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Developing the Carbon Capture and Utilization (CCU) Market in the EU: An Analysis of the Legal and Policy Framework

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ABSTRACT

Carbon capture and utilization (CCU) technologies have the potential to reduce carbon emissions while creating new economic opportunities. In doing so, CCU offers a potential win-win solution to contribute to climate change mitigation efforts, create new economic opportunities, and promote a sustainable future.

The study presents a comprehensive analysis of the European Union (EU) and the United States (US) legal and policy framework concerning CCU technologies. The objective of the thesis was to evaluate whether the EU supports the full potential of CCU deployment.

Qualitative research methods were used in this thesis, including comparative research and legal content analysis to examine the consistency, credibility, and comprehensiveness of the EU's legal and policy framework concerning CCU.

The study shows that EU policy strategies recognize the significance of CCU in decarbonizing industries, yet lack unified legislative frameworks dedicated to CCU. Despite initiatives highlighting CCU's importance, inconsistencies exist within policy instruments.

Moreover, concerning the development of the CCU market in the EU, the study emphasizes the need for regulatory clarity and comprehensive legislation to boost CCU technologies forward. Based on this, the study proposes a set of recommendations, such as establishing a clear CCU definition, implementing horizontal legislation covering all CCU pathways, and setting binding deployment targets for CCU products to foster commercialization and innovation.

Keywords: CCUS, CCU, carbon management, decarbonization policies

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1 INTRODUCTION

1.1 Background

Limiting the global average temperature increase to “well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”, as stipulated in the Paris Agreement (2015) requires swift and immediate actions and effective climate policies.

The European Union (EU), as one of the key players in the United Nation climate change talks and a key signatory to the Paris Agreement, has introduced different types of policy measures and set legally binding targets to reduce greenhouse gas (GHG) emissions. Under the European Climate Law (EC 2021b), the EU sets a binding objective of achieving climate neutrality, or as it is commonly referred to as “net-zero emissions balance”, in the EU by 2050 in line with the long-term temperature goal set out in the Paris Agreement. Additionally, as an interim target towards the 2050 climate neutrality goal, the EU has set GHG emissions reduction target by at least 55% by 2030 compared to 1990 levels (EC 2019b).

In 2022, global carbon dioxide (CO_2) emissions from energy combustion and industrial processes reached a new record high of 36.8 gigatons, marking a 0.9% increase or 321 million tons, as reported by the International Energy Agency (IEA 2023a). Alongside other available climate mitigation options, such as emission free electricity and heat, energy efficiency, circular material flows, and waste reduction, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change lists carbon capture and use (CCU) and carbon capture and storage (CCS) as climate mitigation options. The report projects that CCS and CCU will play a significant role in the decarbonization of production in the short to medium term. (IPCC 2022.)

Carbon capture, utilization, and storage (CCUS) technologies have the potential to reduce carbon emissions while creating new economic opportunities. By capturing and utilizing carbon dioxide or solid carbon to produce high-value products, CCU technologies offer a potential win-win solution for mitigating

environmental impacts, creating new economic opportunities, and promoting a sustainable future.

CCUS is gaining momentum increasingly. Countries around the world are acknowledging the importance of CCUS technologies as an option to support the achievement of their climate goals. The investment in and deployment of CCUS technologies, however, falls behind other emerging low-emission technologies (Guidehouse 2023). This is partially because most of the CO_2 conversion processes and the CO_2-derived products and services are still in the early stage of development. This makes it challenging for such products and services to compete with established alternatives, especially in the absence of policy frameworks that support the supply and demand sides of lower-carbon options. (IEA 2019.)

According to the International Energy Agency, in the scenario of achieving net zero emissions by 2050, CCUS contributes to 8% of the total cumulative emissions reduction by 2050. This entails achieving a reduction of approximately 1 gigaton of CO2 by the year 2030, contributing to a total abatement of 15 gigaton of CO2 by that date, and reaching a net-zero emissions level of 5 gigaton of CO2 by 2050. (IEA 2023b.) Scaling up energy technologies generally requires some sort of risk-sharing approach between the public and private sectors. This is especially essential to initiate the first projects and ultimately develop a commercially viable market.

In terms of CCUS, governments around the world have taken various initiatives to scale up CCUS technologies, including the European Union, the United States of America, the United Kingdom, and Canda, among others. Such policy initiatives have either focused on offering broad funding incentives or targeted support for selected projects (IEA 2023b). Having strong policy initiatives in place would provide the financing and market certainty needed for deployment and to develop CCUS supply chains and eventually attract the private sector to invest in CCUS technologies.

1.2 Scope of the Research

1.2.1 Research Aim

There is a consensus among scholars and policymakers that the emergence and deployment of climate-friendly technologies require, in addition to the availability and readiness of the technology, active policy support to create the conditions necessary for driving long-term investment and push for the deployment of such technologies into a commercially viable market (Quitzow 2015; Thielges et. al. 2022; IEA 2023b). The aim of this study is to develop a comprehensive understanding of the existing legal and policy frameworks in the EU applicable to the deployment of CCU technologies. Further, this research aims to assess the effectiveness of the current legal and policy frameworks in supporting the deployment of the CCU technologies and developing a commercial CCU market.

1.2.2 Research Objectives

Considering the aim of the study, the research objectives are set as follows:

- to conduct a comprehensive analysis of the existing EU legal and policy frameworks related to CCU
- to conduct a comparative analysis between the EU and the US legal and policy framework regarding CCU
- to identify key opportunities and challenges within the existing EU legal and policy frameworks related to CCU, assessing their impact on the development of the CCU market in the EU in comparison to the CCU market in the US
- to provide insights into the obstacles within the EU policy and regulatory framework and to propose recommendations aimed at improving the development of the CCU market in the EU

1.2.3 Research Questions

Taking the research aim and objectives into account, this research will attempt to answer the following questions:

1. Does the legal framework in the EU support the full potential of different CCU technologies?

2. How does the current legal framework in the EU compare to the legal framework in the US regarding CCU, and what insights can be drawn from the US experience to enhance the development of the CCU market in the EU?

1.2.4 Limitations of the Research

The CCUS value chain encompasses both carbon capture and use (CCU), transportation, and carbon capture and storage (CCS), as illustrated in Figure 1.

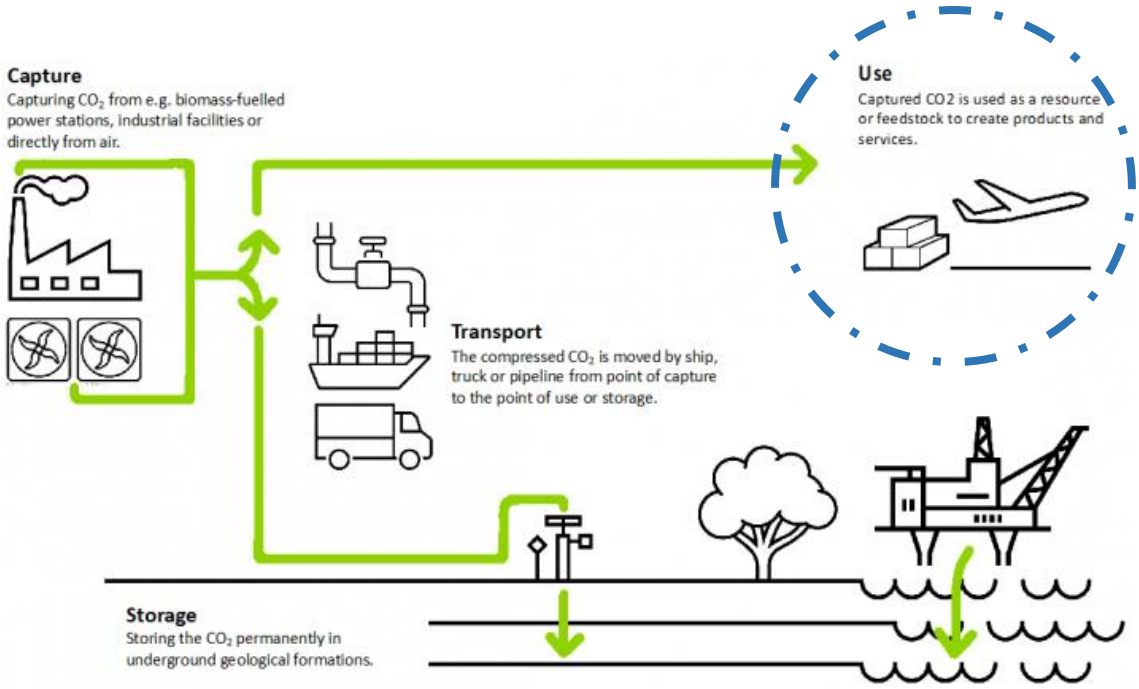

Figure 1. Carbon capture, utilization and storage value chain (European Commission 2023)

Despite the potential of CCU in the decarbonization efforts of industries, there is limited amount of academic research focusing on the legal and policy aspects affecting the development of CCU (Thielges et. al. 2022). Hence, this study will primarily focus on CCU, as highlighted in Figure 1 above. Conversely, CCS is well covered in academic research; therefore, the transport and storage segments are not covered in this study. Further, this research is subject to the following limitations:

- the comparative analysis provided herein focuses on policy and regulatory frameworks at the EU level and US federal level. No policy or regulatory frameworks in any EU member states or US states are analyzed; and
- the CCU pathways are extensive. This analysis focuses on different CCU pathways, but it excludes the utilization of CO2 synthetic fuels, as the production of synthetic fuels is incentivized through sector-specific synthetic fuels targets, such as the ReFuelEU Aviation (EC 2023i) and the FuelEU Maritime (EC 2023f) a key part of the EU's Fit for 55 legislative package.

1.3 Structure of the Study

Following this introductory chapter, Section 2 elaborates on the methodologies employed in this research as well as the methods used for data collection and analysis. Section 3 provides an overview of the concept of carbon capture utilization and highlights its potential in combating climate change and advancing circular economy. Sections 4 and 5 follow the same structure. Firstly, each section conducts a comprehensive examination of how CCU is addressed in the strategy documents of the EU and the US. Subsequently, the research delves into an exploration of how these strategy documents are translated into actionable initiatives. Section 6 provides a comparative analysis of the CCU legal and policy frameworks in the EU and the US. Drawing on the data presented in the previous sections, Section 7 concludes with a critical assessment of the CCU legal and policy framework in the EU and presents a set of recommendations.

2 METHODOLOGY AND DATA COLLECTION

2.1 Research Method

The research methodology adopted to answer the research questions is based on a multidisciplinary approach, recognizing the complex and interconnected nature of the subject matter. This research draws upon insights from various academic disciplines, including engineering, chemistry, environmental science, economics, and legal policy analysis.

The methodology aims to provide a comprehensive understanding of concept of carbon capture and utilization and its development by integrating diverse perspectives and methods. Specifically, qualitative research methods are used to address the research questions effectively. The essential legal and policy research methods, such as legal content analysis and comparative research, were deemed appropriate.

Legal content analysis allows for a comprehensive examination of the existing laws, regulations, and policies applicable to CCU. By systematically analyzing the legal and policy frameworks, this method enables the identification of key policy and legal mechanisms and their implications for the CCU development.

Additionally, comparative research methodology is used to examine the impact of the regulatory and policy frameworks on market development in different regions. The selection of specific countries and regions with distinct regulatory environments is guided by the aim of uncovering patterns, trends, and lessons that can inform policymaking and market strategies in the CCU domain.

By combining legal content analysis and comparative research, this methodological framework offers valuable insights into the nuanced relationship between regulatory and policy frameworks and their impact on the CCU market dynamics. Furthermore, the rationale for this research to select the comparative analysis of the policy and legal frameworks in the EU and the US, as a case study, is twofold:

Firstly, the US and the EU are two major players in CCUS technological development, as evidenced by the accumulative venture capital investment in CCUS in these two regions from 2015 to 2022, which constitutes 92% of the global venture capital investment in CCUS (IEA 2023d), as illustrated in Figure 2. Further, both regions have implemented initiatives to scale up CCUS technologies.

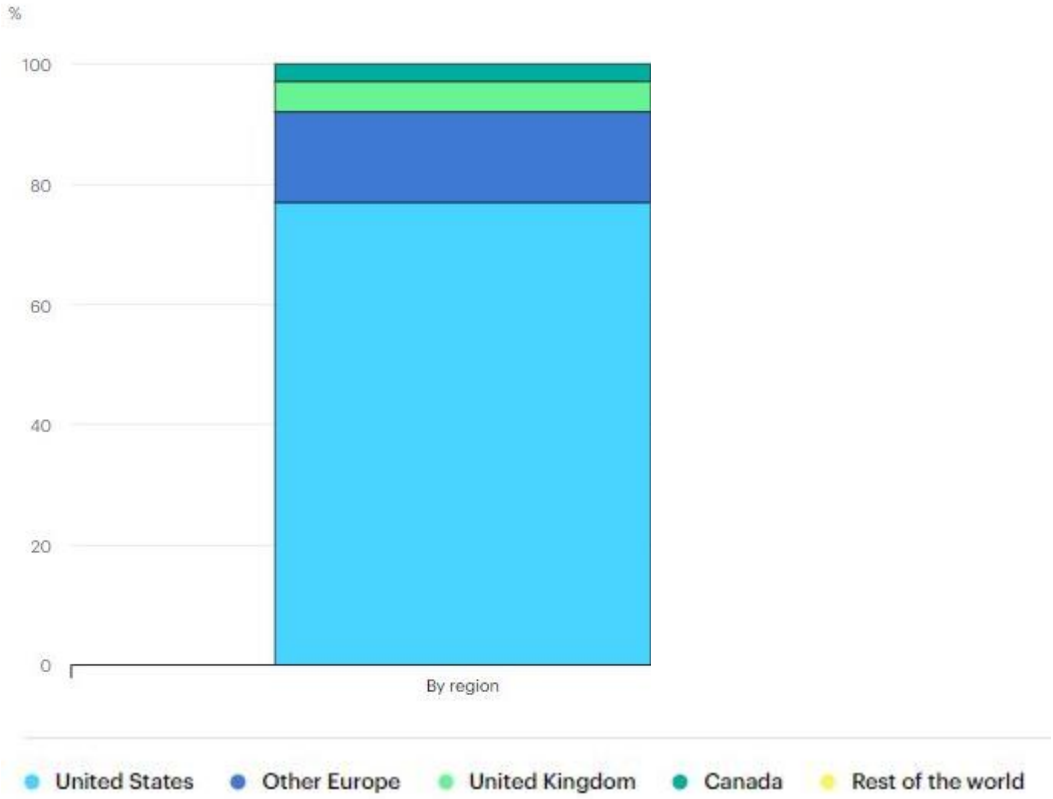

Figure 2. Cumulative venture capital investment in CCUS by region, 2015-2022 (IEA 2023d)

Secondly, the commissioning company's strategic business target is to expand its market reach into the customer markets beyond Finland, with a specific emphasis on capturing opportunities in the US market as the primary target market. Therefore, the comparative analysis will offer the commissioning company regulatory and policy insights into differences between these two regions. This information will enable the commissioning company to make informative investment decisions.

2.2 Analytical Framework

To organize the comparative analysis effectively, a set of analytical categories developed for analyzing policy mixes by Rogge and Reichardt (2016) are adopted. In their influential article titled "Policy mixes for sustainability transitions: An extended concept and framework for analysis", Rogge and Reichardt (2016) provide for a thorough analytical framework for examining policy mixes.

Rogge and Reichardt (2016) assert that the elements of policy mixes essentially consist of policy strategy and policy instruments, as shown in Figure 3. The authors define "**policy strategy**" as a set of (a) policy objectives and targets that tend to be long term, and (b) principal plans for achieving these objectives, playing a pivotal role in guiding governmental decisions and company-level R&D activities for emerging technologies. As for "**policy instruments**", the authors explain that such instruments are concrete tools to achieve the identified objectives in the policy strategy.

