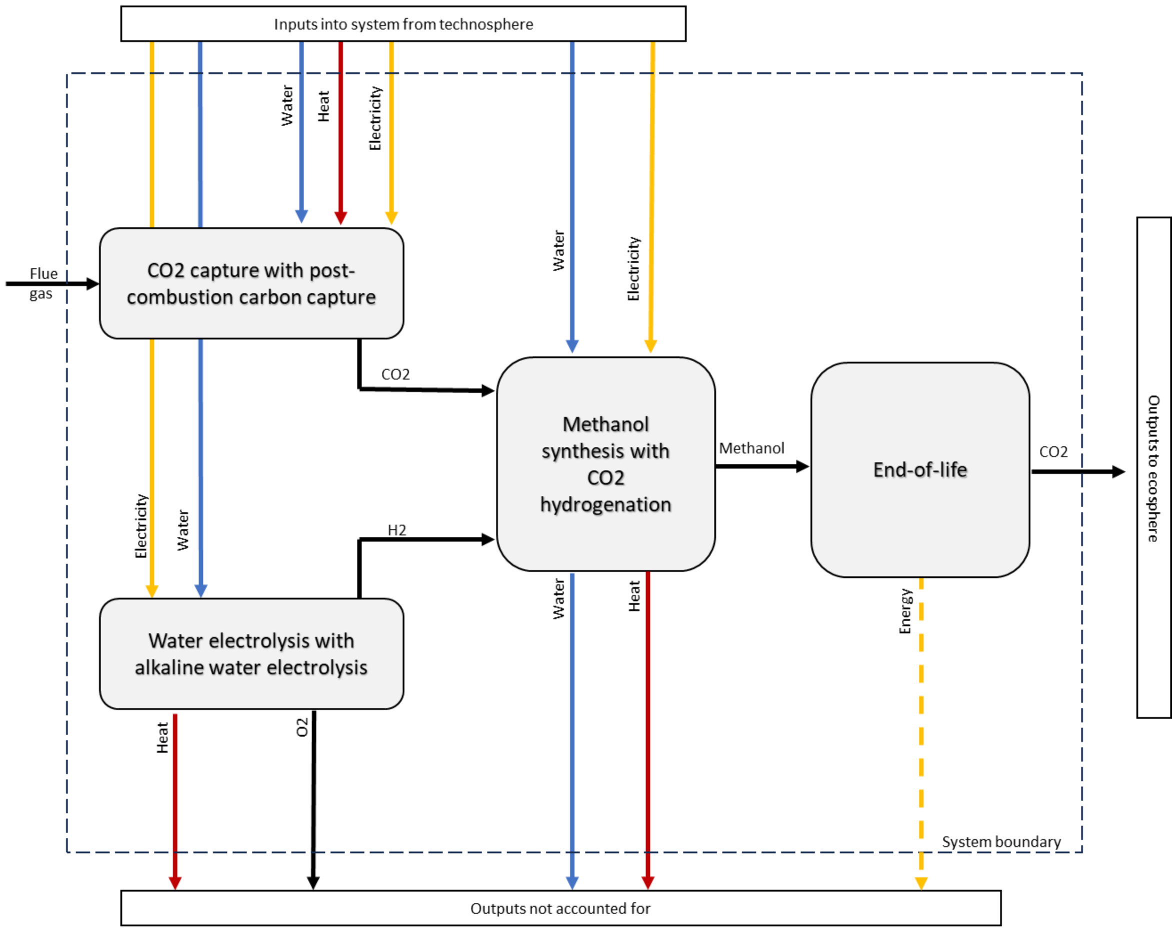

Figure 5. System boundary and process chart for power-to-methanol

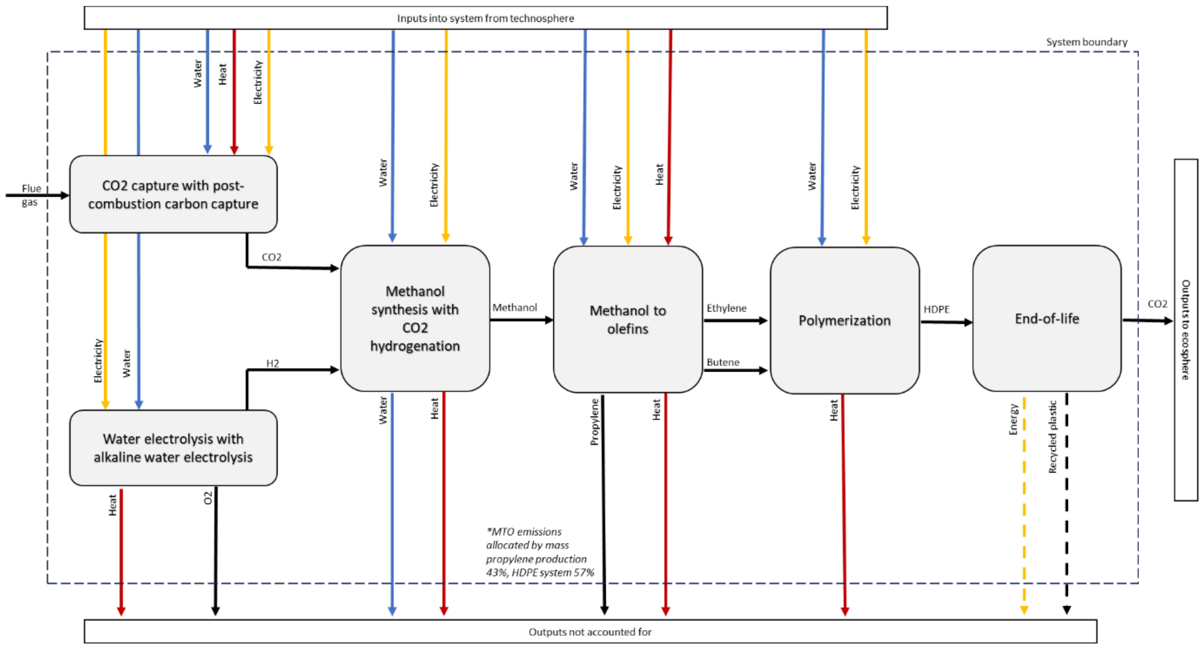

Figure 6. System boundary and process chart for power-to-HDPE

The functional unit of the calculations is chosen to be 1 kg of the end-product and the results as well as life cycle inventories are presented in relation to this functional unit. The functional unit was chosen to be mass even though the function of methanol is mainly as an energy source in order to have some comparability between different CO_2 utilization options. The calculations only examine the climate impact i.e., GWP, and results are presented in CO_2eq.

Data for the calculations was gathered from literature and may not represent the most accurate picture for certain processes. Data was sought out from recent studies, but some exceptions were forced to be made due to data availability. The data also has some geographical variation.

Comparisons are made to the CCU products' fossil counterparts in order to better understand the possible climate impacts. The carbon footprint data for the fossil counterparts was gathered from literature and legislation. The levels of accuracy and completeness may be differing between the calculations made for the purposes of this thesis and the gathered fossil counterparts' carbon footprint data. Many factors such as the high TRL of fossil counterpart's production technology compared to low TRL of CCU may also have an effect. Thus, definitive comparative assertions on the climate impact between CCU products and their fossil counterparts should not be made according to the results since the carbon footprints may vary in accuracy.

5.3. Life cycle inventory

Full life cycle inventories for both methanol and HDPE are presented in this part. Specific data on the different processes regarding both power-to-X chains are presented below. Other data requirements for the carbon footprint calculations which are not power-to-X specific include emission factors as well as data on the characteristics of materials. These were sought out mostly from official sources such as EU legislation.

5.3.1. Methanol

The electricity requirements for water electrolysis by AEL are described by an electrolyser manufacturer to be in the region of 3.8-4.4 kWh/Nm^3H_2 which translates to roughly 42-49 kWh/kgH_2 (with H_2 density of 0.0887 kg/m^3). (Nel Hydrogen, 2018). Water requirements are mentioned by an electrolyzer manufacturer to being 9.6 kg of deionized water required to manufacture 1 kg of H_2 (Sunfire.de, 2022). The output of oxygen from the AEL installation is in the region of 7,9 kgO_2/kgH_2 (Sakas et al., 2022). Water electrolysis also releases heat. The amount of heat released from the process is in the region of 14 kWh/kgH_2 (Zhang et al., 2017).

Post-combustion carbon capture requires external energy, but the amount of electricity required has some variation in literature. Feron et al. (2020) defines the electricity consumption to be in the range of 0.08-0.45 MJ/$kgCO_2$ and the amount of heat required falls in the range of 2.2-3.6 MJ/$kgCO_2$ (Feron et al., 2020). For both variables an average was used in the calculations.

As for methanol synthesis by CO_2 hydrogenation the external energy requirements are somewhere in the region of 2 MJ of electricity required to synthesize 1 kg of methanol (Zang et al., 2021). The amount of heat released from the synthesis is around 1.75 MJ/kgMeOH (Eggemann et al., 2020). By stoichiometric examination 1.37 kg of CO_2 is necessary to produce 1 kg of methanol, this is however dependent on the efficiency of the processes' carbon conversion. Current technologies enable carbon conversion in the range of 96% which translates to CO_2 requirement of 1.43 $kgCO_2$/kgMeOH. (Dieterich et al., 2020). The excess CO_2 is assumed to become leaks. The amount of hydrogen needed for methanol synthesis is 0.19 kgH_2/kgMeOH (Eggemann et al., 2020).

The end-of-life treatment for methanol is assumed to be burning in some form. This is also the use phase of methanol. Incineration of methanol releases 1.37 kg of CO_2 per 1 kg of methanol as well as the energy contained in methanol. The lower heating value of methanol is 19.90 MJ/kg. Emission factor for methanol in relation to energy is 97.1 gCO_2/MJ. (European Commission: Joint Research Centre, 2019). This value is slightly higher than that of RED II Delegated Acts' fossil fuel comparator which is set at 94 gCO_2/MJ (Commission Delegated Regulation on RFNBO GHG methodology, 2023).

