CCU in Scandinavia: an uncertainty analysis regarding the future state of captured carbon in the region.

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Nomenclature

BECCS	Biomass energy carbon capture and storage
BEJF	Bio electro jet fuels
CAPEX	Capital expense
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CUP	Carbon uptake potential
EC	European commission
EU ETS	European emissions trading system
FT	Fischer-Tropsch
GHG	Greenhouse gas
LCA	Life cycle analysis
MC	Mineral Carbonation
OPEX	Operational expense
PtL	Power-to-Liqued
RED II	Renewable energy directive II
TRL	Technology readiness level

Sammanfattning

Det akuta behovet av att mildra klimatförändringarna har lett till utvecklingen av strategier för att minska utsläppen av växthusgaser. Carbon Capture and Utilization (CCU) har vuxit fram som en lovande teknik som inte bara syftar till att fånga upp koldioxidutsläpp (CO_2) utan också använder den infångade koldioxide för att skapa produkter, och därigenom tillhandahålla en potentiell väg mot hållbara och cirkulära ekonomier.

Denna avhandling undersöker potentialen för CCU i den skandinaviska regionen efter 2030. Genom att analysera miljömässiga -, policy -, och tekniska osäkerheter bedömer forskningen genomförbarheten av att implementera CCU-lösningar i sammanhanget av regionens unika socioekonomiska och miljömässiga egenskaper. Resultaten avslöjar betydande potential för CCU i regionen efter 2030. Tillgången till rikliga förnybara energiresurser i kombination med starkt statligt stöd för klimatåtgärder och innovation skapar en gynnsam miljö för CCU-utveckling. Dessutom, eftersom det finns potentiella överlappningar med ett ekosystem för avskiljning och lagring av koldioxid (CCS) som för närvarande är under uppbyggnad, förenklar detta ytterligare utbyggnaden av CCU-system. Den potentiella övergången från traditionell produktion har ett delvis etablerat ekosystem av stöttande infrastruktur. Ett exempel är den etablerade CO_2-transporten som krävs för både CCS och CCU. Även om detta är fallet krävs statligt stöd för att katalysera denna utveckling. Den nuvarande oharmoniska blandningen av sektorunik legislation hindrar storskalig implementering. Osäkerhet om den potentiella lönsamheten, starkt relaterade till utsläppsbaserade incitament och skatter samt begränsade etablerade storskaliga processer, kan begränsa utbyggnaden i regionen.

Sammanfattningsvis är avhandlingen postitiv till utveckling och etablering av CCU i regionen, och uttrycker möjligheten för denna typ av tekniks påverkan på den rådande utläppskrisen.

Keywords— CCU, E-kerosene, Precast concrete, CO_2 utilization, Scandinavian region, Defossilization

Abstract

The urgent need to mitigate climate change has prompted researchers to investigate novel strategies to reduce greenhouse gas emissions. One promising technology that might ease the way for sustainable and circular economies is carbon capture and utilization (CCU), which not only captures CO_2 emissions but also uses them to produce valuable products.

This thesis investigates the potential of CCU in the Scandinavian region beyond 2030. By analyzing environmental -, policy -, and technological uncertainties, the research assesses the feasibility and viability of implementing CCU solutions in the context of the region's unique socioeconomic and environmental characteristics. The findings reveal significant potential for CCU in the region beyond 2030. The availability of abundant renewable energy resources coupled with strong government support for climate action and innovation creates a favorable environment for CCU development. Furthermore, as there are potential overlaps with a carbon capture and storage (CCS) ecosystem currently under construction, this further simplifies the deployment of CCU systems as the transition from traditional production has a partially established supporting ecosystem. One example is the established CO_2 transportation required for both CCS and CCU. While this is the case, governmental support is required to catalyze this deployment. The current anharmonic mixture of sector-unique legalization hinders large-scale implementation. Uncertainties regarding the potential profitability, highly related to emission-based incentives and taxes, as well as limited established large-scale processes, can restrict the deployment in the region.

In summary, the thesis is optimistic about the development and deployment of CCU in the region and expresses possibilities for this type of technology's impact on the current emission crisis.

Keywords— CCU, E-kerosene, Precast concrete, CO_2 utilization, Scandinavian region, Defossilization

Foreword

First and foremost, we would like to extend our deepest gratitude to our supervisor, Professor Jens Klingmann, for his support, guidance, and encouragement. His insightful feedback have been instrumental in shaping the direction and quality of this research.

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Lastly, we want to express our appreciation to all the participants who willingly participated in the data collection process for this research. Their contributions have been invaluable, and their willingness to share their experiences and insights has greatly enriched this study.

Chapter 1

Introduction

1.1 Background

Global warming is primarily caused by greenhouse gas, or GHG, emissions from human activity. Scientists agree that the unprecedented rate of temperature increase will have irreversible effects. Many efforts have been made to keep GHG concentrations below dangerous interference levels over time. One of the best-known efforts is the Paris Agreement, approved at the 21st Paris Conference in 2015. Its main goal is to *"hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would reduce the risks and impacts of climate change*" [1].

The Intergovernmental Panel on Climate Change (IPCC) has published comprehensive assessment reports, in short, ARs. The purpose of the ARs is to detail the causes of climate change, its potential effects, and available retaliation options. AR5 introduces the RCPs, Representative Concentration Pathways, which describe GHG concentration trajectories, rather than focus on emissions levels. The RCP2.6 scenario is the only one compatible with the Paris Agreement goal and would probably keep global warming below 2 °C. According to RCP2.6, anthropogenic emissions of CO_2 should decrease before 2050 by 40 % -70 % compared to 2010 emissions and continue the trend until achieving net-negative emissions before the end of the century [2]. Recently, the IPCC published the Sixth Assessment Report, or AR6, changing the RCPs to a new classification called IMP, or Illustrative Mitigation Pathways. The IMPs analyze different pathways compatible with meeting the long-term goals of the Paris Agreement. The new scenarios, shown in figure 1.1, are assigned to one of eight "climate categories" based on the warming result implied by the scenario [3]. The figure depicts both CO_2 emissions (right) and total GHG emissions (left) for the IMP (colored lines), as well as the full range of current policy scenarios.

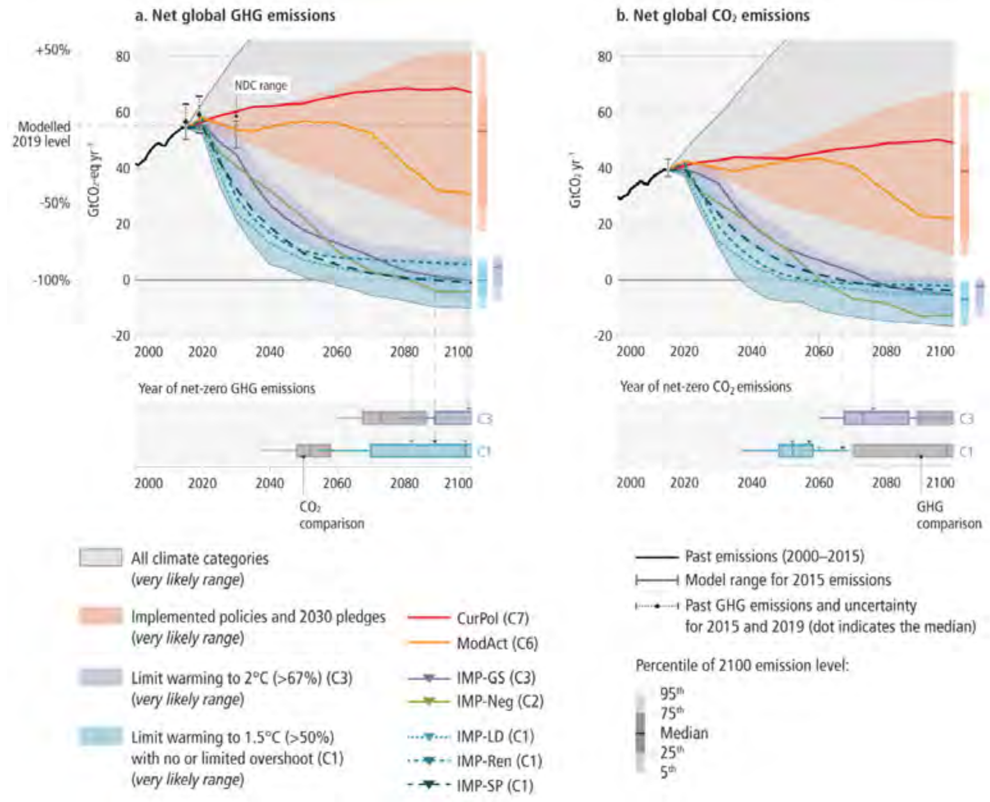

Figure 1.1: Net GHG emissions and net CO_2 emissions (positive emissions minus carbon dioxide removal) under the seven illustrative mitigation pathways that limit global warming to 1.5 °C, and 2 °C [3].

The most crucial element of RCPs, or IMPs, is not the trajectory over time but the surface they define. In other words, the carbon budget available to stabilize the temperature at the limit of the Paris Agreement. It is thus possible to assert that there are infinite paths to the same goal. Yet, emissions trends and countries' commitments are not aligned with the Paris Agreement's goal, and a large part of the carbon budget has already been exhausted [4]. Hence, the European Commission (EC) announced new initiatives in 2020. The European climate law is a relevant initiative that aims to achieve net-zero GHG emissions by 2050 and gives guidelines in concordance with the Paris Agreement [5]. This new law endorses that by 2030, net GHG emissions should be reduced by at least 55 % compared to 1990 levels [6].

1.1.1 Scandinavia and Sweden road towards carbon neutrality

All EU Members States must contribute to the achievement to meet the new EU target. The individual goals and national mitigation roads of the Scandinavian countries vary between them. Norway aims to achieve climate neutrality by 2030, Sweden aims to achieve net zero emissions by 2045, and Denmark by 2050 [7].

In Sweden, emissions have decreased by 35 % since 1990, from 71.4 to 46.3 million tonnes of CO_2 equivalents in 2020 [8], but progress is too slow. If there are no changes in existing policy instruments, the reduction percentage in 2050 would be only 36 % compared to 1990 levels [9]. Therefore, it is essential and mandatory to take action plans, additional measures, and a climate policy framework to achieve the climate goals.

The parliament (Riksdag) aims to reduce GHG emissions from the Swedish territory by at least 85 % compared to 1990, at the latest by 2045. At the same time, Sweden also has an overall target of zero-net GHG emissions, which means that the remaining 15 % can be achieved through so-called complementary measures [9]. EU negotiators reached a similar deal agreeing on the need to prioritize emission reductions over removals for the 2030 target [10]. The main highlighted options for achieving net negative emissions after 2045 in Sweden, according to Sweden's long-term strategy for reducing greenhouse gas emissions report are [9]:

- Capture, transport, and storage of biogenic carbon dioxide, BECCS;
- Enhanced carbon stores in forests and land;
- Emissions reductions verified in other countries.

However, other measures that can help reduce net emissions could be biochar or CCU. In contrast to those mentioned above, sustainable power is more complex and therefore brings more significant uncertainties about their impact on the net emissions balance [4]. Nevertheless, CCU will have a key role in achieving climate goals, mainly by substituting fossil resources in those sectors where defossilization is more challenging such as transport, aviation, and chemical sectors.

1.1.2 CCU role to achieve climate goal

There is agreement on how to prioritize the actions needed to achieve the climate goals. The preferred actions should be the increase in energy efficiency and the participation of renewable electricity production. Still, it is not feasible to reach the target of 1.5 °C or 2 °C by reducing emissions alone, and it is necessary to rely on carbon dioxide removal, or CDR systems. However, removal systems should not be used to extend the life of avoidable fossil CO_2 sources. Specifically, CCU's main potential is to generate sustainable molecules for applications that require a high energy density, such as maritime transport, aviation, and raw materials for chemistry, among others, where few alternative defossilitzation options are available. Figure 1.2 shows a wide variety of CO_2-based e-molecules that could be produced, changing current industries from a linear system to a circular industrial environment, where CCU values CO_2, and displaces hard-to-abate emissions [11].

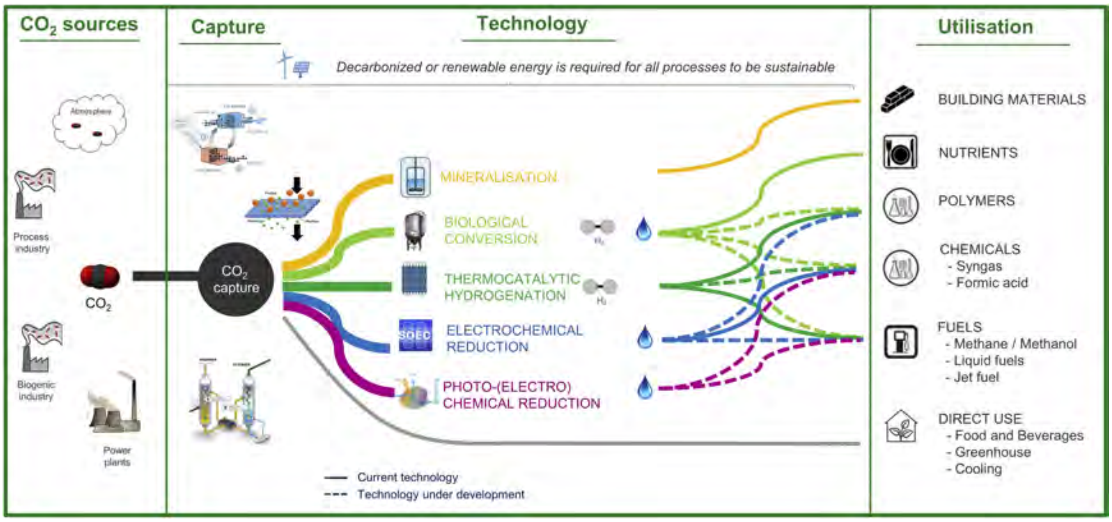

Figure 1.2: Variety of chemical and biological pathways that enable the production of CO_2-based e-molecules, which can be used as building materials, fuels, chemicals, nutrients, or direct use [11].

Article by Mertens, Breyer, Arning *et al.* highlights two terms that, from their point of view, are misused, and more care must be taken in their use. On the one hand, the term CCUS used in reports such as IEA's reports must be avoided. CCU and CCS are fundamentally different regarding their impact and business case. The main difference relates to the end of the value chain and will be discussed later in the report. On the other hand, the article highlights the difference between the term *decarbonization* and *defossilization*, and claims that decarbonization gives a bad connotation to carbon and CO_2. CCU aims to valorize CO_2 and use it as a resource, as carbon remains crucial to the functioning of our society. Therefore, what will allow to achieve the climate ambitions, is to use carbon circularly and not add fossil carbon to the atmosphere, so the term defossilization would be more appropriate [11].

Finally, to achieve the goal of carbon negativity, the CCU should use biogenic CO_2 (i.e. from biomass) or CO_2 capture from the atmosphere using direct air capture (DAC) technologies. Fossil-fuel based sources are not relevant for CCU due to continued dependency and significant conversion losses.

1.2 Energy mix in the Scandinavian region

The following table represents the energy mix in the Scandinavian region [12] [13] [14]. The sustainability of CCU, as well as the probability of large-scale implementation, are highly dependent on a renewable energy mix. The sustainability of many of the processes presented in this thesis relies on the availability of renewable energy. The table presents the energy mix as of today, with the estimation that fossil fuels will be replaced by renewable alternatives like wind power moving forward. Increased production of sustainable energy is a definite requirement for the sustainability of many industrial processes, including the continued development of CCU.

Table 1.1: Summary of the energy mix in the Scandinavian region in 2021

Type / Country	Coal	Oil	Natural Gas	Biogas	Waste	Hydro	Nuclear	Wind	Solar	Other	Total
Sweden [GWh]	677	394	373	9,557	5,080	71,127	52,777	27,108	1,507	0	168,600
Norway [GWh]	188	400	305	35	368	144,339	0	11,779	175	383[a]	157,972
Denmark [GWh]	4,364	258	1,536	7,741	1,765	16	0	16,054	1,309	0	33,043
Sum [GWh]	5,229	1,052	2,214	17,333	7,213	215,482	52,777	54,941	2,991	383	359,615
Percentage of total [%]	1.4	0.03	0.06	4.8	2	60	14.7	15.3	0.8	0.1	100

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[a] "Other sources include generation from chemical heat and other sources."

1.3 Carbon Capture and Utilization

Carbon Capture and Utilization, or CCU for short, is abbreviated name for three processes.

- Carbon Capturing, the act of isolating and removing the carbon-dioxide gas from a mixture.
- Transport, moving the captured carbon from the point of capture to the point of utilization.
- Utilization, directly or indirectly using the carbon as a raw material in a process.

Combined, the processes can be summarized as CO_2 recycling.

Firstly, Carbon Capture (CC) includes the separation and collection of CO_2 from a mixture, usually flue gas which is the exhaust gas from combustion plants, or capturing and separating the CO_2 directly from the air. This is either done at industrial sites with high concentrations of CO_2 emissions, or through direct air capture. Secondly, the carbon captured needs to be transported to the location of storage or utilization. This can be done through onshore transportation (trains or lorries), offshore transportation (boat), or pipelines [15]. These methods can be combined depending on the requirements of the route. The first two steps are the same whether its a utilization or storage process. Thirdly, the carbon captured is utilized as a raw material in different types of processes. This step is what differentiates CCU and CCS. For Carbon Capture and Storage (CCS) the carbon captured is seen as "waste" and is sent to long term sequestration. The CO_2 is usually stored down deep underground where high pressures liquefy it. The method can be likened to nuclear power plant's waste management solution.

Carbon Capture and Utilization divide into two general types, direct- and indirect utilization. Direct utilization is defined by the usage of CO_2 as is. Thus, the molecule is not chemically altered before being utilized as end product. Indirect utilization is defined by chemically altering the CO_2 to generate molecules that replace traditionally sourced alternatives. Depending on how the CO_2 is produced and processed, the final product can shift from generating emissions to being carbon neutral. Carbon neutral CO_2 from the point of view of a industrial consumer includes direct air capture, and biomass based CO_2. Both groups contain several types of subgroups, which will be further analysed and explained in chapter 1.7. These processes' combined ecosystem are well defined and one example is shown Figure 1.3.

Estimations for carbon capture projects calculate a total of 8.4 Mt CO_2 capture potential in Scandinavia in the year 2030. The estimated capture potential includes all current, under construction, and proposed CO_2 capture plants with a capacity of more than 100,000 tonnes per year as well as direct air capture projects with a capacity of more than 1,000 tonnes per [17].

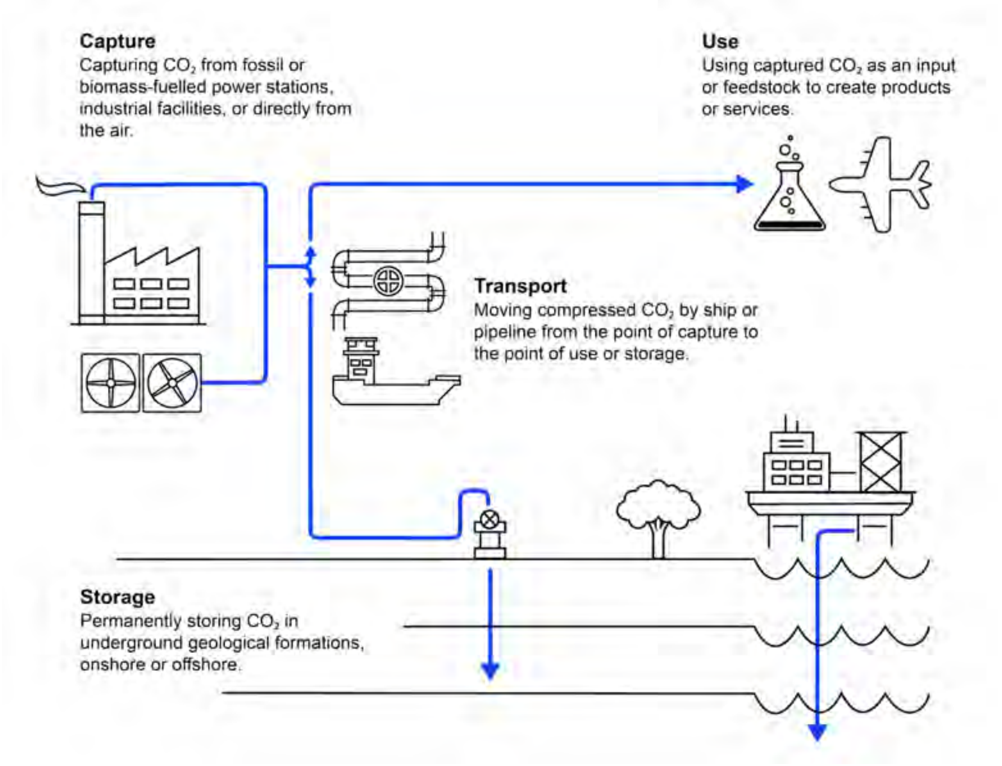

Figure 1.3: CCUS Ecosystem, showing the main sectors of both CCU and CCS [16].