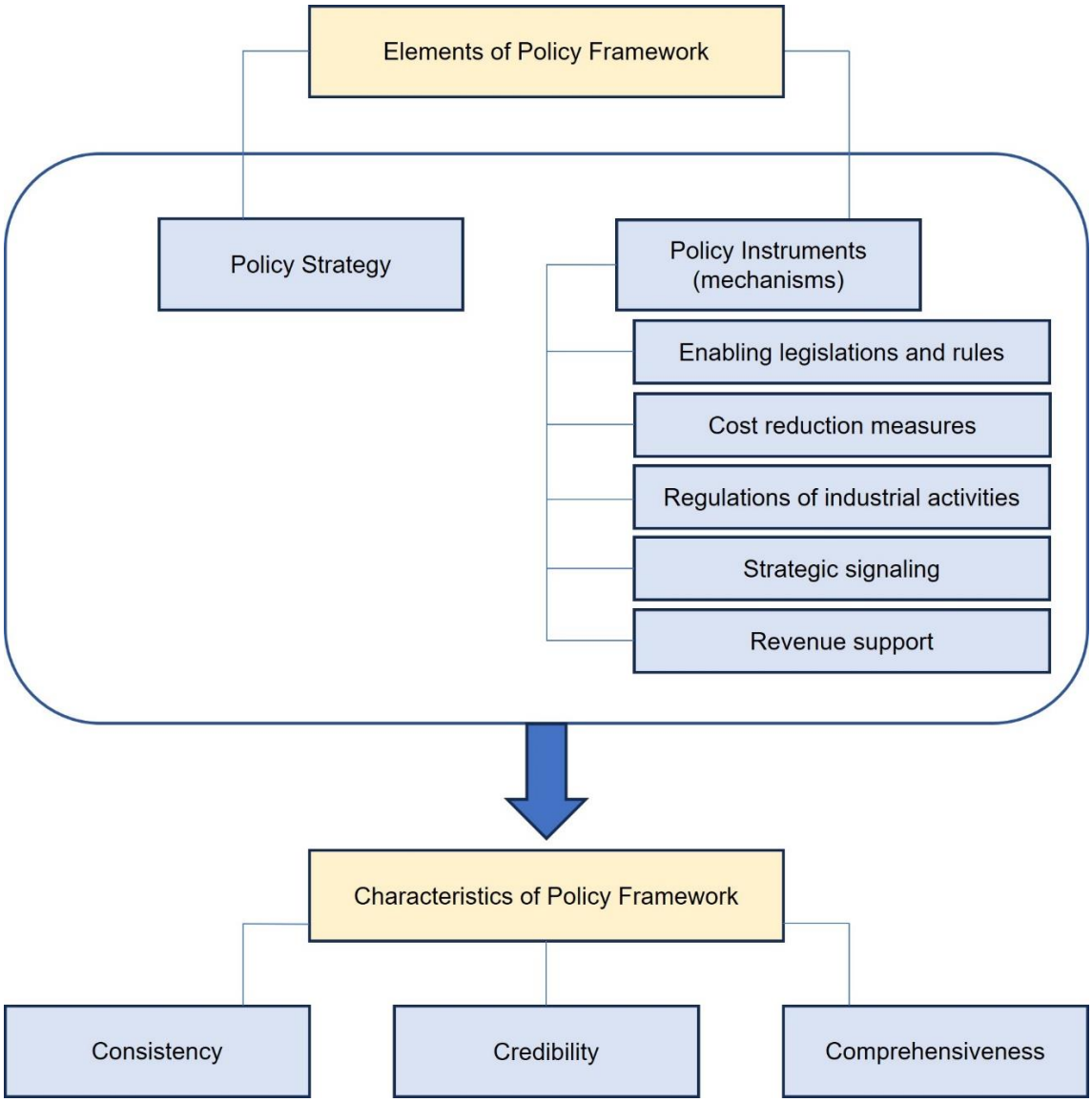

Figure 3. Elements and characteristics of policy mix. Adopted from Rogge and Reichardt 2016 and IEA 2023b.

Rogge and Reichardt (2016) propose categorizing policy instruments into three distinct types: economic instruments, regulation, and information. The IEA (2023b) emphasizes that there is no singular approach to building a commercial

CCUS market. Nevertheless, the IEA specifies that, in order to operationalize the policy strategies and tackle the challenges relating to the CCUS deployment, particularly the economic viability barrier that hinders wide scale deployment of CCUS, governments have several policy instruments to support the development of CCU, categorizing them into five general areas:

- **enabling legislation and rules** providing a platform for CCU deployment,
- **cost reduction measures** aiming to lower capital and operating costs through mechanisms like grants, tax credits, or loans,
- **regulation of industrial activities** targeting emissions reduction in specific or multiple sectors via carbon pricing,
- **strategic signaling** representing long-term governmental commitment to attract private sector investment, and
- **revenue support** like offering carbon contract for difference.

While the latter four mechanisms focus on incentivizing CCU deployment, enabling legislation establishes the foundational framework for CCU activities. (IEA 2023b.)

As shown in Figure 3, for the analysis of CCU policy instruments in the EU and US, this research applies the five categories specified by the IEA (2023b) as they offer broader and more structured scope, rather than the three categories of policy instruments (economic instruments, regulation, and information) identified by Rogge and Reichardt (2016).

The analytical framework presented by Rogge and Reichardt (2016) offers an excellent set of criteria for assessing policy mixes. The criteria are based on specific characteristics that enable a comprehensive assessment of policy mix. Illustrated in Figure 3, the characteristics are consistency, credibility, and comprehensiveness.

The consistency of a policy mix refers to the assessment of how well the components of such policy are aligned with the goal of achieving the identified policy objectives. Credibility, another crucial characteristic, is the measure of how

believable and reliable a policy mix is. There are several factors that can impact the credibility of the policy mix, such as the political leadership commitment and consistent use of the policy instrument to achieve certain objectives. Lastly, comprehensiveness is assessed by how well the policy mix addresses all market, system, and institutional failures, including barriers and bottlenecks. (Rogge & Reichardt 2013; Rogge & Reichardt 2016; Rogge & Dütschke 2018.)

In conclusion, the analytical framework developed by Rogge and Reichardt (2016), complemented by the categories of policy instruments outlined by the IEA (2023b), offers a structured and insightful approach to assessing the existing CCU legal and policy frameworks and formulating policy recommendations. This choice aligns with the aim and objectives of this research.

2.3 Data Collection and Data Analysis

In their analytical framework Rogge and Reichardt (2016) emphasize that, as a starting point for policy analysis, the researcher needs to identify key policy instruments and their design features. To achieve this, they propose that, depending on the research question and case, data from policy instruments database, such as the one provided by the International Energy Agency can be used. On the policy instruments design feature, they suggest that the researcher can extract information from original laws and regulations, governmental strategies, and other publications.

Building on the analytical framework developed by Rogge and Reichardt (2016), Ossenbrink et al. (2019) address the challenge of mapping out the policy mixes by proposing shared heuristics to create a consistent research framework. They identified two approaches for mapping out policy mix components: top-down and bottom-up. They further highlighted the importance of making a conscious decision between the two approaches. They explained that the top-down approach begins with an overall strategic policy goal and identifies relevant policy instruments to implement it. In contrast, the bottom-up approach starts with a focused impact area (e.g., a specific technology or sector), searching for all policies that influence decision-making in that area.

Given that the focus of this research is on the development of the CCU market, the top-down approach is deemed more suitable for guiding the research process. The research first identifies the policy strategies related to the development of the CCU market in both the EU and the US, then identifies the relevant policy instruments implemented by both jurisdictions to achieve such strategy goals, hence addressing the complexities of policy formulation and implementation within the context of the research topic.

The intricacies of how policy processes affect the path of sustainability transitions are not well-explored in the literature, especially regarding what influences the creation of comprehensive policy instead of single policy tools (Edmondson et al. 2019; Kern et al. 2019). Although this is an interesting area to study, the policy process is beyond the scope of this research. Drawing from these insights and on the elements and characteristics of policy mixes presented in Figure 3 above, a methodology was developed to meet the objectives of this research, consisting of four main tasks, as shown in Figure 4 below:

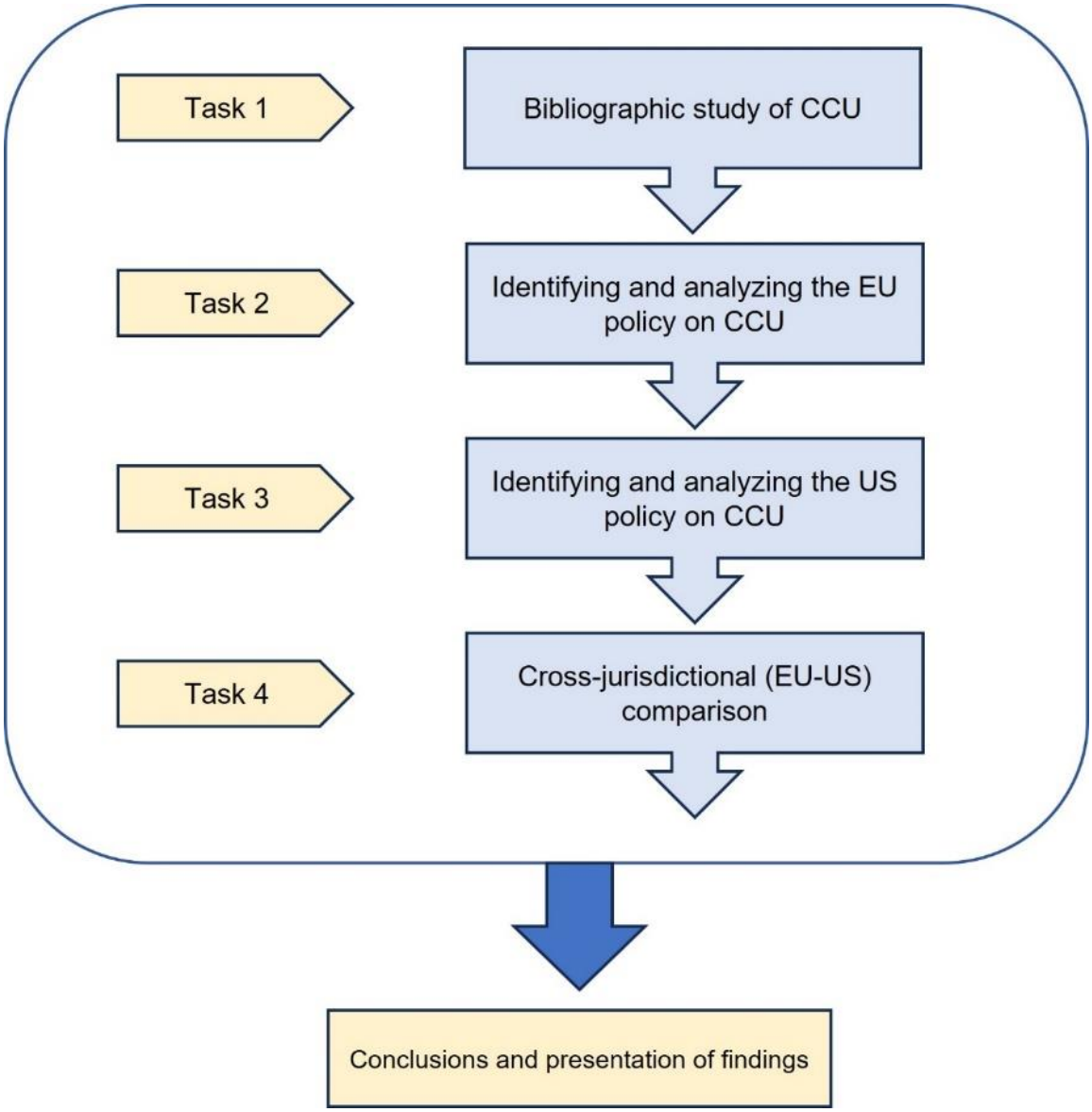

Figure 4. Overview of research methodology.

The data collection for task 1 primarily relied on desk research, where a set of academic literature and industry association reports was identified and analyzed to ensure up-to-date information regarding the deployment of CCU. To achieve a comprehensive understanding of the research topic, the literature review conducted during this task 1 was multidisciplinary, including literature from engineering, chemistry, environmental science, economics, and legal policy analysis.

For task 2 and task 3, in addition to academic literature such as Thielges et al. (2022), the policies database provided by the International Energy Agency served

as the initial reference for identifying the main policy instruments applicable to CCUS in both the EU and the US jurisdictions. The importance of the IEA's polices database is that it provides access to information on past, current, or planned government policies and measures. However, it is worth noting that the IEA's polices database was not up to date.

Each task 2 and task 3 involved two steps in collecting data affecting the deployment of CCU technologies and the development of the CCU market. The first step was to identify policy strategies applicable to CCUS in general, given that CCU is often considered together with CCUS. Considering the limitations of the research, the second step was to identify policy instruments or specific provisions of such policy instruments applicable only to CCU. Then, such policy instruments are classified according to the IEA's five categories of policy instruments listed in Figure 3.

For task 4, the cross-jurisdictional comparison was carried out based on the data collected from task 2 and task 3. This comparison involved analyzing the data gathered on policy strategies and policy instruments identified for CCU in both the EU and the US. By examining the results of the data analysis obtained from task 2 and task 3, significant similarities and differences in the policy approaches towards CCU between the two jurisdictions were identified and subsequently highlighted in Table 1. The data collection for this research was conducted between October 2023 and mid-February 2024.

Furthermore, during the development of this research, the author gained valuable insights from the work of Thielges et al. (2022), which enriched this study. Also, alongside several meetings held with the commissioning company, the author attended several webinars and international conferences on topics relevant to this research. During these events, the author gained valuable insights from expert presentations and engaged in multidisciplinary discussions with professionals in the field. Oester et al. (2017) emphasize the importance of researchers attending professional conferences, where they engage in conversations with other researchers. This provides a valuable opportunity not

only to discuss the success of research but also to share insights into failed attempts. Understanding what has not worked for other researchers can be fundamental in saving resources. (Oester et al. 2017.) This particularly influenced the development of this research and its design.

3 DECODING CCU TECHNOLOGIES: CHALLENGES AND OPPORTUNITIES

3.1 CCU&S Value Chain

The value chain of carbon capture, utilization, and storage (CCUS) technologies includes a diverse array of options, creating a high level of complexity and misunderstanding even for experts in the field (Olfe-Kräutlein et al. 2022; Mason et al. 2023). Figure 5 illustrates the primary segments of the CCUS value chain, where the value chain is based on sourcing CO2, capturing it, transporting it, and eventually utilizing it. Each segment highlights the essential aspects that play a significant role in the overall process. (Philbin 2020.) To simplify matters, the term CCUS encompasses both carbon capture and storage (CCS) and carbon capture and utilization (CCU).

Figure 5. Description of CO2 value chain. European Commission 2024 (EC 2024).

While both CCS and CCU involve capturing CO2 from industrial emissions, their ultimate goals differ significantly. CCS primarily aims to store CO2 underground, whereas CCU offers the possibility to utilize the captured CO2 as a valuable resource to potentially reduce the need for fossil-based products and close the carbon cycle. (Olfe-Kräutlein et al. 2016.) Further, despite using the terms CCS

and CCU as distinct terms to distinguish between two sets of technologies, it should be noted that the total separation may not be applicable in industrial processes such as cement or plastics production (Olfe-Kräutlein et al. 2022). In these examples, both CO2 storage and CO2 utilization can be intertwined to different extents.