Table 3. LCI of power-to-methanol

LC phase		flow	value	unit	reference
CO2 capture	input	electricity	0,38	MJ	Feron et al., 2020
		heat	4,14	MJ	Feron et al., 2020
	output	Required CO2 output	1,43	kg	Dieterich et al., 2020
AEL	input	electricity	31,62	MJ	Nel Hydrogen, 2018
		water input	1,83	kg	Sunfire.de, 2022
	output	O2	1,50	kg	Sakas et al., 2022
		required H2 output	0,19	kg	Eggemann et al., 2020
		heat	14,94	MJ	(Zhang et al., 2017)
MeOH synthesis	input	electricity	2,04	MJ	Zang et al., 2021
		CO2 required	1,43	kg	Dieterich et al., 2020
		H2 required	0,19	kg	Eggemann et al., 2020
	output	heat	0,49	MJ	Eggemann et al., 2020
		CO2 not converted	0,06	kgCO2	Dieterich et al., 2020
		water	0,56	kg	Eggemann et al., 2020
		Methanol	**1,00**	**kg**	***functional unit***
End-of-life	input	**Methanol**	**1,00**	**kg**	***functional unit***
	output	combustion	1,37	kgCO2	Definition of input data to assess GHG default emissions from biofuels in EU legislation
					**all values in relation to functional unit*

5.3.2. HDPE

The specific data on methanol-to-HDPE is scarcer in literature compared to power-to-methanol. The HDPE process expands onwards from the power-to-methanol chain the MTO process being the first in the HDPE chain after methanol production. Overall, the manufacture of 1.02 kg of ethylene from the MTO process requires around 3.5 MJ of electricity, 11.8 MJ of heat and feedstock of 5.45 kg of methanol. Along with 1.02 kg of ethylene, co-products of 0.90 kg of propylene and 0.20 kg of butene are also produced (Xiang et al., 2014). An allocation procedure was done according to the mass of required products (ethylene and butene) and unwanted co-product (propylene). This leads to 57% of the MTO phase emissions allocated to the HDPE system and 43% allocated to propylene and not accounted in the system.

Polymerization phase is assumed to be the same for regular plastic and CCU plastic and thus data from literature was acquired from processes representing conventional polymerization. According to a report by Plastics Europe (2014), 1.56 MJ of electricity and 1.32 MJ of heat is required for the polymerization phase of 1 kg of HDPE (PlasticsEurope, 2014, 33). The amount of feedstock required to manufacture 1 kg of HDPE was estimated in Hoppe et al. (2018) to be 1.02 kg of ethylene and 0.02 kg of butene. (Hoppe, Thonemann & Bringezu, 2018).

The end-of-life for HDPE is assumed to be either recycling or incineration. The use phase for HDPE is assumed to have no emissions and is thus not considered. The sub-division between the two end-of-life treatment options is done according to the current data on the share of municipal solid waste heading into recycling and incineration. Currently 56% of municipal solid waste is headed into incineration and 43 % is recycled in some fashion (Bröckl et al., 2021, 16). Although HDPE plastic can also become for instance building material which does not become municipal solid waste, but this still represents a good estimation on the share of plastic incinerated and recycled. When incinerated polyethylene plastic releases around 3 kgCO_2 per kg of PE. Recycling of polyethylene causes roughly 0.40 3 kgCO_2/kgPE (ecoinvent, 3.8).

The production emissions of regular fossil HDPE are around 1.8 kgCO_2eq./kgHDPE (PlasticsEurope, 2016, 5). The end-of-life was assumed to be the same division of recycling and incineration for the conventional HDPE. This leads to the total carbon footprint for the conventional counterpart for the HDPE plastic to be 3.65 kgCO_2eq./kgHDPE.

Table 4. LCI of power-to-HDPE

LC phase		flow	value	unit	reference
methanol-to-ethylene	input	electricity	3,55	MJ	Xiang et al., 2014
		heat	12,03	MJ	Xiang et al., 2014
		methanol	5,54	kg	Xiang et al., 2014
	sub-input	*total CO2 for meoh*	*7,90*	*kgCO2*	
	output	ethylene	1,02	kg	Xiang et al., 2014
		butene	0,22	kg	Xiang et al., 2014
		propylene	0,92	kg	Xiang et al., 2014
	allocation	*HDPE system (ethylene + butene)*	*57*	*%*	allocation by mass
		away from system (propylene)	*43*	*%*	allocation by mass
Polymerization	input	electricity	1,56	MJ	Plastics Europe 2014
		heat	1,32	MJ	Plastics Europe 2014
		ethylene	1,02	kg	Hoppe et al 2018
		butene	0,02	kg	Hoppe et al 2018
	output	**HDPE**	**1,00**	**kg**	***functional unit***
End-of-life	input	recycled	43 %	%	Bröckl et al., 2021, 16
		incinirated	56 %	%	Bröckl et al., 2021, 16
		HDPE	**1,00**	**kg**	***functional unit***
	output	'treatment of waste polyethylene, municipal incineration - RoW - waste polyethylene	1,69	kgCO2	ecoinvent 3.8
		market for waste polyethylene, for recycling, sorted - Europe without Switzerland - waste polyethylene, for recycling, sorted	0,16	kgCO2	ecoinvent 3.8

5.4. Life cycle impact assessment

The life cycle impacts of the previously introduced CCU products are presented in this part. Life cycle impact assessment phase of an LCA study aims to present more information on the environmental impacts of the whole life cycle, so that the full importance of these impacts can be interpreted later on. (ISO 14040:2006).

5.4.1. Methanol cradle-to-grave EF 2022 and 2035

The overall lifecycle impacts (in kgCO_2eq.) for 1 kg of methanol produced from CO_2 both by using fossil and biogenic CO_2 as a feedstock are presented first. The life cycle emissions for the methanol chain are calculated first by using the grid electricity emission factor for 2022. The overall emissions are presented in the table below.

Table 5. LCIA of power-to-methanol for 2022 scenario

LC phase	e-methanol from fossil CO2 (kgCO2eq.)	e-methanol from biogenic CO2 (kgCO2eq.)
CO2 capture	0,19	0,19
AEL electrolysis	0,53	0,53
MeOH synthesis	0,09	0,03
End of life	1,37	0,00
TOTAL	***2,18***	***0,75***
conventional %	*16,4 %*	*-60,0 %*

As we can see from the table, the power-to-methanol route using fossil CO_2 as a feedstock has higher emissions than compared to the power-to-methanol chain using biogenic CO_2. Also, the power-to-methanol using fossil CO_2 has higher life cycle emissions than conventional methanol manufactured from fossil fuels.

To calculate the 2035 scenario, the same calculations were performed again but by using an estimate for the grid electricity emission factor for 2035. The life cycle emissions for methanol produced from CO_2 for the 2035 scenario are presented in the table below.

Table 6. LCIA of power-to-methanol for 2035 scenario

LC phase	e-methanol from fossil CO2 (kgCO2eq.)	e-methanol from biogenic CO2 (kgCO2eq.)
CO2 capture	0,05	0,05
AEL electrolysis	0,12	0,12
MeOH synthesis	0,07	0,01
End of life	1,37	0,00
TOTAL	1,60	0,18
conventional %	*-14,2 %*	*-90,6 %*

As expected, the emissions are lower for the 2035 scenario. This time the e-methanol manufactured using fossil CO_2 has lower emissions than the conventional methanol and the e-methanol manufactured using biogenic CO_2 has over 90% lower emissions than the conventional route.

5.4.2. HDPE cradle-to-grave EF 2022 and 2035

Emissions were also calculated for the power-to-HDPE route similarly as for methanol both by using fossil and biogenic CO_2 feedstock and using 2022 and 2035 grid mix emission factors. The life cycle emissions for the 2022 scenario for this power-to-X route are presented in the table below.

Table 7. LCIA of power-to-HDPE for 2022 scenario

LC phase	HDPE from fossil CO2 (kgCO2eq.)	HDPE from biogenic CO2 (kgCO2eq.)
MTO	2,89	2,71
Polymerization	0,08	0,08
End of life	1,85	0,16
TOTAL	4,82	2,95
comparison to conventional %	*32,2 %*	*-19,1 %*

The results for power-to-HDPE chain are similar than for the power-to-methanol chain in the sense that HDPE from fossil CO_2 has a higher carbon footprint in the 2022 scenario than conventional HDPE production and production from biogenic CO_2 achieves greater reduction in emissions.

The life cycle emissions for power-to-HDPE using the estimated grid mix emissions factor for 2035 are presented in the table below.

Table 8. LCIA of power-to-HDPE for 2035 scenario

LC phase	HDPE from fossil CO2 (kgCO2eq.)	HDPE from biogenic CO2 (kgCO2eq.)
MTO	0,82	0,79
Polymerization	0,02	0,02
End of life	1,85	0,16
TOTAL	2,69	0,97
comparison to conventional %	*-26,3 %*	*-73,5 %*

The results for the 2035 scenario for HDPE are also as expected with the overall emissions being lower than in the 2022 scenario. These results also follow a similar pattern with the methanol case with both biogenic and fossil CO_2 achieving a reduction in carbon footprint compared to the conventional fossil production.

5.5. System expansion for power-to-methanol

The aforementioned process descriptions and LCIs represent a basic carbon footprint calculation that only takes into account the emissions within the system boundary. However, the defined system boundary leaves out a significant proportion of potential avoided emissions arising from replacing conventional production such as conventional fossil methanol production. The previous calculations don't also consider the multifunctionality of the whole power-to-X process chain nor the logic of "two products with one emission" which has been presented earlier on in this thesis. Since avoided emissions are a prominent reason for utilizing CO_2, the impact of replacing conventional production must be examined using system expansion.

System expansion is defined in the ILCD Handbook as "*Adding specific processes or products and the related life cycle inventories to the analysed system. Used to make several* *multifunctional systems with an only partly equivalent set of functions comparable within LCA."* For the purposes of this thesis, system expansion is used to consider the avoided emissions related to replacement of conventional production. The system expansion for methanol is illustrated below.