1.4 Current political and regulatory frameworks

Clear and specific CCU laws and regulations are required to standardize operational processes and provide investors and operators with the clarity they require on various aspects of CCUS project development. Despite the technical feasibility of some routes, CCU technologies have not yet reached the commercialization stage. CCU deployment will undoubtedly be slow in the absence of additional incentives [18], [19].

The EC launched its "Fit-for-55" package in line with the European Union's goal of achieving carbon neutrality by 2050 and reducing GHG emissions by at least 55 % by the year 2030. It consists of communications from the Commission, as well as 15 different legislative proposals aimed at adjusting EU policies to reduce GHG emissions and enable the implementation of the European Green Deal [20], [21]. Among the various published proposals, the EC published draft legislation to revise policy instruments relevant to CCU, such as the *Renewable Energy Directive II*, or REDIII, the *Trading Schemes Directive of emissions*, or ETS, the *RefuelEU Aviation*, the *FuelEU Maritime* and the *Directive on energy taxation*, or ETD. In addition, the EU has funding instruments that directly support the CCU, such as the Innovation Fund and the Horizon Europe fund [21]. These policies and regulations are expected to provide a strong legal framework as well as financial incentives to invest in, and accelerate the deployment of CCU technologies, which is critical to achieving the EU's ambitious climate goals.

The overview of all pieces of legislation examined in this study has been organized according to the different thematic policy frameworks to which they belong. This classification emphasizes the importance of waste management and circular economy policies to reduce greenhouse gas emissions and promote sustainable production and consumption, as well as the role of climate change policies in encouraging the adoption of CCU technologies.

1.4.1 Climate change mitigation and energy policies

Emissions Trading System

The EU Emissions Trading Scheme or Scheme, commonly known as the EU ETS, is a market mechanism designed to limit GHG emissions under a cap-and-trade principle. In essence, the system puts a cap on the total amount of CO_2 emissions that the installations included in the system can emit. Then, the cap is reduced over time to reduce total emissions. Therefore, each installation receives an emission allowance for every tonne of CO_2 emitted, which they can trade [22], [23].

As it will be shown through the present work, CCU technology can play an essential role in reducing emissions in industries that are difficult to defossilise, such as the manufacture of chemicals and fuels. As of now, the EU ETS Directive excludes CCU technologies as a recognized mechanism to reduce GHG emissions. Only one specific CCU pathway is included as a carbon reduction measure in the current ETS directive, this being the production of precipitated calcium carbonate, under a ruling by the Court of Justice of the EU in the Schäfer-Kalk case [24]–[26].

According to the “Fit-for-55” package, the EC proposes a revision of the EU ETS to introduce CCU into the directive. Yet, some aspects make this effort challenging. One of the reasons is the complexity of accurately quantifying the CO_2 emission reduction potential, as it depends on multiple factors such as the specific application, the source of the CO_2, and the life cycle emissions associated with using the CCU product. The ETS was initially designed to reduce emissions from point sources and is unsuitable for tracking emissions over the life cycle of a CCU product. Many authors point out that for CCU to be recognized under the ETS, the first and indispensable step is to harmonize life cycle assessments, abbreviated as LCAs, and appropriate monitoring protocols. Without a transparent methodology, only carbon capture processes that permanently sequester carbon dioxide could be stimulated under the ETS Directive as currently stipulated[1] [21], [23], [26].

Recognizing CCUs in the current ETS directive would introduce another issue, such as internal carbon leakage and double counting of avoided emissions. For this reason, EC set among the new ambitious goals, within the latest revision, to end the double counting of CCU fuels and chemicals. For example, as Thielges *et al.* [21] states, CO_2 capture cannot be attributed as avoided emission under the ETS Directive because otherwise avoided emissions would be counted twice if CCU fuels are considered “emission fuels zero” or “reduced emission fuels” in the REDII Framework.

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[1] The EU ETS provides an exemption from accounting for GHG emissions only for CCS under the CO_2 Geological Storage Directive.

Another example where there would be double counting is in emissions associated with RFNBO, since the ETS directive would count CO_2 emissions twice: once for the initially emitted CO_2 that is used to produce RFNBO, and again when RFNBO is used, and the same CO_2 is remitted [20], [22], [23], [27]. Thus, the EC proposed the following text [28]:

Greenhouse gases that are not directly released into the atmosphere should be considered emissions under the EU ETS, and allowances should be surrendered for those emissions unless they are stored in a storage site in accordance with Directive 2009/31/EC of the European Parliament and of the Council, or they are permanently chemically bound in a product so that they do not enter the atmosphere under normal use and disposal.

However, as Bernier and Perimenis [20] points out, more guidance and specification are required to understand how "normal use" is defined, including how end-of-life is included, to prevent confusion and ensure ETS implementation is harmonized.

Renewable Energy Directive

The Renewable Energy Directive, abbreviated as RED, is a framework that promotes renewable energy across all economic sectors. Moreover, the RED defines sustainability standards for biofuels and bioliquids. Explicitly RED II includes two types of fuels as qualifying pathways to meet the 2030 target, which is relevant in a CCU context: recycled carbon fuels and renewable fuels of non-biological origin (RFNBOs)[2] [23]. It should be noted that for fuels to qualify as renewable, GHG emissions must be reduced by 70 %, and renewable electricity for CCU must not consume electricity that could otherwise be used for more energy-efficient alternative applications [21].

In December 2018, the revised RED 2018/2001/EU, or REDII, entered into force as part of the Clean Energy Package for All Europeans [29]. The potential for CO_2 and renewable energy fuels is recognized in RED II by requiring that at least 14 % of all transport fuels in all Member States should come from renewable sources by 2030 [23].

An article by Thielges, Olfe-Kräutlein, Rees *et al.* [21] identifies RED II as an incentive for CCU only in energy-intensive sectors difficult to defossilise, and as a deterrent for other applications. However, RED II is currently under revision in the context of "Fit for 55" package. The revision RED III, introduces that in 2030 at least 2.6 % of the energy supplied to transport will have to be covered by RFNBO. It is also the first time that RFNBO has been extended to sectors other than transport, with the aim of RFNBO accounting for 50 % of the hydrogen used in industry by 2030 [20]. As a result, REDIII encourages the production and usage of RFNBO by acting as a clear incentive for CCU and becomes a favorable framework for the defossilisation of all industries [21].

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[2] Renewable fuels of non-biological origin are fuels 'whose energy content comes from renewable energy sources other than biomass, and which are used in transport' (such as in power-to-fuel technologies [23].

1.4.2 Waste management and circular economy

By recycling carbon and carbon-based products, CCU can contribute to a circular economy and reduce GHG emissions. Therefore, the Waste Framework Directive (2008/98/EC, WFD) and the Circular Economy Action Plan (CEAP) can potentially improve CCU development by promoting their recognition as a type of waste recovery and supporting their implementation within a circular economy framework. These policies are inextricably linked because they address the end-of-life issue of products; however, while the CEAP mentions the reuse of gaseous effluent, specifically CO_2, the WFD is still subject to different interpretations and does not address CO_2 [23]. The CEAP aims to reduce waste and promote the sustainable use of resources in the EU. CCU technologies are seen as a way to promote a circular economy and reduce emissions, so they must adhere to its principles to contribute to the transition to a more sustainable and resource-efficient economy. This framework may result in incentives to close the carbon loop [23], [26].

The Waste Framework directive is an EU Command and Control (CAC) instrument[3] that establishes an EU waste management policy intending to protect human health and the environment by preventing or mitigating the adverse effects of waste generation and management. CCU technologies have the potential to contribute to waste management goals by converting CO_2 waste into valuable products, and at the same time, the WFD could provide an increased market acceptance of carbon-recycled products. However, the EU rules on waste disposal still need to be fully harmonized, and integrating CCU technologies within the WFD framework is complex and requires deep analysis [21], [23], [24].

In general, the waste and circular economy framework has significant implications for developing and integrating CCU technologies and options for addressing existing regulatory barriers and supporting the market for CCU-based products. Nevertheless, CCU products have yet to be incorporated within this legislation.

1.5 Technology readiness level

The technology readiness level is an established measurement system constructed to evaluate and rank the state of a technology or ecosystem of technologies. The scale was created by NASA in the 1980s and was first developed to sort and rank the technological solutions related to space travel and exploration developed there. Since then, the scale has been generalized to be applicable in a more extensive array of sectors. More specifically, the metric-based process determines how far technology is from being deployed and established in a specific sector or industry.

In this report, the scale is applied to CCU methods to provide a comparable metric of the technological state of the methods, and together with financial estimations and potential environmental impact, provide an overview of the potential of CCU in the Scandinavian region. The scale consists of 9 levels, with some niche applications adding two additional levels. As seen in the figure 1.4, the nine metrics are split into three groups: Research, Development, and Deployment. Important to note is that a specific technology's level is its current state. For example, if a

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[3] Command-and-control instruments impose direct regulatory intervention by setting standards. Different specific CACs will apply to different products that can be manufactured using CCU technologies [24].

technology has been “validated in a lab” (see level 4), it has acquired level 4. It does not earn level 5 until it has completed level 5.

Figure 1.4: Technology readiness level structure [30].

1.6 Project scope and delimitation

This thesis will only analyse the possibilities of CO_2 utilization, limited to the Scandinavian Region with the year 2030 as starting point.

As previously mentioned, any CCU ecosystem can be split up in to three main parts. Capture, transportation, and utilization. Methods and solutions for capturing and transporting the CO_2 will be excluded from the thesis. This thesis will not include any analysis of current or future carbon storage solutions.

The goal of this thesis, based on the described background, try to answer the following questions. By providing answers to the questions, the hope is to provide a detailed analysis of potential of CCU technologies in the Scandinavian region, its strengths and weaknesses as well as the barriers limiting CCU´s roll to play in cutting emissions in the region.

1.6.1 Research Questions

- What is the current state of carbon capture and utilization (CCU) technologies in Scandinavia? And what is the potential sequestration of the analyzed methods?
- What are the main uncertainties for CCU methods, and how do these affect their feasibility for large-scale implementation?
- How does CCU based products compare to the traditional products, and what is required for specific CCU-based products to become standard?

1.6.2 Thesis Structure

The thesis contains four main chapters. Firstly, the introduction provides a background of the current state of emissions, emissions targets for the region and relevant policies, and an overview of the most established CCU methods, their technological state, and their potential impact in Sweden as well. The data collected provided a hierarchy, with the two most prominent methods further analyzed in the results. Secondly, the method, where the theory behind the methodology used and the application of the theories is presented. The framework utilized for the analysis is defined and broken down into its constituents in this chapter. Thirdly, the results, where the framework is applied to the two main CCU methods of this thesis, e-kerosene, and precast concrete. Fourthly, and last, the discussion, where the results from the previous chapters are expanded to CCU technology as a whole, and utilized to analyze the impact on the large-scale implementation of the uncertainties related to CCU technology in the region past 2030.

1.7 Primary CCU Methods

CCUs are spread across industries, utilizing CO_2 for a multitude of different applications, all with unique resource requirements, potential emission reduction, and technical readiness level (TRL).

The following sections summarize six utilization methods (four indirect- and two direct methods) and their estimated potential uptake in Sweden. The six CCUs chosen represent unique markets and the most prominent CO_2 utilizations on the global market. While the six methods do not cover every potential market for CCU, they provide an overview of the potential markets where CCU can have a potential impact. For all except “Building Materials”, the example projects referenced in the specific sections below are in the Scandinavian region. The six methods reduce emissions through different processes. Some sectors utilize CO_2 to produce a portfolio of unique end products. For these, one specific utilization method is explained to provide a more in-depth view of the utilization process and its potential. This specific utilization method is presented inside the parentheses “()” in the heading of that specific section. A general overview of the potential CCU pathways is presented in figure 1.5. It should be noted that urea can be seen as both direct and indirect utilization, depending on how the CO_2 is utilized in the process. See section 1.7.1 *Urea* for the difference in yield boosting and defossilization.

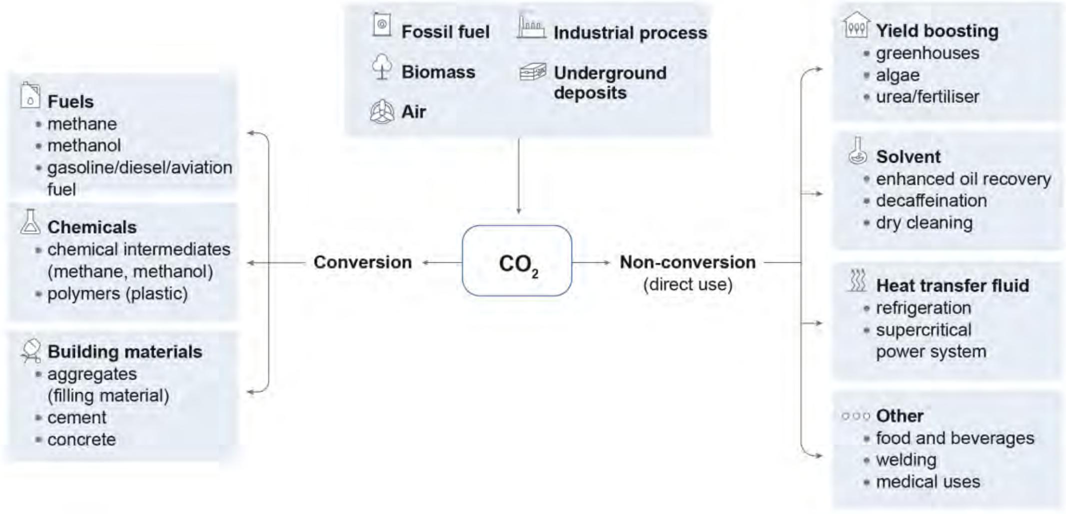

Figure 1.5: Indirect and Direct utilization pathways for CCU [31].

Either, the reduction comes from sequestration, or through replacing fossil fuels with carbon neutral alternatives in different processes. These two different types of reduction will be labelled *carbon uptake potential* and *abatement potential*, respectively. Uptake locks carbon in solids or complex carbon chains, while abatement reduces the emissions by offering a carbon neutral alternative, thus defossilizing processes. The numbers for the total potential of CO_2 uptake are rough estimates presented to provide a comparison between the methods. These numbers should not be taken as absolute truths, but instead as a indication of the possible impact of CCU solutions. More in depth estimations for two of the methods is presented in the results section.

1.7.1 Indirect utilization methods

As previously mentioned, indirect utilization methods are defined by chemically altering the CO_2 before utilization. Chemical altering requires supplementary raw material and energy. Examples of these types of methods, their processes, and total potential, is presented below.

Building Materials (Precast Concrete)

Mineral carbonation (MC) process offers an opportunity for CO_2 utilization. MC is the formation of solid carbonate products, based on a reaction between carbon dioxide and alkaline materials composed by calcium and magnesium rich oxides and silicates [32]. The general MC reaction is shown in Eq. 1.1, where M is a divalent metal cation, typically Mg^{2+} or Ca^{2+} [33].

$$MO + CO_2 \longrightarrow MCO_3 \tag{1.1}$$

Typical carbonate minerals are magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$, commonly known as limestone), and can be used in a wide range of industries, including construction, paper and pulp, pharmaceutical, agricultural and refractory metals. Among the suitable applications, the constructing industry presents the largest opportunity in terms of consumption volume, overall emissions avoidance, and readiness for commercial scale [33]. And, CO_2-cured concrete (i.e precast-concrete) and building aggregates are the most mature applications of CO_2-derived building materials. Both application pathways are shown in figure 1.6.

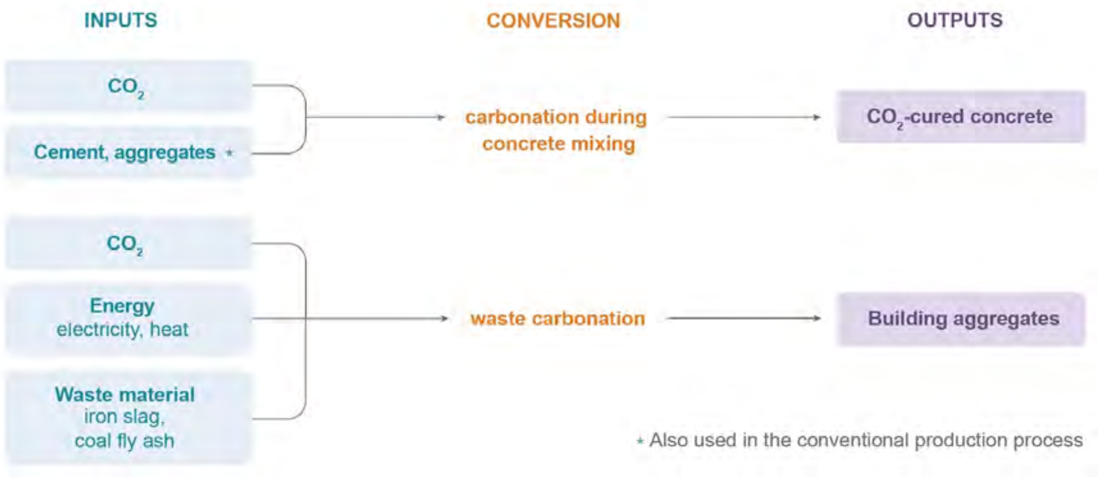

Figure 1.6: Mature conversion pathway for CO_2-derived building materials [31].

As an illustration, the following text describes the use of CO_2 in the building materials sectors, specifically concrete curing. Concrete is a composite material resulting from mixing cement (binder), water, and aggregates of varying size (gravel, sand, crushed stone).

The cement industry not only has the potential for CO_2 removal (CCU) but also has to drastically reduce its contribution to GHG emissions emitted in its processes. For example, only the cement industry (an essential ingredient for concrete) corresponds to about 6 % -7 % of global anthropogenic emissions, where the 60 % of these emissions are due to mineral decomposition ($CaCO_3$ to CaO), and the rest is from fuel combustion [34], [35]. Therefore, the cement and concrete industry plays an essential role in achieving net-negative emissions. To that effect, CEMBUREAU, the European Cement Association, announced their intention to align with the EU plan and the European Green Deal objectives [36]. Concrete, together with aggregates and chemicals/fuels, are end-products with the potential to sequester CO_2. There are several approaches to using CO_2 in concrete, the most studied and applied being CO_2-mixing and CO_2-curing. In CO_2-mixing, high-purity CO_2 is injected into fresh concrete during batching and mixing, whereas in CO_2-curing (carbonation curing), CO_2 is used as a curing agent to speed up the manufacture of precast concrete [37]. Article by Ravikumar, Zhang, Keoleian *et al.* reviews CO_2-curing and -mixing studies and concludes that CO_2 curing of precast concrete has significantly greater CO_2 absorption potential than CO_2 mixing [37]. Carbonation curing of concrete offers several advantages to the final product [38]:

- Improve concrete performance (increase concrete strength) due to the formation of carbonate minerals during concrete curing while reducing curing time.

- Reduction of emissions due to low use of cement. The reduction in cement material is also expected to reduce energy demand and water consumption.

The carbon uptake potential, CUP, per ton of precast concrete and the TRL of concrete curing differs from source to source. Generally, the TRL for this specific method is 7 or 8 [32], [35], [39], [40]. CUP values found for concrete cure are dispersed, with a minimum of 0.06 tCO_2 per tonne of precast concrete and a maximum of 0.19 tCO_2 per tonne of precast concrete [32], [35], [39], [40]. Estimating an average CUP factor of 0.125 tCO_2 per tonne of precast concrete produced, and a yearly production of 3.1 Mt of cement in Sweden, and estimation of the total CUP for Sweden can be calculated [41]. The calculation assumes all products are cured by carbonation and that concrete consist of circa 14 % of cement and circa 30 % of the concrete market is made up of precast concrete [42], [43]. This estimation is shown in equations 1.2 & 1.3.

Carbon uptake potential:

$$\frac{\text{Cement Production} \cdot \text{Concrete to Precast} \cdot \text{CUP}}{\text{Cement to Concrete Conversion}} = \text{CUP}\ [kg/year] \tag{1.2}$$

$$\frac{3\,100\,000 \times 10^3 \cdot 0.31 \cdot 0.125}{0.14} = 858 \times 10^6\ \text{kg/year} \tag{1.3}$$

Carbonation curing technology is currently progressing toward small-scale demonstration implementation. Several companies are investing in the injection of CO_2 into concrete as a reinforcing material like CarbonCure, Carbicrete, Coalstone, and SolidiaCement. For example, CarbonCure, a Canadian company, injects CO_2 into the concrete mixture, and this reacts with the calcium ions present in the cement, forming calcium carbonate crystals ($CaCO_3$). In this way, it is permanently captured in the new concrete produced. According to CarbonCure, in addition to capturing CO_2 in mineral form, the final product meets the required characteristics of the material and does not affect its properties [34].

Chemical industry (E-methanol)

Being a key component of many chemical compounds, carbon is utilized in a wide range of chemical industrial processes. CO_2 is used extensively in the manufacturing of polymers (plastics and synthetic rubbers) and chemicals (methanol and methane). Figure 1.7 shows a Sankey diagram displaying fossil fuel to chemicals flow in the chemistry industry in 2015. Theoretically, both coal for ammonia syntheses, as well as natural gas for methanol syntheses could be replaced by CCU as the primary feedstock in these processes is CO_2 and CO. As seen in figure 1.7, one key component for chemical production is methanol. Furthermore, crude oil is partially utilized as feedstock for butylene synthesis. Similarly to other hydrocarbons, butylene (butene) can be synthesized with CO_2 as a feedstock. The possibilities for defossilisation through CCU in the chemical industry are considerable due to the availability of possible value chains. Dependencies on coal and natural gas could diminish, and crude oil consumption would decrease if the adoption of CCU-based technologies increases. The process of synthesizing methanol is what will be further explained in this section, but it only represent a part of the potential for CCU in the chemical industry. For the process of ammonia synthesis see section 1.7.1 *Urea*.