3.1.1 CCS

For CCS, the definition is rather straightforward, as the EU CCS Directive (EC 2009) on geological storage of carbon dioxide defines CCS as consisting *"of the capture of carbon dioxide (CO2) from industrial installations, its transport to a storage site and its injection into a suitable underground geological formation for the purposes of permanent storage*". This implies that CCS involves separating CO2 from industrial emitting sources and subsequently transporting it to a permanent storage location, which is typically geological storage reservoirs. Nevertheless, CO2 can also be stored permanently as minerals or carbon-containing products that remain chemically stable over time (Kujanpää et al. 2023).

Various carbon capture technologies are currently commercially available and operational. These include (a) direct air capture, which extracts CO2 directly from the air, (b) precombustion capture that removes CO2 before combustion is completed (typically linked with high CO2 concentrations), (c) post-combustion capture, the most prevalent method for capturing carbon emissions from specific sources that removes CO2 from the flue gas produced during combustion, and (d) oxyfuel combustion, which rely on pure oxygen instead of air for burning fuel, contribute to effective carbon capture efforts. (Philbin 2020; Orujov et al. 2023; Kujanpää et al. 2023.)

3.1.2 CCU

Unlike CCS, there is no comprehensive definition of CCU in the current EU legal framework. However, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change defines CCU as "*a process in which carbon dioxide*

(CO2) is captured and the carbon then used in a product" (IPCC 2022). Others elaborate further on its elements, such as the Science Advice for Policy by European Academies (SAPEA 2018), that defines CCU as "*those technologies that use CO2 as a feedstock and convert it into value-added products such as fuels, chemicals or building materials*" (SAPEA 2018). These definitions indicate that CCU involves capturing CO2 and subsequently utilizing the captured CO2 as a raw material for the creation of products, presenting a broad approach to carbon utilization. Although the term CCU is often associated with the utilization of CO2, it can also refer to the utilization of carbon monoxide (CO) from industrial sources before they are flared or undergo other conversions to CO2 prior to its potential release into the atmosphere (vom Berg & Carus 2023).

Considering this context, from a system perspective, CCU involves four key segments, as outlined below and illustrated in Figure 6.

1. Capturing CO2 from industrial emission sources or directly from the air, representing CO2 sources;
2. Utilizing CO2 either directly (i.e., not chemically altered) or indirectly (i.e., transformed into carbon-rich products, often with the carbon atom in a reduced state compared to its original oxidized form in CO2), representing CO2 utilization options;
3. Delivering carbon-rich products to provide societal services, representing CO2 utilization options; and
4. Disposing of the carbon atom, either through landfill or by recycling, indicating the end of CO2 life cycle. (SAPEA 2018.)

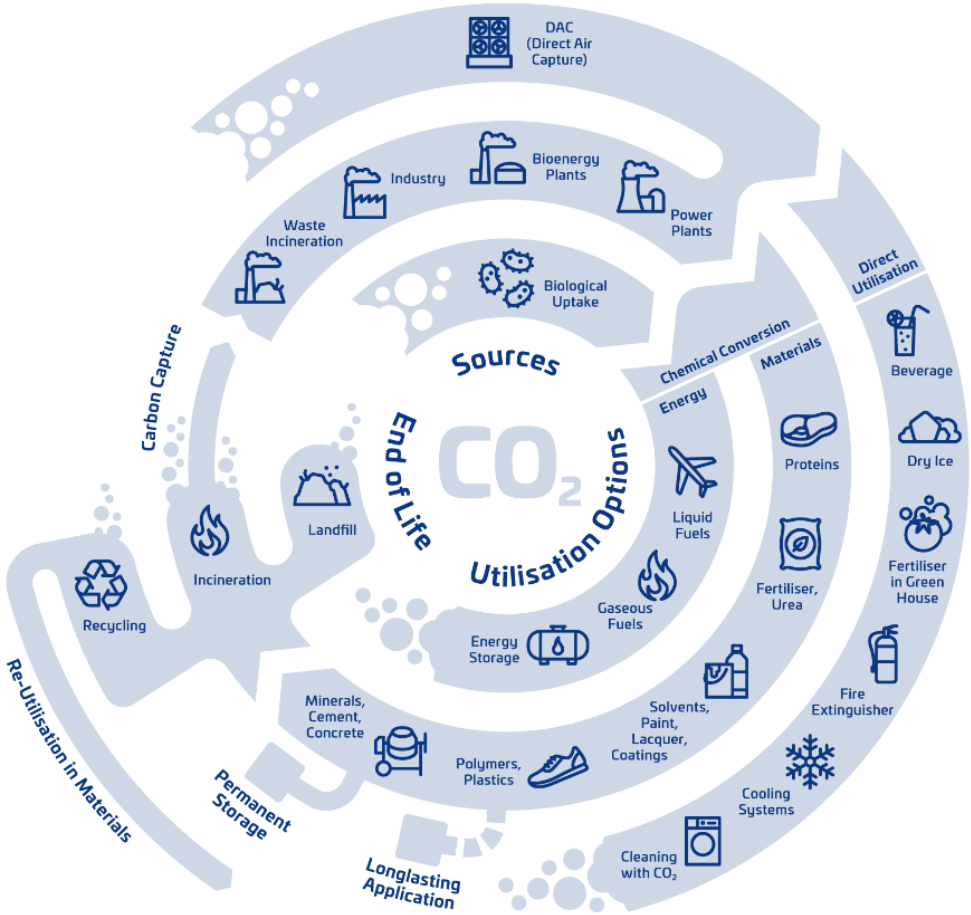

Figure 6. CO2 as a feedstock (vom Berg & Carus 2023)

In hard-to-abate process industries like cement, steel, chemical production, and waste incineration, CCUS provides an important method for reducing industrial emissions. In these industries, CO2 emissions are inherent to the process itself rather than resulting from the combustion of fossil fuels, therefore, CCU can be integrated as part of the portfolio of decarbonization methods to address hard-to-abate or unavoidable emissions. The feasibility of deploying CCUS for emission reduction depends on the nature of the industrial emission sources and the overall decarbonization strategy. It may either be the only viable option or contribute to an economically efficient decarbonization pathway. (CCUS Vision Working Group 2023.)

3.2 CCU Applications

As illustrated in Figure 6 and in the below examples, the utilization of CO2 brings with it economic benefits across a range of economic sectors. In general, CCU

refers to the process where CO2 is captured and utilized either directly without chemical alternation or indirectly in various products following chemical transformation (IEA 2023b; Kujanpää et al. 2023). Below are some examples for CCU technology applications.

Direct utilization of CO2: In this case, CO2 is used without chemical alternation, where CO2 is currently in use in various products, such as carbonic acid in drinks, in fire extinguishers, or in food packaging (Olfe-Kräutlein et al. 2016). According to the IEA (2023b), the main current direct use of CO2 is in enhanced oil recovery, where CO2 is used to enhance hydrocarbons extraction.

Utilization as a material following chemical transformation: In this utilization method, CO2 can be chemically transformed into carbon compounds of higher or lower value, serving as a raw material for the production of pharmaceuticals, fertilizers, plastics, foams, paints and coatings, and building materials, among others. These innovative utilization pathways are still in an early development phase and have become viable because of the technological advancements in catalysis research. (Olfe-Kräutlein et al. 2016.)

Utilization in energy sources following chemical transformation: In this utilization pathway, CO2 can be used as a raw material to produce energy sources like liquid fuels (methanol, diesel) and synthetic gas. These sources can directly fuel the mobility sector or serve as energy storage. (Olfe-Kräutlein et al. 2016.)

To understand the environmental impact of CCU technology, it is essential to examine not only the environmental impacts of the utilization pathways but also the source of the captured CO2 feedstock (IEA 2023b). The CCU climate impact is dependent on various factors, including the lifetime of the CCU product, the displaced product, and the source of CO2 (IPCC 2022). In principle, there are many potential sources of CO2, ranging from natural sources like rocks, to industrial emissions from power plants, cement factories, and even the CO2 captured from surrounding air (Olfe-Kräutlein et al. 2016).

CO2 conversion pathways into chemicals and materials can be grouped into two categories. The first category includes products like mineralization in concrete and aggregate, in which the captured CO2 is permanently chemically bound. This prevents the released CO2 from entering the atmosphere when the products are used and disposed in the conventional manner. The other category comprises “short-lived” products, such as fuels, fertilizers, plastics, in which the CO2 is not permanently pound. Instead, CO2 is later released, leading to potential CO2 emissions upon their use or disposal. (Olfe-Kräutlein et al. 2016; CCUS Vision Working Group 2023.) Yet, to accurately evaluate the carbon footprint of any CCU technology, it is necessary to take into consideration the entire life cycle of a CCU product (Olfe-Kräutlein et al. 2016; Philbin 2020). Figure 7 illustrates the sources of CO2 and the duration of storage.

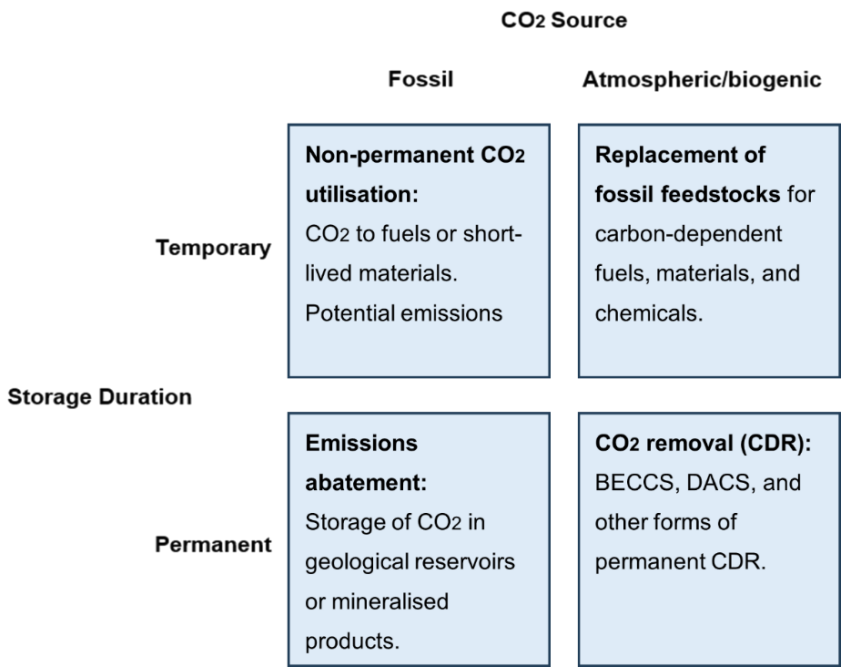

Figure 7. The distinct decarbonization services delivered by CCUS technologies depending on the source of CO2 and duration of storage (CCUS Vision Working Group 2023)

While CO2 utilization can contribute to reducing emissions, CCU is considered only as a complement or part of a comprehensive approach to addressing climate change, rather than an alternative to CCS (IEA 2019). In the net zero emission scenario by 2050, the IEA predicts that a vast majority (95%) of CO2 captured in all CCUS applications will be directed towards CO2 storage rather than utilization (IEA 2023b). Therefore, the prospect of CO2 utilization leading to negative

emissions is rather limited (IEA 2019). Despite this, CO2 utilization remains an essential component in the broader strategy to mitigate climate change, and it is acknowledged that "*no CCUS, no net zero*" (CCUS Vision Working Group 2023).

3.3 CCU: A Path to Sustainability

Although carbon is essential for life and our economy, relying on fossil fuels as a primary source of carbon contributes significantly to GHG emissions. Given the limited availability of environmentally friendly biogenic carbon, the deployment of CCU technologies to convert CO2 into non-fossil carbon products and fuels will be essential to advance the circular economy (EC 2021d; Jensen 2022). Despite its availability, CCU technologies are still in the early stage of technological development (IEA 2019). In addition to other barriers hindering the scaling up of CO2 utilization, such as higher costs in comparison to traditional production paths (Olfe-Kräutlein 2020), the primary obstacles are more policy (as discussed in Section 7) and market-related in nature rather than technological (Olfe-Kräutlein et al. 2016; IEA 2019).

One of the key advantages of CCU technologies over CCS is that CCU technologies can be decentralized and deployed without the need for significant infrastructure investments, unlike CCS, which requires an extensive network of pipelines and storage facilities for the transportation of the captured CO2. CCU technologies can be implemented at the source of industrial emitters, such as cement plants, power plants, or industrial parks (vom Berg & Carus 2023). Most of these industrial emitters meet local carbon demands using fossil fuels (oil and natural gas), making CCU a promising solution for converting these emissions into value-added products (Srinivasan et. al. 2021; vom Berg & Carus 2023).

This approach, where emissions from industrial processes are transformed into raw materials for other uses, promotes the creation of sustainable carbon cycles and effectively closes the loop between the emissions and demand (vom Berg & Carus 2023). This not only contributes to the development of a market for CO2 capturing technologies, but also holds the potential to lower their prices (Namis, 2016; IEA 2023b). Moreover, CCU technologies offer a pathway to provide a

sustainable and non-fossil source of carbon, which contributes to the transition to a circular economy. (Olfe-Kräutlein 2020; vom Berg & Carus 2023.) By utilizing carbon that is already in circulation, whether sourced from point source emissions or direct air capture, CCU technologies play an important role in achieving sustainable carbon cycle (vom Berg & Carus 2023).

The growing demand for sustainable solutions has become a catalyst for the rapid expansion of the CCU market. In 2022, the market size for global carbon dioxide utilization exceeded USD 4.02 billion. It is anticipated to reach approximately USD 14.32 billion by 2032, showcasing a growth rate of 13.60% over the forecast period from 2023 to 2032. (Precedence Research 2023.) Embracing CCU technologies not only offers new revenue streams for the developers and users but also plays a pivotal role in promoting job creation and fueling economic growth. As society increasingly acknowledges the importance of combating climate change, the momentum behind CCU is growing, driving further innovations in the field. Research and development in this area is essential to create sustainable alternatives that reduce carbon emissions and promote a greener future.

In the following Section 3.4, this thesis examines a case that exemplifies the practical implementation of CCU technology. This case study not only highlights the current use of CCU technology but also suggests the future potential of this technology and its impact on sustainable business practices.

3.4 Strategic Synergy: Co-Producing Hydrogen and Value-Added Solid Carbon Products

The commissioning company, Hycamite TCD Technologies Oy (Hycamite), is a growth technology company founded in 2020, specializing in innovative technology that produces hydrogen and solid carbon through thermo-catalytic decomposition of methane. As illustrated in Figure 8 below, Hycamite's cutting-edge technology decomposes methane (CH_4) into its component elements, hydrogen (H_2) and carbon (C).

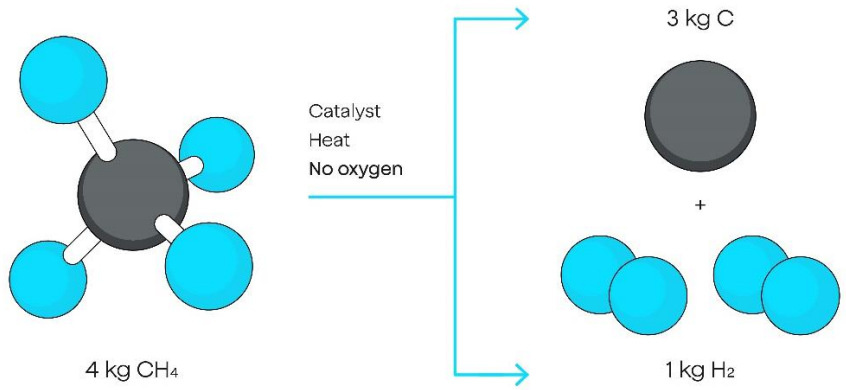

Figure 8. Thermo-catalytic decomposition of methane (Hycamite's website)

The hydrogen (H_2) and carbon (C) resulting from the methane decomposition represent the main product segments of Hycamite. The mass ration between hydrogen (H_2) and solid carbon (C) co-products from methane (CH_4) pyrolysis is one to three (Parbowo et al. 2024).