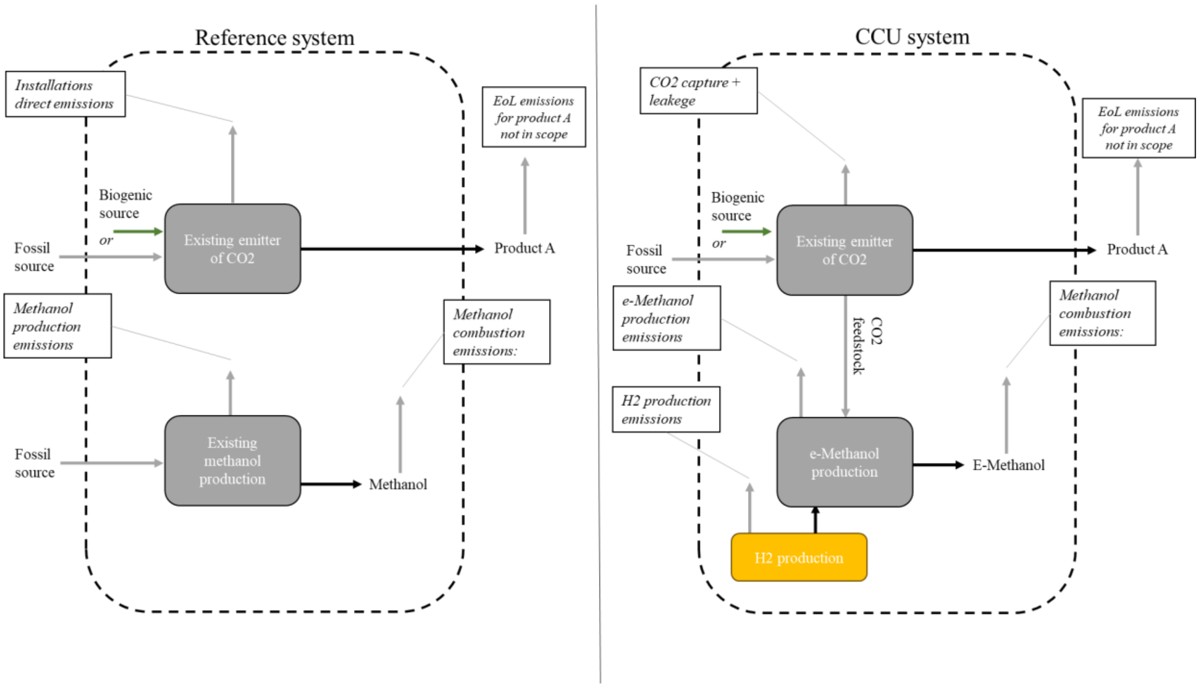

Figure 7. System expansion illustrated for power-to-methanol

5.5.1. LCI of system expansion for power-to-methanol

The data for the system expansion is the same as in the first iteration of calculations regarding processes that are included in both system boundaries. As for processes that are included only in the system expansion (direct emissions of "product A" production, conventional methanol production emissions, and conventional methanol combustion) new data is gathered.

The data for direct emissions of "product A" production was decided to be the scope 1 emissions of St1. Scope 1 emissions for St1 were 576 000 tons of CO_2 in 2022 (St1 Nordic, 2023, 12). The emissions for methanol production as well as methanol combustion were gathered from EU's defined values. These are presented in g/MJ but were converted to kgCO2/kgMeOH using methanol's defined lower heating value. Additionally, the rate of carbon capture from the production of product A was defined to be 90% as this was a realistic value based on the literature review of this thesis. The annual capacity of methanol production for both conventional and CCU cases were set to be the same in order for the two cases to be comparable. This value was calculated to being the amount of CCU-methanol that can be manufactured from the amount of CO_2 captured.

The conventional production case is relatively straightforward to quantify for the case of CCU from fossil CO_2, but for CCU from biogenic CO_2 the conventional production case is less clear. For the purposes of this thesis the conventional production for the case of biogenic CCU was determined to be the same as in fossil CCU case with the exception that the CO_2 emissions from the production of "product A" was assumed to be biogenic. This is because these emissions are the ones that are captured and made into a CCU product and thus the emissions should be biogenic when producing CCU from biogenic CO_2. The comparator of conventional production of methanol is the same in both the fossil CCU case and biogenic CCU case, so it is assumed that CCU methanol replaces conventional fossil methanol. Full LCIs for system expansions for methanol for both 2022 and 2035 scenarios are presented in the appendix I and in appendix II respectively.

5.5.2. LCIA of system expansion for power-to-methanol

The life cycle impact assessment for the reference scenario of power-to-methanol system expansion is presented below.

Table 9. LCIA of power-to-methanol's reference system for 2022 scenario

REFERENCE SCENARIO		
product A		
yearly CO2 emissions	***576 000 000***	***kgCO2***
CONVENTIONAL METHANOL		
Yearly MeOH production	378 394 161	kg
Yearly methanol production emissions	212 347 235	kgCO2
combustion emissions	518 820 018	kgCO2
total conventional MeOH	***731 167 253***	**kgCO2**
total emissions	***1 307 167 253***	***kgCO2***
total emissions if assumed bio	***731 167 253***	***kgCO2***

The life cycle impact assessment for the power-to-methanol system expansion using 2022 emission factors is presented below.

Table 10. LCIA of power-to-methanol system expansion for 2022 scenario

EMISSIONS			
CO2 capture	electricity input	2 385 000	kgCO2
	heat input	68 730 000	kgCO2
	CO2 not captured	57 600 000	kgCO2
	total	***128 715 000***	***kgCO2***
AEL	electricity input	199 392 819	kgCO2
	water input	24 171	kgCO2
	total	***199 416 990***	***kgCO2***
MeOH synthesis	electricity input	12 847 186	kgCO2
	CO2 not converted	20 736 000	kgCO2
	total	***33 583 186***	***kgCO2***
End-of-life	combustion emissions	518 820 018	kgCO2
	total	***518 820 018***	***kgCO2***
total emissions fossil CO2		**880 535 194**	**kgCO2**
total emissions in bio-CO2		**283 379 176**	**kgCO2**

Overall, the total emissions went down in the system expansion for both biogenic and fossil CO_2 feedstock compared to the reference scenario. When using fossil CO_2 to make methanol the overall system emissions went down -33%. When using biogenic $CO_{2,}$ the system emissions went down -61%.

As for the system expansion using the emissions factors for 2035 the emissions went down even more as could be expected. In the 2035 system expansion the overall emissions when using fossil CO_2 and biogenic CO_2 as a feedstock went down -54% and -95% respectively. The LCIA for the 2035 system expansion can be found in appendix III. A table gathering the results of the system expansions can be found below.

Table 11. Overview of the results for power-to-methanol system expansion

system expansion for power-to-MeOH		**FOSSIL CO2**	**BIOGENIC CO2**
2022	Absolute GHG emission avoidance (tCO2e)	-426 632 tCO2eq.	-447 788 tCO2eq.
	Emission reduction (%)	-33 %	-61 %
2035	Absolute GHG emission avoidance (tCO2e)	-701 661 tCO2eq.	-1 241 217 tCO2eq.
	Emission reduction (%)	-54 %	-95 %

5.6. System expansion for power-to-HDPE

The system expansion for HDPE plastic production from CO_2 was performed in similar fashion than the system expansion for power-to-methanol. The reference scenario was selected to be regular HDPE production. The system expansion is presented below in figure 8.

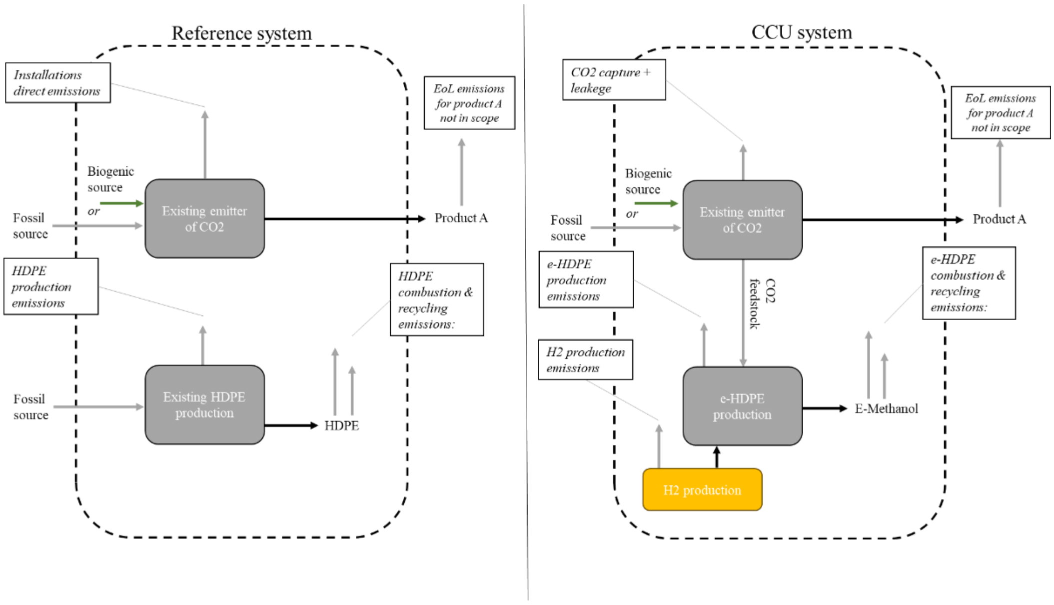

Figure 8. System expansion illustrated for power-to-HDPE

As for the power-to-methanol system expansion, the system expansion for power-to-HDPE was calculated using St1's annual reported scope 1 CO_2 emissions as a starting point and from there the amount of HDPE that could be produced was calculated. The full LCIs of HDPE's system expansion can be found in appendix IV for 2022 and in appendix V for 2035.

5.6.1. LCIA of power-to-HDPE system expansion

The LCIA of the reference system for system expansion of power-to-HDPE is presented in the table below.

Table 12. LCIA of power-to-HDPE's reference system for 2022 scenario

REFERENCE SCENARIO		
	value	unit
product A		
yearly CO2 emissions	576 000 000	$kgCO_2$

CONVENTIONAL HDPE		
Yearly HDPE production	68 291 726	kg
Yearly HDPE production emissions	122 925 106	$kgCO_2$
EoL emissions incineration	115 494 966	
EoL emissions recycling	10 865 214	$kgCO_2$
total conventional HDPE	**249 285 286**	**$kgCO_2$**
total emissions	**825 285 286**	**$kgCO_2$**
total emissions if assumed bio	**249 285 286**	**$kgCO_2$**

The emissions from the system expansion of HDPE plastic production from CO_2 can be seen in the LCIA in the table below.

Table 13. LCIA of power-to-methanol system expansion for 2022 scenario

EMISSIONS			
MTO	electricity input	4 041 804	$kgCO_2$
	heat input	36 044 003	$kgCO_2$
	fos CO_2 methanol's emissions	378 087 827	$kgCO_2$
	bio CO_2 methanol emission	283 149 763	$kgCO_2$
	total fossil	418 173 634	$kgCO_2$
	total after allocation fossil	**238 358 971**	**$kgCO_2$**
	total after allocation bio	**184 244 275**	**$kgCO_2$**
	CO_2 not captured	57 600 000	$kgCO_2$
polymerization	electricity input	1 775 585	$kgCO_2$
	heat input	3 956 367	$kgCO_2$
	total	**5 731 952**	**$kgCO_2$**
EoL	incinerated	115 494 966	
	recycled	10 865 214	$kgCO_2$
	total	**126 360 180**	**$kgCO_2$**
	total emissions fossil CO_2	**428 051 103**	**$kgCO_2$**
	total emissions bio CO_2	**240 927 248**	**$kgCO_2$**

Overall, the total emissions went down in the system expansion for both biogenic and fossil CO_2 feedstock compared to the reference scenario, but biogenic CO_2's emission avoidance was much lower. When using fossil CO_2 to produce HDPE the overall system emissions went down -48%. When using biogenic CO_2, the system emissions went down only -3%. In the 2035 scenario the emission avoidance was larger with fossil CO_2 utilization causing an emission avoidance of -51% and biogenic CO_2 utilization -24%. The LCIA of the system expansion for power-to-HDPE for the year 2035 can be found from appendix VI of this thesis. A table presenting the main results from the system expansions is presented below.