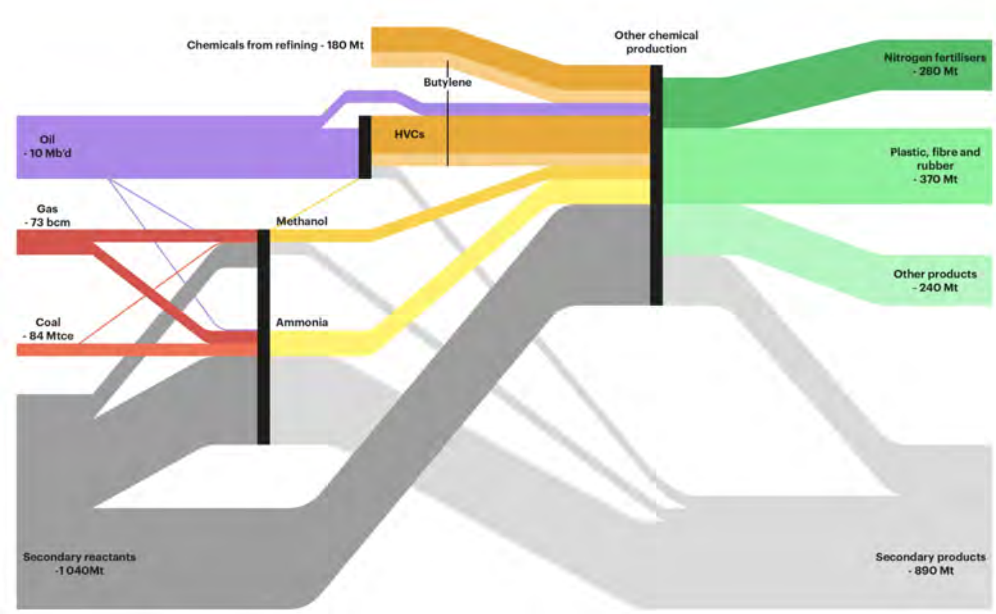

Figure 1.7: Sankey diagram of carbon-based raw material to chemicals globally [44].

Synthesizing methanol (CH_3O_2) using fossil fuels as feedstock is an established and researched chemical reaction. Methanol is seen as one of the building blocks in modern chemistry, as it lays the foundation for further synthesis of important molecules like formaldehyde [45], [46]. Furthermore, methanol is an alternative fuel in combustion engines as it has the potential both as a standalone fuel, as well as a part of a mixture. Research has shown that the purity required for the transportation industry is lower than the chemical industry (99.85 % to 90 % purity), providing the producers with an alternative market [47].

The standard process turns syngas (a mixture of CO, CO_2 and H_2 generally generated by burning fossil fuels) to methanol through the synthesis seen in equation 1.4 which represents the one step process [48]. An alternative is a two step process, due to the mixture of molecules in the syngas, seen in equation 1.5 & 1.6. The reactions are competing for the feed, where 1.5 is undesirable [49]. This can be minimize by optimizing for temperature and pressure, as well as through purification of the syngas feed. If only CO_2 and H_2 are available, the synthesis is presented in equation 1.6. Both equations 1.6 & 1.4 are exothermic, and methanol synthesis is more conducive at low temperatures [48]. This means that both CO_2 conversion, as well as methanol selectivity, are the most efficient at low temperatures. Thus, the temperature increase due to the exothermic process can cause an issue in methanol synthesis and the system will need cooling [50].

One step process:

$$CO_2 + 3H_2 \longleftrightarrow CH_3OH + H_2O \tag{1.4}$$

Two step process:

$$1.\ CO + H_2O \longleftrightarrow CO_2 + H_2 \tag{1.5}$$

$$2.\ CO + 2H_2 \longleftrightarrow CH_3OH \tag{1.6}$$

By utilizing CO_2 combined with H_2 generated from electrolysis, methanol can be synthesized without added syngas. Combining a carbon-neutral CO_2 source with renewable electricity, the methanol becomes carbon-neutral. This product is called e-methanol. The processes related to the synthesis of liquid hydrocarbons like methanol are well-established with a TRL ranging from 7-9 [51] [40]. Methanol is currently produced through these processes, but implementation with CC-technology is uncommon. One example of the implementation of e-methanol in the chemical industry in Scandinavia is the company Perstop Chemicals AB in the south of Sweden. The plant, with a planned operational start in 2025, will produce 200,000 tonnes of e-methanol per year [52].

In 2021, Sweden imported 300,000 tonnes of fossil based methanol [53]. The total uptake potential of e-methanol is equal to the current imported amount of fossil based methanol, multiplied with an assumed conversion rate of 1.37 tonnes of CO_2 per tonne of Methanol [54]. The conversion rate disregards further changes to the emissions through utilization of by-products from the process as well as inefficiencies in the unique real-life systems. An estimation of the total uptake potential is calculated in equations 1.7 & 1.8.

Carbon uptake potential:

$$\text{Methanol Potential} \cdot \text{Conversion Rate} = \text{Potential Uptake} \tag{1.7}$$

$$300\,000 \times 10^3 \cdot 1.37 = 411 \times 10^6\ \text{kg/year} \tag{1.8}$$

Furthermore, it is shown that there are some advantages of synthesising methanol from a pure CO_2 and H_2 source, instead of the traditional syngas mixture. These benefits are specifically related to impurities in the final product [55]. Methanol can be used both as a fuel and as a feedstock, and is relevant as a possible replacement of fossil-based shipping fuel [56].

E-Fuel (E-kerosene)

In 2020, transportation accounted for circa 33 % of the total emissions in the Nordics [57]. These emissions are energy-related, thus calculated from the emissions released due to the consumption of fuels. As seen in figure 1.8, the primary fuels responsible for the emissions are diesel, gasoline, and “other liquids”. Both diesel and gasoline are crude oil derivatives. Other liquids primarily consist of aviation and shipping fuel, which consist of kerosene and heavy fuel oil (HFO) respectively, as well as bio-fuels [58] [59]. Since kerosene and HFO also are derivatives of crude oil, all major fuel sources can be replaced by synthetic alternatives. Synthetic versions are based on renewable electricity, CO_2 and H_2, and are referred to as e-fuels. Estimations for 2050 show increases in e- & bio-fuel can lead the defossilisation in the transportation sector by outcompeting fossil fuel alternatives [60].

A general chart of liquid to fuel synthesis, i.e production of e-fuels, is presented in figure 1.9. As seen in the figure several different hydrocarbons are relevant as sustainable substitutes for the different transportation sectors, including aviation.

The aviation sector is facing difficulties in decreasing GHG emissions. High demand for fossil-based fuels, due to insufficient viable substitutes and the long cycle time of air fleets, are the main factors hindering a shift into a more sustainable alternative. Furthermore, there is an

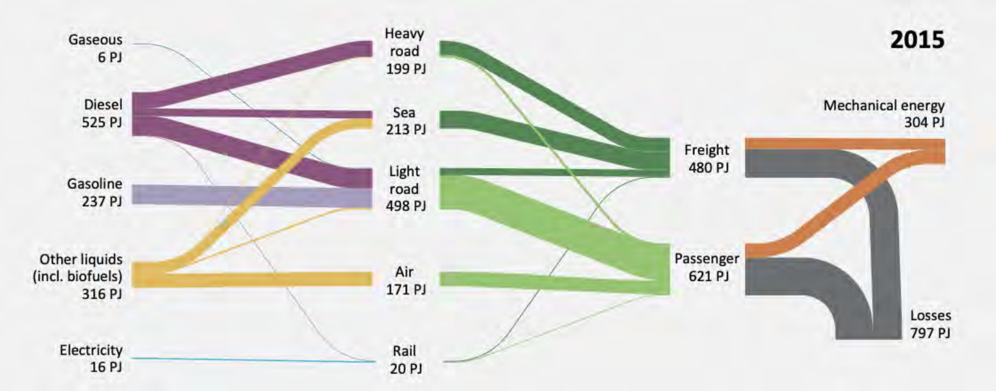

Figure 1.8: Sankey diagram of fuel source for modes of transportation in the Nordics [60].

estimated shortage of biofuel generated from biomass, limiting the potential impact of biomass as a long-term solution. Another solution is the development of carbon-neutral synthetic liquid fuels similar in composition to the fossil fuels used today. Depending on the source of the CO_2, this would provide an opportunity for carbon-neutral aviation.

For aviation, kerosene is the primary molecule-mixture refined for jet fuel. Kerosene consists of a mixture of different hydrocarbons ranging from 10 to 16 carbon atoms per molecule [62]. Synthesis of carbon-neutral "e-kerosene" is a process similar to the e-methanol production previously mentioned in the chemical industry section. Both processes utilize the same foundational molecules (CO and H_2) combined with renewable electricity. The processes related to the synthesis of liquid hydrocarbons like kerosene are well-established. TRL is assumed to be the same as e-methanol (7-9) due to similarities in production processes.

The most developed method for the synthesis of e-fuels is through the Fischer-Tropsch process. Fischer-Tropsch synthesis transforms CO and H_2 to liquid hydrocarbons [63]. From this process, crude oil is synthesised which then can be refined into desired hydrocarbons. To attain the required CO, process seen in equation 1.5 is "reversed", with the goal to find the optimum molar ratio of CO to H_2. The process is called a reversed water-gas-shift reaction [63].

Two step process:

$$1.\ CO_2 + H_2 \longrightarrow CO + H_2O \tag{1.9}$$

$$2.\ nCO + (2n+3)H_2 \longleftrightarrow C_nH_{2n} + nH_2O \tag{1.10}$$

The countries and stakeholders in the Scandinavian region are closely following and investing in these types of processes. Most prominent developments are seen in Denmark, which with their "Green fuel for Denmark" initiative are set to produce e-kerosene to cover Denmark's total domestic aviation by 2030 [56], [64]. Furthermore, a feasibility study of bio electro jet fuel (BEJF) production with CO_2 from a CHP bio-plant in the north of Sweden has been conducted. The study concluded that BEJFs can achieve the policy-set emission reduction goals and offer a promising substitute for the aviation industry in Scandinavia [65]. An overview of a cyclical ecosystem for general BEJFs production is presented in the figure 1.10.

Sweden has similarly to Denmark targeted net-zero emissions domestic flights before 2030 [66].

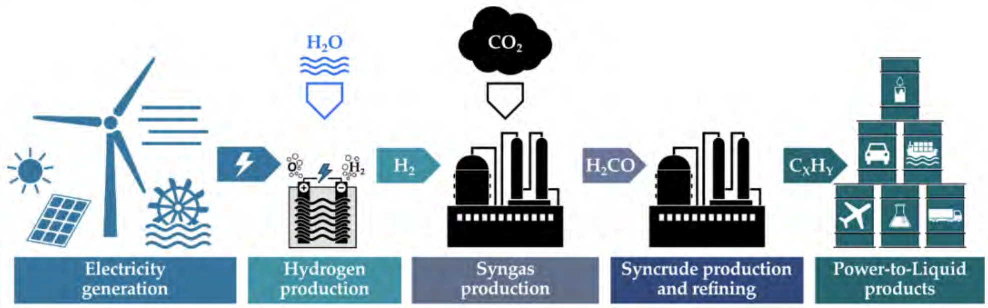

Figure 1.9: Generic chart of Liquid-to-fuel production [61].

The total potential abatement can be assumed to be equal to the total emissions of Swedish domestic aviation today. Emissions from domestic air travel in Sweden accounted for circa 1 % of Sweden's total domestic emissions 2019 [67]. In 2019, Sweden's total domestic emissions were 55.3 million metric tonnes of CO_2 equivalents [68].

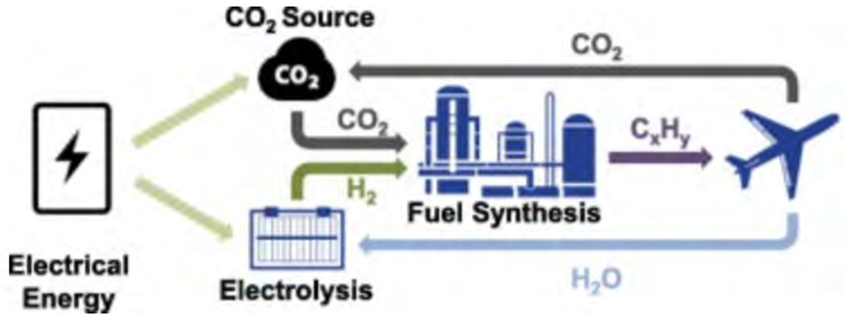

Figure 1.10: Generic chart of synthetic liquid fuel based aviation ecosystem [69].

Potential abatement:

$$\text{Total Emissions} \cdot \text{Domestic Flight Percentage} \tag{1.11}$$

$$55\,300 \times 10^6 \cdot\ 0.01 = 553 \times 10^6\,\text{kg/year} \tag{1.12}$$

These calculation assume that domestic aviation is constant year to year. Popularity of domestic flight, thus potential abatement, is dependent on a multitude of domestic and international factors like development of alternative modes of transportation or global pandemics adding uncertainty to these numbers.

Urea (Fertilizer)

Urea (NH_2CONH_2) is mainly used as a fertilizer (a rich source of nitrogen) and as a raw material to produce other important chemical compounds such as plastics, resins, and adhesives. The synthesis of urea at an industrial level is carried out from liquid ammonia (NH_3) and CO_2 at high pressure and high temperature to form ammonium carbamate ($NH_2CO_2NH_4$), which decomposes into urea and water, as seen in equations 1.13 & 1.14 [70].

$$CO_2 + 2NH_3 \longleftrightarrow NH_2CO_2NH_4 \tag{1.13}$$

$$NH_2CO_2NH_4 \longleftrightarrow NH_2CONH_2 + H_2O \tag{1.14}$$

The most common urea production method is natural gas reforming; however, excess ammonia is usually produced. The increase in urea yield aims to increase the conversion of ammonia to urea by using the excess ammonia from the upstream process and combined with additional CO_2. Urea yield boosting is a proven CO_2 reuse technology, widely used in the fertilizer industry and therefore considered mature [70]. Urea yield boosting has a TRL of 9 [51] [40] [71]. The final product then has a large amount of CO_2 bound to the compost. Still, when the product is applied to agricultural land, it reacts with water, and the CO_2 is quickly released into the environment, and the NH_3 decomposes to supply nitrogen to crops. Considering this, CO_2 fixation times are relatively short [70]. Alternatively, other promising application areas of urea for CO_2 fixation are urea-formaldehyde and melamine-formaldehyde resins [72]. For the most common usage (fertilizer), the potential CO_2 reduction comes from switching synthesis gas to CO_2 as a feed-stock source. To summarize there are two potential utilization methods for urea. Both yield boosting, as well as defossilization through changes to syngas sourcing, has the potential do decrease the emissions in the sector. Assuming a conversion rate of 0.74 tonnes of CO_2 and urea import of 150,911 tonnes (in 2020), the total potential reduction for Sweden can be calculated [32], [39], [51], [73].

Carbon uptake potential:

$$\text{Urea Potential} \cdot \text{Conversion Rate} = kg/year \tag{1.15}$$

$$150\,911 \times 10^3 \cdot 0.74 = 111\,674 \times 10^3 \text{ kg/year} \tag{1.16}$$

In November 2020, the INITIATE project was officially launched which aims to demonstrate a symbiotic and circular process by using carbon-rich steel gases as feedstock for urea production. The project will be integrated into Swerim's facilities in Luleå, Sweden [74].

1.7.2 Direct utilization methods

As previously mentioned, indirect utilization methods are defined by not chemically altering the CO_2 before utilization. Instead, the CO_2 is used as is in different, often by stimulating organic processes. Examples of these types of methods, their processes, and total potential, is presented below.

Algae

Algae are a diverse group of photosynthetic organisms with high oil and protein contents, making them an attractive alternative for CO_2 gas sequestration from a perspective of eco-sustainable process productivity. As phototrophic organisms, algae need sunlight, CO_2, nutrients (nitrogen, phosphorus, potassium), and water with a temperature of 20 -30 °C for optimal growth [75], [76].

Based on cellularity, microalgae and macroalgae are the two main types of algae. Most scientific articles that review CCUs methods refer to the cultivation of microalgae. For this reason, the following information refers to microalgae, a species of unicellular algae that can live alone or in colonies. Microalgae production does not require arable land and can be grown on marginal lands, such as deserts, brackish water, and embankments, and hence does not compete with food crops or renewable fuel production for resources. However, it still requires large land areas, and a source of nutrient-rich water together with CO_2 source [75], [77]. Microalgae cultivation can use CO_2 from flue gases of power plants containing SO_x and NO_x [78].

Due to the existence of a large diversity of algal species, a wide variety of products can be produced, such as lipids (used to produce biochemicals/pharmaceuticals), proteins (used as animal feed), biomass (used as solid, organic fuel, fertilizers, etc.), carbohydrates (used in bioethanol production/energy generation), and oxygen. Nowadays, commercial microalgae biomass is mainly used to produce cosmetic and nutraceutical ingredients [79].

Due to the unique complexities and technological developments related to the different end products of algae, an overall TRL for the process does not provide a fair overview of the CCU method. Sources estimate the TRL of algae as a CCU process between 5 and 8 [71] [80]. Algae-end products are split into two general groups to provide a clearer overview of the different processes and TRLs in the CCU algae landscape.

1. **Biomass.** Similar to other agricultural products, the algae are grown and utilized as the end product. This does not require large development of supporting processes for successful utilization; instead, increasing the CO_2 level of the growing chamber stimulates growth. This includes farming for cosmetic and nutraceutic ingredients. The partial utilization as biomass is the most established method, with a TRL of 8 [80]. There are factors limiting the prominence of algae biomass as a CCU. These are related to the re-release of CO_2 during consumption. Low water solubility and mass transfer efficiency leads to only circa 10 % of the CO_2 being stored and utilize [81].
2. **Fuels.** Know as "Algae fuel", algae can produce an alternative to traditional biofuel sources, where the fuel synthesized through cultivation in an CO_2 enriched environment. Algae fuels include two main subgroups. Firstly, methane through "anaerobic digestion of the algal biomass" [82]. Secondly, biodiesel through oil from microalgae, as algal contains a high oil content compared to traditional terrestrial crops [83]. The technological development of these submethods differ, due to the different processes required for a financially and environmentally justifiable large-scale process. Related to the TRL scale, utilizing algae as a possible fuel source has a TRL level of 5 [80].

There is a growing interest in microalgae cultivation in Sweden. Swedish Algae Factory, Simris Alg and AstaReal are examples of companies developing products from cultivated microalgae. Swedish Alga Factory claims that in its production of 1 kg of Algica (which is algae) at least 8 kg of CO_2, 1 kg of nitrogen and 0.1 kg of phosphorus are trapped [84]. Production volume, and thus potential uptake, is not available. Along with carbon sequestration other benefits can be obtained from the cultivation of microalgae. Proof of this is the partnership between Vattenfall and AstaReal, which used the excess heat from the algae cultivation process to heat 2,500 apartments in Gustavsberg, Sweden. The companies claim that Gustavsberg residents gets about 20 per cent of their heating needs from the new technology [85]. Due to the many applications of algae depending on type and target, as well as the relatively unknown potential of algaes in the region, potential abatement have not been calculated for this method.

Agriculture

Currently, 689 companies are conducting vocational agriculture in greenhouses in Sweden. This amounts to a total of 291 hectares of area cultivated [86]. Due to the controlled environment of a greenhouse, where temperature, light, and irrigation are regulated, CO_2 is the limiting factor of growth rate for plants in greenhouses. One example of utilization in agriculture is Sweden's largest tomato farmer Nordic Green Trelleborg. In 2016, Nordic Green Trelleborg purchased and utilized 165 tonnes of CO_2 a week at the peak of the season [87]. Increasing the CO_2 concentration from an atmospheric 412 ppm to between 600 and 1200 ppm stimulates growth rate and increases yield [88] [89] [90]. The rate of injection is dependent on the absorption rate of the specific plants, but assuming an injection rate of 10 kg/1,000 m^2/hour to reach 1,000 ppm the total potential sequestration can be calculated as seen in equations 1.17 & 1.18 [89].

Carbon uptake potential:

$$\text{Total Hectars} \cdot \text{Injection Rate} \cdot hours/year = kg/year \tag{1.17}$$

$$291 \cdot 100 \cdot 8760 = 254\,916 \times 10^3\ \text{kg/year} \tag{1.18}$$

These calculations assume that the greenhouse is seen as a airtight structure without leakage. The realistic total potential of CO_2 sequestration is less due to seasonally fluctuating demands as well as aforementioned leakage.