For the hydrogen, a life cycle assessment (LCA) conducted by FfE Munich - a German non-profit research institute – indicates that Hycamite's hydrogen offers a low-emissions alternative for low-cost hydrogen production. Figure 9 illustrates how Hycamite's technology stands out as an environmentally sound alternative, especially when compared to traditional steam methane reforming (SMR) practices.

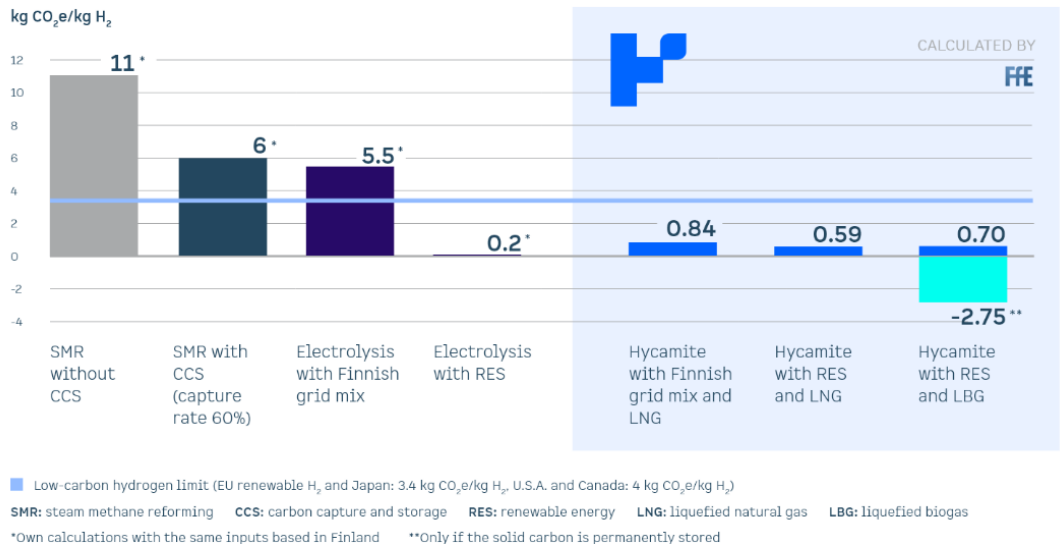

Figure 9. Lifecycle emissions of different hydrogen production technologies (Hycamite's website)

Figure 9 demonstrates that Hycamite's technology has lower emissions than even so-called green hydrogen production. This hydrogen can be used as either industrial raw material or fuel.

Regarding the other segment of products, Hycamite's thermo-catalytic decomposition of methane technology plays a pivotal role in preventing the release of CO_2 emissions into the atmosphere (Parbowo et al. 2024). The decomposition process involves the entry of methane and the exit of hydrogen, both in a gaseous state. In contrast, the resulting carbon is in a solid form. Notably, oxygen plays no role in this process, and as a result, no carbon monoxide (CO) or carbon dioxide (CO2) is generated. (Timmerberg et al. 2020.) Therefore, with every 1 kilogram of solid carbon produced, approximately 3.67 kilogram of CO2 emissions are avoided. This conversion relies on the molecular weights of carbon (C = 12) and carbon dioxide (CO2 = 44), resulting in a ratio of 3.67.

Hycamite's technology has the potential to produce solid, industrial-quality carbon, setting it apart from the conventional (SMR) method that employs carbon capture. Unlike SMR method, which yields carbon as carbon dioxide - a form challenging to store or reuse and is typically released into the atmosphere – Hycamite's process generates solid carbon materials.

Solid carbon is easily storable and can be further processed and sold for use in the manufacturing of various products, including but not limited to the manufacturing of batteries, supercapacitors, electronic components, polymers, composite material additives, and concrete. (Timmerberg et al. 2020; Parbowo et al. 2024.) This underscores the significance of Hycamite's technology to facilitate the increased production of the captured carbon into added-value products, especially that carbon products can be tailored for customers' needs using suitable catalyst family.

Hycamite is currently building its Customer Sample Facility in Kokkola, Finland. Hycamite's goal is to expand its market reach into the customer markets beyond Finland, with a specific emphasis on the USA as the primary target market.

The utilization pathways offered by CCU technologies can provide a revenue stream for CO2 capturing facilities. The technology is expected to evolve further, providing opportunities to convert potential industrial emissions into value-added products. The economic feasibility of these innovative conversion pathways depends on several factors, including technology performance, market demand, energy prices, and policy-related revenue streams (IEA 2023b).

4 CCU IN THE EU POLICY FRAMEWORK

4.1 Key Policy Strategies for CCU in the EU

The European Union (EU) has been a frontrunner in taking measurable actions to combat climate change. Directives such as the CCS Directive (EC 2009), the implantation of the EU Emission Trading Scheme Directive in 2005, along with its recent reform in 2023 (EC 2023d), and the ratification of the Paris Agreement in 2016, all demonstrate the EU continued commitment to addressing climate change and to supporting industrial carbon management technologies like CCS and CCU. CCU has been a longstanding component of several EU policy strategies, particularly those addressing the EU's vision on energy and climate change. However, in these strategies, CCU is often discussed alongside other long-term decarbonization efforts, and they, in one way or another, address aspects related to CCU together with CCS.

A Clean Planet for all: In November 2018, the EU Commission set out a clear long-term vision of how to achieve net-zero emission by 2050, entitled "A Clean Planet for all" (EC 2018a). In this strategy, CCU is addressed as a key approach to reduce GHG emissions in the EU industry, especially in hard-to-abate process industries such as cement, steel and chemical production. The strategy further connects CCU to the circularity of raw materials to reduce the EU's dependence on critical materials from third countries, especially in sectors and technologies

where new dependencies on critical materials like rare earths or graphite might emerge.

The strategy was accompanied by in-depth analysis documentation (EC 2018b), which highlighted the potential benefits, as well as the challenges of both CCS and CCU technologies, particularly related to costs, market condition, and established standards and practices. Despite these challenges, the analysis emphasized the crucial role of CCS and CCU in achieving net-zero emissions goals. The documentation underlined the need for increased research and development investments and the implementation of supportive policy frameworks to accelerate the deployment of these technologies and unlock their potential in mitigating GHG emissions.

The Green Deal: In December 2019, the European Commission published its ambitious Green Deal for the European Union (EC 2019b), consisting of a comprehensive package of policy initiatives that outlines the path towards a transition to a green economy. The Green Deal sets out an ultimate target of achieving climate neutrality i.e. net-zero emission by 2050 in alignment with the EU's 2018 strategy "A Clean Planet for all".

The significance of the Green Deal for CCU is twofold. Firstly, it underscores the need for a revision of the existing regulatory framework for energy infrastructure to ensure its alignment with the target of achieving climate neutrality. The Green Deal emphasizes that the regulatory framework should "*foster the deployment of innovative technologies and infrastructure, such as smart grids, hydrogen networks or carbon capture, storage and utilisation, energy storage, also enabling sector integration. Some existing infrastructure and assets will require upgrading to remain fit for purpose and climate resilient*" (EC 2019b).

The second aspect highlights the Green Deal's emphasis on the need for the EU industry to have "climate and resource frontrunners" leading the way in the development and commercialization of breakthrough technologies in key industrial sectors by 2030. Specifically, the Green Deal identifies priority areas,

including CCS and CCU, among others (EC 2019b). This dual focus on regulatory alignment and industry leadership reflects a holistic strategy within the Green Deal, that makes it as a pivotal driver for the advancements of CCU as a component of the EU climate policy in comparison to the preceding climate and energy policy frameworks in the EU (Turnau et. al. 2019; Thielges et. al. 2022).

Furthermore, in the communication addressing the 2030 Climate Target Plan (EC 2020b), the EU emphasized that "*to allow industry to truly decarbonize after 2030, zero or very low carbon technologies and business concepts, including system integration, access to sustainable resources and increased circularity, medium and high heat electrification, hydrogen and carbon capture, utilization and storage, will need to be developed and tested at scale in this decade*". This also underscores the increased focus on CCU in the EU decarbonization efforts.

Based on the goal set out in the Green Deal for the EU to become climate neutral by 2050, the previously agreed upon domestic GHG emissions reduction target of at least 40% (EC 2018c) has been increased to a more ambitious target of at least 55% compared to 1990 GHG emissions levels to be achieved by 2030, as stipulated in the newly introduced European Climate Law (EC 2021b). The objective of the European Climate Law is to ensure all EU policies actively support the realization of this ambitious goal, involving the participation of every sector in the economy. Additionally, the European Climate Law recognizes the potential role of CCS and CCU technologies in the decarbonization efforts for the EU Member States that choose to deploy such technology, although it does not set any targets or incentives for such deployment.

To achieve the EU's 2030 climate goal, as outlined in the European Climate Law, a package of legislative measures entitled "Fit for 55" was introduced by the EU in July 2021 (EC 2021c). By October 2023, the EU had successfully adopted 12 key pieces of legislation as part of the Fit for 55 package of measures (EC 2023j). These legislative actions are designed to update and revise existing EU laws, facilitating the reduction of GHG emissions across major sectors of the economy. The ultimate objective is to fulfill the ambitious EU target associated with the

2030 climate goal. Among these legislative measures, certain actions relate to specific CCU applications, such as the EU Regulations relating to synthetic aviation and maritime fuels.

Circular Economy Action Plan (CEAP): Aligned with the Green Deal's climate goals and building on the circular economy efforts implemented since 2015 (EC 2015), the EU adopted the new CEAP in March 2020 (EC 2020a). The objective of the CEAP is to promote circularity across all sectors, with the aim to transform Europe into a more competitive and environmentally friendly economic powerhouse. The CEAP introduces a set of initiatives to establish a strong product policy framework, promoting sustainable products, services, and business models while reshaping consumption patterns to prevent waste generation.

The CEAP also emphasizes strengthening the EU's capacity to responsibly manage its waste, highlighting that circularity is a prerequisite for achieving climate neutrality. Concerning CCU technologies, CEAP has introduced the EU's commitment to establish a regulatory framework for certifying carbon removals. (EC 2020a) This initiative seeks to promote the adoption of carbon removal and increase the circularity of carbon while fully observing biodiversity objectives, as currently presented in a proposal for a regulation establishing a certification framework for carbon removals (EC 2022b).

Sustainable Carbon Cycles: To advance the goals of the Green Deal, the EU published a pivotal strategy on Sustainable Carbon Cycles in December 2021 (EC 2021d). The strategy presents a vision for policy, market development for capture, utilization, and storage of CO2, and certification for removal of carbon. Within the strategy, the EU mapped out three key actions aimed at establishing sustainable and climate-resilient carbon cycles. These actions include reducing dependence on carbon, recycling carbon from waste streams, and upscaling carbon removal solutions, ultimately leading to emissions reduction and carbon removal. Furthermore, one of the main issues highlighted by the strategy is the

need for the EU to support the emerging technologies required to achieve the 2050 climate neutrality goals.

In 2018, the EU relied on approximately one billion tonnes of carbon sources to sustain its economy, with 45% being biogenic and 54% fossil, while recycled sources of carbon made up only 1% of the total carbon intake (EC 2019a). Recognizing the need to transition to climate neutrality by 2050, the Sustainable Carbon Cycles emphasized the EU's necessity to reform its approach to sourcing carbon for industry. This shift involves replacing fossil carbon with sustainable alternatives such as recycled carbon, biomass, and atmospheric capture. Additionally, the EU climate-neutrality objective requires the EU to capture between 300 million tons and 500 million tons of carbon dioxide by 2050.

The Sustainable Carbon Cycles sets aspirational objectives, including the requirement to report the origin of all CO2 (whether captured, transported, utilized, or stored by industries) by 2028. Also, it aims to reach a share of at least 20% of sustainable non-fossil carbon in the carbon utilized as a feedstock in chemical and plastic products by 2030 and remove 5 million tons of CO2 annually by 2030 through innovative projects. The significance of this strategy lies in its role as a cornerstone for developing a framework for circularity of carbon and for certifying carbon removals. To achieve this, the EU has put forward a regulatory proposal aimed at certifying carbon removals, which will be discussed under Section 4.2.

Industrial Carbon Management Strategy: To put the EU's net-zero industry in the lead, the EU introduced its Green Deal Industry Plan in February 2023, which builds on previous EU initiatives. Under the Green Deal Industrial Plan, carbon capture and storage technologies have gained prominence as crucial technology to meet the EU's climate-neutrality goals. (EC 2023a.) In line with the objective of achieving climate neutrality by 2050 and adhering to the targets set by the European Climate Law (EC 2021b), the EU launched an open public consultation in June 2023 for the "Industrial Carbon Management".

The open public consultation was concluded at the end of August 2023, which aimed at gathering stakeholders' perspective on various aspects of industrial carbon management technologies including CCS, CCU, and industrial carbon removal, with the objective of developing a strategy within the framework for these technologies (EC 2023e). Subsequently, in February 2024, the European Commission adopted the Industrial Carbon Management Strategy (EC 2024), which outlines the potential of CCS, CCU, and carbon removal technologies in reducing emissions by 90% by 2040 and achieving climate neutrality by 2050.

The strategy predicts an 80% drop in fossil fuel consumption for energy by 2040 compared to 2021. This reduction is projected to be accomplished through the adoption of renewable energy, circularity, industrial cooperation, energy efficiency, and carbon reuse. It further outlines steps to be taken at both EU and national levels to establish a single market for CO2 within Europe and foster a more favorable environment for investments in industrial carbon management technologies.

The Industrial Carbon Management Strategy acknowledges the challenges hindering large-scale carbon management projects in Europe. These challenges include difficulties in establishing viable business cases due to high upfront costs, uncertain CO2 prices, and the lack of a comprehensive regulatory framework throughout the entire value chain, particularly for certain uses of CO2 and for industrial carbon removal. Additionally, the strategy points out that insufficient incentives further impede private and public investment in industrial carbon management.

For CCU, according to the Industrial Carbon Management Strategy, the EU Commission plans to assess demand-pull possibilities in collaboration with industries to boost the adoption of sustainable carbon as a feedstock in industrial sectors. Additionally, the EU Commission intends to develop a comprehensive framework to address all industrial carbon management activities and incentivize the deployment of innovative CCU applications capable of permanently and non-permanently storing carbon. (EC 2024.)

The recently adopted Industrial Carbon Management Strategy holds considerable significance as it represents the most comprehensive policy to addressing the challenges associated with CCU in the EU. It offers valuable insights into the EU Commission's perspective on the potential role of CCU in the industrial decarbonization efforts of the EU. Also, the strategy provides an overview of the EU's plans for the adoption and advancement of CCU technologies. This could signal a positive step forward for the industry, indicating a proactive stance towards the deployment of CCU in future activities.

4.2 Legislative Drivers of CCU: Policy Instruments in the European Union

Over the years, the EU has developed several policy instruments addressing issues related to the development of CCU, either directly or indirectly. Such supporting legislation typically creates a foundational framework and serves as a starting point for CCU development, rather than actively promoting it (IEA 2023b). However, unlike CCS, where the EU CCS Directive (EC 2029) regulates the geological storage of carbon dioxide, there is no single policy instrument exclusively dedicated to CCU development. This lack of specificity may be attributed to the diverse and complex nature of CCU application pathways. For CCU, the primary focus is on comprehending the climate mitigation potential of its technologies.

Renewable Energy Directive: On the regulatory side, CCU technology is mainly regulated in the recast of the Renewable Energy Directive (EC 2018d), known as "RED II". RED II promotes the utilization of energy from renewable sources and supports renewable fuels derived from non-biological origins, including those fuels derived from captured CO2. Further, RED II established an EU binding target of at least 32% renewable energy by 2030.