Table 14. Overview of the results for power-to-HDPE system expansion

system expansion for power-to-HDPE		FOSSIL CO_2	BIOGENIC CO_2
2022	Absolute GHGemission avoidance ($tCO_2eq.$)	-397 234	-8 358 038
	Emission reduction (%)	-48 %	-3 %
2035	Absolute GHG emission avoidance ($tCO_2eq.$)	-418 970 428	-60 568 193
	Emission reduction (%)	-51 %	-24 %

5.7. RED II delegated acts calculation for methanol

RFNBOs were introduced previously along with the relevant guidance on calculating their GHG emission reduction. The GHG emission reduction calculation methodology is presented in RED II’s delegated act on the subject which was presented and discussed in chapter 4. Calculation related to RFNBOs were performed for the power-to-methanol route. The calculations were performed according to the delegated act methodology and with the same data as in the cradle-to-grave methanol calculations. The exception from the cradle-to-grave calculations is the fact that the functional unit for RFNBO calculations is MJ not kg. LCIs for RFNBOs are similar than the LCI for the cradle-to-grave methanol. A table presenting full RFNBO calculation can be found from appendix VII of this thesis. RFNBO calculation results are presented in the next chapter.

6. Life cycle interpretation and comparison of different ways of quantifying emissions of CCU products

In this chapter, the results of the different ways of quantifying carbon footprint of CCU products are interpreted and calculation methodologies compared. The quantification methods are compared in consideration of how they can help or affect decision making.

6.1. Cradle-to-grave CCU pathways

The aim of the first set of calculations for power-to-methanol and power-to-HDPE was to examine the carbon footprint of both products using different feedstocks. The results of these could for instance help decide what is the best way of utilizing captured CO_2 from a climate point of view or to help decide on the CO_2 feedstock that would be the most beneficial to capture (biogenic or fossil). The carbon footprints for the different routes for the 2022 scenario are presented in the table below.

Table 14. Overview of the results of cradle-to-grave carbon footprint calculations for both CCU products

grid mix 2022	**power-to-MeOH**	**power-to-plastic (HDPE)**
fossil CO2	2.2 kgCO2eq.	4.8 kgCO2eq.
biogenic CO2	0.8 kgCO2eq.	3.0 kgCO2eq.

For the power-to-methanol chain the overall carbon footprints in relation to the fossil methanol comparator and are presented in graph below. The graph also presents the percentual decrease or increase in carbon footprint compared to the fossil methanol comparator.

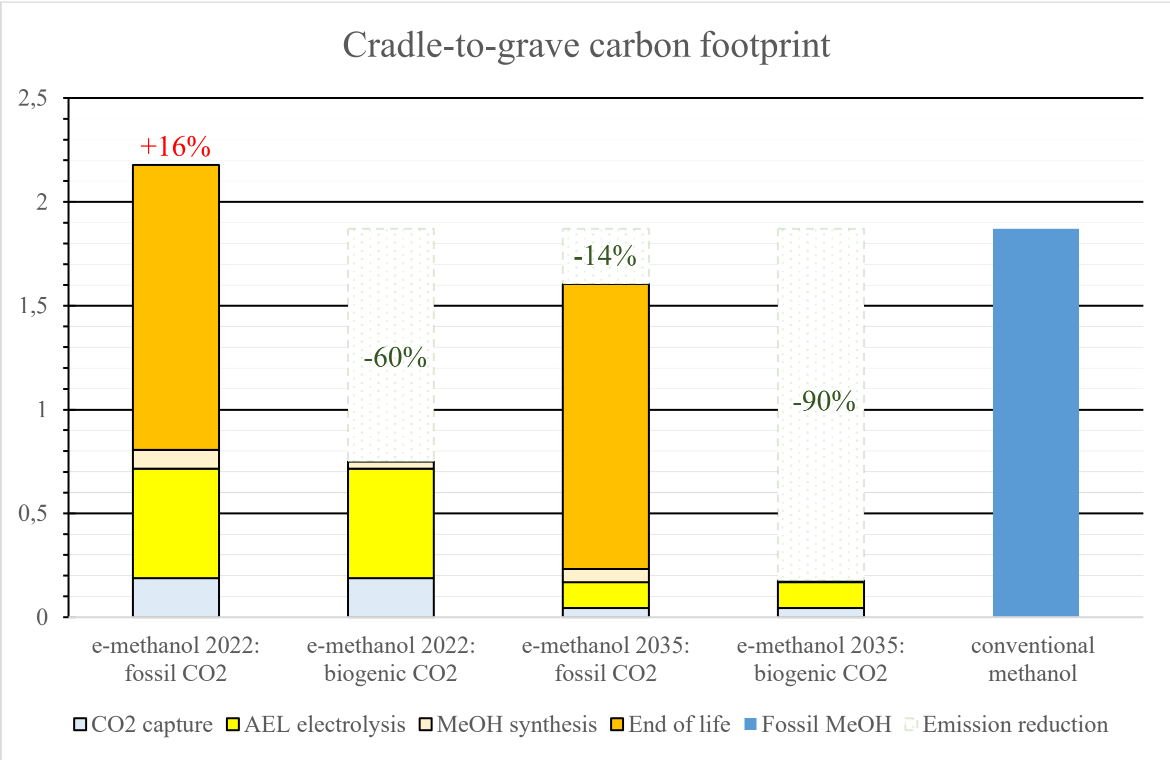

Figure 9. Overview of carbon footprint calculations for power-to-methanol

As we can see from the graph above, in the 2022 scenario the carbon footprint e-methanol utilizing fossil CO_2 is larger than that of the fossil methanol comparator. The carbon footprint for e-methanol utilizing biogenic CO_2 in the 2022 scenario is significantly lower than both fossil counterpart and the e-methanol manufactured from fossil CO_2. In the 2035 scenario, the carbon footprints for both e-methanol cases are lower. This is not unexpected since the emission factors for electricity and heat were significantly lower for the 2035 scenario and energy inputs have great impact on carbon footprint.

Largest contributors to the carbon footprint of e-methanol out of the different life cycle phases are electrolysis and the end-of-life (only for fossil CO_2 inputs). The main difference between the power-to-methanol route utilizing fossil CO_2 and biogenic CO_2 is that the release of CO_2 is regarded as zero for the case of biogenic CO_2 as was mentioned in chapter 2.1.1 and 3.2. Because of this, the end-of-life phase is zero for the biogenic CO_2. As for the fossil CO_2 we can see that the end-of-life phase is clearly the largest single contributor to the carbon footprint. If we were to omit the end-of-life from the carbon footprint calculations and define the system boundary as cradle-to-gate, the carbon footprint of the methanol utilizing fossil CO_2 would decrease significantly and the carbon footprint of the methanol utilizing biogenic CO_2 would stay the same. Hence, the carbon footprints would be around in the same proportions for both e-methanol pathways in cradle-to-gate approach.

As for power-to-HDPE route the carbon footprints followed a similar pattern than the methanol calculations, with carbon footprints for power-to-HDPE being lower than the conventional HDPE production in all other scenarios except the 2022 scenario utilizing fossil CO_2 as a feedstock. All the cradle-to-grave results for power-to-HDPE can be seen from the graph below.

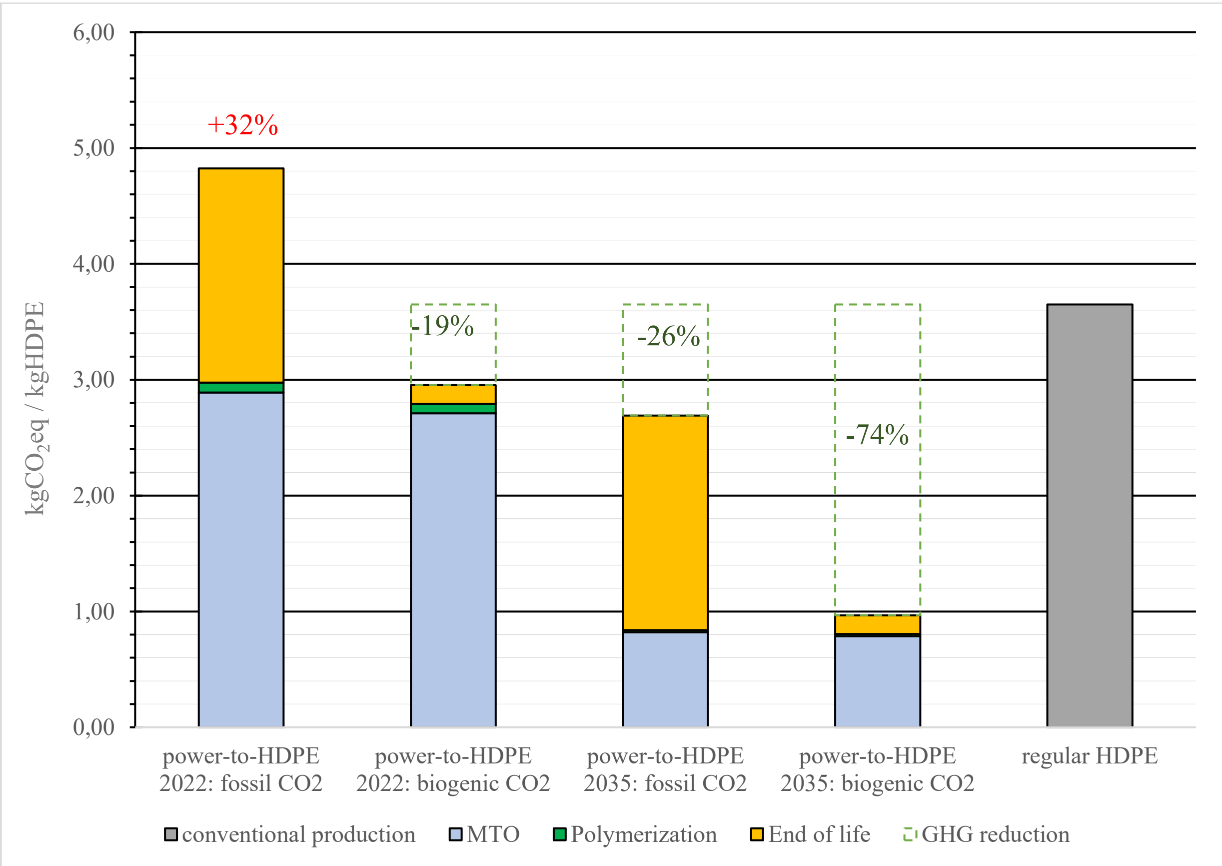

Figure 10. Overview of carbon footprint calculations for power-to-HDPE

As we can see from graph 10 the main contributors to the carbon footprint are the MTO synthesis and end-of-life (especially to the routes utilizing fossil feedstocks). MTO's large

GHG emissions however are mainly because the input of e-methanol is attributed to this particular phase, so the emissions of MTO also include the emissions of e-methanol production. End-of-life has a large contribution to the carbon footprint due to the emissions caused by the portion of HDPE assumed to be incinerated. Similarly, as for e-methanol the incineration of HDPE produced from biogenic CO_2 has significantly lower end-of-life phase since the output of CO_2 is regarded as being zero.