As seen in figure 1.4 level 9 is defined by an actual system proven in operational environment. Since greenhouse-farming is well established globally, the utilization is partially limited in regards to technical development by the availability and purity of CO_2. The primary technical limiting factors are related to the carbon capture and transport processes. Furthermore, technology like censors and gauges related to the distribution of CO_2 in a greenhouse is relatively basic. This means that there are no big technical limitations within the sector related to the process of utilizing CO_2. With this background, TRL for agriculture is set as a 9.

1.7.3 CCU methods summary

To summarize, there is a multitude of CCU methods with the potential to decrease the emissions of some of the most polluting sectors in the region by providing new production lines for in demand compounds. Furthermore, CCU can be combined with bio-ecosystems like agriculture and algae to increase yield and efficiency while simultaneously consuming CO_2. Some sectors even have more potential synergies with traditional industries than just CO_2. Two example is algae and e-methanol, providing CHP-plants with waste heating generated from the cultivation process.

Table 1.2 summarizes the current potential uptake of the methods from previous section. Furthermore TRL, type, and presence of projects in the region is added to provide an overview of the landscape. Without accounting for land use change, Sweden emitted 35.85 million tonnes of CO_2 from fossil fuels and industry in 2021 [91]. The carbon reduction potential of these 6 methods would thus be 6.1 % of Sweden's total CO_2 emissions

As mentioned, two methods will be the subject of further analysis with the hope that they compared will provide sufficient background to draw conclusions related to the CCU sector as a whole. Market size combined with established projects are the two most relevant markers when deciding the relevance of further analysis for the methods. Taking this into account, e-kerosene in the aviation industry is the most suitable method for further analysis. Due to the similarities in process and feedstock demands, and due to the purpose of providing an overview and estimation of the CCU landscape in 2030, analyzing both e-kerosene for aviation and e-methanol in the chemical industry would be redundant. Therefore, the method with the third largest potential abatement, precast concrete in building materials, is chosen as the second method for analysis. By selecting utilization methods in different sectors, as well as different types, the thesis hopes to show the differences, and similarities, in the environmental benefits, commercial strength, as well legislative and resource requirements for CCU methods. The comparison is made to show overlapping and individual strengths and weaknesses to be able to draw conclusions about the state of an arbitrary CCU technology.

To conclude, out of the six most prominent CCU sectors, two have been chosen for further analysis. These two are building materials, and e-kerosene.

Table 1.2: Summary of CCU methods.

Industry	Building Materials	E-Methanol	E-Kerosene	Urea	Algae	Agriculture
Emission reduction in Sweden [Tonnes/year]	858,000	411,000	553,000	112,000	-	255,000
TRL [1-9]	7-8	7-9	7-9	9[a]	5-8[b]	9
Type of Utilization [Direct/Indirect]	Indirect	Indirect	Indirect	Indirect	Direct	Direct
Current project in Scandinavia [Yes/No]	No	Yes	Yes	Yes	Yes	Yes

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[a] Number relates to yield boosting

[b] Dependent end-compound. See heading "Algae"

Estimations and Assumptions

The potential CO_2 reduction in table 1.2 are rounded to the closest thousand tonnes. The reduction is only calculated from the CO_2 emissions “saved” for of the supplier/producer of the CO_2. The estimation do not consider any potential reduction of emissions related to any changes to the emissions connected to changes in the process. The purpose of the estimations are to provide an overview of the potential market size of the methods, and not the environmental effects of large-scale implementation. Examples of potential changes of emissions that could affect the total emission reduction but are not included in the calculations are changes to the supply chain, energy requirements for the CO_2 utilization process, and regional differences to the energy mix due related to changes to production location. It is assumed that the estimations of the potential reduction in Sweden fairly represent the Scandinavian region as a whole and that the results are translatable in terms of relative size to the Scandinavian region. Furthermore, the estimations of TRL of the different methods are an range of the data from different sources to provide a comparative picture of the current CCU landscape.

Chapter 2

Methodology

2.1 Theoretical methodology

This chapter discusses the different analytical techniques used to answer the research questions (RQs). Different aspects, such as resource availability, the type of data required, and the nature of the RQ, make it necessary to use different research methods. As a result, selecting the appropriate research methods is critical to the research project's success and providing an adequate answer to the RQ.

A qualitative approach was used for the present research. Specifically, a literature review, semi-structured interviews, and a case study approach have all been used, and are described below. The purpose is to introduce what a literature review, semi-structured interview, and case study research comprise rather than attempt to cover all the technical details of conducting the methods.

2.1.1 Literary review

The literature review has become a well-established research method in technical writing, used to synthesize sources that relate to a particular topic and guiding concepts [92]. A literature review can serve many different purposes and thus take many different approaches. Particularly, the current research is based on a scoping review methodology. Davies *et al.* [93] define scoping reviews as synthesizing and analyzing a wide range of research and non-research material to provide greater conceptual clarity about a specific topic or field of evidence.

Scoping reviews are beneficial in fields where the research literature is large, diverse, and rapidly evolving, which makes it challenging to undertake systematic reviews [93]. According to Arksey and O'Malley [94], it is possible to identify at least four common reasons for conducting a scoping study, only two of which are considered a method in their own right:

- Summarizing and disseminating research findings
- Identifying research gaps in the existing literature.

Scoping review methodology has evolved since the Arksey and O'Malley framework was introduced in 2005. Arksey and O'Malley guidance is a six-stage methodological framework that includes the following steps: 1) identify the research question, 2) search relevant literature, 3) select studies, 4) map out the data, 5) summarize, synthesize, and report the results, and finally, 6) consult with experts to inform or validate study findings [94], [95]. Figure 2.1 illustrates the six stages of conducting a scoping review. It should be noted that the method should be approached as an iterative process, requiring researchers to engage with each stage thoughtfully and, add additional steps when necessary. Articles by Levac, Colquhoun and O'Brien and Westphaln, Regoeczi, Masotya *et al.* have reviewed the scoping methodology outlined by Arksey and O'Malley provide recommendations to clarify and improve each stage, as well as additional steps.

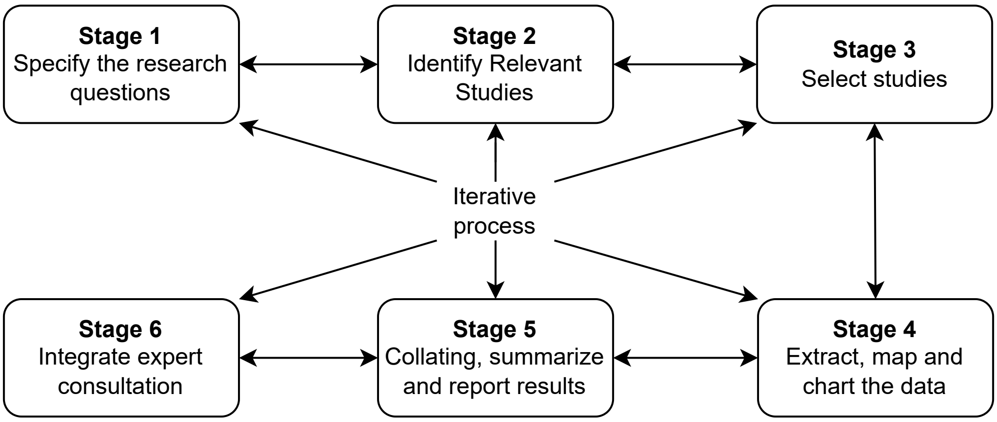

Figure 2.1: Arksey & O'Malley's framework stages for conducting a scoping review. Adapted from [95].

2.1.2 Interview research

Interviews are a common qualitative data collection strategy used across many disciplines to investigate individuals' views, beliefs, and/or motivations on specific issues through direct communication [96]. Interviews can occur in an individual or a group setting, called focus groups [97]. Qualitative interviews have been classified in several ways, the most common being; structured, semi-structured, and unstructured.

Structured interviews are verbally conducted questionnaires; by definition, they only allow for limited responses and, as a result, there is no space for follow-up questions to answers that require more elaboration. At the other end of interview methods, unstructured interviews have more open-ended questions that allow participants to provide detailed responses. Unstructured interviews are performed without much or no organization; the interviewer must generate, adapt, and develop follow-up questions that reflect the research's primary goal. Due to the lack of defined interview questions, they are considered time-consuming and challenging to manage and participate in, which provides very few guidelines regarding what to discuss [96], [97].

In this paper, the method of interest is semi-structured interviews. According to Kallio, Pietilä, Johnson *et al.* [98], this is the most common technique used in qualitative research. Semi-structured interviews are characterized by their versatility and flexibility and can be used with individual and focus groups. They require some prior knowledge of the research topic and are typically organized around a set of predetermined open-ended questions [98]. Both the interviewer and the interviewee participate in the interview, which incites additional questions through an interpersonal dialogue and may lead to further investigation of new topics [96], [97].

Several authors have established a method to conduct qualitative interviews. Creswell [99] exposes two authors' work, with seven stages method, with similar scope. The main difference falls in the logical sequence of the process, which can be strictly followed or considered as not fixed, and therefore changed during the process.

1. Research questions
2. Identify interviewees
3. Type of interview (Telephone, focus group, or a one-on-one interview)
4. Use adequate recording procedures
5. Design an interview protocol or interview guide
6. Pilot testing

Kallio, Pietilä, Johnson *et al.* [98] analyze ten different scientific articles to produce a framework for the development of a semi-structured interview guide and identify five main phases: a) the preparation for the interview (selecting participants), b) the constructing effective research questions, and 2b) Pilot testing, c) the actual implementation of the interview(s), d) interpretation data.

2.1.3 Case Study research

Crowe, Cresswell, Robertson *et al.* define case study as a "research approach that is used to generate an in-depth, multi-faceted understanding of a complex issue in its real-life context" [100]. In a typical case study, the data collection is extensive and draws from multiple sources such as observations, interviews, documents (e.g., newspaper articles), and past records [101].

According to Creswell there are three types of qualitative case studies; Intrinsic, instrumental, or multiple instrumental case study also called a collective case study [99]. The collective typology is of major interest in approaching this research. The main stages of planning and conducting a collective case study research are; 1) defining and selecting the cases, 2) collecting the data and 3) analyzing, interpreting, and reporting the cases studies. Figure 2.2 shows a schematic of the collective case study research method, where multiple cases are described and compared to provide insight into a topic, with the goal of developing a greater understanding. Creswell states that only a few "cases" are needed because for each case examined, the researcher has less time to spend exploring the scope of a particular case. Crowe, Cresswell, Robertson *et al.* provides a more detailed explanation of the main stages of conducting as well as key pointers to assist those conducting case study research [100].

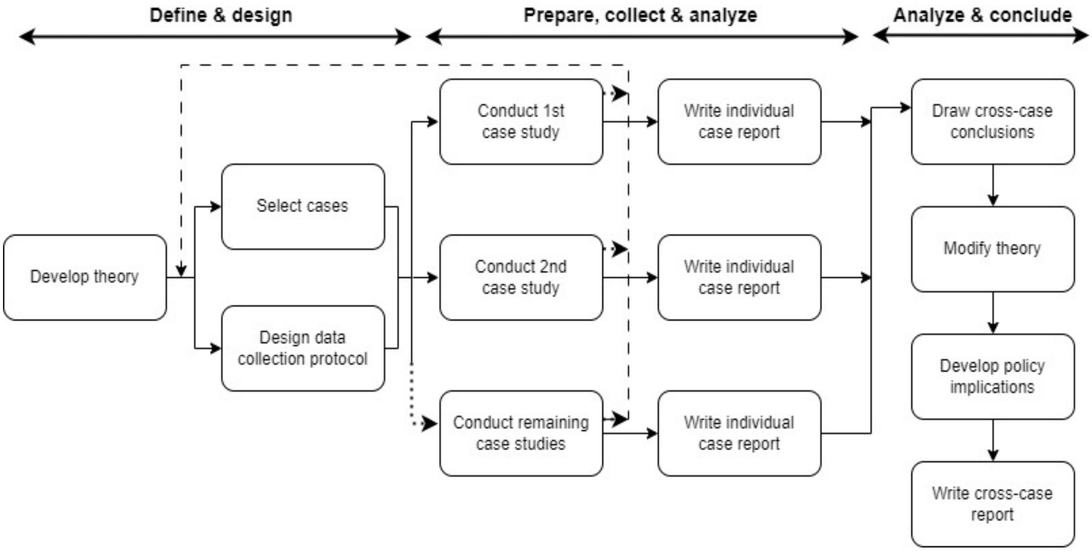

Figure 2.2: Multiple instrumental case study method scheme. Adapted from [102].

2.2 Applied method

To efficiently and fairly structure and compare the two CCU routes, a framework was constructed split into three main metrics. These are: “Technical”, representing external resources required for an successful operation. This includes raw material, geographical requirements, as well demands set on the CO_2 in terms of purity and quantity. “Commercial”, representing the overall commercial feasibility of the CCU methods both from a competing solutions and regulatory point of view. “Environmental”, representing the overall effect the method has on emissions and other environmental aspects of the original non-CCU process. This framework combined with the TRL of the respective methods will hopefully provide sufficient material to make educated estimations for the potential of the methods past 2030. The data gathering and subsequent analysis of these themes required different approaches due to the availability and confidentiality of information on ongoing projects and developing technology.

Literary research

Literary research initiated the data-gathering process. Primarily, the research focused on CCU globally, without limiting the searches to specific methods or regions. This provided the foundation required to formulate relevant research questions, and was the base for the background. The search was conducted in an iterative manner where sources provide information which helped define and limit future searches. Sources were acquired through search engines like *Google Scholar*, databases with reports from national institutes like *IVL*, and internally and externally generated material shared by the supervisor from Kraftringen. The searches were based on keywords like the following: *CCU, Carbon Capture and Utilization, Bio-mass, CHP plant, SAF, E-fuels, Sustainable Concrete, Concrete* CO_2 *, Algae, Agriculture,* CO_2*, Techno-economic analysis, BEJF*. Furthermore, combinations of keywords were also considered to maximise search accuracy. To minimize the risk of outdated information and to regulate and prioritize available source material, an age restriction of 10 years was set for CCU processes. Preferably, the source was younger than five years old at the time of access. For methodology, the source material was restricted to insure that no source older than 20 years was cited. The difference in limits between these two groups is due to the difference in maturity in the two fields.

The literary research fills two functions. Primarily, as a process parallel throughout the thesis to provide and verify data and analysis related to a specific paragraph or theme. Secondarily, as a sort of funnel, narrowing down the scope and finalizing target methods for further analysis by providing information on TRL, available projects, and potential. From the information gathered in this phase two utilization methods were chosen for further research.

Since CCU is a relatively new technique for reducing emissions, many of the larger projects in the region are still in the development phase. The data relating to actual production for each case is unavailable. In cases like this, literary research can falter, due to inferior availability of accurate real-life data. This increases the importance of expert opinions and estimations, especially from individuals closely related to each specific case. Increased weight of expert statements led to interviews being chosen as the complementing method to literary research.

2.2.1 Interviews

The interviews were conducted in a qualitative semi-structured manner, targeting experts within the different fields. A qualitative approach was chosen because of a “limited” amount of expertise available due to the degree of maturity in the two sectors and related projects. By targeting professionals in the respective projects, and relating them to the three metrics set for the case study, the scope of the interview could be narrowed down. In total, five interviews were held, and two questioner was send to two other experts. The interview actors are classified into three groups and listed below. Different actors were contacted to better understand the development of the CCU methods since their implementation demands views from several perspectives. Hence, all interviews were unique; particular questions were asked based on the interviewee’s subject knowledge, aside from broad concerns about CCU. Except for one actor, all were from the Scandinavian region.

- **Academic.** Research institutes were contacted since they could provide insight into how the research field within CCU is advancing. Furthermore, they also can highlight the needs from a policy perspective based on academic research. One institution was interviewed, and a questionnaire was sent to a second research organization.
- **Industry.** This second group is comparable to the academic category but adds competencies acquired with experience in pilot projects or production already in the commercial phase. Questions focused more on the process’s technical characteristics of specific projects or products. As with the academic category, information was gathered through one online interview and expert responses via a questionnaire.
- **Policymakers.** Governmental agencies and independent organisations involved in the specific CCU route were contacted to address the policy, politics, and regulation development concerning sustainable fuels and CCU in greater depth. Differences between the two actors

can be identified. While governmental organisations are in several ways accountable for providing incentives for early technologies to emerge, the independent organisation further supports the certification process. Two of the interviewees are included in this category.

By focusing on open-ended questions, disregarding structured and formalized lists required for structured interview studies, the goal was achieve dynamic interviews. Prepared questions set a foundation from which the interview could evolve. This allowed for interviews where the expertise of the interviewee could steer the conversations in relevant directions. Due to interviewees' relation to each of the methods, interviews had organic structure related to the metrics previously mentioned. Interviewees were chosen due to their relevant expertise in one or more of the specific CCU methods, or due to their relevant expertise in one or more of the specific CCU metrics set up for the case study.

After determining the research questions, the first step in interview preparation is identifying experts in the study areas. The following information is obtained from potential interviewed actors: name, role, and email address to establish contact, explain the purpose of the investigation, and request their cooperation by conducting an interview. In all of the interviews, the experts were asked to identify other individuals in their field who were knowledgeable about the topic under consideration to conduct follow-up interviews with them.

2.2.2 Framework

The analysis stage of the case study is shaped after a uncertainty based framework. To structure the thesis, as well as provide a sustainable and broad foundation from which conclusions could be drawn, a framework containing the main indicators related to the health and future strength of the CCU methods, as well as the uncertainties related to these indicators is created. Uncertainty assessments provide a valued overview of the landscape with the goal to directly effect the decision and policy making. The uncertainty assessment framework is divided into three main parts, with increasing generalization and decreasing specificity:

1. Indicator.
2. Uncertainty.
3. Metric.

From a structural point of view, indicators can be viewed as the building blocks that together make up the levels (uncertainties) that together provide insights into the metrics. As mentioned, the metrics are technical, commercial, and environmental. Similarly to the case study methodology described in figure 2.2, the individual metrics (called cases in the figure) can then be analyzed separately for each CCU method to draw cross-case conclusion related to the uncertainties of the sector. For some of the indicators, specific numeric estimations are relevant, for others, comparative estimations where traditional value chains are compared to the CCU-based alternative. For these, "lower", "unchanged" or "higher" are used to mark the comparative result.

To construct the framework, the primary structure of indicators, uncertainties, and metrics was developed to simplify the metrics by separating them into their constituents. The intention off this structure is to, by defining and analyzing the individual indicators, clarify and define the state of the uncertainties.

Figure 2.3 provides an overview of some of the main indicators for a market consisting of products and services derived from CO_2. The figure is one example of data retrieved from the literary analysis which, combined with inputs from expert interviews and other literary sources, provided the most relevant and valid indicators. The indicators were structured and grouped into uncertainties, and sorted into the correct metric. The indicators represent the main method for assessing each uncertainty. The resulting framework is presented in the table 2.1.

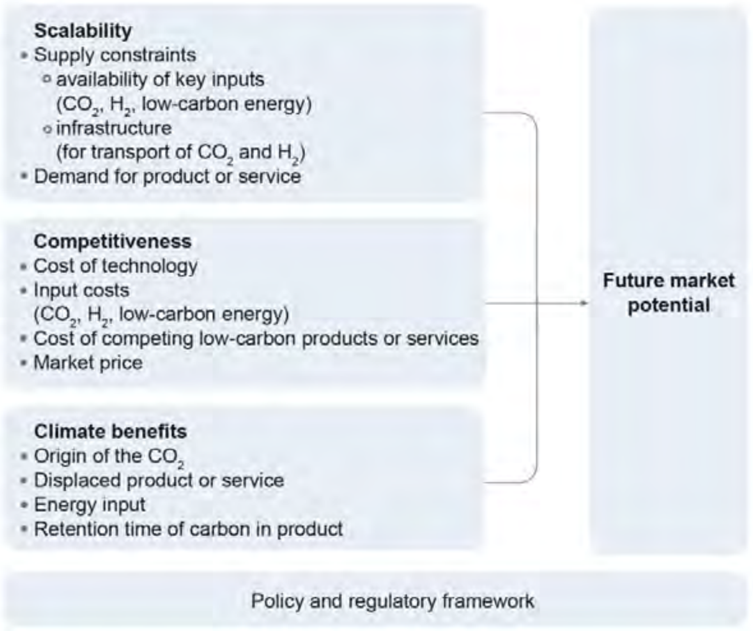

Figure 2.3: Main indicator for a future market potential of products and services derived from CCU [31].

The division into uncertainties and their constituent indicators allows for a simplification of data that standardizes the comparisons between the selected CCU methods. Through this overview, key uncertainties related to the continued development and deployment of CCU methods in the Scandinavian region can be determined. The system combines quantitative and qualitative data to define and draw conclusions, where individual indicators are defined by one or both of these data types.

2.3 Uncertainties

To understand the importance and impact of the different uncertainties related to the potential development and deployment , it is relevant to understand the constituents and their definition. The key indicators, and their definition, for each uncertainty is presented below.