To accelerate the clean energy transition, the EU revised RED II with the adoption of the Renewable Energy Directive III (EC 2023k), known as "RED III". RED III introduces new targets, aiming for an overall renewable energy share of at least 42.5% by 2030, with an aspiration of reaching 45%. Statistical data from Eurostat indicates an increase in the proportion of energy derived from renewables in the EU, rising from 21.9% in 2021 to 23.0% in 2022 (Eurostat

2024). This suggests that such legislative measures may have played a significant role in driving the uptake of renewable energy in the EU, as the EU Member States are required to comply with the targets set by the EU for the use of renewable energy.

ReFuelEU Aviation and FuelEU Maritime: Given the climate objectives outlined in the European Climate Law (EC 2021b), all economic sectors, including the challenging-to-electrify transport sector, are required to implement rapid measures for decarbonization. To address this imperative, the EU has adopted key initiatives focusing on transport, such as ReFuelEU Aviation and FuelEU Maritime in 2023. These initiatives fundamentally aim to encourage CO2 utilization by setting sector-specific synthetic fuel targets. In doing so, the EU aims to drive progress in sustainable aviation and maritime practices, in parallel with the overarching goal of mitigating climate change. Considering the limitations set out outlined for this research, the sector-specific synthetic fuel targets will be acknowledged without delving into an exhaustive analysis.

The ReFuelEU Aviation Regulation (EC 2023i) establishes a mandate for aviation fuel suppliers at EU airports to include a minimum percentage of sustainable aviation fuel in all fuel provided to aircraft operators, starting at 2% in 2025 and increasing to 6% in 2030, ultimately reaching 70% by 2050. Additionally, from 2030 onwards, a minimum percentage of 1.2% synthetic aviation fuels is required, gradually rising to 35% by 2050.

On the other hand, the EU Regulation on FuelEU Maritime initiative (EC 2023f) outlines measures to systematically reduce the GHG gas intensity limit of fuels utilized in the shipping sector. The regulation aims for a gradual reduction, starting with a 2% decrease in 2025 and progressing to an 80% reduction by the year 2050.

The adoption of both initiatives, ReFuelEU Aviation and FuelEU Maritime, has the potential to expedite the technological advancements in sustainable fuel production by providing clear signals to the market, including clear and binding

targets and guidelines. Such legislative measures promote commercial innovation by allowing economic operators to explore these technologies as they mature and become commercially viable. Furthermore, they enhance market certainty, predictability, and act as an incentive for essential investments in these new technologies.

EU Emission Trading Scheme: The EU Emission Trading Scheme (EU ETS), a system designed to reduce GHG emissions via carbon market, represents a fundamental element of the EU's strategy to combat climate change. Entities subject to the EU ETS can either purchase or receive emissions allowances, which are then tradable among themselves as needed. This compliance system serves as a source of revenue for entities that successfully manage to reduce their emissions, particularly when the carbon pricing remains as high as USD 85 per ton CO2 (IEA 2023b). The EU ETS was initially launched in 2005 (EC 2003) and has undergone multiple reforms, with the most recent reform proposal was introduced by the EU Commission as part of the Fit for 55 package of measures.

The recent reform of the EU ETS (EC 2023d) has brought several changes, including, among others, more ambitious emissions reduction goals, an extension of the ETS coverage to new sectors such as maritime transport, and the introduction of a separate new ETS for buildings, road transport and fuels for additional sectors. In the context of CCU, the recently revised EU ETS (EC 2023d) makes explicit references to CCU in its preamble, emphasizing that projects involving CCU must lead to net reduction in emissions or permanent storage of CO2. Nevertheless, the revised EU ETS makes an explicit exception for CCU with specific limitations. It stipulates that the obligation to surrender ETS allowances will not arise if the emissions are captured, utilized, and become permanently chemically bound within a product. This prevents their release into the atmosphere during both regular use and any subsequent activities after the end-of-life of the product, including processes such as reuse, remanufacturing, recycling, and various disposal methods like incineration and landfill.

Despite this exceptional case of CCU being included in the revised EU ETS, it is worth noting that this exception is not entirely novel (Turnau et. al. 2019; Thielges et. al. 2022). Under the provisions for monitoring and reporting of GHG emissions under the EU ETS Directive (EC 2018e), operators are directed to subtract from their installation's emissions any CO2 originating from fossil carbon. This deduction applies when the CO2 is not emitted from the installation but is instead transferred out for use in precipitated calcium carbonate production, leading to the chemical binding of the CO2. However, one point to highlight is that the majority of CCU processes do not involve the permanent storage of CO2. Instead, they utilize CO2 as a means to reduce emission in other areas rather than storing it indefinitely.

While the revised EU ETS does not currently provide criteria for determining when emissions are considered permanently chemically bound in a product, the revised EU ETS Directive (EC 2023d) requests the EU Commission to establish detailed requirements through delegated acts. This may include considerations such as obtaining a carbon removal certificate, as a condition to be specified in the delegated acts by the EU Commission. This points to a potential regulatory requirement associated with the ongoing development of EU standards for certifying carbon removal efforts.

Certification framework for carbon removals: In the absence of a regulated compliance carbon market, such as the ETS, emitters have the option to voluntarily offset their emissions by purchasing carbon credits from projects that reduce or remove carbon emissions. The voluntary carbon market is growing rapidly as more companies seek to achieve their net-zero emissions targets. (IEA 2023b.) Given that the EU Emissions Trading System (ETS) only acknowledges one exceptional case of CCU, which incentivizes the case where the emissions are captured, utilized, and become permanently chemically bound within a product, installations utilizing CCU may have the potential to benefit from the certification framework for carbon removal that the EU is currently in the process of developing.

At the end of 2022, the EU published a legislative proposal for certification of carbon removal framework (EC 2022b). The primary goals of this proposal are twofold: firstly, to establish a voluntary certification framework that incentivizes the uptake of high-quality carbon removal initiatives within the EU, and secondly, to institute a comprehensive EU-wide governance system for carbon removal certification to prevent greenwashing practices. The proposal represents a proactive step taken by the EU to achieve its commitment to achieving the 2050 climate neutrality objectives and the other environmental targets outlined in the Green Deal. Moreover, the proposal aligns with the action plan set in the Sustainable Carbon Cycles (EC 2021d) to achieve the aspirational objectives for carbon removal.

The currently proposed framework for certifying carbon removal (EC 2022b) is voluntary but includes key provisions to ensure its effectiveness. Firstly, it sets forth quality criteria governing carbon removal activities within the EU, which must be met for certification. Secondly, it defines rules for the verification and certification process of carbon removals. Lastly, it outlines rules governing the functioning and recognition of certification schemes by the EU Commission, with the goal of creating a harmonized and reliable system for endorsing carbon removal efforts.

Importantly, the current proposal recognizes the possibility for storing carbon in long-lasting products as a form of carbon removal activity, alongside carbon farming and the permanent storage of carbon. However, the proposal is still in the development stage and was last updated in October 2023, with expectations for finalization in early 2024. Notably, the current proposal does not yet establish certification methodologies, nevertheless, it requests the EU Commission, supported by an expert group on carbon removal, to adopt delegated acts for setting up comprehensive certification methodologies tailored to the different types of carbon removal activities (EC 2022b).

Upon adoption, the certification of the carbon removal framework has the potential to create a revenue stream for companies proficient in deploying

technologies that successfully achieve carbon removal within the parameters of the proposed regulatory framework. This framework would validate and recognize the effectiveness of such technologies while also establishing a mechanism for generating income, incentivizing businesses to actively engage in and excel at carbon removal efforts. This multifaceted approach not only contributes to environmental objectives but also supports economic sustainability by offering financial incentives for companies at the forefront of implementing certified carbon removal technologies.

Net-Zero Industry Act: To maintain the competitiveness of the EU industry amidst growing global competition facilitated by ambitious support initiatives from other economies such as the US Inflation Reduction Act (US Congress 2022), the EU introduced the “Green Deal Industrial Plan for the Net-Zero Age” in February 2023 (EC 2023a). This plan outlines the EU’s strategy to expedite the transition of its industrial sector, with the goal of achieving net-zero emissions by 2050 and forming a part of the EU Green Deal. As an integral part of this strategy, the EU suggested the introduction of a Net-Zero Industry Act (NZIA) to support the industrial production of key technologies within the EU. (EC 2023a.)

The proposed NZIA focuses on supporting the manufacturing of key technologies that are supposed to play a key role in decarbonizing the EU’s economy. By addressing key challenges like investment uncertainty, administrative complexity, and limited market access, the NZIA aims to create a more supportive environment for the development and production of clean technologies such as solar photovoltaic and solar thermal systems, batteries and storage, electrolyzers, CCS, and CCU. (EC 2023b.) This, in turn, is expected to lead to a significant transformation of the manufacturing sector, making Europe a leading producer of net-zero technologies and strengthening the resilience of its energy system. Furthermore, the NZIA is also expected to create new job opportunities and promote innovation in the clean technology sector. (Ragonnaud 2023.)

The current draft of the proposed NZIA aims to establish a target manufacturing at least 40% of the EU’s annual demand for eight strategic net-zero technologies

by 2030 to meet the EU's 2030 climate and energy targets. The selection of the strategic net zero technologies was guided by three key criteria: 1) their technology readiness level (TRL), evaluated according to the IEA TRL scale of 11 levels (IEA 2020), with a focus on TRL 8 or above (TRL 8 denoting first of a kind commercial – commercial demonstration, full scale development in final form); 2) their contribution to the EU decarbonization efforts and competitiveness; and 3) their potential in addressing security of supply risks, especially regarding imports from a single third country, by enhancing manufacturing capacity for critical components in the net-zero technology value chain. (EC 2023b.)

Despite the recognition of both CCS and CCU as net-zero technologies in the proposal of the NZIA, among other net-zero technologies, CCU, unlike CCS, was excluded from the net zero technologies listed as strategic net-zero technologies (EC 2023b). According to the NZIA Commission Staff Working Document (EC SWD 2023), CCU was excluded from the list of strategic net-zero technologies as CCU technologies "cannot be considered as a manufacturing technologies". Additionally, the Commission Staff Working Document pointed out that there are no identified significant gaps for the development of CCU, unlike the case of CCS technologies, although it did not provide detailed elaboration on these conclusions.

Being designated as a "strategic" net-zero technology means that such technologies would benefit from specific enabling conditions for manufacturing. These include simplified and shorter administrative processes, access to regulatory sandboxes, as well as facilitated market access, and administrative support in securing finance (Ragonnaud 2023; EC 2023b). The exclusion of CCU from the list of strategic net-zero technologies raises concerns about the EU's commitment to fully harnessing the potential of CCU in its decarbonization efforts as well as the consistency in aligning policy objectives with measures taken.

4.3 Cost Reduction measures: EU Support Schemes for CCU

Energy projects typically require substantial upfront investments. Governments can use policy tools such as grants, loans, and tax credits to reduce these

expenses, which can be implemented through various policy schemes (IEA 2023b). The EU has established several funding schemes to support research and development as well as demonstration projects in CCS and CCU.

Innovation Fund: At the forefront of the EU funding schemes that could potentially support CCU projects is the Innovation Fund. The Innovation Fund is considered as one of the largest funding programs globally and directs its support towards flagship projects and innovative technologies that hold potential for significant emission reductions. Moreover, it serves as the EU's primary financing tool for advancing the green transition and promoting Europe's position as a leader in clean technologies in accordance with the EU's ambitious climate objectives. (EC 2023l.) The Innovation Fund is not about funding early-stage research, instead it provides financial support to bring proven innovative technologies to commercial scale (EC 2019c), and it covers the European Economic Area. The explicit listing and including of CCU among the sectors covered by the Innovation Fund (EC 2023l) indicates a specific recognition of its importance and eligibility for support within the fund's framework.

The Innovation Fund, initially established in 2018 (EC 2018f), has undergone significant enhancements following the recent revisions to the EU ETS Directive in 2023 (EC 2023d). These revisions have not only strengthened the role and scope of the fund but have also led to notable changes. The monetary size of the fund has been increased from 450 to 530 million ETS allowances, while its scope has been expanded to include new sectors, such as maritime and aviation. As a result, the overall funding of the Innovation Fund depends on the price of carbon and is projected to reach approximately 40 billion euros from 2020 to 2030. (EC 2023l.) Additionally, the revisions have introduced new financing options for projects through different types of competitive auction-based mechanisms, specifically through fixed premium contracts, carbon contracts for difference, or contracts for difference, among other changes (EC 2023d). The goal of implementing such mechanisms is to facilitate the development of decarbonization technologies that might not be adequately incentivized by the European carbon pricing and regulatory framework (EC 2023m). This could

provide a significant new incentive, accelerating the development and deployment of CCU technologies (Thielges et. al. 2022).

The eligibility criteria for projects seeking support from the Innovation Fund encompass the assessment of the project's potential for emission reductions, the degree of innovation, project maturity, potential for widespread application or replicability, and cost efficiency. The Innovation Fund utilizes both open calls for (small-scale and large-scale) projects and competitive bidding processes to allocate grants. (EC 2023h.) The Innovation Fund has already held three small-scall calls, awarding EUR 100 million in grants in each round (EC 2023n), and three large-scale calls, awarding EUR 1.1 billion, EUR 1.8 billion, and EUR 3.6 billion in grants to projects covering a wide range of sectors (EC 2023o). Among the 41 large-scale clean tech projects selected following the third call for large-scale projects, according to announced 41 projects, more than ten projects have connection to CCU value chain (EC 2023p).

Horizon Europe: Another initiative that could provide support to the development of CCU in the EU is the Horizon Europe funding program. This program, designed to run from 2021 to 2027, allocates a budget of EUR 95.5 billion to support research, development and innovation, of which more than EUR 15 billion is allocated to address matters related to climate, energy and mobility. (EC 2021a.) Horizon Europe is open for the participation of EU legal entities as well as third countries associated to Horizon Europe.

Horizon Europe channels its support through work programs, which outline funding opportunities for research and innovation activities. The primary work program of Horizon Europe for the period 2023 – 2024 (EC 2023c) for climate, energy and mobility, highlights that one of the anticipated impacts accelerating the development under the work program is to accelerate the development of CCUS infrastructures, with a specific emphasis on the creation of hubs and clusters. Additionally, the work program highlights the pivotal role of CCU and CCS as a viable option for mitigating emissions in industrial applications, including the conversion of CO2 into products. (EC 2023c.)

The distinctions between the Innovation Fund and Horizon Europe are noteworthy in their goals and application criteria. The Innovation Fund is focused around demonstrating and constructing large-scale industrial projects with cutting-edge technologies. The Innovation Fund allows applications from single entities, and the selection criteria encompass technical, business, and financial considerations. On the contrary, Horizon Europe serves as a research and innovation program, underscoring collaborative endeavors by mandating applications from at least three legal entities spanning a minimum of three countries. The selection criteria for Horizon Europe specifically focus on research-related factors. These differences emphasize the Innovation Fund's dedicated focus on pioneering industrial ventures and Horizon Europe's commitment to fostering collaborative research initiatives.

State Aid Guidelines for Climate, Environmental Protection, and Energy: Furthermore, the European Commission enables EU Member States to provide financial assistance to the development of CCU. This support is governed by the stringent guidelines established in the 2022 State Aid Guidelines for Climate, Environmental Protection, and Energy (CEEAG) (EC 2022a). Under the aid directed towards the reduction and removal of GHG emissions and energy efficiency, the CEEAG Guidelines state that, in principle, all technologies contributing to emissions reduction are eligible for state aid. CCU is explicitly listed as an eligible type of technology among other qualifying technologies. By adhering to these guidelines, EU Member States are enabled to advance initiatives involving CCU, in harmony with the Commission's overarching objectives of climate action, environmental protection, and sustainable energy.