6.1.1. Retention time's influence

As was explained in chapter 2.1.4 the climate impact of the carbon's retention time in the CCU product is not entirely clear. The literature on the subject is somewhat divided and there is no consensus on an appropriate retention time of carbon that would provide climate benefits. There is also no legislation or policies that would determine any timelines or emission factors that would take in account the retention time of carbon. However, some emission factors have been calculated that consider the timeframe of emission release as was presented in chapter 2.1.4.

The retention time of carbon in the product provides any climate benefits only if the carbon is biogenic (or atmospheric) since only then the radiative forcing of the atmosphere is lowered for the duration of the carbon's retention time. (de Kleijne et al., 2022) (Ramirez Ramirez et al., 2020). If we assume that the HDPE plastic is used in buildings for instance as HDPE piping then the life expectancy of a HDPE pipe can be assumed to be 50 years, although the life expectancy can rise even up to 100+ years (Plastics Pipe Institute, 2009). If we compare these life expectancies to the table of dynamic emission factors presented in chapter 2.1.4. from de Kleijne et al. (2022) we can see that emissions are lowered drastically (de Kleijne et al., 2022). The dynamic emission factors and their corresponding results are presented in the table below.

Table 15. Examination of carbon retention time's effect on the carbon footprint for power-to-HDPE

GWPstorage-100 (time)	*Dynamic emission factor value (kgCO2eq.)*	*HDPE pipe from biogenic CO_2 case 2022*
0-6 months	1	2,95
0.5-1 year	0,99	2,92
1 year	0,98	2,89
5 years	0,92	2,72
10 years	0,85	2,51
25 years	0,67	1,98
50 years	0,42	1,24
100+ years	0	0,00

As mentioned in chapter 2.1.4, the use of dynamic emission factors is debated. ILCD Handbook also has mentions on the temporary carbon storage and advises against them unless it is "*explicitly required to meet the needs of the goal of the study*" because even though the emissions are delayed, they have still the emissions equivalent full radiative forcing. The dynamic emission factors are after all based more on the logic of how the widely used GWP 100-year emission factors work, rather than any natural science-based research on temporary carbon storage. (European Commission: Joint Research Centre, 2010, 226-227).

From a decision-making perspective it could be beneficial in some cases to examine temporary carbon storage. However, the question is rather would it be correct or trustworthy as there is a lot of uncertainty. Also, using dynamic emission factors could make the calculations seem void as there is no clear guidance in relevant LCA and carbon footprint guidelines that they should be used.

6.1.2. System boundary's influence on results

ISO standards recommend using cradle-to-grave system boundary unless the omission of life cycle emissions beyond factory gates can be well justified. (ISO 14040:2006, 19) However, Langhorst et al. (2022) somewhat defers from this recommendation in their report on

"*Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO_2 Utilization (Version 2)*" as does the related article by Müller et al. (2020) by explaining that omittance is justified "*in situations where technical performance and, thus, downstream emissions are identical, a cradle-to-gate approach, in particular for comparative studies, is sufficient*" (Müller, Kätelhön, Bachmann et al., 2020) (Langhorst et al., 2022). This of course has major implications to the results of the LCA, and as was mentioned in chapter 3.3 the viewpoint is not entirely agreed upon.

If we were to omit the end-of-life from the cradle-to-grave calculations and redefine the system boundary to only cradle-to-gate the results would be drastically altered. Albeit omittance would not be entirely justified neither from the ISO standards viewpoint nor from the Langhorst et al. (2022) viewpoint since the function of the calculations is not entirely of comparative nature to the fossil counterpart. The results for methanol from cradle-to-gate can be seen below.

Table 15. Examination of carbon footprint for power-to-methanol with a cradle-to-gate system boundary with end-of-life omitted

2022			
	e-methanol from fossil CO_2 (kgCO_2eq.)	**e-methanol from biogenic CO_2 (kgCO_2eq.)**	**regular methanol RED2 (kgCO_2eq.)**
TOTAL	0,81	0,75	0,56
conventional %	+44 %	+33 %	-
2035			
TOTAL	0,23	0,18	0,56
conventional %	-58 %	-69 %	-

From a decision-making perspective this system boundary is not without its problems. The redefinition of system boundary can cause major changes in interpretation of results. As we can see from the table above, the results are changed due to the omission of end-of-life at least for the fossil CO_2 emitting cases. When interpreting the table above, one could assume that the carbon footprint of e-methanol utilizing fossil CO_2 as a feedstock would be somewhat similar with the one utilizing biogenic CO_2 however as we can see from previously introduced cradle-to-grave results, the carbon footprint for fossil CO_2 case is much greater the biogenic CO_2 case because of the large end-of-life emission that are accounted only for fossil CO_2. Also, based on the results above the production of conventional fossil methanol seems much more favorable. This could lead to an assumption that power-to-X increases emissions, and even increase the quite drastically regardless of the CO_2 feedstock.

6.2. System expansion

Earlier in this thesis it has been addressed that a significant hurdle when assessing environmental impacts of CCU products is the problem of multifunctionality. Multifunctionality was not addressed in the cradle-to-grave calculations, and the results differ somewhat from the results of the system expansion. System expansion is a way of dealing with the problem by eliminating the need to calculate separate impact to the CCU product but rather by calculating the impact of the entire system.

System expansion was performed on both power-to-methanol route and power-to-HDPE route in two scenarios, 2022 and 2035. For methanol, the overall emissions of the entire system expansion decreased in all cases on both fossil and biogenic CO_2 feedstocks and for both the 2022 and 2035 scenarios. These results can be seen in table 11. The system expansion for the 2022 scenario using fossil CO_2 as a feedstock is presented below in a graph form.

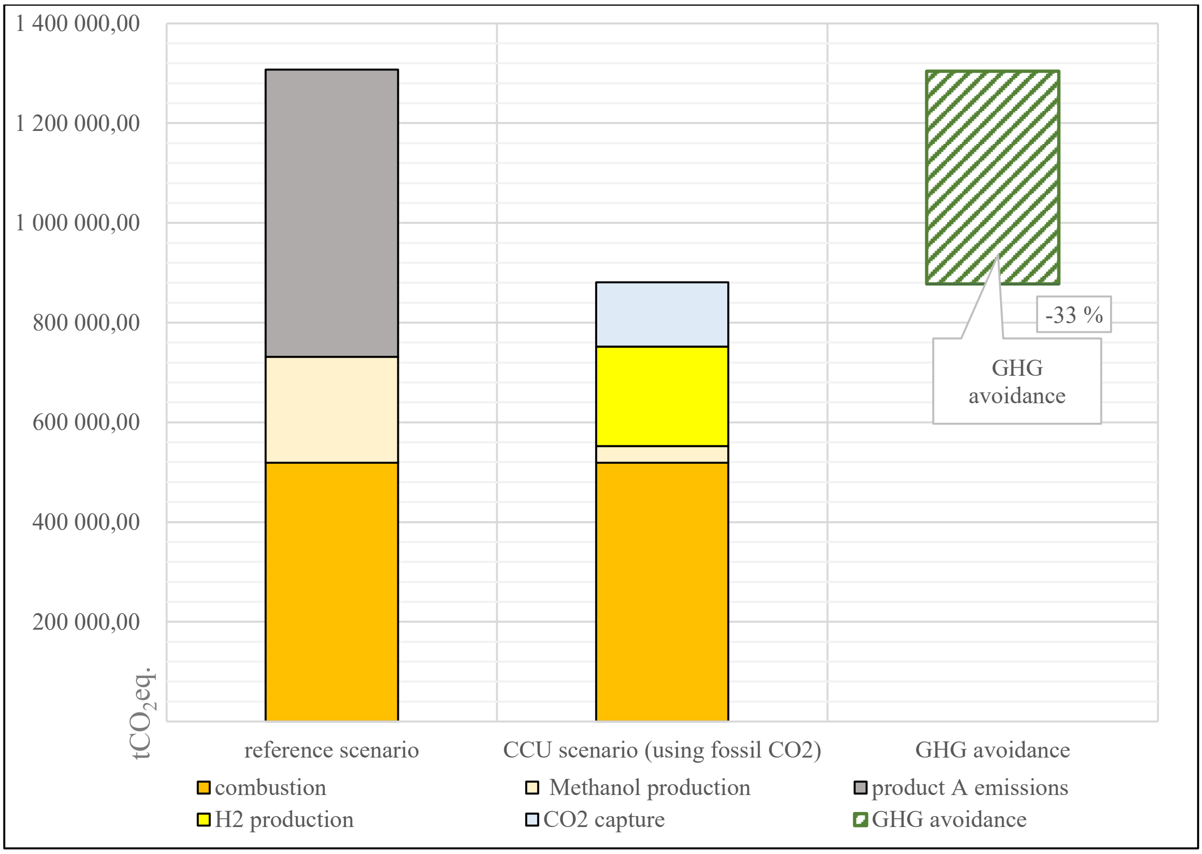

Figure 11. GHG avoidance from system expansion for power-to-methanol from fossil CO_2

As we can see from the graph above, the decrease in emissions is quite significant in the case that had the highest cradle-to-grave carbon footprint. Even though the 2022 scenario for power-to-methanol using fossil feedstock had a larger carbon footprint than regular fossil methanol, the overall system emissions are lower if we consider the avoided emissions. The avoided emissions arise from the "two products with one emission" principle that has been previously introduced in chapter 2. The emission avoidances for all system expansion cases conducted for the power-to-methanol route can be seen in the graph below.