Table 2.1: Framework for evaluating CCU methods

Uncertainties	**Key Indicators**
Technical Uncertainties:	
1. *Technical capability and scalability* - The uncertainty relates to the technological strength of a system and the requirements for large-scale implementation.	- TRL the of systems & dependent subsystems - Established projects - Scalability
2. *Energy and resource requirements* - The dependency and availability of resources required for a large-scale implementation is unclear.	- CO_2 requirements - Other raw material requirements - Energy requirements
Commercial Uncertainties:	
3. *Economic viability and market potential* - The financial strength and possible profitability presents an uncertainty for potential investments in the sector. Related to *"Policy, politics, and regulations"*	- Primary market potential - Secondary market potential - Comparable market price of end product - Post-production competition
4. *Policy, politics, and regulations* - CCU depends heavily on the design and developments in policy and regulations; uncertainties related to the structure of these instruments affect the implementation.	- Political commitment to CCU - Public perception - Landscape of policy, regulations and financial support
Environmental Uncertainties	
5. *Long-term environmental impact* - It is unclear what the environmental impact of large-scale implementation is long-term. And how these effects relate to other emission-decreasing solutions.	- Climate impact - Sector associated emissions and non-CCU competitive routes - CO_2 retention time
6. *Availability & sustainability of geographical resources* - It is unclear how sustainable resources will be secured without negative effects on surrounding ecosystems.	- Land requirements - Water requirements

It is important to note that all indicators might not be as relevant for both of the two methods due to the innate differences related to the different technologies. Furthermore, the chosen indicators might not be the optimum metric for a specific method. While this is the case, by compiling and analyzing groups of indicators, it is possible to draw conclusions about the general state of the uncertainty for that method. While the individual complexity of each method might be lost, an overview and general picture of the state of the methods is gained, which in the focus of this thesis.

Uncertainty 1. "Technical capability and scalability"

"The uncertainty relates to the technological strength of a system and the requirements for large-scale implementation."

It is necessary to explore uncertainties related to capability and reliability of a system as the continued investment into the development of the system is highly dependent its technological state. Furthermore, the flexibility of a system, both related to raw material and scalability, will impact its solidity once up and running. The relevant indicators that need to be assessed to understand the state and uncertainties related to the capability and scalability of a CCU system are presented below:

- TRL of the system and dependent subsystems

- Established projects
- Scalability

Established projects providing a proof of concept in the region combined with the TRL of a system and its constituent subsystems are important indicators of the state of technology in a potential market. While TRL provides an overview of the current state of the relevant technologies and further investments required for the large-scale implementation, established competitive solutions provide stakeholders with a non-theoretical measurable metric that the CCU solution is feasible. Potential versions of competing solutions further strengthen the sector as the cost of product innovation is higher than the cost of product imitation. Furthermore, it is a well-understood phenomenon that competition increases innovation. With high uncertainties related to policy and regulations (See *"Uncertainty 4. Policy, politics, and regulations"*), the possibility of beneficial implementations and changes to these instruments increases with the size, strength, and volume of stakeholders in a field. The lack of large-scale projects adds uncertainty to the scalability and reliability of the technology. Furthermore, through decreased political presence, uncertainty increases.

Scalability divides into two types: "Technical scalability", related to the TRL of the subsystem as dependencies on underdeveloped systems can limit scalability, and "Environmental scalability", related to the production site, like land requirement and expansion possibilities. Scalability in a system effects the long-term flexibility of the system. Furthermore, high scalability possibly decrease CAPEX as growth and expansion is flexible with time.

To understand the uncertainties related to the technical capability and scalability of a system, the technical state, and scalability need to be well understood. Without these inputs, estimations related to the future state of a system will be incomplete.

Uncertainty 2. "Energy and resource requirements"

"The dependency and availability of resource required for a large-scale implementation is unclear"

It is necessary to explore uncertainties related to energy and resource requirements as the validity and sustainability of a production system are highly dependent on the raw material required for the production of the end product. Similarly to the indicators explored in Uncertainty 1, availability, scalability, and flexibility of raw material are relevant factors when investigating uncertainties of a system. The relevant indicators assessed to understand the state and uncertainties related to the energy and raw material demands of a CCU system are presented below:

- CO_2 requirements
- Other raw material requirements
- Energy requirements

The requirements set on CO_2 and other raw material affect its availability and the productions sensitivity to fluctuations within the supply. Uncertainties related to CO_2 and other raw material required for production are divided into two types. Firstly, "Qualitative requirements" relates to the qualitative standards set on the raw material for production. High qualitative requirements limit flexibility as increased demands on quality limits both supply and available suppliers. Secondly, “Quantitative requirements” relates to the volumetric demands set on the supply of the raw material. This relates to both demanded volume for production and cycle time of delivery. Furthermore, quantitative requirements are related to the sensitivity to short term changes in supply. Some processes require a constant and steady supply of raw material with a specific quality, while others are not as sensitive to the availability, but are instead more adaptive. Factors relating to the sensitivity in these sectors include the possibilities of long-term storage of the raw material and the stability of consumption rate.

Other raw material requirements are related to the availability of added resource required for the CCU process outside CO_2. This includes resources previously not required in the sector, which now is added due to the addition of CCU. It also includes large changes in the demand for raw materials currently used within the sector. The indicator provides aims to highlight changes to raw material consumption required when comparing traditional production to CCU-based production. Materials that overlap in volume and type will not be analyzed in this section, as it is not affected by CCU processes and is thus outside the scope of the thesis.

The requirements on energy, related to the amount consumed by production and the price sensitivity, affect the flexibility of production and possible production sites in the region. The methods’ sensitivity to fluctuating energy prices, partially through energy requirements per unit of product, affect the quantity of possible production sites. Furthermore, a flexible method with dynamic and agile production, adaptive to the cost of electricity without negatively affecting efficiency, benefits in times of the increased price fluctuations. Dependent on a method’s consumption, electricity prices might deter production in regions that otherwise are vastly favorable in other important metrics.

Uncertainty 3. “Economic viability and market potential”

“The financial strength and possible profitability presents an uncertainty for potential investments in the sector.”

It is necessary to explore uncertainties related to the economic viability and market potential of a method, as the validity and sustainability of a production system are highly dependent on its financial state and strength. Supply and demand set the foundations for the profitability, and thus the viability, of a method. Regulated through policies and regulations, see Uncertainty 4, the indicators presented provides an overview of the potential of a product in a market. The relevant indicators assessed to understand the state and uncertainties related to the economic viability and market potential of a CCU system are presented below:

- Primary market potential
- Secondary market potential
- Comparable market price of end product
- Post-production competition

The size of the primary market in relation to competition and the actors inside the market affects the potential profitability of a solution and the probability of large-scale implementation. The market potential is an important marker that can incentivize or deter actors when deciding where to develop solutions.

Some end products fill functions outside its main market, opening up the possibility for alternative revenue streams to cover the cost. The definition of the secondary market used in this thesis refers to potential markets which currently are not utilized by companies within the method's sector but which one day can provide an alternative, although smaller, income streams outside the primary target market. The presence of these markets decreases risk as the dependency decrease due to an increased pool of potential consumers. Furthermore, some processes produce by-products that can generate income outside of the primary market. These alternative income streams also decrease risk, similar to the availability of alternative markets for the main product.

Comparisons between the market price of the end product and the current non-CCU solution provide an overview the state of the technologies. Furthermore, the required support policies and regulations for large-scale implementation can be estimated through this comparison. The relationship between the differences in both pricing and emissions of a CCU solution to its competing non-CCU counterpart is one of the most important indicators when discussing the overall potential of a solution. Solutions with a higher price-level and low environmental potential are unlikely to become established solutions on the market. Especially without regulatory support, which is unwarranted if the solution does not have the environmental advantages.

The indicator "Post-production competition" targets the extent of similar and competing CCU solutions within the sector. While the results might be similar to "Established projects" in uncertainty 1, this targets the battle for the market share.

Uncertainty 4. "Policy, politics, and regulation"

"CCU depends heavily on the design and developments in policy and regulations; uncertainties related to the structure of these instruments affect the implementation."

It is necessary to explore uncertainties related to the policy, politics, and regulations related to a method, as the development and financial stability of a production system whose primary benefits are noncompetitive on a free market, they provide decreased emissions but at a higher cost, are highly dependent on the support from government institutions. Furthermore, the absence of suitable policies and regulations can be a central obstacle in the development and large-scale CCU implementation in the region. The relevant indicators assessed to understand the state and uncertainties related to the policy, politics, and regulations for a CCU system are presented below:

- Political commitment to CCU
- Public perception
- Landscape of policies, regulations and financial support

The political commitment to CCU relates to the priority set on facilitating development and implementation. One of the primary barriers presented in the interviews with experts within

CCU was the challenges of the currently underdeveloped policy and regulatory frameworks, both on a regional and EU level. The political commitment provides a preview of the character of policy and regulatory frameworks that may be implemented. While this does not provide a definite answer to the uncertainties related to the future state of the policy and regulation, it provides a glimpse of the direction of these legislative tools. The political commitment sets the foundation for the materialization of policies and regulations for the supported implementation of CCU methods.

The public perception of CCU is an influential driver of political commitment and the implementation of regulatory frameworks and policies. The public acceptance of CCU solutions, compared to available alternatives for decreasing emissions, can either be a driver or brake for the implementation of new technologies [103]. One example of public perception and opinion affecting the environmental policy in the region is the political shift regarding nuclear power seen in Sweden. Nuclear power has gone from an outdated temporary power source soon to be dismantled to an important factor securing cheap green energy within the country [104].

As mentioned, the status quo of policies, legislation and financial support are highly dependent on the political commitment and the public perception of CCU. “Landscape of policies, regulations and financial support” indicator aims to “find” the legislative policies, regulations and financial support related to developing, constructing, and implementing CCU solutions. These tools target easing legislative anchors that slow down large-scale implementation, making end-products more financially viable and motivating investments in the sector.

Uncertainty 5. “Long-term environmental impact”

“It is unclear what the environmental impact of large-scale implementation is long-term; and how these effects relate to other emission-decreasing solutions.”

It is necessary to explore uncertainties related to the long-term environmental impact of a method, as the validity and potential investments into a CCU system are highly dependent on its potential to decrease emissions long-term. The environmental benefits of a large-scale implementation of a CCU method, combined with the current state of implementation of solutions decreasing emissions, set the foundation for all investments, including regulatory and policy investment through subsidies and other governmental tools. The relevant indicators assessed to understand the state and uncertainties related to the long-term environmental impact of a CCU system are presented below:

- Climate impact
- Sector associated emissions and non-CCU competitive routes
- CO_2 retention time

In section 1.7 *Primary CCU Methods* in the background, a first approximation of CO_2 emission reduction was calculated; and two different approaches were use. Now, a climate impact indicator is use which takes into consideration the carbon uptake potential and the carbon footprint of CCU-based product. The potential carbon uptake potential is related to the current consumption of the end product and the CO_2 required to produce an equal amount of the end product. The estimation assumes that the consumption of the CCU-based end product produces the same amount of emissions at the time of consumption. Furthermore, the carbon uptake is closely related to the "CO_2 requirements indicator". While CO_2 requirements account for CO_2 consumed during production, it does not take the GHG emissions produced during production into account. For this reason, the carbon footprint reduction of the CCU-product is also indicated. The *Climate impact*indicator provide a comparative overview of the potential environmental impact of the large-scale implementation of a method which, when combined with the other indicators, provides the long-term environmental impact of a method.

The indicator "Sector associated emissions and non-CCU competitive routes" solutions represent the availability and utilization of alternative solutions for decreasing emissions within a sector. As the name suggests, this includes both the current sector associated emissions, the difficulty of decreasing these emissions, and the non-CCU alternatives available. One example of this could be compensating emissions by planting trees. The spread of the utilization of these alternative methods depends on factors like the availability, the technological requirements of systems and subsystems, and their cost. For CCU methods to be a relevant alternative, the state of current non-CCU methods must be subpar to CCU in one or more of these dependencies. How difficult it is to decrease emissions within a sector depends on a large set of factors. For sectors with difficulties decreasing emissions, compensating actions to offset the emissions can be utilized. By analyzing these alternatives, the willingness to implement CCU-based methods into the ecosystem of the method can be estimated. Overall, the willingness to implement CCU-based methods are dependent on the current emissions and the alternatives available to reduce these. The indicator provides an overview of the availability and efficiency of the current attempts to decrease emissions within a sector.

The CO_2 retention time is how long the time it takes for the CO_2 to enter the atmosphere. Depending on the method, some have instant feedback of emissions to the ecosystem, while some utilization methods are almost semi-storage. For methods with instant consumption and emissions, where the CCU product is a replacement, the environmental benefit does not come from decreasing emissions at the consumption site. Instead, the benefits come from reduced consumption and dependency on fossil fuels.

Uncertainty 6. "Availability & sustainability of geographical resources"

"It is unclear how sustainably raw material will be secured without negative effects on surrounding ecosystems"

It is necessary to explore uncertainties related to the availability and sustainability of geographical resources for a method, as the potential of a specific CCU in a specific region is highly dependent on the availability of locally required resources like water and land. If a region cannot meet the demands of foundational resources, which are difficult/impossible to source, a method can be excluded as a prospect in the region.The relevant indicators that need to be assessed to understand the state and uncertainties related to the availability foundational resources of a CCU system are presented below:

- Land requirements

- Water requirements

Similar to Uncertainty 2, the indicators analyzed here are hyper-connected to the location of the production site, as these indicators relate to the physical location of production. Furthermore, these indicators represent resources that are in high demand on a societal level and that are limited to local availability. For these indicators, the requirements of a specific method can limit the possible sites for large-scale implementation available globally.

The indicator “Land requirements” relates to the area and type of land required for large-scale implementation of a method. The indicator includes both area for the production site and the land area required for the infrastructure meant to support production, like land required for area sources. Furthermore, land requirements related to siting also include competition for the land, as large-scale implementation should not displace highly valuable utilization methods like food production, nature reserves, or settlement space.

Similarly to land, water is a highly contested resource, as it is one of the basic requirements for human life. This means that in case of scarcity, resources will be allocated accordingly, with drinking water being prioritized. Furthermore, it is a resource affected by regional abundance and regional scarcity depending on the geographical location. This locality, related to the unique availability of the resource, limits possible sites for CCU methods with high demand. The effects on the ecosystem locally due to increased consumption of water should be taken into consideration when evaluating siting.

Chapter 3

Results

Two CCU methods will be analyzed and graded in three main metrics, commercial, environmental, and technical, according to the uncertainty matrix 2.1 presented in section 2.2. The two types of CCU were chosen due to their potential abatement, the availability of relevant large-scale projects in the region, and clear differences between their target markets and sectors.

Furthermore, to be able to do a more thorough technical analysis of the different methods, one pathway with a single end product for each method has been chosen. These are precast concrete for building materials and e-kerosene through PtL and FT routes for the aviation industry.

Precast concrete in the building industry and e-kerosene for the aviation sector both represent a high possible abatement in sectors with formidable usage of fossil fuels, providing a valuable substitute for reducing the emission burden of the end product.

3.1 Results Precast-concrete

Below are the results of each indicator detailed in the previous chapter for the case of carbon-cured precast concrete. This overview aims to highlight both the opportunities and drawbacks of CCU in the precast concrete sector and its contribution to achieving net-negative emissions. It should be noted that the public perception indicator is not specific to the analyzed CCU route, and results are shown for all CCU technologies.

3.1.1 Technical capability and scalability

TRL of the system and dependent subsystems

As mentioned in the background, the TRL for precast concrete is 7-8. See table 1.2. Overall, while carbonation is a well-understood process, large-scale implementation is still under development, with a limited number of actors providing large-scale proof of concepts.

Established projects

Although there are currently no ongoing projects for CCU within the building materials industry in the region, projects are being developed globally. These are primarily in North America and Europe. See “Building Materials” in section 1.7.1 for examples of companies in this sector. In pre-cast concrete production, the process of mineralization due to reaction with the CO_2 in the air is a natural process which happens in all pre-cast concrete production sites. Since these production sites do not use increased CO_2 concentration during the curing phase, these are not counted as CCU methods.

Scalability

CCU for building materials is the mineral carbonation process where CO_2 is captured during the mixing and curing phase. The scalability of this method is directly related to, and dependent on, the scalability of concrete manufacturing. Scalability up to the current max capacity of the cement production is high, while the scalability to increase the CO_2 utilisation depends on the utilisation location. Land area for the carbonation processes and precast concrete are the main limiting factors for environmental scalability, but this is not related to the CCU process itself. Therefore, the relative scalability of CCU for building materials is estimated to be equal to traditional methods.

3.1.2 Energy and resource requirements

CO_2 requirements

The conversion rate, i.e. tonnes of CO_2 per tonne concrete, for precast concrete with CCU carbonation ranges from 0.06–0.19 [32], [40]. As presented in “Primary Market Potential” below, the estimated market potential in the Scandinavian region is roughly 16.9 million tonnes yearly. To meet the amount of CO_2 required for the market potential, between 1-3 million tonnes of CO_2 would have to be captured yearly. And, CO_2 demand should range between 1.4 and 4.6 million tons annually to meet the estimated market potential in 2030.

For concrete, the CO_2 requirements range from low-medium when compared to other CCU methods like FtL-processes [32], [105]. Furthermore, the process is relatively unaffected by pollution like NOx and SOx in the CO_2 based emission mixture. The qualitative requirements of CO_2 for carbonation in concrete are estimated to be low, meaning that the gaseous mix input does not need to have a high purity of CO_2.

Other raw material requirements

Precast concrete production uses a mixture of cement and aggregates which hardens and cures over time. The curing/mixing process locks CO_2 into the material during a carbonation process where the CO_2 molecule reacts with minerals like calcium while simultaneously driving out the water. While CO_2 utilization decreases time and increases carbonation, no extra nor new materials are required outside of the added CO_2, compared to traditional precast concrete production. This means that there are no other raw material requirements when compared to traditional precast concrete production. Summarized, since there are no added other raw material requirements, it is estimated that other raw material requirements are estimated to be equal to traditional methods.

Energy requirements

Up until the curing stage of the precast concrete, the process does not differ whether CCU is utilized or not. Instead, energy requirements due to CCU are only related to the curing process. Increased curing temperature decreases “time until desired strength” which increases the efficiency of the process; this lead to curing temperatures of as high as 90 °C. Due to weaknesses at high temperatures due to impurities in the cement, the highest curing temperature recommended today is between 65 - 70 °C [106]. By increasing the CO_2 concentration curing through steam heating is made obsolete. While it is difficult to estimate the scale to which energy consumption is affected by implementing CCU-based curing due to the complexity of estimating the energy efficiency of the current steam-based curing system, as well as the energy required for CCU application, studies show that carbonation-based curing is a more energy-efficient alternative when compared to steam curing [38], [105], [107]. The carbonation process is exothermic, meaning that energy is released, limiting the amount of energy required to drive the process. It is estimated that energy requirements are relatively low when compared to traditional alternatives. This means that there should not be any energy constraints when analysing the possible large-scale implementation in the region. The energy requirements for the process are estimated to be lower than traditional curing methods.

3.1.3 Economic viability and market potential

Primary market potential

The size of the concrete market is generally directly measured in the cement market size. As concrete consists of coarse aggregates, water, and cement, the limiting and most important constituent becomes cement. Estimates show that concrete consists of circa 14 % of cement, while circa 30 % of the global concrete market is made up of precast concrete [42], [43]. Assuming that the proportion between the concrete market size and the precast concrete market size is the same in Scandinavia as in the global market, the primary market potential can be calculated according to equation 3.1. The result is presented in table 3.1.

$$\frac{\text{Cement Market} \cdot \text{Concrete to Precast}}{\text{Cement to Concrete}} = \text{Potential} \tag{3.1}$$

The results in table 3.1 represent an estimation of the total market potential as of today. Some sources say there is an upwards trend globally for precast concrete, with an estimated combined annual growth rate of 5.2 % until the year 2050 [43]. Assuming the rate is similar in Scandinavian, the total market potential would increase by 42.5 % and equal to roughly 24 million tonnes yearly by the year 2030.

Table 3.1: The primary market potential for precast concrete in the Scandinavian region.

Market [Million Tonnes / Year]:	Cement [41]	Concrete [42]	Precast Concrete [43]
Denmark	3	21.4	6.4
Sweden	3.1	22.1	6.6
Norway	1.8	12.9	3.9
Total Scandinavia	7.9	56.4	16.9

Secondary market potential

For CO_2 utilization within building materials, the increased CO_2 concentration during mixing or curing does not change the end product from an output or "consumption" point of view. Furthermore, there are no new secondary markets that are not available for non-CCU precast concrete. While the market for precast concrete contains several sub-markets depending on the end use, these fall under the umbrella of the primary market. Furthermore, there are no financially beneficial by-products of this method. The secondary market potential for CCU within building materials is assumed to be low.

Comparable market price of end product

As the difference between conventional precast concrete and CCU-based precast concrete lies in the curing phase, any difference in market price depends on the cost of curing. One of the main contributors to cost is CO_2. Depending on this cost and potential CO_2 credits, the CCU-based precast concrete cost can equal, or even be cheaper than, traditional precast concrete [107]. As mentioned in "Energy requirements", developments in the area can lead to decreased energy requirements and therefore decreased costs. As CO_2 becomes a more readily available cheap resource, the production cost primarily depends on the CAPEX. With technological developments, this is also estimated to decrease. Overall, the comparable market price of the end product is estimated to be equal to, or lower than, traditional product offerings.