5 CCU IN THE UNITED STATES' POLICY FRAMEWORK

In the United States (US), federal policymakers and stakeholders hold diverse perspectives on addressing future climate change actions. Throughout history, the US has demonstrated varying approaches to addressing climate change and participating in GHG reduction efforts, including those outlined in the Paris Agreement. Members of Congress have expressed different views, with proposed legislation ranging from carbon pricing mechanisms to clean energy standards,

research funding, and international cooperation. While some resolutions argue against certain carbon pricing approaches, comprehensive climate change policy votes have been infrequent, as climate change topics are among the most divisive matters between the Republicans and Democrats. (Lattanzio et al. 2021.)

5.1 Key Policy Strategies for CCU in the USA

The United States currently lacks a unified policy strategy to steer the development of CCS or CCU technologies. While CCUS technologies are recognized as potential tools in the national decarbonization strategy, their integration into comprehensive climate change mitigation plans remains fragmented.

US Climate Goals: With the election of President Biden in 2021, the US Nationally Determined Contribution (US NDC) under the Paris Agreement was announced with a new GHG reduction target of 50% - 52% below 2005 levels by 2030 (UNFCCC 2023). To meet the 2030 target, the US NDC outlines examples of actions to decarbonize the energy sector. These include achieving 100% pollution-free electricity by 2030, promoting vehicle electrification and efficiency, reducing emissions from heavy industry through R&D support, advancing very low- and zero-carbon industrial processes and products via carbon capture incentives, and using public procurement to stimulate early markets for these goods.

US Long-Term Strategy to Reach Net-Zero Emission by 2050: Further, the Long-Term Strategy of the United States (US LTS) to Reach Net-Zero Emission by 2050 (The White House 2021b) builds on the US NDC and outlines multiple pathways to achieve net-zero emissions no later than 2050. It underlines the importance of federal leadership in achieving the climate targets of 2030 and transitioning to net-zero emissions by 2050. This could be achieved by using investments and incentives to deploy clean technologies across sectors, as emphasized in the US LTS. While the US LTS acknowledges the potential role of carbon capture and other CO2 removal technologies in the decarbonization efforts, CCU does not receive explicit support, except for the case of direct air

capture and storage, where it mentions that captured CO2 could be permanently stored underground or converted into synthetic aggregate material for use in concrete production.

Despite the announcement of the US LTS and net-zero targets, it's important to note that these targets are not yet enshrined in US law (Climate Action Tracker 2023) and remain part of US policies, making them subject to potential change with the election of a new government (Lattanzio et al. 2021). Further, the US LTS mentions "the U.S. National Climate Strategy", which, according to the US LTS, is forthcoming and expected to detail how the US will fulfill the US NDC. Despite numerous references to the U.S. National Climate Strategy since 2021 - including in the US LTS (The White House 2021b), it has not yet been published by the US government. This signals uncertainty about how the US will achieve its climate goals. If eventually released, it has the potential to serve as a framework supporting CCU initiatives.

Federal Sustainability Plan: As a step toward meeting the US NDC targets, the Federal Sustainability Plan was established through the President's Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability (Federal Register 2021) and the accompanying document titled "Federal Sustainability Plan" (The White House 2021c). The aim of the Federal Sustainability Plan is to channel the annual procurement power of the federal government, amounting of USD 650 billion, to achieve five primary goals, including, among others, achieving net-zero emissions from federal procurement and overall federal operations by 2050, along with 65% emissions reduction by 2030 in alignment with the US NDC.

Building on the momentum of the Federal Sustainability Plan, the US federal government was authorized to launch a "buy clean" initiative aimed at promoting the purchase of low-carbon materials and "made in America" sustainable products, such as those used in the construction industry, which exhibit lower embodied emissions when considering the lifecycle emissions of their production (CEQ 2023a). This initiative is considered as a key strategy for emissions

reductions tied with the procurement activities of the federal government. Through the expansion of low-carbon procurement practices, this initiative sends a clear signal to the market by encouraging the production of low-carbon products and materials as well as the purchase of sustainable, American-made goods and services. (The White House 2021c).

Since the launch of the “buy clean” initiative, various measures have been implemented to expedite the achievement of its objectives. These include, among others, the announcement of qualifying requirements for what constitutes low embodied carbon material, specifically for four key construction materials: concrete (and cement), asphalt, steel, and glass. These criteria are set to apply to 150 Federal Inflation Reduction Act projects, totaling USD 2 billion in IRA low-carbon materials. Additionally, funding has been allocated to support building projects that qualify for low embodied carbon material. Furthermore, US Department of Energy (US DOE) has unveiled a USD 100 million grant for carbon utilization procurement, designed to assist eligible governmental recipients in acquiring products derived from the conversion of carbon emissions, which will be discussed further under Section 5.3. (CEQ 2023b.)

US DOE Industrial Decarbonization Roadmap: Building on the US LTS, the US DOE, a federal executive department responsible for overseeing the country’s national energy policy and energy productions among other responsibilities, released its Industrial Decarbonization Roadmap in September 2022 (US DOE 2022b). This roadmap outlines transformative technology pathways to achieve net-zero emissions by 2050. For industrial decarbonization, the roadmap establishes four fundamental pillars: energy efficiency, industrial electrification, low-carbon fuels, feedstocks, and energy sources, and carbon capture, utilization, and storage (CCUS). While the first three pillars can collectively reduce 40% of targeted emissions and be deployed sooner than CCUS, the roadmap acknowledges that these measures alone are insufficient for achieving net-zero emissions. Both CCU and CCS are considered critical to meeting the targeted carbon reductions. The roadmap identifies opportunities for CCU to utilize CO2 across various economic sectors and emphasizes the need for R&D

to reduce energy input requirements, enhance CO2 reduction efficiency and yields, and integrate CCU technologies into existing installations.

FECM Strategic Vision: In support of the climate goals set forth by President Biden, the Office of Fossil Energy and Carbon Management (FECM) – an office of the US DOE, with its core mission to address the climate crisis, released its "Strategic Vision: The Role of Fossil Energy and Carbon Management in Achieving Net-Zero Greenhouse Gas Emissions" (FECM Strategic Vision) in April 2022 (US DOE 2022a). The FECM Strategic Vision aims to guide the US DOE in making informed decisions regarding strategic carbon management. Further, it ensures that the utilization of fossil fuels is placed within the appropriate context of addressing climate change and is tailored to achieve net-zero GHG emissions.

Additionally, the FECM Strategic Vision seeks to support the demonstration and eventual deployment of carbon management technologies. Within its Strategic Vision, FECM prioritizes three key strategic directions, along with other related priorities: (i) advancing justice, labor, and engagement; (ii) advancing carbon management approaches toward deep decarbonization, such as CO2 conversion and carbon dioxide removal; and (iii) promoting technologies that contribute to sustainable energy resources, such as hydrogen with carbon management and methane mitigation. (US DOE 2022a.)

In the context of CO2 conversion, an alternative term for CCU, within the FECM Strategic Vision, CO2 conversion is addressed in a dedicated chapter. The topics within this chapter emphasize the necessity to invest in RD&D, to understand the technological limitations of carbon conversion, and support the development of an ecosystem that facilitates the implementation of technologies for recycling CO2 into economically viable, value-added products. The overall FECM vision statement emphasizes: "*Research, develop and demonstrate a broad suite of technologies that convert CO2 into environmentally responsible, equitable and economically valuable products, and enable low-carbon supply chains to meet the goal of a decarbonized economy by 2050*". The FECM Strategic Vision emphasizes the federal government's role in utilizing its procurement power and

developing policies to foster early markets for CO2 conversion. This involves verifying carbon reductions in CO2-based products to instill consumer confidence. (US DOE 2022a.)

The technical strategy outlined in the FECM Strategic Vision for CO2 conversion focuses on R&D efforts to overcome critical technological challenges. The primary goal is to decrease energy requirements and confirm carbon reduction in comparison to conventionally produced alternatives. Three carbon key pathways for carbon conversion are highlighted: carbon uptake in algae system, mineralization, and catalytic conversion. As an example, catalytic conversion can transform CO2 into diverse products, such as plastics, chemicals, and solid carbon products like nano fibers. The FECM Strategic Vision emphasizes researching non-traditional CO2-derived products with Carbon-Carbon bonds like carbon nanotubes and polymers. Near-term (i.e., less than five years) objectives involve testing and evaluating promising catalytic conversion pathways and technologies, establishing benchmarking standards for various pathways, and conducting pre-feasibility studies to define engineering, technical, and financial parameters (US DOE 2022a).

Net-Zero Game Changers Initiative: In November 2022, the White House launched the Net-Zero Game Changers Initiative to advance innovation solutions in game-changing technologies, with the goal of meeting the US NDC target and achieving the net-zero emissions by 2050. To launch the Net-Zero Game Changers Initiative, the Biden Administration established an interagency working group to identify, prioritize, and expedite the development of innovative net-zero technologies. The efforts of the working group led to the identification of 37 net-zero research and development opportunities from across the US interagency. (The White House 2022a).

Then, the Biden Administration outlined five initial priorities to kick start clean energy innovation, grouping the 37 net-zero game-changers into broader research areas to advance the achievement of the US climate goals. These five priorities are efficient building heating and cooling, net-zero aviation, net-zero

power grid and electrification, fusion energy at scale, and industrial products and fuels for a net-zero, circular economy, including secure supply chain and alternative methods to produce low-carbon aluminum, steel, chemical production among others. The justification for selecting this set of priorities is based on the belief that these solutions will strengthen the U.S. innovation ecosystem, spanning various economic sectors and U.S. research and development programs. (The White House 2022c.)

These game-changers are further categorized based on potential impact into three groups: (i) transformational impact - innovations with a system-wide impact, such as CO2 capture, utilization, & storage; (ii) broad impact - innovations benefiting one or more economic sectors, like circular economy & secure supply chain; (iii) targeted impact - innovations benefiting specific sub-sectors, such as low CO2 cement or low CO2 chemicals. To accelerate their impact, the Net-Zero Game Changers Initiative is designed to provide funding to these technologies throughout the R&D, demonstration, and deployment phases to increase their impact through cost reduction and performance enhancements. (The White House 2022c.)

Carbon Management strategy: The U.S. Department of Energy's Office of Fossil Energy and Carbon Management (FECM) announced its intention to initiate a "Responsible Carbon Management Initiative" in August 2023 (FECM 2023a). The initiative is a framework designed to recognize and motivate carbon management project developers and industry participants to adhere to best practices in the development of carbon management projects. The initiative is planned to unfold in two phases.

The first phase involves FECM releasing "Principles" for Responsible Carbon Management Projects, covering categories such as community engagement, transparency, and environmental responsibility. These Principles apply to all approaches of carbon management, including CCS and CCU. Project developers interested in participating will need to submit an intake form to showcase their commitment to the responsible carbon management. In the second phase, FECM

aims to offer technical assistance through funding for projects seeking to meet the Principles. This phase focuses on evaluating the implementation of the Principles, accountability, and leadership. Participation in the first phase is not mandatory for the participation in the second phase. (Federal Register 2023.)

The funding for Responsible Carbon Management Initiative is derived on the funds allocated to the US DOE under the Bipartisan Infrastructure Law (US Congress 2021), totaling approximately USD 12 billion for new carbon management over five years, and under the Inflation Reduction Act (US Congress 2022). The FECM announcement of the “Responsible Carbon Management Initiative” invited stakeholder input through a request of information which concluded at the end of September 2023. FECM is currently reviewing the received comments that it received from stakeholders and plans to launch the first phase of the initiative in the first half of 2024. (FECM 2023b.)

5.2 Legislative Drivers of CCU: Policy Instruments in the USA

At the federal level, both CCU and CCS projects operate without a dedicated regulatory framework tailored specifically to govern CCU or CCS (CEQ 2021). Nevertheless, the regulatory guidelines are sourced from existing legislative frameworks applicable to sectors like the energy sector, industrial facilities, and infrastructure development (Thielges et. al. 2022; Eckardt et al. 2023).

Currently, enhanced oil recovery (EOR) is the primary utilization pathway for CO2 utilization in the US. The concept of CO2 utilization for EOR has been commercially viable since 1970, with the oil industry actively utilizing CO2 streams generated by various industrial processes for this purpose (CEQ 2021). However, this dynamic is undergoing a shift in the research and attention of the US Congress toward alternative utilization pathways beyond EOR (Jones & Lawson, 2022). This shift is evident in the definition of carbon utilization under the Bipartisan Budget Act of 2018 (US Congress 2018), which, among other things, broadened the scope of the 45Q provisions, as discussed under Section 5.3. The Bipartisan Budget Act of 2018 explicitly excludes EOR from its definition, by stating that “*utilization of qualified carbon oxide means*:

(i) *the fixation of such qualified carbon oxide through photosynthesis or chemosynthesis, such as through the growing of algae or bacteria,*

(ii) *the chemical conversion of such qualified carbon oxide to a material or chemical compound in which such qualified carbon oxide is securely stored, or*

(iii) *the use of such qualified carbon oxide for any other purpose for which a commercial market exists (<u>with the exception of use as a tertiary injectant in a qualified enhanced oil or natural gas recovery project</u>), as determined by the Secretary"*.

The definition of carbon utilization, as provided in the Bipartisan Budget Act of 2018, takes a nuanced approach by explicitly excluding EOR, which could be interpreted as a step to scale up and advance other utilization pathways. According to the Bipartisan Budget Act of 2018, the "utilization of qualified carbon oxide" (i.e., both carbon dioxide and any other carbon oxide) refers to specific processes, including the fixation of carbon oxide through photosynthesis or chemosynthesis, the chemical conversion leading to secure storage, and the commercial use of carbon oxide, excluding its use as a tertiary injectant in enhanced oil or natural gas recovery projects.

In December 2020, the US Congress passed the Energy Act of 2020 and the Utilizing Significant Emissions with Innovative Technologies Act, also known as the "USE IT Act", as part of a comprehensive omnibus bill titled "Consolidated Appropriations Act, 2021" (US Congress 2020). Both the Energy Act of 2020 and the USE IT Act included provisions that provide support for the development of CCU, primarily through the authorization for the US DOE to establish the carbon utilization program, as outlined below:

Energy Act of 2020: In title IV (Carbon Management), the Energy Act grants authorization to the US DOE to establish "Carbon Utilization Program" for RD&D in carbon utilization. This program aims to, among other things, evaluate and monitor potential lifecycle changes in CO2 and other GHG emissions, and to identify and evaluate "*novel uses for carbon, including the conversion of carbon and carbon oxides for commercial and industrial products and other products with potential market value*".

Further, in carrying out the Carbon Utilization Program, the Energy Act directs the US DOE to establish and operate a national “Carbon Utilization Research Center” for early-stage R&D activities, including R&D activities for carbon dioxide conversion technologies into valuable products. Overall, the Energy Act supports cutting edge research, and the Carbon Utilization Research Center is funded with over USD 280 million for the fiscal years 2021 to 2025.

USE IT Act: In conjunction with the Energy Act, the USE IT Act provides additional guidance to the US DOE for the implementation of the RD&D program, as well as for the commercialization of CCU technologies. Under the RD&D program, the US DOE is directed to “*identify and evaluate novel uses for carbon (including conversion of carbon oxides) that, on a full lifecycle basis, achieve a permanent reduction, or avoidance of a net increase, in carbon dioxide in the atmosphere, for use in commercial and industrial products*”. It also provides examples of such products, including chemicals, building materials, plastics, cement, or any other products that demonstrate market value.