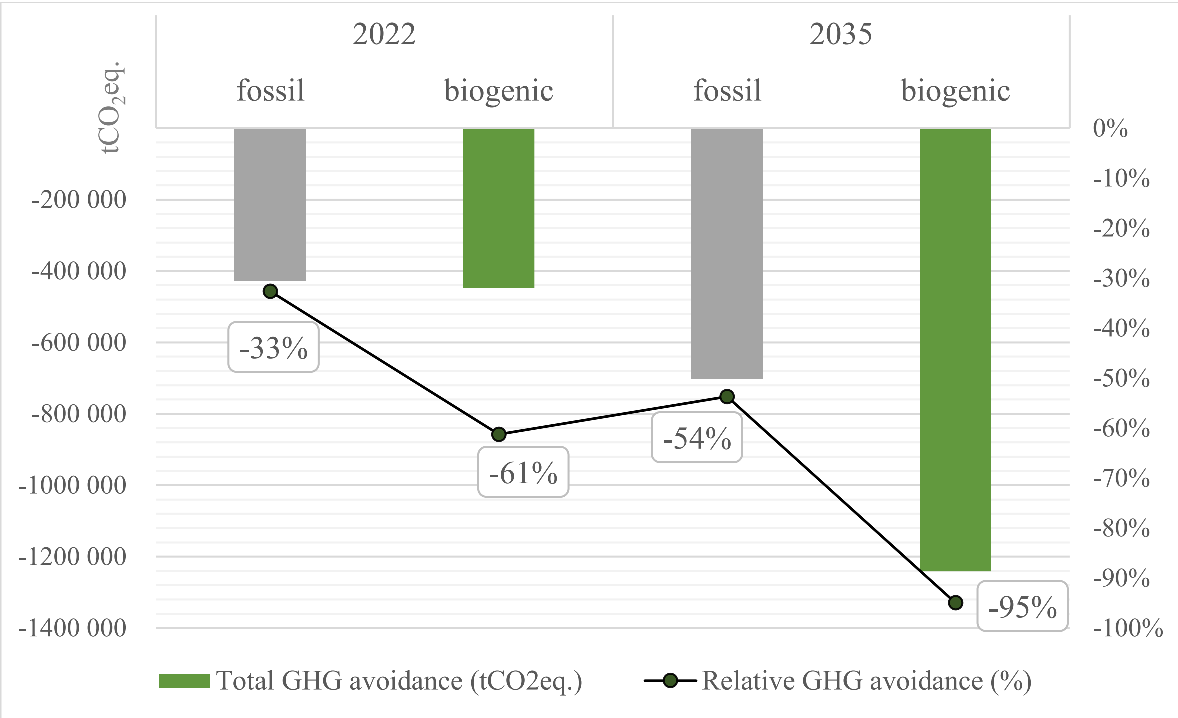

Figure 12. GHG avoidances for all system expansion for power-to-methanol

It is quite clear from the system expansion results that adding a system expansion to carbon footprint calculation for CCU products would be quite beneficial from a decision-making point of view. This is because the system expansion can provide information on the avoided emissions and the overall decrease in wider scale GHG emission balance. The system expansion also solves the problem of multifunctionality without the need of allocating emissions or crediting avoidances to only one specific product system which in turn can also distort the results and affect decision-making.

The results for system expansion for HDPE followed a similar patter to power-to-methanol system expansion with GHG avoidance getting greater in the 2035 scenario and with even HDPE produced in 2022 from fossil CO_2 turning out to provide avoided emissions even though the cradle-to-grave carbon footprint was larger than the conventional production. Results for the system expansion of HDPE production from CO_2 can be seen in the graph below.

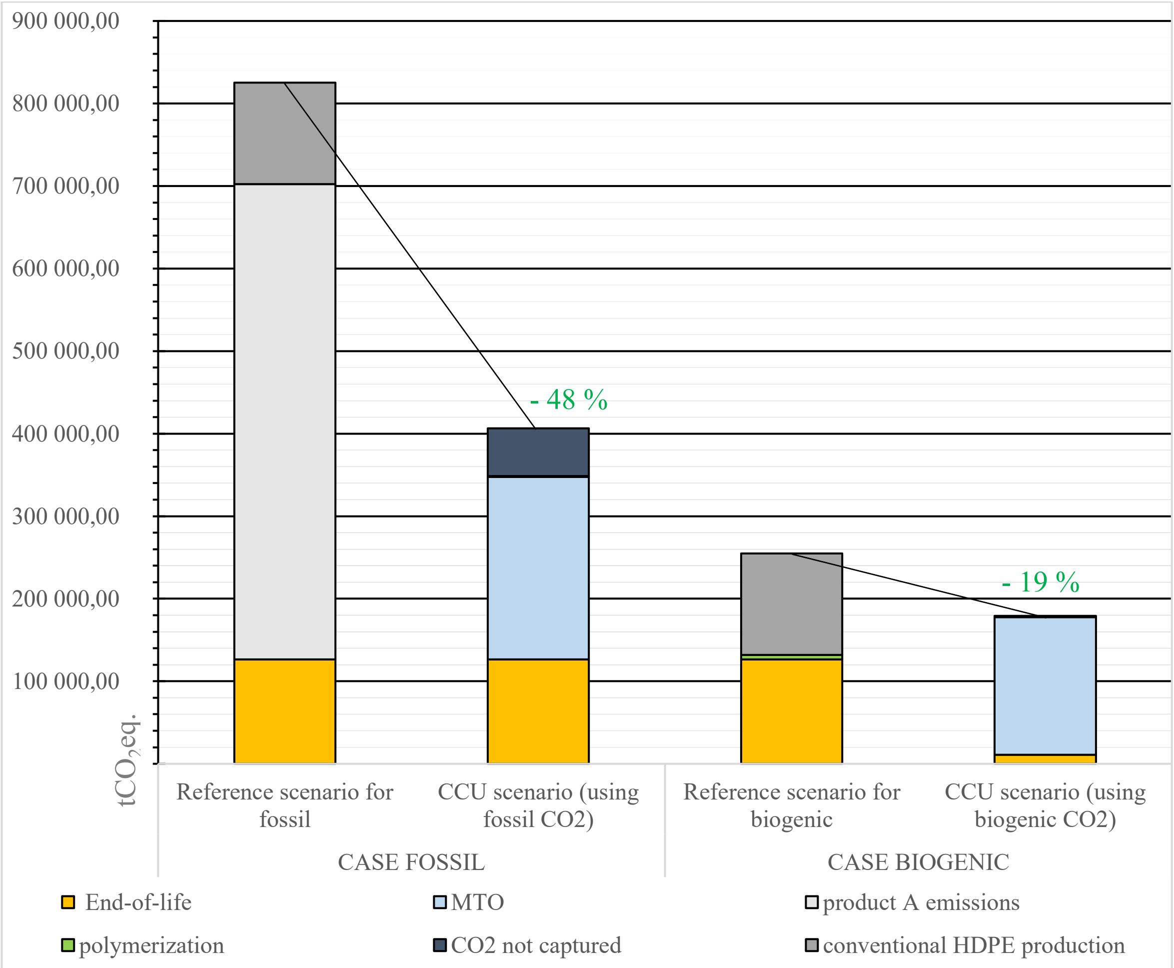

Figure 13. Overview of the results for power-to-HDPE system expansions

Perhaps the most interesting result from the power-to-HDPE system expansion is that power-to-HDPE from biogenic CO_2 in 2022 provided less GHG emission reduction than HDPE produced from fossil CO_2. This is an interesting result given that the cradle-to-grave carbon footprint of the biogenic case was less than for fossil case. This seemingly illogical result is due to the fact that in order to provide an accurate reference, the existing emitter in the reference system for both e-methanol and e-HDPE produced from biogenic CO_2 was selected to emit only biogenic CO_2 which than in the CCU system would be captured. Since biogenic CO_2 is calculated as being zero value, the emission avoidance from redirecting otherwise emitted biogenic CO_2 emissions to a CCU system is not as visible in the numbers as is in the fossil CO_2 cases. As we can see from the graph above, the percentual avoided emissions can be considered rather calculative since the emissions from the biogenic systems are much lower due to the zero-value biogenic CO_2.

This however proves a consideration in system expansion and calculation of avoided emissions, in the selection of reference system. It would seem that calculating emission avoidance for CCU systems utilizing biogenic CO_2 can be trickier since the original emissions that would be captured are zero-value and thus utilizing them doesn't really show in the results. However, the calculations in this thesis only considered climate change impacts (GWP) and other impact categories could help in distinguishing clearer environmental benefits between the two systems.

System expansion is not without its limitations, one being related to assumptions on the reference system's emissions in the future. It can be assumed that installations producing fossil CO_2 will over time become rarer and thus the reference system's emissions are harder to assume in the future than in the current moment where there is an abundance of fossil CO_2 sources to be replaced. (de Kleijne et al., 2022). Time considerations could be very relevant for CCU emission calculations from a decision-making point of view. For instance, in the Innovation Fund calculation methodology, the avoided emissions are calculated for a certain period (10 years in Innovation Fund) which provides more information on the system's impact over time (European Commission, 2023a). Added uncertainty related to the selection of reference system is caused by the fact that many CCU technologies are at a low TRL and comparing them to today's established technologies run the risk of distorting the results. (Ramirez Ramirez et al., 2020).

6.3. RFNBO and "ex-use"

As has been previously established in chapter 3.1.3, RFNBOs have major exemptions and added incentives in EU legislation. RFNBOs also have quite strict qualifications and calculation guidelines. In order to reach the required emission reduction for RFNBO qualification must the calculations de facto be eligible for the so-called "ex-use" variable of the RFNBO delegated acts. Eligible production chains include utilization of biogenic CO_2 but also utilization of fossil CO_2 until 2035 or 2040 at the latest. Results for the RFNBO calculations are presented in the graph below.