Post-production competition

The primary competitor to CCU-based precast concrete is the traditional production lines. While the pricing of end-product and availability today may differ due to limits within the CCU ecosystem, this gap will decrease with time. Furthermore, due to the similarities in the process developments, traditional production methods will almost definitely spill over and affect and benefit CCU-based concrete. With the increased demand for sustainable options, a growing market, and limited alternatives due to niche product offerings and the relatively "low" level of technology required, post-production competition is estimated to be low.

3.1.4 Policy, political and regulatory uncertainty

Political commitment to CCU

At the EU level, there has been a political commitment to decarbonizing cement and concrete industries following the EU's carbon neutrality goal. For example, the EU's New Circular Economy Action Plan (CEAP), adopted in March 2020, includes carbon removal through long-term storage in products such as mineralization in building materials. In addition, it mentioned that the commission would explore the development of a regulatory framework for carbon removal certification, and it should be completed by 2023 [36], [108].

Likewise, from CEMBUREAU, the European Cement Association, there is the ambition to reduce CO_2 intensity along the value chain to reach carbon neutrality by 2050. Their plan mentions implementing technologies such as CCUS explicitly [109]. Report [110] highlights the difference in decarbonizing cement over concrete, as the CEMBUREAU target implies with the CO_2 emissions reduction percentage; 30 % for cement, and 40 % down the value chain by 2030 compared to 1990 [110]. At a country level, it has been possible only in Sweden to find a defined target for the cement and concrete sector. The goal is to have carbon-neutral concrete on the market by 2030 and used everywhere in Sweden by 2045 [111].

Public perception

Public perception or social acceptance of CCU plays an important role in developing CO_2 utilization technologies. Several authors [25], [112]–[114] have conducted studies on public awareness of CCU. For the present work, four key factors influencing support for CCU have been established: awareness of the solution, the safety of technology, contribution to mitigation effort, and acceptance & general attitude. Table 3.2 summarizes the public perception results according to four key factors for each GHG emissions reduction pathway based on article's findings. It is important to recall that the public perception described in this table might range according to geographic location, cultural background, and other specific factors. It is based on assumptions and generalizations.

Landscape of policies, regulations and financial support

Several policies and regulations already govern specific significant challenges in the EU's cement sector. Some of the directives under which the EU has jurisdiction to regulate pollutant emissions are the *Industrial Emissions Directive*, the *Renewable Energy Directive*, and the *Waste Framework Directive*, which are all mentioned in the general overview done in section 1.4. These directives and their corresponding minimum requirements are transposed into national legislation. Each EU member state can choose how to meet these minimum requirements and whether to go beyond them. Furthermore, the concrete and cement industry is subject to the EU ETS, a key instrument for driving decarbonisation [109]. The EU has also funded research and development of low-carbon cement and concrete through its Horizon 2020 program, Innovation Fund, and Modernisation Fund.

Table 3.2: Comparison of public perception for five GHG reduction pathways

Key factors	CCU	CCS	Renewable Energy	Energy Efficiency	Planting trees
Awareness of the solution	Less well-known and less understood than CCS	Relatively low	Well-known and understood	Well-known and understood	Well-known and understood
Safety of technology	Sceptical	Concerns, particularly in communities near storage sites	No concerns	No concerns	No concerns
Contribution to mitigation effort	Viewed as potential solution, but uncertain about effectiveness	Viewed as potential solution	Viewed positively	Viewed positively	Positively, but concerns about the actual impact
Acceptance & general attitude	High level of initial acceptance	Mostly favourable, but there can be some opposition in communities near storage sites	Favourable, but some opposition in communities near sites	High level of acceptance	High level of acceptance

As evidenced by the political commitment, more effort must be made at the state level. In the case of Denmark and Norway, no specific policies for decarbonising the industry and cement sectors existed at the time of this study. In contrast, work has been produced by the Swedish research institute, RISE, under the BETCRETE 2.0 and 3.0 project, a multi-stakeholder partnership to enable and accelerate the implementation of the roadmaps' goal for the development of climate-neutral concrete [111].

3.1.5 Long-term environmental impact

Climate impact

As described in the methodology, the climate impact regarding emissions on the CCU route must be taken carefully. *Climate Impact* indicator differentiates between *carbon absorption potential*, or CUP, and *the prospect of emission reduction in the production line*. Estimating these values is a challenging task. Generally, finding a unified value in the literature is difficult due to different assumptions, system boundaries, and life cycle stages in LCA analysis. Consequently, a detailed analysis is outside the scope of the project. However, an estimate is shown to get an idea of the potential to reduce precast concrete's carbon footprint and contribute to a more sustainable future. The CUP for the Scandinavian region is estimated using the same approach as in section 1.7.1, which calculates the amount of CO_2 that can be captured during the curing process of precast concrete using CO_2. The calculations consider the cement content in precast concrete, the proportion of precast concrete replaced by carbon-cured concrete, and how much CO_2 is captured per unit of carbon-cured concrete. Results are shown in Table 3.3.

Table 3.3: Carbon uptake potential of precast concrete in the region.

	CUP [Million tonnes CO_2]
Denmark	0.80
Sweden	0.83
Norway	0.49
Total Scandinavia	2.11

However, CUP measurement is not directly tied to the ability of a specific CCU method to reduce net CO_2 emissions. The use of CO_2 curing instead of the typically utilized steam curing procedure reduces energy usage as well as CO_2 emissions throughout the process [40]. Several model cases show that incorporating CO_2 into the production of conventional concrete reduces the carbon footprint by around 5 %. According to CarbonCure, this decrease translates to avoiding 6.5 kg of CO_2 per ton of concrete [34].

Sector associated emissions and non-CCU competitive routes

The cement industry faces significant challenges in reducing GHG emissions; the sector is rapidly expanding to meet the increasing need for infrastructure, especially within developing countries. However, demand for cement in Europe has remained constant over the past 20 years and is anticipated to do so for the following decades, as shown by Favier, De Wolf, Scrivener *et al.* [115]. In addition to increasing global demand, manufacturing concrete is energy intensive and heavily reliant on fossil fuels. Despite efforts to develop new low-carbon concrete and cement technologies, large-scale implementation remains challenging due to the higher costs of these solutions [35], [115], [116].

Consistent with the literature, different strategies are proposed to reduce the carbon footprint of concrete, such as alternative fuels, reuse, and energy and resource efficiency [115]. Following these routes, however, will not be enough to achieve climate neutrality in the concrete industry, as mineral decomposition ($CaCO_3$ to CaO) accounts for 60 % of the CO_2 emissions (CaCO3 to CaO) [35], [117]. Given this, CCUS has a remarkable opportunity to benefit the industry. CO_2 mineralization, in particular, has the potential to impact emissions from mineral decomposition. According to studies, mineralization products could replace up to 1 Gt per year of the cement market [116]; but even so, the requirements for these products are several orders of magnitude lower than the amount of CO_2 that would have to be captured [115].

Certain companies attempted to offset their emissions by planting trees, along with investing in renewable energy, improving energy efficiency, and investing in CCUS. Large-scale tree planting has been advocated as a cost-effective and straightforward way of reducing carbon emissions. Additionally, it provides non-carbon advantages like restoring degraded landscapes and supporting local livelihoods. However, planting trees as a carbon offset strategy has some limitations. For instance, a number of variables, such as the type of tree, the soil, and the climate, can affect how much carbon trees store. On average, over one year a mature tree will take up about 25 kilograms of CO_2 from the atmosphere. However, as noted, the storage capacity depends mainly on its mass, as observed with the specific uptake of these three species: Poplar (400 kg/m^3), Weymouth Pine (1,000 kg/m^3) and Ebony (1,400 kg/m^3) [118]. Furthermore, newly planted trees require time to grow and mature, during which they absorb less carbon [119]. To get an idea of the carbon absorption efficiency of trees in terms of CO_2 curing CCU method, the company Solidia Technology states that 30 Solidia concrete blocks will absorb 22 kg of CO_2 in production. In contrast, for one tree, it will take a year to do the same [120].

CO_2 retention time

CCU technologies are a proven approach to reuse CO_2 (a commonly considered waste element) in other products, thus reducing the amount of CO_2 released into the atmosphere. Alternatively, even a method of reducing CO_2 concentrations, if this is captured directly from the atmosphere. However, depending on the CCU-based product, the carbon retention time can vary, with the carbon being either permanently stored in the product or eventually released back into the atmosphere. When CO_2 is used to cure concrete, it becomes a permanent storage solution because CO_2 combines with calcium ions in the cement to form calcium carbonate, which becomes a permanent component of the concrete structure.

3.1.6 Availability & sustainability of resources

Land requirements

The evidence in CO_2 curing suggests that its development has little impact on land use. CO_2 curing, according to Solidia Technology company, requires no additional land for specialized facilities and can be implemented using existing infrastructure [121]. As a result, the land use requirements of CO_2 curing are comparable to those of traditional curing methods. It is important to note that this comparison only considers the curing process and does not consider CO_2 capture and transport, as this is beyond the scope of the current analysis. This may have implications for the technology's land use requirements.

Water requirements

CO_2-curing, as previously mentioned in section 1.7.1, is a process used in the production of concrete that involves using CO_2 to cure the concrete instead of traditional methods that use water and steam. Water's function during CO_2-curing is to provide the initial hydration required by the cement to react and form the concrete's solid structure. Unlike traditional methods, which require continuous wet curing with large amounts of water, CO_2-curing requires only a small amount of water during the initial hydration stage. This is due to the fact that the CO_2-curing process can take place at ambient temperatures and pressures, eliminating the need for water to control the curing process's temperature [31], [107]. After the initial hydration stage, the CO_2 curing process takes over and hardens the concrete. The water utilized during the initial hydration process is no longer required at this stage and can be recovered and reused. Solidia

Technologies, a cement and concrete technology company, has developed a sustainable concrete curing technology, and indicate that during the CO_2 curing process, between 70 % and 80 % of the water used in the concrete composition can be recovered [122].

The potential for water reduction with CO_2 curing concrete depends on several factors, such as the type of concrete mixture, the curing temperature, and the duration of the curing process. The water-to-cement ratio for a typical concrete formulation varies from 0.35 to 0.4 tons of water per ton of cement [122]. Based on these numbers and the market potential calculated in section 3.1.3, the yearly water footprint, WF, in Scandinavia Region in 2030 can be calculated according to equation 3.2.

$$\text{WF} = \text{PreCast Market} \cdot \text{Precast to Cement} \cdot \text{Water to cement ratio} \tag{3.2}$$

Solidia Technologies, a cement and concrete technology company, reports water consumption reductions of 30 % - 40 % during concrete production using CO_2-curing. Considering these values, table 3.4 shows the yearly WF in Scandinavia in 2030 using CO_2-cured concrete instead of conventional curing.

Table 3.4: Yearly water consumption for production of conventional curing process and CO_2-curing.

Water consumption [Million liters]	Conventional curing	CO_2-curing
Denmark	1,069 - 1,222	642 - 733
Sweden	1,105 - 1,263	663 - 758
Norway	642 - 733	385 - 440
Total Scandinavia	2,816 - 3,218	1,689 - 1,931

3.2 Results E-kerosene

Below are the results for the CCU product: e-kerosene, as has been done in the case of precast concrete. For some of the indicators, detailed product information is unavailable; therefore, e-fuels are analyzed as a whole. The public perception indicator is not specific to the analyzed CCU route. The results are for all CCU technologies and shown in the previous section 3.1 *Results Precast-concrete*.

3.2.1 Technical capability and scalability

TRL of the system and subsystems

As mentioned in the background, the TRL for precast concrete is 7-9 (See table 1.2). The primary limiting subsystem of e-kerosene production is electrolysers. See section 3.2.1 *Scalability* for further explanation of electrolyser dependencies.

Established projects

In 2022 the Prime Minister of Denmark, Mette Frederiksen, announced the target to make domestic aviation fossil-free by the year 2030 [64]. Green Fuels for Denmark (GFDK), led by Ørsted, is one example of the large-scale implementation of this CCU method. By constructing a large production plant combined with the required infrastructure like energy production, the plant will produce e-kerosene for the region's aviation sector. The project, which also includes e-methanol for shipping and hydrogen production for long-haul trucking, can potentially reduce Denmark's total emissions by 1.77 %, by replacing 270,000 tonnes of fossil fuels annually by the year 2030 [123]. Ørsted cooperates with logistic companies like A.P Möller-Maersk & DVS, airports and airlines like SAS & Copenhagen Airports, technological partners like TOPSOE, Nel & Everfuels, and consultancies like COWI [56].

Scalability

According to experts within the field, the most significant barrier to the scalability of the e-kerosene systems is the technical scalability of the electrolyzers required to produce hydrogen gas (H_2). Furthermore, electrolyzers stand for the largest contribution capital and operational costs [65]. Combined, scalability is primarily dependent on the development and cost of electrolyzers. E-kerosene is, when compared to the other methods analyzed, an elaborate process highly dependent on several complex subsystems. Limits to critical subsystems and the complexity of the process mean that the relative scalability of e-kerosene is estimated to be lower than traditional fuels.

3.2.2 Energy and resource requirements

CO_2 requirements

The following calculations present quantitative CO_2 requirements [kg] for e-kerosene to meet the estimated demand in 2030. Fagerström *et al.* [65] composed the estimated values for the CO_2 requirements for BEJFs synthesis. The estimated yearly demand for sustainable jet fuel in the region in 2030 is 6.64, 5.65, 6.57 PJ for Denmark, Sweden, and Norway, respectively [124]. To produce 1 MJ of FT BEJFs, 0.2425 kg of CO_2 is required, i.e. to produce 1 PJ of FT BEJFs 242,500 million kg of CO_2 is required [65].

$$\text{Convert [t/PJ]} \cdot \text{Demand [PJ/year]} = \text{Total [t/year]} \tag{3.3}$$

Experts have, in interviews, stated that the CO_2 purity requirements of these processes are high. This is due to the sensitivity of the catalysts required in the process, as they are highly affected by pollution from molecules like SOx. While no literary sources have been found related to the purity demands of e-kerosene production specifically, studies show that the qualitative requirements for the synthesis of other liquid fuels, like methanol, have high qualitative requirements set on the CO_2 [32], [125]. With expert opinions combined with requirements of similar processes, the qualitative requirement of CO_2 for e-kerosene production is estimated to be high, meaning that the gaseous mix input does need to have a high purity of CO_2.

A summary of the quantitative CO_2 requirements per country, as well as the total quantitative CO_2 requirement for the region, and the qualitative requirement of each method, is presented in table 3.5.

Table 3.5: The qualitative and quantitative CO_2 requirements for the e-kerosene in the respective countries.

	Qualitative and quantitative CO_2 requirements
Qualitative Requirements	High
Denmark [million tonnes/year]	1.6
Sweden [million tonnes/year]	1.4
Norway [million tonnes/year]	1.6
Total Scandinavia [million tonnes/year]	4.6

Other raw material requirements

For the production of e-kerosene, the two raw materials necessary is H_2O (for electrolysis of H_2) and CO_2. See "CO_2 requirements" (Uncertainty 2) and "Water requirements" (Uncertainty 6) for further analysis of these. No other raw material is directly required for the process.

Energy requirements

The production of e-kerosene can be broken into three main steps (CO_2 capture and transport, and electrolyser production excluded) [65]. An overview of the step-by-step process of Power-to-Liquid production is presented in figure 1.9. The three main production steps are:

1. Electrolysis. Generation of hydrogen gas from water.
2. Flue gas generation. Generation of syngas-rich stream.
3. Fuel synthesis. Generation of BEJF through Fischer-Tropsch process.

The following calculations present the energy requirements, in MJ, for producing 1 MJ of fuel. Fagerström *et al.* [65] composed the estimated values for the energy requirements for BEJFs synthesis used in the calculations below.

$$\text{Electrolysis} + \text{Flue gas} + \text{Fuel synthesis} = \text{Total Energy} \tag{3.4}$$

$$6.0975\,\text{MJ} + 1.893\,75\,\text{MJ} + 0.996\,\text{MJ} = 8.987\,25\,\text{MJ} \tag{3.5}$$

This roughly means that for every 9 units of energy put into production, 1 unit of energy is output in the form of e-kerosene. The conversion rate of electricity to fuel, 8.99, is the sum of the energy requirements, which is calculated in equation 3.5. As previously mentioned, the estimated yearly demand in 2030 is 6.64, 5.65, 6.57 PJ for Denmark, Sweden, and Norway, respectively [124]. Furthermore, the conversion rate of PJ to GWh 1 to 278 [126]. From this, the total yearly electricity demand in GWh for the estimated demand of BEJFs for each of the nations can be calculated.

$$\text{Convert [PJ/PJ]} \cdot \text{Demand [PJ/year]} \cdot \text{Convert [GW h/PJ]} = \text{Total [GW h]} \tag{3.6}$$

Table 3.6: The estimated energy demand for e-kerosene 2030

	Energy demand [GWh]
Denmark	17,127
Sweden	14,573
Norway	16,946
Total Scandinavia [GWh]	48,646

To meet the estimated demand for BEJFs in the region, it will require circa 49 TWh (48,646 GWh) yearly. As seen in table 1.1, the yearly energy production in the region is 359.6 TWh, which means that large-scale implementation would need circa 14 % of the total electricity produced in the region today.

3.2.3 Economic viability and market potential

Primary market potential

While the total potential of e-kerosene technically equals the total amount of jet fuel consumed in the region, this estimate does not account for the TRL, the political commitment, the differences in production cost, and the developments/investments required to reach production, which can meet this demand. This taken into consideration, the estimated market potential within the region in 2030 decreases substantially. Currently, there are limits to the blending level of bio-jet fuels, and it is not allowed for more than 50 % of the fuel blend to come from these types of sources [127]. While this does not currently include e-kerosene due to its very limited availability, it is reasonable to expect that similar limits will be in place when large-scale production is more readily available. This should also be considered when estimating the total potential of e-kerosene. As previously mentioned, the estimated yearly demand for sustainable jet fuel in the region in 2030 is 6.64, 5.65, 6.57 PJ for Denmark, Sweden, and Norway, respectively [124]. For a realistic estimation of market potential, where the previously mentioned reduction factors are taken into consideration, these values will be used for the estimation. For e-kerosene, the table shows the previously mentioned yearly demand, which is in the unit PJ, in liters. Conversion from PJ to liter is presented in equation 3.7.

$$\frac{\text{Estimated Demand [PJ]} \cdot 10^9\,\text{[MJ/PJ]}}{\text{Lower Heating Value[MJ/kg]} \cdot \text{Density[kg/L]}} = \text{Estimated Demand[L]} \tag{3.7}$$

The primary market potential of e-kerosene within the region is presented in table 3.7 below.

Table 3.7: Estimated primary market potential for e-kerosene

	Market Potential [Million Liters]
Denmark	188
Sweden	160
Norway	186
Total Scandinavia	534

Secondary market potential

During the production of BEJFs through FT, secondary products are produced. These include gasoline, diesel, paraffin wax, and light fractions which are assumed to be burned internally [65]. Per 1 MJ of e-kerosene, 0.918 MJ gasoline, 0.331 MJ diesel, and 0,165 MJ paraffin wax are produced as "net-zero" by-products, which are alternatives to traditional fossil fuel-based products [65]. "E-diesel" and "e-gasoline" has the potential to be utilized in other vehicles outside aviation, primarily cars and trucks. In addition to making candles and crayons, paraffin wax is frequently utilized as a lubricant and electrical insulation. While the market for e-kerosene is less prominent outside aviation, the market for by-products is. Considering this, the secondary market potential is estimated to be high.

Comparable market price of end product

Some sources estimate a net production cost of between 0.94 and 2,4 €/L [65], [128], [129]. Others, where minimum selling price (MSP) has been estimated, calculated a MSP between 0.64 and 2.92 €/L [130]. The spread in cost/price depends on the cost and quality of H_2, CO_2, volume produced per hour, the revenue from by-products and CO_2 credits. Through sensitivity analysis on H_2 price, CO_2 price and CO_2 credits, the sources used have analyzed different scenarios leading to the price range presented. The market price of jet fuel in 2021 was 0.45 €/L. This means shifting to e-kerosene-based jet fuels would mean a fuel price increase between 42 % and 649 %.

Post-production competition

Aviation is well-established means of transportation, with fossil-based propulsion being the global standard. Competition within the sector is fourfold. The sustainable transport fuels are presented in figure 3.2, with fossil fuels included as a non-sustainable competitor. The potential competition from these four types of fuels will be ranked as "low", meaning a low potential threat to large-scale implementation, "medium", meaning a medium potential threat to large-scale implementation; and "high", meaning a high potential threat to large-scale implementation.

1. Fossil fuels

2. Synthetic biofuels
3. E-fuels
4. Hydrogen

The differences between the end product of e-kerosene and fossil-based fuels are displayed in environmental impact and cost of production. With the increased demand for a sustainable solution, combined with a political commitment to this CCU method (see Uncertainty 4), the long-term competition from fossil fuels decreases. Competition from fossil fuels is currently high but with long-term competition estimated to be low.