The USE IT Act emphasizes specific priorities for supporting research projects under the program of RD&D. The US DOE is directed to give preference to projects that have access to a carbon dioxide emissions stream of at least 250 metric tons per day from a U.S. stationary source. Additionally, projects with on-site equipment for testing small-scale carbon dioxide utilization technologies, along with access to larger test bays for scaling up, are prioritized. It also highlights the importance of existing partnerships with national laboratories, institutions of higher education, private companies, or government entities as a key consideration for project selection.

Furthermore, the USE IT Act mandated the Council on Environmental Quality (CEQ), in consultation with other agencies, to prepare a report on Carbon Capture, Utilization, and Sequestration (CCUS Report). The purpose of this CCUS Report is, among other matters, to compile federal permits, inventory activities transforming captured carbon dioxide into commercial products, and

identify regulatory gaps in deploying CCUS projects. In response, CEQ delivered the CCUS to the US Congress in June 2021 (The White House 2021a).

Regarding carbon utilization, the CCUS Report underscores the lack of specific federal regulations but highlights the potential for the federal agencies to boost early markets through procurement influence. The report also stresses the ongoing need for refining lifecycle assessment (LCA) methods and making analyses of different utilization options publicly accessible. To facilitate efficient and responsible deployment of CCUS, the CCUS Report suggests collaboration between CEQ and federal agencies, focusing on identifying procurement opportunities and improving LCA methods. (CEQ 2021.)

Building on the USE IT Act and the CCUS Report, in February 2022, CEQ delivered new guidance to federal agencies to ensure that the advancement of CCUS technologies is carried out responsibly. Concerning CCU, the new guidance highlights that the commercialization of CCU requires greater transparency to enhance public confidence in emissions reductions and project durability. Transparency, as outlined in the guidance, can be achieved by making publicly accessible analyses like LCAs and the implementation of standards or certifications for CCU products. (Federal Register 2022.)

Additionally, the guidance suggests that agencies overseeing CCU should consider the consolidation and publication of a repository containing LCA methodology, results, and information. Furthermore, as the US DOE develops standards and certifications to expedite the commercialization of CCU technology under the Infrastructure Investment and Jobs Act (discussed below), the guidance recommends assessing how these measures can strengthen the federal procurement of CCU technologies. (Federal Register 2022.)

Infrastructure Investment and Jobs Act: In 2021, the US Congress enacted the Infrastructure Investment and Jobs Act (US Congress 2021), commonly referred to as the Bipartisan Infrastructure Law (BIL). The BIL is an extensive investment instrument in sectors such as rail and transit, clean energy, and

water, just to name a few. Concerning CCU, the BIL directed the US DOE to establish the Carbon Utilization Program to offer grants to states, local governments, public utilities, or agencies. These grants are intended for the procurement of commercial and industrial products that: (i) utilize or originate from anthropogenic carbon oxides, and (ii) demonstrate significant net reductions in lifecycle GHG emissions when compared to existing products, technologies, and processes.

Manufacturers interested in participating in the Carbon Utilization Program, with the intention of having their products to be procured under this initiative, are required to provide the lifecycle assessment for their carbon conversion product. The assessment should demonstrate a significant net reduction (initially a minimum of 10% compared to the baseline provided by the National Energy Technology Laboratory (NETL)) in lifecycle GHG emissions when compared to currently available products. (NETL 2023.) The BIL provides more than USD 310 million for the Carbon Utilization Program for FY2022-FY2026 (The White House 2022b), and it is discussed further under Section 5.3.

Inflation Reduction Act of 2022: Building on the US climate and clean energy objectives, along with the objectives of the Infrastructure Investment and Jobs Act, the Inflation Reduction Act (IRA) was enacted in August 2022 (US Congress 2022). The IRA aims to address domestic inflation while also stimulating economic growth and tackling climate change. It incorporates federal policies aimed at advancing the deployment of clean energy technologies and prioritizing industry decarbonization, among other initiatives. Alongside the substantial investments from the Bipartisan Infrastructure Law, this comprehensive legislative package offers unprecedented support for the implementation of carbon management technologies.

Through a combination of grants, tax measures, loans, and additional incentives, the IRA aims to accelerate the implementation of clean energy solutions, electric vehicles, sustainable building practices, and environmentally friendly manufacturing processes. (The White House 2023a.) Relating to CCU, the IRA

introduced and expanded fiscal incentives in the form of tax credit that is provided under section 45Q of the Internal Revenue Code of 1986, as detailed under Section 4.3. Section 45Q of the Internal Revenue Code of 1986 offers a “credit for carbon oxide sequestration”, applicable to CO2 (carbon dioxide), CO (carbon monoxide), and C3O2 (carbon suboxide) (Beck 2020). This provision grants monetary credits for permanently storing carbon oxide through methods such as usage, stored through enhanced oil recovery, or in geologic formations. Initially, the 45Q tax credit was enacted in 2008 and underwent reform in 2018, resulting in an expansion of the eligibility for this tax credit to include various industries and applications. (Beck 2020.)

Carbon Tax: Currently, there is no federal carbon tax implemented in the United States. Nevertheless, active carbon pricing programs are in place in thirteen States, including California and New York (C2ES 2023a). These thirteen States are part of the Regional Greenhouse Gas Initiative, which was initially established in 2005 as the first mandatory cap-and-trade program in the US to limit CO2 emissions from the power sector (C2ES 2023b).

5.3 Cost Reduction measures: USA Support Schemes for CCU

The United States has implemented specific measures to promote the advancement of CCUS projects. While there is currently no dedicated funding executively allocated for the development of CCS and CCU projects, various policy measures have been established to drive the progress of clean technologies in the country, including those related to CCU.

Carbon Utilization Procurement Grants: This grant, established under the Bipartisan Infrastructure Law in 2021, aims to incentivize states, local governments, public utilities, or agencies to establish procurement preferences to facilitate the achievement of key climate policy objectives. This grant, under the Carbon Utilization Program, is designed to assist the recipients in offsetting 50% of the costs associated with procuring products manufactured from converted carbon emissions. This support is intended to foster the growth of the carbon utilization market. (US DOE 2023a.) The total allocation for these grants exceeds

USD 310 million and is earmarked for the period between 2022 and 2026 (The White House 2022b). In July 2023, the US DOE issued a funding notice of up to USD 100 million in total, with individual grants varying between USD 50,000 and 500,000 (US DOE 2023c). Specifically, both the supply-side and demand-side provisions of carbon utilization stand to gain significant economic advantages from this grant (National Academies of Sciences 2023).

Loan Program: The US also makes available loans and loan guarantees for innovative clean energy projects through the Loan Programs Office. The Loan Programs Office offers, among others, financing for projects that either deploy innovative clean energy technologies on a commercial scale, including CCU technologies (Innovative Energy) or utilize innovative manufacturing processes to produce innovative technologies at a commercial scale (Innovative Supply Chain) (US DOEa).

The Loan Programs Office was originally established under the Energy Policy Act of 2005 (US Congress 2005) and since then has been enhanced further through the Energy Act of 2020 (US Congress 2020), and recently with the introduction of the IRA (US Congress 2022). The IRA allocates approximately USD 11.7 billion to the Loan Programs Office within its energy and climate provisions, supporting the issuance of new loans. This funding also increases the loan authority in Loan Programs Office existing programs by approximately USD 100 billion. Further, the IRA introduces the Energy Infrastructure Reinvestment Program (EIR). (US DOE 2023b).

In addition to the standard eligibility criteria of the Loan Programs Office, EIR projects shall either enable the retooling, repowering, repurposing, or replacement of inactive energy infrastructure, or enable the existing energy project to avoid, reduce of utilize, or store air pollutants or human-caused GHG emissions (US DOEb). The IRA allocates USD 5 billion until end of September 2026, to implement the EIR program, with a maximum loan cap set at USD 250 billion (US DOE 2023b).

In addition to the favorable loan terms, the benefit for the projects financed by the Loan Programs Office is that they could demonstrate to private debt and equity

investors that innovative clean energy technologies are financially viable and prepared for widespread implementation on a large scale. The successful backing from the Loan Programs Office serves as a testament to the bankability of these technologies, instilling confidence among private investors in supporting their deployment.

Tax Credits: To accelerate the advancement of clean energy technologies, including CCU technologies, the Inflation Reduction Act (IRA) introduced substantial improvements to the existing 45Q tax credits (US Congress 2022). Primarily, the IRA increased the tax credit amounts for eligible CCU projects from USD 35 (2018) to USD 60 per ton of emissions captured through CCU from industrial and power generation facilities. Also, the IRA increased the incentive from USD 50 (2018) to USD 130 per ton of emissions for direct air capture and utilization. (US Congress 2022; CCC 2022.)

Additionally, the IRA significantly lowered the annual carbon capture thresholds requirements to qualify for the 45Q tax credits, allowing more projects to benefit from such incentives. Specifically, for direct air capture projects, the threshold was lowered from 100,000 to 1,000 tons of emissions per year. Similarly, for power generation facilities the threshold was reduced from 500,000 to 18,750 metric tons of emissions per taxable year. For any other facility, the threshold was decreased from 25,000 to 12,500 metric tons of emissions per taxable year. Further, to qualify for these tax credits, the project must adhere to the detailed criteria outlined by the IRA, which includes demonstrating emissions reductions through a lifecycle assessment. (US Congress 2022; CCC 2022.)

Project developers eligible for 45Q tax credits can choose between two monetization options of such credits: direct pay, which involves receiving an immediate cash payment from the government, or transferability, which allows them to sell the credit to parties with sufficient tax liabilities (CCC 2022). The IRA also extended the deadline for the start of the project construction window from the previous deadline of January 1, 2026, to January 1, 2033. The 45Q tax credits can be claimed for claiming over a 12-year span after a facility is commissioned, provided that the facility becomes operational before January 1,

2033. (The White House 2023a.) The significant changes implemented to the 45Q tax credits under the IRA are poised to significantly stimulate investment in clean energy technologies, including CCU technologies. By offering increased fiscal incentives, the IRA lays a solid foundation for innovation to flourish.

Moreover, in February 2023, a bill titled the “Captured Carbon Utilization Parity Act” was introduced in the US Congress (US Government Info 2023). The primary objective of this proposed legislation is to increase the existing 45 tax credits for CCU projects, bring it into line with the tax incentives provided for CCS, meaning that the bill seeks to raise the tax credit for CCU projects from the current USD 60 per ton of CO2 to USD 85 per ton of CO2 (The White House 2023b). Should this act be successfully enacted, it would serve to significantly enhance the incentives for the development of CCU projects. By equalizing the tax benefits with those afforded to CCS, the Captured Carbon Utilization Parity Act would provide an added impetus for the advancement and implementation of CCU projects. This increased financial support and flexibility in tax credits would contribute to making CCU projects more economically viable and, consequently, further stimulate their development.

6 CROSS-JURISDICTIONAL EU-US COMPARISON

When comparing the EU and US policy and legal frameworks regarding CCU, it is evident that neither the EU nor the US has a unified framework addressing CCU. Both regions address CCU alongside other carbon management technologies, such as CCS or carbon removal. Nevertheless, differences and similarities become apparent.

6.1 Policy Strategy for CCU

Both the EU and the US address the challenges posed by climate change through their respective policy strategies. However, while the EU has set an ambitious binding objective of achieving climate neutrality by 2050 under the European Climate Law (EC 2021b), the US approach to achieve the announced net-zero emissions by no later than 2050 remains uncertain, as such a target is not yet enshrined in US law as discussed in Section 5.1. Nevertheless, both

jurisdictions recognize the role that CCU technologies could play in achieving their respective climate goals.

In the EU, CCU is integrated into a more comprehensive policy strategy documentation, especially within initiatives such as the Clean Planet for All strategy (EC 2018a), the Circular Economy Action Plan (EC 2020a), and the most recent Industrial Carbon Management Strategy (EC 2024). CCU is addressed as a key approach to reducing GHG emissions in hard-to-abate sectors like cement and steel production and as a solution to provide sustainable non-fossil carbon as a feedstock in industrial sectors. Furthermore, the EU's strategies highlight CCU's potential role in promoting circularity of raw materials and reducing dependence on critical materials from third countries. This holistic approach positions CCU as an integral component of the EU's broader climate policy.

Similarly, in the US, CCU is acknowledged as a potential tool in the national decarbonization strategy. Initiatives like the Federal Sustainability Plan (Federal Register 2021; The White House 2021c) and the Industrial Decarbonization Roadmap (US DOE 2022b) recognize the importance of CCU in achieving net-zero emissions by 2050 and utilize the US federal government procurement power to promote the purchase of low-carbon materials and stimulate markets for sustainable products. Unlike the EU, which lacks a similar public procurement initiative at the EU level, this effort in the US can be considered a significant step forward in the development of CCU offerings, as it sends a clear signal to the market to produce low-carbon products and materials, in addition to contributing to the US climate goals.

Both the EU and the US emphasize in their respective policy strategy the need for increased research and development investments to accelerate the deployment of CCU technologies. However, the US goes the extra mile catching up with the technological advancements. The FECM Strategic Vision (US DOE 2022a), in addition to conventional CCU, highlights the need to invest in RD&D to understand the technological limitations of carbon conversion, such as catalytic

conversion, which transforms CO2 into diverse products like chemicals and solid carbon products. This vision extends beyond the concept of CO2 capture and use to include non-traditional CO2-derived products with Carbon-Carbon bonds, such as carbon nanotubes and carbon nano fibers. Furthermore, CO2 capture, utilization, and storage are classified as one of the game-changers net-zero technologies with a transformational impact under the Net-Zero Game Changers Initiative, which is designed to provide substantial funding throughout the RD&D and the development phases.

Despite similarities in objectives, there are differences between the EU and the US in their approaches to CCU integration. The EU has proposed regulatory frameworks for certifying carbon removals and intends to establish a legal framework for industrial carbon management, including CCU. In contrast, the US initiatives focus more on policies and guidelines for carbon management projects without explicit certification frameworks.

6.2 Legislative Drivers for CCU

Similar to the status of the policy strategies in the EU and US, neither jurisdiction offers a unified legal framework for CCU. While the US, through the Bipartisan Budget Act of 2018 (US Congress 2018), explicitly defines carbon utilization to include carbon dioxide alongside other carbon oxides, the EU lacks a comprehensive definition of CCU within its legislative framework, and it primarily focuses on carbon dioxide in its respective policy frameworks. This disparity is particularly important to recognize when considering what could potentially be classified as CCU.

In the EU, the focus lies on integrating CCU within broader climate and energy policies. For instance, the Renewable Energy Directive (RED II (EC 2018d) and RED III (EC 2023k)) promotes the utilization of renewable energy sources, including fuels derived from captured CO2 to drive the transition towards cleaner energy sources. While not exclusively dedicated to CCU, these directives provide a regulatory framework that indirectly supports CCU development by incentivizing renewable energy sources. Additionally, initiatives like ReFuelEU Aviation (EC

2023i) and the FuelEU Maritime (EC 2023f) specifically target the challenging-to-electrify transport sector, aiming to encourage CO2 utilization through clear binding synthetic fuel targets. The revised EU ETS (EC 2023d) explicitly recognizes and incentivizes one CCU case when the emissions become permanently chemically bound within a product.

In contrast, the US legislative approach to CCU centers on specific acts tailored to incentivize research, development, and deployment. The Energy Act of 2020 and the USE IT Act (US Congress 2020) provide support for CCU projects, emphasizing the need to identify and evaluate novel uses for carbon and funding early-stage research activities for carbon dioxide conversion technologies, while the Bipartisan Infrastructure Law (US Congress 2021) allocates significant funding for the Carbon Utilization Program. Moreover, the Inflation Reduction Act of 2022 (US Congress 2022) introduces fiscal incentives, such as tax credits under section 45Q, to stimulate investment in clean energy solutions and carbon management technologies.