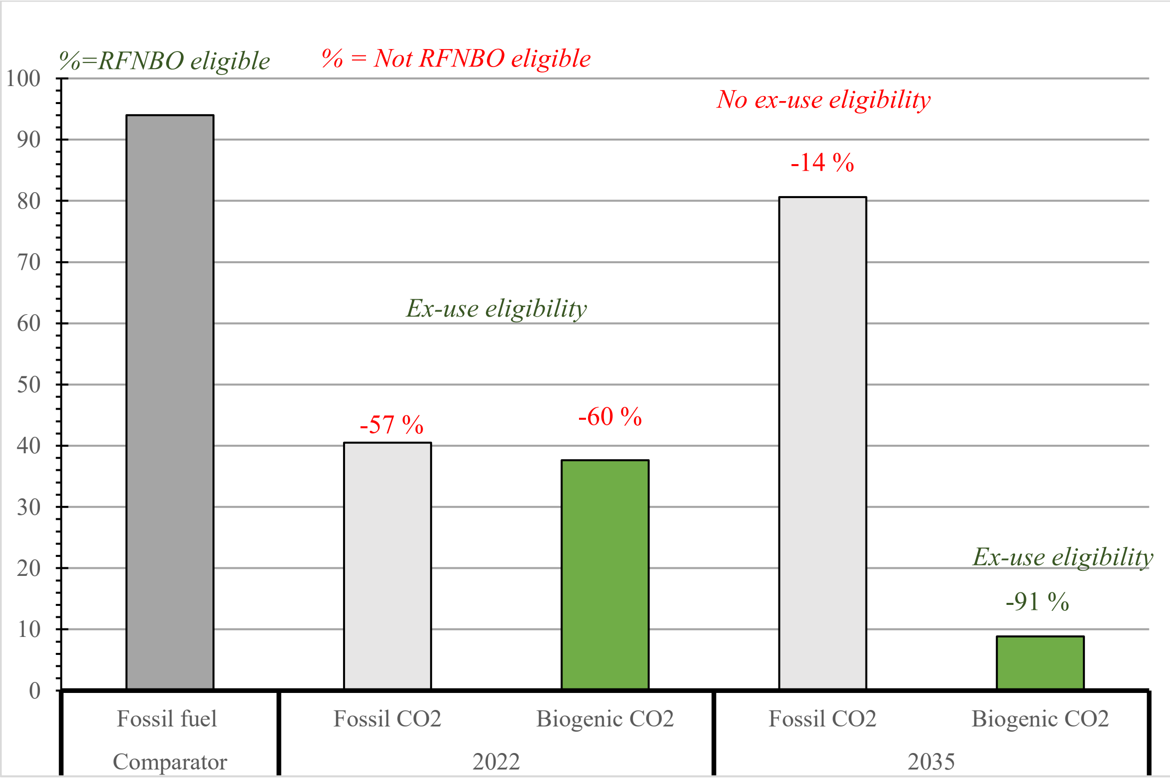

Figure 14. Overview of the results for RFNBO methodology calculations

As we can see from the graph above the emission reduction requirement for RFNBO eligibility is very hard to reach with fossil CO_2 even with the ex-use variable eligibility however perhaps not impossible. With fossil CO_2 and without eligibility for the ex-use variable, the -70 % emission reduction is impossible to reach. Utilizing biogenic CO_2 for RFNBOs makes the emission reduction target easier to reach because end-of-life combustion emissions are calculated as zero-value. However, even though utilizing biogenic CO_2 allows for the ex-use variable, the existing use of biogenic CO_2 is also considered zero-value. The RFNBO calculations for biogenic CO_2 in 2022 are not RFNBO eligible because the emission factor for energy use in 2022 is large enough so that the -70 % is out of reach and even though the ex-use variable is eligible to be used, the ex-use values are zero, so it does not show in the carbon footprint. The emission factor for 2035 is lower and because of that the CCU-methanol utilizing biogenic CO_2 is RFNBO eligible.

6.4. Comparing different ways of quantifying CCU's climate impacts

Carbon footprint calculations should always be conducted for the specific context that they are used in. For example, RFNBO calculations do not necessarily provide an accurate picture on the environmental impacts of the fuel, since the methodology is only designed for legislative purposes. If calculations are used in a decision-making context, the methodological choices of the calculation should suit the decision-making.

From a decision-making perspective the omission of any life cycle step could lead to misleading results. Omittance of end-of-life on the assumption that the emissions are the same for both the CCU and conventional scenarios can be very misleading as was discussed earlier. Results can become also even more misleading if the utilized CO_2 is treated as a "*consumed CO_2*" which means that the CO_2 captured and utilized in the product is accounted as being negative until the eventual carbon emission at the end-of-life. In CCU the CO_2 is a feedstock (until its eventual release to the atmosphere) and should be treated in LCA and carbon footprint calculations like any other feedstock in order to maintain realistic results. (Müller, Kätelhön, Bachmann et al., 2020).

Conducting a system expansion seems to be important on CCU products, since the avoided emissions play a big role in accounting of the climate impacts. From a decision-making perspective it would be imperative to know the potential emission reductions on a wider scale than just the cradle-to-grave boundary. For instance, when looking at only the cradle-to-grave results for e-methanol in 2022 one could conclude that the technology in question increases emissions when in reality it could help avoid emissions elsewhere. This problem of multifunctionality can be solved by system expansion as was done in this thesis, but one way could also be to opt for a consequential LCA study instead of attributional as was discussed in chapter 3.3. CLCA is also recommended by for instance Ramirez Ramirez et al. (2020) especially for decision making since its results clearly show the impacts of decisions. (Ramirez Ramirez et al., 2020, 45).

The selection of the reference system plays a large role in emission avoidance calculations and much care and consideration should be used in determining the reference system as it is not always straightforward. The selection of the reference system has great impact on the emission avoidance calculations. If we consider the reference system in the calculations of this thesis for instance the emission source (existing emitter of CO_2) from which the CO_2 is captured was not defined. This choice was made because the accuracy of the system expansion was deemed to be sufficient on a quite low data completeness. However, the choice of the source of CO_2 could alter the results for instance due to the fact that not all flue gases are equally easy to achieve carbon capture in, as was mentioned in the literature part of this thesis. Large emission reduction potential can seem positive but can also only be a result of an over-estimation of the reference system's emissions.

6.5. Discussion

When thinking from a sort of deterministic climate point of view one could argue that it does not matter if the utilized CO_2 is biogenic or fossil because the emission was anyways being released to the atmosphere before being captured. The main advantage of CCU is after all the emissions that it helps to avoid in replacing regular fossil fuel use (and extraction). Since the CO_2 used to manufacture power-to-X products was otherwise destined to become a carbon emission before it was captured it could be clearer to just account the emissions that are captured to the original emitter of CO_2 and consider the CCU-products' eventual carbon release as zero-value. It could also be argued that even if the CO_2 is of biogenic origin, it actually comes from the technosphere (i.e. a power plant or some other installation) and is a consequence of human actions. Especially in cases where the flue gas contains both fossil and biogenic CO_2 that are captured it would seem irregular to separate these according to some mass allocations when they are derived from the same system and are captured by the same system. At the moment, EU law especially RED II delegated acts opt utilizing biogenic CO_2 with the end-date for fossil CO_2 use. This can be understood from a viewpoint that fossil CO_2 shouldn't be encouraged. However, the EU already has regulation such as the ETS to ensure that such activities are becoming more challenging anyways. It would seem sensible to encourage fossil CO_2 emitting facilities to capture their emissions and put that carbon to use or rather just have policies incentivizing carbon capture wherever it would be the most efficient and feasible.

The assumption that the new carbon dioxide-based product will replace existing conventional fossil-based products may not always be entirely correct. This assumption is seemingly logical but may not be the case in real life when major variables like price and availability are considered. In reality the replaced product may be hard to define. The replaced product for instance in the case of e-methanol could be some other alternative fuel which would change the reference system and thus the emission reduction calculations.

One of the main considerations for the future is how should CO_2 be treated or considered as and whether it is an emission, waste or should it be considered as a material that should be in circulation such as plastics, metals, or other materials. This thesis did not consider policies and legislation on waste and circular economy due to recommendations by an expert to leave it out because of the vast size and complexity of EU law regarding the topic but this is one key element of CCU related policy context. Especially when considering CCU products that are not fuels (e.g., plastics) and thus are not covered by energy legislation, the waste status is an important and rather open questions at least from the point of view of this thesis.

Argument could be made that the EU is more prepared for CCS than CCU, for example with its own CCS directive. CCU and power-to-X should not be considered as any type of carbon removal or carbon sequestration. Current emission trends and accelerating climate change undeniably requires carbon removal, but future emissions will still be emitted due to societies being dependent on certain materials and GHG emitting installations having locked-in emissions. These emissions could be captured, and important materials manufactured from the captured carbon emissions. Maybe the current viewpoint of CCU as an emission reduction technology and subsequent comparisons to CCS regarding the carbon balance of these two methods (as was illustrated in figure 1 in the introduction of this thesis) is ill-advised. CCU should be perhaps viewed as a way of achieving circular economy and cutting societies loose of fossil fuel dependency.

Further research topics are abundant in the field of CCU with the context around the technologies quickly evolving. Major uncertainties are related to timeframes of CCU's carbon retention. Thorough natural science and atmospheric science-based answers related to questions on the potential benefits of temporary carbon storage are perhaps needed in order to fully determine any methodologies on quantification of temporary carbon storage. From the methodological side more development could also be needed in regard to the methodology of consequential LCA, which may be a better fit in quantifying CCU product systems' impacts than the more commonly used attributional LCA (Ekvall, 2019). Circular economy point of view could also provide interesting research topics for instance examining material flows and requirements and creating a road map for the future of circular carbon in the EU or in Finland. Also, other impact categories than just GWP should be considered for CCU specific LCA modelling. Studies could also be done comparing CCU fuels from biogenic CO_2 to biofuels and examine their impacts to species extinction, land use and land use change. Research could also be done to map out CCUS systems' risks of carbon lock-in and risks of locked future emissions.

7. Conclusions

This thesis was assigned by St1 Oy as a part of a wider co-operation project with two other companies Metsä Group and AFRY who also appointed a thesis worker to examine CCU topics from different angles. This thesis covers CCU from a climate and carbon footprint angle. The two other theses cover the subject from a legislative (Wallén 2024) and from a business value (Tognetty 2023) angle. The findings of all theses were presented together at a seminar that had attendees from many relevant fields and organizations.

The main objective of this thesis was to compare different methods for quantifying the carbon footprint of power-to-X products via carbon capture and utilization (CCU). The thesis also aimed to examine the impact and difference of using fossil or biogenic CO_2 as a feedstock for CCU products. The literature part of this thesis examined CCU technologies' climate impacts, current policy context of CCU within the EU as well as power-to-X technologies and processes. Carbon footprint and other relevant emission calculations were conducted for two selected CCU products: methanol and high-density polyethylene (HDPE) plastic. The methods and the results of the calculations were then compared, interpreted and discussed in relation to the current literature, policy framework, and climate context of CCU.

Multiple variables define the overall emissions of a CCU technology. High energy demand is one of the most prominent issues related to CCU and power-to-X. Other variables affecting CCU's GHG emissions are the source of captured carbon, scalability of the technology, retention time of carbon in the product as well as the conventional product that the CCU product is replacing. The overall carbon balance is heavily related to the source of the energy. When CCU products are manufactured with renewable energy they provide a means of reducing emissions as well avoiding emissions that would've otherwise been emitted.

Legislation and policy landscape of CCU can be considered somewhat incomplete. EU's overall stance on the role of CCU in achieving carbon neutrality is not clear and policies reflect that. Some incentives exist in policies arising from for example RFNBO legislations, but all in all the policy field around CCU is fragmented. The ETS does not take in account emissions avoided using CCU, and installations must surrender emission allowances even for the emissions that are captured and utilized. Exemptions from having to surrender ETS allowances are given to CCS.