E-fuel is an umbrella term for fuels synthesized from hydrogen and raw materials like carbon dioxide or nitrogen. Similar TRL and availability to FT e-kerosene include alcohol-to-jet, liquefied methane, and ammonia. While these are not the focus of this thesis, the technical and financial state of these do not differ greatly from FT-based process [131]. With this said, FT is the target method for the large-scale production of sustainable aviation fuels. FT-based e-kerosene has the largest commercial presence in the region, with the Green Fuels for Denmark consortium as well as Norsk e-fuel AS currently constructing large-scale production plants [56], [132]. Even though there are many similarities within the different e-fuels, the lack of commercial plants for the other methods decrease competition. Overall, the competition from other e-fuels is estimated to be medium.

While synthetic biofuels are more readily available, question marks arise related to the long-term sustainability of the dependency on biomass. The potential supply of sustainable biomass limits the production of bio-jet fuel. Competition from biofuels is on the short to medium timescale high but, with the long-term competition estimated to be medium.

Alternative energy sources, like hydrogen and battery, often mentioned when discussing the decarbonization of sectors, are not sustainable solutions for aviation. This is due to the size of batteries and gas tanks required to meet the demands of flight. Furthermore, implementing these demands a total transformation of the current fleet, while the other alternatives are so-called plug-and-play and can be used in today's fleet. Due to the practical difficulties related to the specific energy of these alternatives, combined with the total renovation of the fleet necessary for implementation, the competition from energy sources is estimated to be low.

Overall, the post-production competition is estimated to be medium.

3.2.4 Policy, political and regulatory uncertainty

Political commitment to CCU

The targets or mandates established by each Scandinavian government for the aviation sector relevant to the CCU method are exposed below to assess the CCU political commitment in the region. All three Scandinavian countries have communicated their targets and are working on policies to encourage the use of SAF in line with the overall climate goals and national mitigation roads to reduce GHG emissions:

- **Denmark**. In 2020, the Prime Minister of Denmark, Mette Frederiksen, announced the target to make domestic aviation fossil-free by the year 2030 [64].
- **Sweden** In 2015, the Swedish government established the *Fossil Free Sweden Initiative*, which connects actors to implement politically standard measures. In its flight plan, they state that domestic flights should be fossil-free by 2030 and that international flights should be fossil-free by 2045 [133]. In addition, the Swedish Government Official Reports "Biojet för flyget", released in 2019, put forward a reduction obligation quota for domestic jet fuel. However, e-fuels are not a certified process route for jet kerosene, nor are they under certification [127].
- **Norway**. The Norwegian government has not declared any specific targets for domestic flights; however, Avinor, which operates the majority of civil airports in Norway and is entirely controlled by the state, aims to electrify all domestic aviation by 2040. Alternatively, the government introduced a biofuel blending mandate. However, at the moment, e-fuels do not fall under the blending mandate for advanced biofuels [134]. In the *Aviation in Norway. Sustainability and social benefit. 4th Report* [134] its mentions that there are concrete plans for establishing the production of e-fuels in Norway but does not go into specific details.

Public perception

This indicator is not analyzed according to the specific CCU method; instead, a general view of the public perception of five GHG emissions reduction pathways is considered; CCU, CCS, Renewable Energy, Energy Efficiency, and Planting trees. Results are shown in precast concrete evaluation, table 3.2.

Landscape of policies, regulations and financial support

This section provides an overview of the current situation in the EU and each Scandinavian country regarding e-fuel policy, regulation, and financial support mechanisms. It should be noted that this is not an exhaustive analysis and that other relevant policies and initiatives may indirectly or directly impact e-fuels development. The most representative is displayed and considerate enough to recognize the effort to develop strategies and plans to advance e-fuels[1]. At the EU level, some policy actions to encourage and increase the use of SAF already exist, in line with the EU's commitment to achieving net-zero GHG emissions by 2050.

The *RED* and *EU ETS* are two essential directives and rules, as mentioned in section 1.4. With an e-fuel vision, RED II specifies that 14 % of transport energy must come from renewable sources by 2030, and RED III sets a particular objective for the usage of RNFBO in transport: 2.6 % of transport energy must be covered by RFNBO. Furthermore, e-fuels are covered in the directive's definition of renewable energy sources. Concerning the EU ETS, civil aviation in the EU/EEA has been a part of the EU emissions trading scheme since 2021 [134].

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[1] Section 1.4 gives an overview of more generic work on the CCU framework

Another comprehensive policy framework is the *Aviation Strategy for Europe*, which aims to promote a competitive and sustainable aviation industry in the EU by setting a target of a 60 % decrease in greenhouse gas emissions by 2050 compared to 2005 levels. In addition, an European industry road map to net-zero European aviation emissions has been developed under the name *Destination 2050*.

Other key initiatives are the *Fuel Quality Directive* (FQD) which sets fuel quality standards and emissions limits for transportation fuels, and *CORSIA* (Carbon Offsetting and Reduction Scheme for International Aviation), a quota system for GHG emissions, developed by the International Civil Aviation Organization (ICAO) to offset CO_2 emissions from the aviation industry.

Finally, mention the *ReFuelEU Aviation – Sustainable Aviation Fuels Legislative Initiative*, within the “Fit for 55” package, that aims to increase the supply and demand for SAF in the EU, including advanced biofuels but also e-fuels. It sets targets for using SAFs in aviation fuel and establishes a framework for producing and certifying SAFs. It also provides funding for the research and development of SAFs. For e-fuels to be eligible as SAFs, a reduction of at least 70 % of GHG emissions compared to fossil jet fuel is needed [135].

There are no specific funds for e-fuels; nevertheless, the Innovation Fund and Horizon Europe are financial mechanisms that encourage research and innovation in low-carbon technologies, including e-fuels.

The following points summarize each Scandinavian country’s national actions on CO_2 emissions reduction activities for international aviation, based mainly on State Action Plans submitted to ICAO and from the NISA report [136]–[138]. The measures listed below are complementary to the collective actions taken in Europe.

- **Denmark**. In cooperation with public-private stakeholders, the Danish government initiated the Climate Partnership for Aviation. The overall purpose of the partnerships is to establish a 2030 vision and a plan for the sector to contribute to the national 70 % CO_2 reduction target compared to 1990 levels for domestic air travel; and a minimum 30 % reduction on international air travel by 2030 compared to 2017. The overall vision for the climate partnership is to achieve climate neutrality by 2050. They introduce three key initiatives and recommendations: a national climate fund financed by a small contribution from each departing passenger, a global CO_2e tax, and a national master plan for PtX infrastructure [139].
- **Sweden**. In May 2021, the Swedish parliament adopted a regulation establishing conditions for fuel suppliers to meet reduction quotas from 2021 to 2030, as well as encouraging the use of SAF by exempting high-blend SAF from energy and carbon taxes. Still, e-fuels have not yet been considered or included as an alternative in the reduction obligation. A tax on commercial flights was established on 1st April 2018 to offset the climate impact of aviation, and it is paid by passengers departing from Swedish airports [137], [140], [141].
- **Norway**. In January 2021, the Norwegian government presented a climate action plan that includes civil aviation and states that the Norwegian quota obligation (blending mandate) for advanced bio-jet fuels will be evaluated. Although e-fuels are not currently covered by the mandate, they are being considered in the action plan. Similarly, Norway’s major airlines are working to reduce emissions. For example, Avinor’s (state-owned) vision is

for domestic air traffic in Norway to be electrified by 2040, and Norwegian Airlines has committed to becoming carbon neutral by 2050. Since 2001, Norway has imposed a CO_2 tax on domestic aviation, which is expected to rise. Furthermore, Norwegian domestic aviation is subject to NOx and SOx taxes, as well as an air passenger duty tax.

3.2.5 Long-term environmental impact

Climate impact

The climate impact assessment for e-kerosene does not take into account the CUP. In this case, it would not make much sense, since as described in section 3.2.5, the CO_2 bond in e-kerosene will be emitted quickly after its use. Hence, discussing CUP is not particularly helpful in this scenario. However, it should be noted that when biogenic carbon is used to produce e-kerosene, the CO_2 emissions emitted when the material is burned should not be regarded as impacting global warming.

In section 1.7.1 the climate impact was calculated as potential abatement, according to the actual emissions caused by domestic flights in Sweden. On the other side, multiple studies [65], [124], [142]–[144] evaluated the GHG intensity of synthesizing e-kerosone. Fagerström *et al.* [65] estimates a global warming potential (GWP) for the BEJF synthesis of 19 gCO_2eq per MJ of fuel, and a baseline GWP of 94 gCO_2eq per MJ of fuel in the case of the fossil fuel pathway. Figure 3.1 displays the climate impact differentiating between the production and use phase of F-T bio-electro-jet fuels compare to conventional fossil-based jet fuel [65].

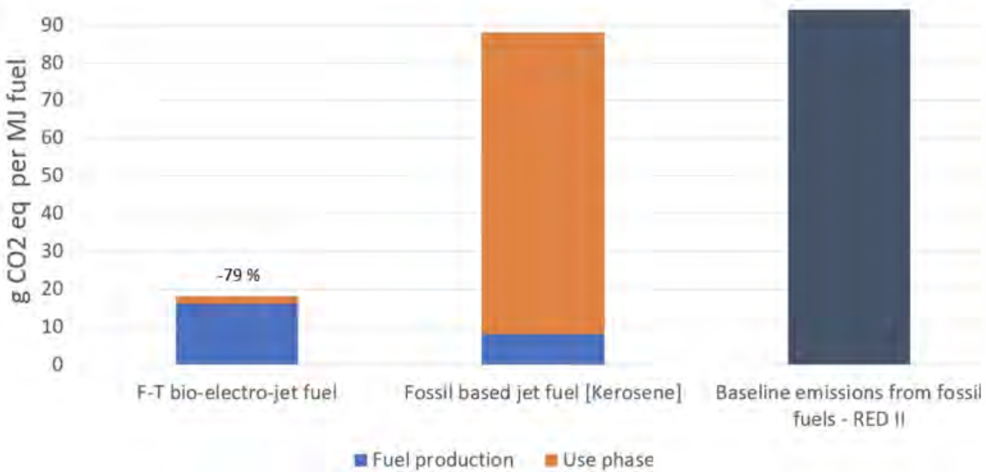

Figure 3.1: Life cycle climate impact and emission reduction potential of F-T bio-electro-jet fuels. Adapted from [65]

The following calculations present the potential abatement in million tones per year for future demand for sustainable jet fuel in Scandinavia countries. Table 3.8 compile the results for each of the Scandinavian countries.

Sector associated emissions and non-CCU competitive routes

Reducing emissions in the aviation sector has proven to be a challenging task; the rapid growth of air travel has made it difficult to meet rising demand while cutting emissions. In the EU in 2017, direct emissions from aviation accounted for 3.8 % of total CO_2 emissions. According to Barke, Bley, Thies *et al.* [145], even if fuel efficiency in new aircraft improves by approximately 25 %, the predicted increase in flights would cause aviation-induced GHG emissions to triple until 2050.

E-fuels, along with direct electrification alternatives, synthetic biofuels and hydrogen, are presented as low-emissions alternatives to fossil fuels for the transport sector. There are numerous pathways to sustainable synthetic fuels, as seen in figure 3.2, together with direct electrification. However, long-distance aviation is inaccessible to direct electric or hydrogen routes, making it a hard-to-abate emissions sector.

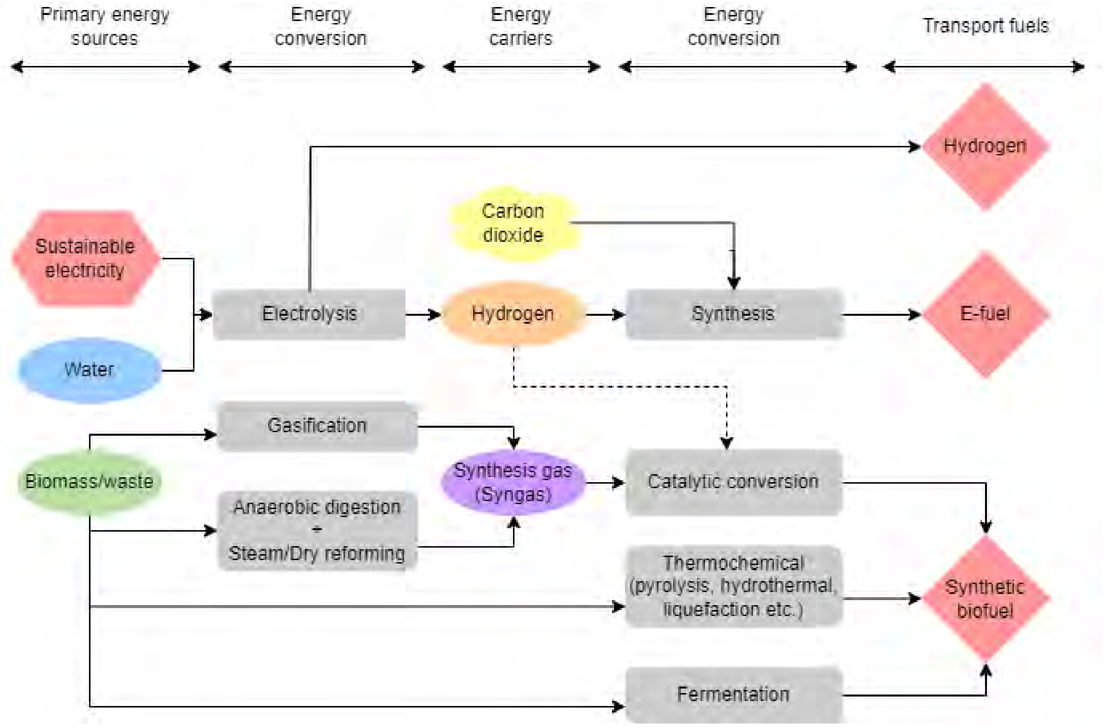

Figure 3.2: Routes to sustainable transport fuels. Adapted from [146].

$$\begin{aligned}[\mathrm{GWP}_{FossilFuel} - \mathrm{GWP}_{BEFJ}] \cdot \text{Demand SAF 2030} =& \\ = \text{Potential abatement } [\mathrm{t}CO_2eq.]&\end{aligned} \tag{3.8}$$

Table 3.8: Potential abatement of e-kerosene in tonnes of CO_2eq. per year

	Potential abatement [tCO_2eq. per year]
Denmark	497.7
Sweden	423.6
Norway	492.4
Total	1,413.1

CO_2 retention time

Carbon retention time in e-fuels is limited to the time between manufacture and use. When the e-fuel is burned, the CO_2 is released once again into the atmosphere, thereby cancelling the carbon capture during manufacturing. As a consequence of this, the carbon retention time is only temporary in this case. The advantage of the carbon capture process is due to out-competing fossil fuels rather than storage.

3.2.6 Availability & sustainability of resources

Land requirements

Land use is another performance indicator of environmental relevance. Although PtL plants do not require much space, renewable power plants, desalination plants, and CO_2 capture facilities will. An advantage noted in many studies is that producing e-fuels does not require agricultural land or fertile forest. Aside from determining the amount of land required for manufacturing, the type of land must also be considered. Renewable energy does not, in principle, depend on arable land [142], [147]. Graph 3.3 show the gross land area in hectare per year of PtL from photovoltaic and wind power compared to fossil jet fuel, for each Scandinavian country, according to future demand for sustainable jet fuels.

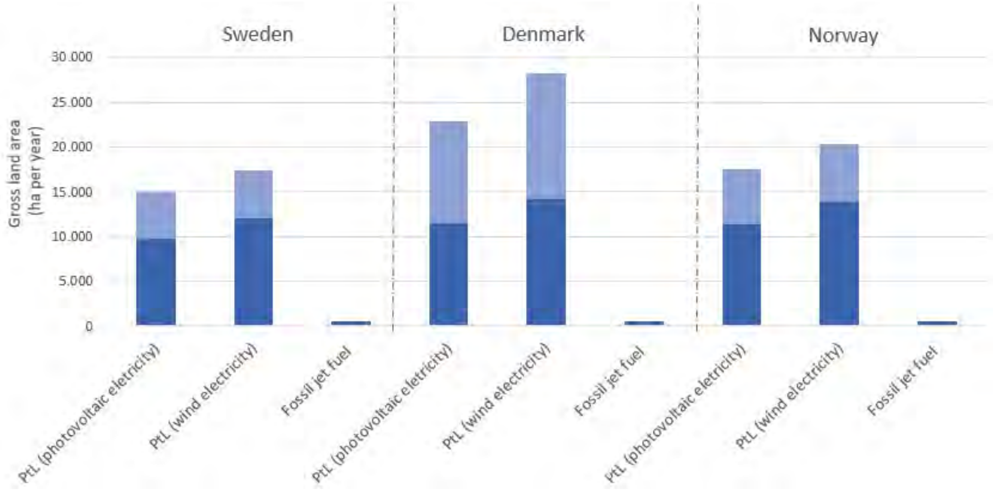

Figure 3.3: Comparison of gross area of PtL fuels from photovoltaic and wind power and fossil fuel. Adapted from [142].

Water requirements

One supply-side constraint in the production of e-kerosene is closely linked to hydrogen production, the primary feedstock for e-fuel synthesis. To generate green hydrogen using electrolysers, purified water and renewable electricity are required. Due to difficulties obtaining specific results for e-kerosene and the uncertainties in the numerous LCA approaches, generic e-fuel data is displayed and considered adequate for further discussion in the next section with other CCU methods.

The water footprint (WF) of e-fuel production differs based on several factors, including the source of water, manufacturing process efficiency, and the type of electricity used. The WF of conventional jet fuel production is not well-established, and the environmental impacts of e-fuels have yet to be compared to those of fossil jet fuel [144]. According to some estimates, the WF of fossil jet fuel can range from 1 to 3 litres per litre of jet fuel, depending on the type of crude oil and refining processes used [148]. Table 3.9 displays some average values of WF for different PtL pathways and the consumption that would correspond to the Scandinavian countries.

Table 3.9: Water demand of E-kerosene depending on energy source

Feedstock/Pathway	WF [l H_20 / l jet-fuel]	Sweden [Million liters]	Denmark [Million liters]	Norway [Million liters]
PtL via FT (wind, PV, CSP)	1.38	221	259	257
PtL fuel (decane) via FT	3.7-4.5	592-720	696-846	688-837
PtL (wind, solar) (kerosene)	1.4	224	263	260
PtL - wind power	4-5	640-800	752-940	744-930
PtL - photovoltaic	5-31	800-4,960	940-5,828	930 -5,766
PtL - CSP	28-438	4,480-70,080	5,264-82,344	5,208-81,468

3.2.7 Results summary

Table 3.10: Framework results for building materials and e-kerosene in Scandinavia

Key Indicators	**Building Material**	**E-kerosene**
Technical Uncertainties:		
- TRL of the system & dependent subsystems	7-8	7-9
- Established projects	No	Yes
- Scalability of the production	Unchanged	Lower
- CO_2 quality requirements	Low-Medium	High
- CO_2 quantity requirements	1.4-4.6 [Mt/ year]	4.6 [Mt/ year]
- Other raw material requirements	Unchanged	Unchanged
- Energy requirements	Decreased demand	4.9 TWh yearly
Commercial Uncertainties:		
- Primary market potential yearly	24 Million Tonnes	534 Million Liters
- Secondary market potential	Low	High
- Market price of end product	Unchanged	Increase with (42-649) %
- Post-production competition	Low	Medium
- The political commitment to CCU	Denmark: Not specified	Denmark: Domestic flights fossil-free by 2030
	Sweden: Carbon-neutral concrete on the market by 2030, and used everywhere by 2045	Sweden: Domestic flights fossil-free by 2030, international flights by 2045
	Norway: Not specified	Norway: Not specified
- Public perception	See table 3.2	See table 3.2
- Landscape of policies, regulations and financial support	Geographical differences see section 3.1.4	Geographical differences see section 3.2.4
Environmental Uncertainties		
- Climate Impact	CUP: 2.11 Million tonnes CO_2	CUP: No uptake, treated as “short cycle carbon”
	Carbon footprint: Reduced by 5 %	Carbon footprint: Reduced by 79 %
- Sector associated emissions	Considered a hard-to-decarbonise sector. Responsible for around 3 % of CO_2 global emissions	Considered a hard-to-decarbonise sector. Responsible for around 7 % of global and 4 % of EU CO_2 emissions
- Non-CCU competitive routes	Use of alternative fuels, material re-use, and energy and resource efficiency, planting trees	Hydrogen, Synthetic biofuel, direct electrification, planting trees
- CO_2 retention time	Permanently stored	Temporary stored
- Land requirements	Unchanged	Increased due to energy requirements
- Water requirements	30 % - 40 % reduction	60 % potential increase

Chapter 4

Discussion

4.1 CCU in the Scandinavian Region, 2030 and onward

Carbon capture and utilization have the potential to largely impact and decrease GHG emissions while simultaneously providing better alternatives to the current market products. Technological improvements, political commitment, and financial investment are required to reach this potential. Furthermore, regional specifics regarding raw material and resource requirements must be analyzed to find CCU solutions relevant to a specific country/region.

Based on the results found for the two primary methods in the thesis, e-kerosene and precast concrete, the primary indicators and their role in the large-scale implementation in the Scandinavian region and their synergies will be discussed to provide an overview of the future of CCU in the region.

4.1.1 Technical capability and scalability

"The uncertainty relates to the technological strength of a system and the requirements for large-scale implementation."