Power-to-X covers numerous different production chains that include many lifecycle steps and different production processes. Usual production chains include carbon capture, water electrolysis and different conversion processes to manufacture chemicals and materials from hydrogen and the captured CO_2. Different power-to-X processes are on varying technological readiness level. Methanol can be produced from CO_2 in a power-to-methanol production chain that includes carbon capture, water electrolysis to produce H_2 and methanol synthesis by for example CO_2 hydrogenation. This technology is on a high technological readiness level. Plastic can also be produced from CO_2 via methanol by a methanol-to-olefins process and polymerization.

This thesis' GHG emission calculations for CCU systems examined two different products manufactured from CO_2; methanol and HDPE plastic. Different calculations were done for the two products, including cradle-to-grave carbon footprint calculations and system expansions. All calculations were performed both by utilizing fossil CO_2 and biogenic CO_2. The cradle-to-grave carbon footprints using emission factors from 2022 were larger for both methanol and HDPE than the conventional fossil comparator in the case of utilizing fossil CO_2. When utilizing biogenic CO_2, the carbon footprints were lower than the conventional production in the 2022 case. When using estimated emission factors for 2035 the carbon footprints decreased significantly for both methanol and HDPE and for both utilizing fossil and biogenic CO_2. In the system expansions for HDPE and methanol all of the cases achieved avoided emissions by both utilizing fossil and biogenic CO_2 and in both the 2022 and 2035 scenarios.

Power-to-X systems producing CCU products are always multifunctional with the installation that the CO_2 is captured from producing one product and the synthesis processes converting the CO_2 to another product. To provide an accurate representation of total emissions into the environment, this multifunctionality should be taken into account when assessing emissions or other environmental impacts of CCU. One way of assessing the total impact is by conducting a system expansion, in which both the total emissions of the whole reference system (i.e. the system before CCU) and the total emissions of the CCU system are calculated and compared. The difference in emissions of the two systems are the avoided emissions.

CCU can help in achieving carbon neutrality, by offering a pathway to decouple from fossil fuels while mitigating emissions. It could however be even more beneficial to consider CCU as a circular economy technology rather than emission reduction technology. The primary benefit of CCU arises from avoiding emissions by substituting regular fossil fuel use and in that sense the distinction between biogenic and fossil CO_2 in CCU may be negligible. Regarding future policies, defining CO_2 entering CCU as either an emission, feedstock, or circulating material is crucial, especially for CCU products beyond fuels. Future research should address uncertainties in timeframes and methodologies for quantifying temporary carbon storage, including advancements in consequential LCA and exploring alternative impact categories beyond GWP. Additionally, studying the risks associated with carbon lock-in and future emissions are crucial areas for further investigation. Interesting avenues for research could also be explored in comparing CCU fuels from biogenic CO_2 to biofuels and in creating roadmaps for circular carbon.

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Appendix I. Full LCI of power-to-methanol system expansion for 2022 scenario

LCI			
CO_2 capture	electricity input	143 100 000	MJ
	heat input	1 566 000 000	MJ
	CO_2 captured	518 400 000	kg
AEL	electricity input	11 963 569 154	MJ
	water input	690 594 547	kg
	O_2	568 720 776	kg
	required H_2 output	71 894 891	kg
	heat	71 894 891	MJ
MeOH synthesis	electricity input	770 831 186	MJ
	CO_2 required	518 400 000	kg
	H_2 required	71 894 891	kg
	heat output	662 189 781	MJ
	CO_2 not converted	20 736 000	kg
	water	211 900 730	kg
	Methanol	378 394 161	kg
End-of-life	Methanol	378 394 161	kg
	combustion emissions	518 820 018	kg

Appendix II. Full LCI of power-to-methanol system expansion for 2035 scenario

LCI			
CO2 capture	electricity input	137 376 000,00	MJ
	heat input	1 503 360 000,00	MJ
	CO2 captured	518 400 000,00	kg
AEL	electricity input	11 963 569 153,79	MJ
	water input	690 594 546,90	kg
	O2	568 720 775,68	kg
	required H2 output	71 894 890,51	kg
	heat	5 651 370 665,89	MJ
MeOH synthesis	electricity input	770 831 186,34	MJ
	CO2 required	518 400 000,00	kg
	H2 required	71 894 890,51	kg
	heat output	662 189 781,02	MJ
	CO2 not converted	20 736 000,00	kg
	water	211 900 729,93	kg
	Methanol	378 394 160,58	kg
End-of-life	Methanol	378 394 160,58	kg
	combustion emissions	518 820 017,52	kg

Appendix III. Full LCIA of power-to-MeOH system expansion for 2035 scenario

EMISSIONS			
CO2 capture	electricity input	534 240,00	kgCO2
	heat input	15 868 800,00	kgCO2
	total	***16 403 040,00***	***kgCO2***
AEL	electricity input	46 524 991,15	kgCO2
	water input	24 170,81	kgCO2
	total	***46 549 161,96***	***kgCO2***
MeOH synthesis	electricity input	2 997 676,84	kgCO2
	CO2 not converted	20 736 000,00	kgCO2
	total	***23 733 676,84***	***kgCO2***
End-of-life	combustion emissions	518 820 017,52	kgCO2
	total	***518 820 017,52***	***kgCO2***
	total emissions fossil CO2	**605 505 896,32**	**kgCO2**
	total emissions bio CO2	**65 949 878,80**	**kgCO2**

Appendix IV. Full LCI of power-to-HDPE system expansion for 2022 scenario

LCI			
MTO	electricity input	242 508 254	MJ
	heat input	821 255 760	MJ
	input bioco2 methanol emissions	283 149 763	kgCO2
	input methanol's emissions	378 087 827	kgCO2
allocation	away	43 %	%
	to system	57 %	%
polymerization	electricity	106 535 092	MJ
	heat	90 145 078	MJ
	ethylene	69 316 102	kg
	butene	1 077 550	kg
EoL	incinirated	115 494 966	kgCO2
	recycled	10 865 214	kgCO2

Appendix V. Full LCI of power-to-HDPE system expansion for 2035 scenario

LCI			
MTO	electricity input	242 508 254	MJ
	heat input	821 255 760	MJ
	input bioco2 methanol emissions	283 149 763	kgCO2
	input methanol's emissions	378 087 827	kgCO2
allocation	away	43 %	%
	to system	57 %	%
polymerization	electricity	106 535 092	MJ
	heat	90 145 078	MJ
	ethylene	69 316 102	kg
	butene	1 077 550	kg
EoL	incinirated	115 494 966	kgCO2
	recycled	10 865 214	kgCO2

Appendix VI. Full LCIA of power-to-HDPE system expansion 2035

EMISSIONS			
	electricity input	943 088	kgCO2
	heat input	8 668 811	kgCO2
	fos co2 methanol's emissions	378 087 827	kgCO2
	bio co2' methanol emission	283 149 763	kgCO2
	total fossil	*387 699 725*	*kgCO2*
	total after allocation fossil	***220 988 843***	***kgCO2***
	total after allocation bio	***166 874 147***	***kgCO2***
	co2 not captured	***57 600 000***	***kgCO2***
polymerization	electricity input	414 303	kgCO2
	heat input	951 531	kgCO2
	total	***1 365 835***	***kgCO2***
	incinirated	115 494 966	
	recycled	10 865 214	kgCO2
	total	***126 360 180***	***kgCO2***
	total emissions fossil CO2	**406 314 858**	**kgCO2**
	total emissions bio CO2	**179 105 195**	**kgCO2**

Appendix. VII. Full LCI for RFNBO calculations

	2022					2035			
	FOSSIL CO2		***BIO CO2***			***FOSSIL CO2***		***BIO CO2***	
	GWP emission (gCO2eq.)					GWP emission (gCO2eq.)			
electricity	0,317	gCO2eq.	0,317	gCO2eq.	electricity	0,074	gCO2eq.	0,074	gCO2eq.
heat	9,127	gCO2eq.	9,127	gCO2eq.	heat	2,195	gCO2eq.	2,195	gCO2eq.
Required CO2 output	0,000	gCO2eq.	0,000	gCO2eq.	Required CO	0,000	gCO2eq.	0,000	gCO2eq.
electricity	26,480	gCO2eq.	26,480	gCO2eq.	electricity	6,179	gCO2eq.	6,179	gCO2eq.
water input	0,003	gCO2eq.	0,003	gCO2eq.	water input	0,003	gCO2eq.	0,003	gCO2eq.
O2	0,000	gCO2eq.	0,000	gCO2eq.	O2	0,000	gCO2eq.	0,000	gCO2eq.
required H2 output	0,000	gCO2eq.	0,000	gCO2eq.	required H2 o	0,000	gCO2eq.	0,000	gCO2eq.
heat	0,000	gCO2eq.	0,000	gCO2eq.	heat	0,000	gCO2eq.	0,000	gCO2eq.
electricity	1,706	gCO2eq.	1,706	gCO2eq.	electricity	0,398	gCO2eq.	0,398	gCO2eq.
CO2 required	0,000	gCO2eq.	0,000	gCO2eq.	CO2 required	0,000	gCO2eq.	0,000	gCO2eq.
H2 required	0,000	gCO2eq.	0,000	gCO2eq.	H2 required	0,000	gCO2eq.	0,000	gCO2eq.
heat	0,000	gCO2eq.	0,000	gCO2eq.	heat	0,000	gCO2eq.	0,000	gCO2eq.
CO2 not converted	2,86851	gCO2eq.	0,000	gCO2eq.	CO2 not conv	2,869	gCO2eq.	0,000	gCO2eq.
water	0,000	gCO2eq.	0,000	gCO2eq.	water	0,000	gCO2eq.	0,000	gCO2eq.
Methanol	0,000	gCO2eq.	0,000	gCO2eq.	**Methanol**	0,000	gCO2eq.	0,000	gCO2eq.
Methanol	0,000	gCO2eq.	0,000	gCO2eq.	**Methanol**	0,000	gCO2eq.	0,000	gCO2eq.
combustion	68,900	gCO2eq.	0,000	gCO2eq.	combustion	68,900	gCO2eq.	0,000	gCO2eq.
existing use	-68,900	gCO2eq.	0,000	gCO2eq.	existing use	0,000	gCO2eq.	0,000	gCO2eq.
	sum		sum			sum		sum	
	40,502	gCO2eq.	37,633	gCO2eq.		80,618	gCO2eq.	8,849	gCO2eq.
	reduction		reduction			reduction		reduction	
	-57 %		-60 %			-14 %		-91 %	