As previously presented in table 1.2, the technical readiness levels of CCU methods are generally high. Currently, limiting factors are mostly related to surrounding ecosystems, like carbon capture and transportation, financial and legislative support, and availability of established markets for end products. Additionally, even though the TRL of these methods is high, the lack of established up-and-running projects further adds to the technical limitations in the region.

As hydrogen is a detrimental feedstock in all hydrocarbon production, electrolysis constitutes a crucial subsystem. As this subsystem makes up a large part of both OPEX and CAPEX, combined with extensive energy demands (see equation 3.5), limitations to the electrolyzers considerably impact the overall system. Electrolysis constitutes a crucial subsystem in a multitude of other non-CCU solutions, from green steel production to hydrogen as an energy source. The prominence and potential of electrolysis technology will lead to investments and research which continuously improves the subsystem. While these actions might not specifically target weaknesses in hydrocarbon synthesis, the developments will benefit the CCU sector.

More investments toward developing large-scale production sites integrated with surrounding ecosystems will present currently unknown technological pain points. Due to the complexity of subsystems and their constituents, these are difficult to predict. While these are not necessarily directly related to the utilization process, it is safe to assume these will present themselves throughout the value chain. Furthermore, established projects can pave the way for competitors within the sector, with increased competition benefiting consumers, producers, and suppliers. The rate of establishment and expansion of a CCU method is highly dependent on policy and regulations discussed in section 4.1.4 below. Without the right financial stimulus, the discovery of and adjustment to the technological limitations will be limited.

Overall, while there are limited full-scale CCU projects in the region, we see no technical indicators hindering the expansion of CO_2 utilization in the region. We note that no system, especially without an established long-term presence in an ecosystem, is perfect, and without technical flaws and inefficiencies. While these are currently unknown, we do not see that the discovery of these will be detrimental to the expansion of a specific solution. Instead, further technological developments will increase efficiency and decrease cost, positively affecting the competitiveness of CCU products on the market.

4.1.2 Energy and resource requirements

“The dependency and availability of resources required for a large-scale implementation is unclear.”

The indicators are affected by the presence, strength, and resource demand from competing consumers concerning the availability of these resources. This includes companies within the same sector as the specific CCU and companies present in markets unrelated to CO_2 utilization. The three primary sectors where pre-production competition could arise are CO_2, energy, and water. For water, see section 4.1.6

CO_2 emissions from point sources with capture capabilities are the limiting factor for the availability of CO_2. Further development in direct air capture would add another potential source, but due to the limited availability and TRL, a combination of investments in carbon capture from point sources like power plants and steel plants is required to limit emissions’ negative effects on the environment. As mentioned in section 1.3, estimations for carbon capture projects calculate a total of 8.4 Mt CO_2 capture potential in Scandinavia in the year 2030. The result in table 3.10 show that up to 9.2 million tonnes would be required to meet the potential estimated demand in the Scandinavian region for building materials and e-kerosene in the same year. A limited supply of CO_2 can and will affect willingness to invest in these types of sectors, as high demand and low supply lead to increases in price. Furthermore, a part of these carbon capture projects are structured around storage, where investments in supply chains, transportation methods, and emission goals like net-negative emissions might hinder the willingness to swap from storage to utilization. Limited availability of CO_2 and complex established ecosystems for competing consumers can lead to further strain on the utilization projects, negatively affecting the willingness to invest in the technology.

Supply of the required quality of CO_2 might also be a limiting factor for specific CCUs, whereas others find flexibility in supply sources. Projects with qualitative demands will be, unless purity is increased onsite, dependent on suppliers, increasing control.

For utilization projects, one solution to this could be to partner up with established point source emitters with sufficient supply. These types of symbiosis are mutually beneficial as it offers consistency in supply and consumption, limiting risks due to fluctuations in supply, demand, and pricing. Additionally, the availability of other symbiotic points, like heating or waste products, would benefit both parties and further strengthen the partnerships.

The sustainability of CCU methods depends on the availability of a stable and renewable energy supply. This is especially true for the methods with a significantly higher energy demand compared to traditional alternatives, as synthetic alternatives are produced to out-compete fossil-fuel-based molecules. Examples of this are molecules used in the transportation or chemistry sectors like methanol, methane, and kerosene. As seen in table 3.6, meeting the estimated yearly demand for sustainable jet fuel would require roughly 49 TWh, equating to 14 % of the annual energy production in the region. While the supply in the region is primarily based on renewable sources, meaning that the source of electricity in the region will not affect the sustainability of CCU projects, recent years have shown increased volatility leading to high prices and limited availability. Even though the energy mix in the region is almost entirely renewable, see table 1.1, the cost and risks associated with fluctuating intermittent energy sources may hinder the large-scale implementation of some CCU methods. The past years, several companies with energy demanding processes has been announced in the region. Examples of these projects are sustainable hydrogen-based steel production from both H2 Green Steel and Hybrit. Assuming that the establishment of demanding processes like these points to continued stabilization in the energy production leading to decreased energy pricing, large-scale implementation of energy-intensive CCU processes should have their energy requirements met.

To summarize, the availability of required CO_2 for large-scale implementation within the region can be a limiting factor for meeting targets set within the region. On the other hand, limited supply increases the price, stimulating the development and construction of carbon capture, both point source and direct air capture-based solutions, until equilibrium is reached and demand is met.

4.1.3 Economic viability and market potential

"The financial strength and possible profitability presents an uncertainty for potential investments in the sector. Related to Policy, politics, and regulations."

As the market potential is unique for each of the different CCU methods and therefore is a relatively arbitrary metric, it is more relevant to discuss the potential market share CCU can take from traditional methods. The product's availability, the comparable market price, and environmental impact (see section 4.1.5) will be the determining factors for the financial success of large-scale implementation. As the availability of products is partially dependent on the investments being made into the sectors, which in turn is dependent on the current or future profitability of the investment, the primary driver of CCU methods' large-scale implementation is the comparable market price. The comparable market price is the market price of a unit of CCU-produced product compared to the price of a unit of traditionally produced product, assuming the price is set at a point with reasonable profit for the different producers. A solution that is substantially more expensive than its competition, without providing a sufficiently superior product in one or more metrics, will generally find it difficult to establish and expand within a sector.

There are two primary factors when discussing the comparable market price. Firstly, the price of the CCU-based end product. This factor is dependent on raw material requirements, where we previously discussed the availability of CO_2 (related to the cost of CO_2) as an important marker of the health of the CCU ecosystem, as well as production cost such, both OPEX and CAPEX, based on technological strength and availability of supporting infrastructure. Furthermore, legislative & policy are also important drivers of price. Secondly, the price of the "traditional" product. Assuming production of the traditional product is a well-established process, both the technology and supporting infrastructure are assumed to be mature, meaning that the stability of these will not affect the prices substantially long-term. Relevant drivers of price are, of course, the cost of raw material, OPEX etc, as well as taxes and tariffs due to emissions from the production or consumption of the product.

Generally, CCU solutions compete with two different types of products. Firstly, products currently dependent on fossil fuels, with limited alternatives. This includes hydrocarbons, like methanol and kerosene, and urea. Secondly, solutions independent of fossil fuel, where CCU methods would assist in capturing CO_2 inside the product. This includes building materials, agriculture, and concrete.

For the fossil fuel-dependent competitors, while fluctuations in raw materials will be seen in the short term, long-term changes in raw materials prices are primarily affected by legislation and policy. The primary driver of the comparable price will be the government and public commitment to the shift to more sustainable alternatives. For the rest of the solutions, investment cost can be the limiting factor for CCU establishment. New technology and production methods, which might have the potential to decrease OPEX, see a demand for investments in the form of CAPEX. As the product, in the end, is the cost-carrier, motivators for these investments must be presented. Similarly to fossil fuel-based methods, these motivators can tax emissions or subsidise their absence.

While we can assume that the price of CCU methods will partially decrease as technological developments and economy of scale are implemented and experience increase, the primary driver in the comparable price in the upcoming years will be the efforts put in by the national and international legislative branches to stimulate the expansion of the sector. Taxes, subsidies, and other stimuli set the tone for how developments and investments will be made in specific sectors and will dictate the comparable pricing of methods. A more in-depth discussion about these will be presented in section 4.1.4 below.

4.1.4 Policy, politics, and regulations

"CCU depends heavily on the design and developments in policy and regulations; uncertainties related to the structure of these instruments affect the implementation."

The political commitment to reduce GHG emissions is evident in the Scandinavian region. Following the European framework, the three countries have set ambitious climate targets. Their commitment to achieve climate neutrality or net-negative emissions is only possible with CCU or CCS. Hence, all Scandinavian countries are incorporating these technologies into their climate mitigation plans. The e-fuels route is evidence of this; the area is very interested in it, especially in Denmark, while Norway is more involved with CCS.

Public perception is a predominant factor influencing political commitment to CCU technologies and the effectiveness of policies and regulations. Compared to concrete, there is a greater understanding and support for lowering emissions, particularly in the aviation sector. Increasing awareness and public understanding of the technology is essential to promote CCU as a viable and effective route to reducing emissions. Stakeholders must educate the public about CCU and its potential role in climate change mitigation. As shown in table 3.2, CCU perception still has a long way to go, and more awareness and knowledge must be provided compared to the other routes presented. This is not surprising considering that the other routes have been considered for longer as emission reduction paths.

Increasing awareness and public understanding of the technology is essential to promote CCU as a viable and effective route to reducing emissions. Addressing any misconceptions or public concerns about CCU, such as its contribution to climate mitigation and security, is also critical. Consequently, accurate information about the technology as well as its policy and regulatory frameworks, is required.

Despite the region and EU's strong commitment and efforts to implement policies and regulations, a cohesive framework still needs to be developed to incentivize CCU technologies. We observed a disparity in the level of commitment between the different routes. The number of regulatory frameworks and policies to reduce emissions in the concrete sector is substantially lower than in the aviation sector. Therefore, securing funding for these projects with policies supporting the development and implementation of CCU technologies is easier.

Carbon pricing tools like carbon taxes, cap-and-trade programs, and subsidies are some regulations and incentives that encourage industries to invest in CCU technologies. For example, a higher blending mandate and carbon price will accelerate the region's transition towards renewable and e-fuels. Another potential tool is the EU ETS directive, the EU's primary tool to reduce GHG emissions. This directive can increase the willingness of industries to search for alternative solutions to reach net-zero or net-negative emissions. It can also provide the necessary incentives for industries to invest in CCU technologies, accelerating their development and implementation. As exposed in Section 1.4.1, CCU technologies still need to be recognized under the EU ETS directive.

In conclusion, the uncertainty surrounding policy, regulations, and financial support is a significant barrier to the large-scale adoption of CCU. Public perception and political commitment heavily influence the level of support for CCU technologies. Similarly, as has also been demonstrated, more effort will be required to increase political support and public awareness in the upcoming years.

4.1.5 Long-term environmental impact

“It is unclear what the environmental impact of large-scale implementation is long-term. And how these effects relate to other emission-decreasing solutions.”

It has been established that rising CO_2 levels have severe consequences for the planet and human life. Polluting industries and governments are increasingly demonstrating their commitment to reducing GHG emissions. The main ways to reduce GHG emissions are to improve energy efficiency, implement renewable energy, CCUS, and plant trees. However, some sectors or industries are challenging to defossilise, as seen in the aviation and cement sectors. Reducing emissions in these sectors is critical to meet global climate goals, and both industries face unique challenges in shifting to more sustainable practices. As seen in the course of the work, new technologies could help defossilise specific sectors and/or produce products with low carbon intensity and help when it is not possible to reduce emissions from renewable energies or improve efficiency. Overall, this is a clear example of why multiple approaches must be implemented in parallel to achieve climate goals and gradually accomplish the defossilization of all sectors, including the more “conservative” ones, such as cement, where new technologies face many barriers to entry.

When promoting CCU as a way to reduce CO_2, caution should be taken. On the one hand, there is evident potential for CO_2 uptake when manufacturing CCU-based products. Nevertheless, CUP is a fixed metric that does not account for GHG emissions associated with the manufacturing process. In this sense, it does not matter if the process is energy-intensive or if renewable or fossil-derived energy is used; that CUP will remain the same. As already discussed in other sections, it is not adequate to solely consider the carbon uptake of a CCU-based product and its impact on the environment compared with the traditional route.

The CCU’s actual benefit from a climate mitigation perspective is still being determined in many cases, with the possibility that some routes may not be as good as they promise. Hence, further research and analysis are needed to properly assess the impact of large-scale production of CCU-based products on reducing GHGs emissions. The current estimates are based on something other than an exhaustive evaluation that accounts for the CO_2 impact from CO_2 capture, transportation, and utilization. As a result, a life cycle analysis, LCA, must be performed to assess the actual environmental impact and contribution of CCU in reducing CO_2 emissions. However, there is currently no standardization in LCA, and it is expressed by the European Commission, among others, that LCAs are necessary to determine which route is beneficial. This is essential because, so far, the CO_2 impact of CCU routes has been difficult to generalize due to inconsistencies in the boundaries and scope of analysis. For example, the energy associated with the capture and transport of CO_2 is included in some studies but not in others. In short, LCAs are likely to be a pillar upon which future policies and funding initiatives will be based, and their standardization is critical to determining the current climate mitigation benefit of CCUs.

It is noticeable that achieving net-zero or negative emissions in Scandinavia will require substantial investment in CCU and CCS technologies. Many studies, including the IPCC’s, have emphasized the importance of large-scale CCU development in meeting climate targets, particularly in areas where desfossilization may be difficult or impossible.

In Scandinavia, the view on biogenic CO_2 as a climate mitigation strategy is well-established, and it enables CCU and CCS to offer near net-zero and net-negative emissions, respectively. From the side of CCU, the offer of net-zero emissions is one of the main barriers to its development compared to CCS. Although CCU has eliminated the concept of waste given to CO_2 and reused it sustainably. Even if CCU only helps to reduce fossil dependency in some cases, it can also offer a way to uptake emissions and perform as CCS, such as in the production of building materials. This highlights the versatility of CCU as a tool for reducing emissions across various sectors.

4.1.6 Availability & Sustainability of geographical resources

"It is unclear how sustainable resources will be secured without negative effects on surrounding ecosystems.

As discussed in previous sections, CCU methods are frequently presented as an innovative solution with environmental benefits, as they can potentially reduce CO_2 emissions while promoting transitional processes towards a circular economy. While CCU products can have environmental benefits and reduce reliance on fossil fuels, their implementation must be approached holistically, considering both the benefits and potential resource constraints. This way, CCU products can contribute to a sustainable and equitable transition to a low-carbon economy. Inefficient use of resources could lead to conflict if CCU methods are implemented on a large scale; therefore, it is crucial to ensure that water and land are handled in a compatible manner with long-term sustainability goals.

Water availability is a critical factor that could limit CCU deployment on a large scale, though not equally across the world or even within the same Scandinavian region. According to the database developed by the Global Facility for Disaster Reduction and Recovery, GFDRR, water scarcity[1] in Norway and Sweden is classified as very low, and it is classified as medium in Denmark, implying that droughts are possible in the next ten years by up to 20 %. Even so, water availability and the risk of depletion are critical for a proper sustainability assessment and feasibility study of CCU, as climate change is expected to exacerbate water stress in the coming years. Conflicts over water access, for example, must be avoided between CCU routes on the one hand and the increased demand for potable water from the growing population on the other.

What is clear is that purified water is needed for e-fuel production, which is in high demand for many other European applications. Using alternative water resources, such as seawater or treated wastewater, can help alleviate freshwater resource depletion. Desalination plants are a potential solution; however, it must be ensured that the development is sustainable, given that desalination raises serious environmental concerns and other potential water conflicts. Meanwhile, it appears that CO_2 cured concrete would have a lower water footprint than conventional concrete. Without examining specific values, Scandinavia is a suitable area for the large-scale development of CCU due to its low level of water scarcity. With their numerous lakes and rivers, Sweden and Norway have relatively abundant water resources compared to other regions. However, water scarcity is becoming a primary concern in certain areas affected by drought and population growth, and the potential impacts of CCU on water resources are significant. Therefore, although Scandinavia could manage it better, to ensure long-term viability and reduce environmental impact, CCU

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[1] Water scarcity describes a lack of available freshwater resources to meet annual water demand.

projects in Scandinavia must consider impacts on water resources in the context of local water availability and its efficient use.

Similarly, CCU plant development should refrain from dispensing with existing land or less profitable land uses such as agriculture, nature reserves, or settlement space. Because of Europe's densely populated areas, land space is more important than in North Africa and the Middle East. Regarding land resources, however, it appears that Scandinavia has enough to support implementing large-scale CCU applications. Added to that, it is important to consider how changing land use will affect nearby communities and ecosystems. The land would be needed primarily to expand renewable energy sources to provide clean energy in manufacturing CCU-based products. However, photovoltaic, thermal, or wind energy does not require arable land; therefore, energy and food production competition risk is significantly reduced [142], [147].

Finally, the uncertainty surrounding the availability and sustainability of land and freshwater resources must be addressed. This uncertainty might prevent large-scale CCU implementation in Scandinavia. CCU development must consider the availability and sustainability of water resources to avoid negative environmental impacts and ensure the long-term success of these applications.

4.2 Conclusion

The Scandinavian region has the potential to significantly contribute to meeting climate goals and reduce greenhouse gas emissions through the adoption of carbon capture and utilization (CCU) technology. Currently, the region is actively engaging in developing CCU, as demonstrated in different projects and initiatives; in the same way, it is heavily involved in achieving net-zero or negative emissions. In the introduction chapter, an estimate of the emission reduction potential from the use of specific CCU routes in Sweden is presented. Adopting them would result in a 6.1 % reduction in total CO_2 emissions in Sweden, with respect to 2021 levels.

Several conclusions have been drawn from the investigation of technological, commercial, and environmental uncertainties related to the potential large-scale implementation of CCU technology in the region. Greater efforts are required to provide funding and incentives for CCU projects, and the harmonization of life cycle assessments (LCAs) and monitoring protocols are essential for fair assessments of the environmental benefits of specific projects. The harmonization of LCA and monitoring would further improve the recognition of the methods, by bringing validity and comparability to analysis and estimations simplifying decision-making on all levels.

The Scandinavian region has a strong political commitment to lowering greenhouse gas emissions, with Sweden, Denmark, and Norway adopting ambitious climate goals based on the European frameworks. Frameworks for policy and regulations are essential for encouraging large-scale implementation of unique CCU technologies. While the countries have demonstrated commitment to decrease emissions with the help of CCUS, there is a disparity in the level of support between different CCU-sectors, exemplified by the legislative differences between building materials and e-kerosene highlighted in the sections 3.1.4 & 3.2.4 in the results.

Although large-scale CCU implementation is effected by the sustainability and accessibility of "geographical resources", if seems feasible that the Scandinavian region can meet these demands sufficiently. While the water scarcity in the region is low, and the solutions do not compete for arable land, problems with water shortages and disputes over land can still cause complications for the large-scale implementation of CCU technologies. The regions further benefit from the energy mix, as a predominant part comes from renewable resources. As previously mentioned, this is crucial as CCU implementation in fossil fuel based systems as a way to reduce emissions become redundant. Instead, the limitations of the region are related to availability of power, as fluctuations in price due to consumption and production peaks and dips affect the financial sustainability of projects.

Furthermore, the availability of CO_2 can constrain investment in CCU technologies. As the amount of carbon captured in the region increases due to investments into CCS, the effects of this limitation should reduce. Limited supply increases price, which stimulates investments into CC, which reduces price, assuming there is a market for the resource. Potential interest in CCU among CO_2 point source emitters can be explained by the combined monetary and environmental opportunities available. Increased regulations and taxes lead to increased monetary risk connected to emissions and incentivize investments in the sector. CCU technologies provides CO_2 producers with an opportunity to be suppliers in a new market. This market can, if combined with appropriate regulation, stimulate and utilize industries required to minimize their emission while simultaneously stimulating investments into carbon capture.

CCU technologies have the potential to make a substantial contribution to Scandinavia's efforts to mitigate climate change and decrease emissions. However, initiatives to raise public perception to motivate governmental support, create enabling regulatory frameworks, and resolve resource limitations are necessary actions to quicken the implementation of CCU. To evaluate the environmental impact and contribution of CCUs in decreasing GHG emissions, further research is required. To effectively integrate CCU technology and support international efforts to battle climate change, Scandinavia must solve these issues and capitalize on the region's dedication to sustainability. By addressing these challenges, Scandinavia can pave the way for the implementation and development of CCU technologies, decreasing the global dependencies on fossil fuels, and combating climate change.

Overall, the main advantages of CCU-based products over conventional ones are that they can reduce carbon footprints and even store CO_2; and are aligned with the principles of circular economics. Meanwhile, multiple requirements must be met before becoming standard, including technological maturity, economic viability, regulatory and political support, and consumer acceptance.

4.3 Future research

The prospect of large-scale CCU implementation is interesting, with research needed for correctly evaluating the relevance and potential of the technology. While each method, and each metric, is complex enough to motivate further research, the largest link missing is the limited development and unification of CCU and policy/regulatory systems. Examples of future research are how harmonization of CCU and regulatory structures like ETS systems can be constructed and implemented. Furthermore, unifying evaluation methods like LCA, which in turn would simplify and generalize the comparative analysis of the potential impact of CCU methods, would further clarify the sustainability of the technology.

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