Overall, while both the EU and the US recognize the importance of regulatory frameworks in promoting CCU technologies, they employ different strategies to achieve this goal. The EU takes a more systematic and organized approach by integrating CCU within existing climate and energy policies. In contrast, the US focuses on a targeted approach with specific and direct fiscal incentives to support CCU research, development, and deployment.

6.3 Cost Reduction Measures

The EU and the US implement distinct strategies to support CCU development and reduce the associated costs of such projects. While both regions aim to foster innovation and mitigate GHG emissions, their approaches differ in terms of funding mechanisms, tax incentives, and public procurement strategies. Understanding these contrasting strategies is essential for evaluating the effectiveness and implications of CCU initiatives in each jurisdiction.

Grants: The EU offers two types of grants for scaling up CCU projects. The first type is directed to support research and development, pilots, and small-scale projects through the Horizon Europe program. The second type is the provided under the Innovation Fund, which offers grants for both small-scale and large-scale projects through competitive bidding processes. It supports the commercialization of proven innovative technologies, including those in the CCU sector.

In contrast, the US offers a different kind of grant under the Carbon Utilization Procurement Grants program. This grant is not offered to project developers, but rather aims to incentivize states, local governments, public utilities for the procurement of products manufactured from converted carbon emissions. These grants aim to offset 50% of the associated procurement costs and encourage the growth of the CCU market.

Loans: There is no explicit loan support scheme for CCU projects in the EU. On the other hand, the US provides loan support through the Loan Programs Office and the Energy Infrastructure Reinvestment Program (EIR). These programs offer financing for innovative clean energy projects, including CCU technologies, aimed at commercial-scale deployment. The EIR specifically targets the retooling, repowering, or replacement of inactive energy infrastructure and offers loans with a maximum cap to support eligible projects.

Tax credits: The IEA (2023b) explains that tax credits serve as a policy tool that can be used to incentivize particular behaviors or accelerate the deployment of specific technologies and practices. Essentially, tax credits offer eligible entities the opportunity to directly reduce the amount they owe in taxes by a specified amount.

The US offers tax credits to CCU projects through the existing 45Q tax credits, which have recently been extended by the Inflation Reduction Act of 2022. This enhancement substantially increases the credit amounts and reduces the annual carbon capture thresholds, thereby incentivizing investment in CCU technologies for both small and large-scale projects. One advantage of this tax credit over

other carbon pricing mechanisms, like the emission trading system, is that the tax credit is fixed and not subject to market volatility (Beck 2020). In contrast, the EU does not offer comparable tax credits at the EU level to promote CCU adoption.

Carbon Pricing: The EU utilizes the EU ETS as a component of its carbon pricing mechanism. However, CCU is generally not covered by the EU ETS, except for one specific case when emissions become permanently chemically bound within a product. Nevertheless, revenue generated from the EU ETS indirectly supports CCU projects through the Innovation Fund, which receives funding from emissions allowance trading revenues. Conversely, there is no similar system at the federal level in the US, and neither jurisdiction has implemented regulations on taxing carbon emissions.

Strategic signaling: While the EU has binding deployment targets for synthetic fuels under the ReFuelEU Aviation and FuelEU Maritime initiatives, there are currently no EU binding targets for other CCU pathways. However, an aspirational objective exists under the Sustainable Carbon Cycles strategy, aiming to achieve a share of at least 20% of sustainable non-fossil carbon in chemical and plastic products by 2030. Establishing this as a binding target in the future could provide a strong market signal for the development and deployment of CCU products. In contrast, the US has not established such deployment targets for CCU technologies. Nevertheless, the US is leveraging its governmental procurement power to stimulate early markets for CO2 conversion.

The following Table 1 provides an overview of the key policy mechanisms illustrated in Figure 3 and the policy tools discussed above, their status in the EU and the US, classified as whether they are associated with corporate capital expenditure (CAPEX) or operational expenditure (OPEX) as provided by La Hoz Theuer and Olarte (2023).

Table 1. Overview of CCU policy mechanisms and policy tools in EU and US

Policy Mechanism	Policy Tool	Status - EU	Status - US	CAPEX	OPEX
CCU regulations		No	No		
Cost reduction measures	**Capital grants**	Yes, For R&D, pilots, and small-scale via Horizon Europe For commercialization of small-scale and large-scale via Innovation Fund	No	X	 X
	Tax credits	No	Yes, the 45Q tax credits offer USD 60 or USD 130 per ton of emissions, depending on whether the emissions are captured through CCU or via direct air capture and utilization	X	
	Loans	No	Yes, for innovative on a commercial scale	X	
Regulation of industrial activities: Carbon pricing	**ETS**	Only for the case of CCU when emissions become permanently chemically bound within a product	No		X
	Carbon tax	No	No		X
Strategic signaling	**Deployment targets**	Only to produce synthetic fuels	No		X
Revenue support	**Contracts for difference**	Yes, via the Innovation Fund, and under CEEAG	No	X	
	Public procurement	No	Yes, for states, governmental entities for the procurement of products manufactured from converted carbon emissions via Carbon Utilization Procurement Grants program		X

Despite the variations between the EU and US, both are at the forefront of global efforts in CCUS. Table 1 outlined a variety of policy tools and their present statuses in these jurisdictions. These measures play a vital role in driving innovation, reducing carbon emissions, and facilitating the adoption of CCU technologies in both the EU and the US. To gain a clearer understanding on the effectiveness of the policy mechanisms in developing CCU market in the EU and US, it is essential to examine statistics comparing the level of projects currently operational or planned in both regions. Presently, there is no database available to provide comparable information on CCU across both jurisdictions. However, the International Energy Agency offers comprehensive data on the entire CCUS chain, including CCU, within the CCUS Projects Database, as illustrated in Figure 10 below.

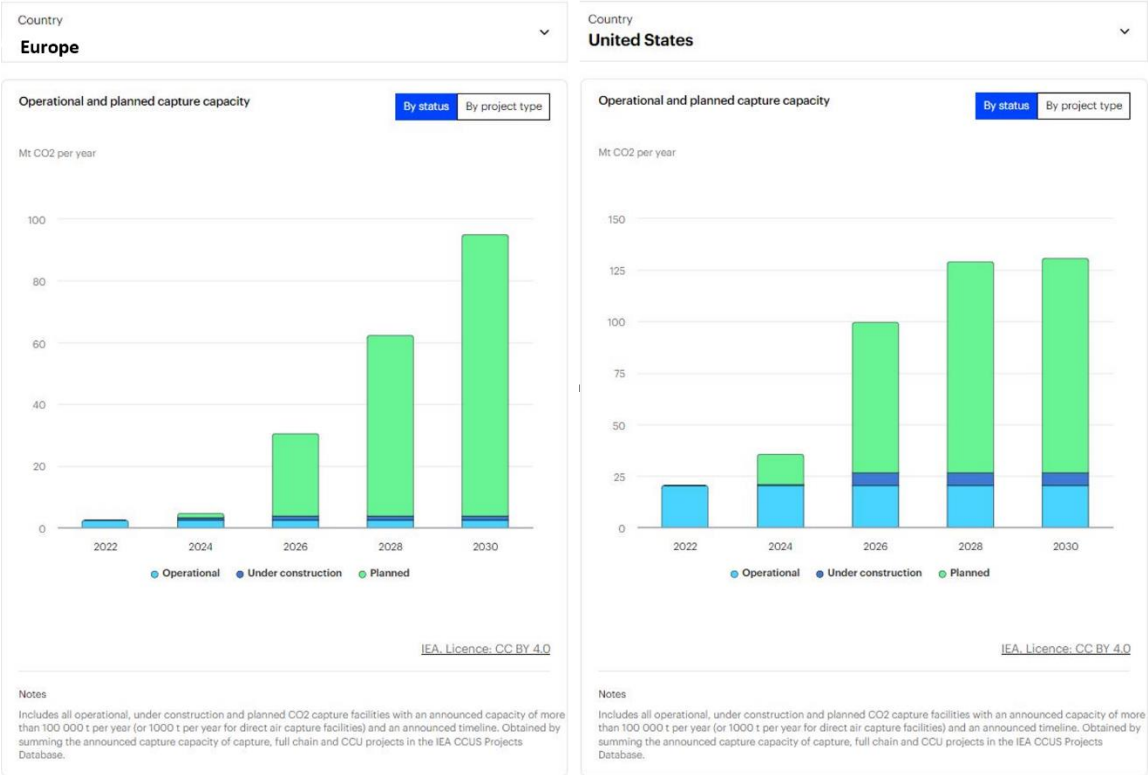

Figure 10. Comparison of operational and planned CCUS capacity in the EU and US (IEA 2023c). Note: The projected figures for Europe include data on projects in the United Kingdom. The IEA 2023c data shows that the planned projects in the United Kingdom alone for the years 2026, 2028, and 2030 are approximately 14, 33, and 51 Mt CO2 per year, respectively.

When comparing the charts in Figure 10 between the EU and the US, it becomes clear that the US is leading in terms of both operational and planned CCUS project capacity. The data illustrates a substantial contrast between the two

regions, with the US demonstrating significantly higher figures across all projected years. For instance, by 2030, while the EU's projected CCUS capacity reaches 91 Mt CO2 per year, incorporating the United Kingdom's contributions of 51 Mt CO2 per year projected for the same year, the United States surpasses this with a projected capacity of 103 Mt CO2 per year during the same period, more than double the projected capacity for the EU for the year 2030. This clearly demonstrates the effectiveness of policy measures implemented by the US in attracting investments, especially the availability of the tax credits for CCUS projects. Despite this, a comparison of emissions statistics from both regions reveals a different trend: while emissions decreased in the EU by a notable 13.5% in 2022, emissions in the US grew by 0.8% (equivalent to 36 megaton), reaching 4.7 gigaton during the same period (IEA 2023a).

Overall, while both the EU and the US share common goals of fostering innovation and mitigating GHG emissions including through CCU initiatives, their strategies differ in terms of the mechanisms used and the scale of projects targeted. The EU's emphasis on large-scale projects and direct grants contrasts with the US's multifaceted approach involving grants, tax incentives, and loan support across both small and large-scale projects. Despite these differences, both regions are taking measures to advance CCUS technologies to combat climate change, albeit through distinct approaches tailored to their respective economic and regulatory landscapes.

7 RESULTS AND RECOMMENDATIONS

7.1 Discussion: Characteristics of the EU Legal and Policy Framework on CCU

To address the main research question of whether the legal framework in the EU supports the full potential of different CCU technologies, the findings of the research will be tested using the assessment criteria outlined by Rogge and Reichardt (2016). These criteria, which include consistency, credibility, and comprehensiveness, as illustrated in Figure 3, will serve as the benchmark for assessing the research findings. This methodological approach aims to provide a

concrete analysis of the EU's legal and policy framework on CCU by shedding light on its strengths and areas for improvement.

7.1.1 Consistency of policy measures

According to Rogge and Reichardt (2016), the consistency of policy measures refers to the degree of synergy among different elements toward achieving their desired objectives. They distinguish between three levels of consistency. The first level is the consistency of the policy strategy, which aims to ensure that the objectives of the policy strategy are not conflicting with each other, for example frameworks, roadmaps, and guidelines should be supportive and not contradictory with each other. The second level refers to the consistency of the policy tools to complement each other, such as regulations and incentives. The last level considers the adequacy of the policy tools to achieve the policy objectives. Further, they emphasize that the level of consistency is crucial for the overall success of the policy framework. When all the three levels are in harmony, it increases the chances of achieving policy objectives.

The analysis of the EU policy framework regarding CCU showed that:

Consistency within the policy strategy documentation: the EU policy strategies dealing with CCU in the context of decarbonizing industries and achieving climate neutrality are consistent and well-integrated.

Initiatives such as "A Clean Planet for all" and "The Green Deal" explicitly acknowledge CCU as a key approach for reducing GHG emissions in hard-to-abate sectors like cement, steel, and chemicals. The Green Deal emphasized the need for regulatory alignment and industry leadership in advancing breakthrough technologies, including CCU technologies.

Furthermore, strategies like the Circular Economy Action Plan and the Sustainable Carbon Cycles emphasize the promotion of circularity and sustainable carbon management, further accentuating the role of CCU in achieving the EU climate objectives. The introduction of the Industrial Carbon

Management Strategy in February 2024 builds upon preceding initiatives and outlines specific measures to promote the adoption of CCU technologies, which also signals the EU's continued commitment to integrate CCU into the broader decarbonization efforts.

Consistency within the policy instruments: except for synthetic fuel production initiatives like ReFuelEU Aviation and FuelEU Maritime, which have created binding deployment targets, the EU lacks a unified legislative framework to address other CCU pathways. Furthermore, the proposed Net-Zero Industry Act, that aims to establish a target manufacturing for strategic net-zero technologies to meet the EU's 2030 climate and energy targets, recognizes both CCS and CCU as net-zero technologies. However, CCU, unlike CCS, was not included in the list of strategic net-zero technologies, which raises concerns about the consistency of prioritizing CCU within the EU policy instruments.

On the other hand, funding schemes such as the Innovation Fund and Horizon Europe provide financial support for research, development, and demonstration activities. These schemes reflect the EU's commitment to promoting innovation and advancing clean technologies, including CCU, to effectively address climate challenges.

Consistency within the policy strategies and policy instruments: overall, there is alignment between the policy strategies emphasizing the importance of CCU and the legislative drivers introducing measures to facilitate emissions reduction, particularly for synthetic fuel production. However, the exclusion of CCU from the list of strategic net-zero technologies in the proposed Net-Zero Industry Act may indicate a gap in harmonizing policy strategies with specific regulatory frameworks that could provide support for the development of the CCU market. This is especially notable given that the Industrial Carbon Management Strategy published in February 2024 outlines the regulatory aspect as one of specific measures that the EU aims to address in the future.

While the advancement of the CCU framework may be progressing at a slower pace, the coherence of the policy process regarding CCU is evident from the structured approach taken towards coordinated communication by the EU Commission and engaging stakeholders via consultations carried out across various levels.

7.1.2 Credibility of policy measures

Rogge and Reichardt (2016) define credibility in policy frameworks as the perceived trustworthiness and reliability of the policies, which reflect trust in their ability to consistently achieve intended objectives over time. They emphasize that when assessing policy effectiveness, it is crucial to focus on factors like political leadership commitment, policy coherence, stability, and stakeholder support.

The examination of the EU policy framework concerning CCU revealed its emergence as within the context of achieving net-zero emissions by 2050. CCU was introduced alongside other options as a key element in decarbonizing the EU industry, especially in hard-to-abate industries such as cement, steel, and chemical production. This emphasis was outlined in the EU policy strategy “A Clean Planet for All”, published by the EU Commission in 2018.

Since then, the analysis has shown that the EU has taken measures to achieve net-zero emissions by 2050. For instance, the European Climate Law has established legally binding climate targets in accordance with the goals set out in the Green Deal, which aims for achieving net-zero emissions by 2050. These actions illustrate the political commitment of the EU to achieving net-zero emissions as well as the structural consistency of the measures taken. Furthermore, the climate goals set by the EU have remained stable and consistent over time, in contrast to the United States, where climate goals are not yet enshrined in binding law and remain part of policy, rendering them susceptible to potential change with the election of a new government.

7.1.3 Comprehensiveness

Comprehensiveness of policy framework, as defined by Rogge and Reichardt (2016), refers to the degree to which a policy addresses all relevant issues and factors. This includes not only the elements within the policy strategy itself but also those within the policy tools used to implement the policy strategy. The authors point out that comprehensive policy tools may address all objectives of the policy including “technology-push, demand-pull and systemic concerns”.

The examination of the EU policy framework regarding CCU showed that the impetus for developing innovative methods and technologies to capture and utilize carbon is driven by the need to address climate change and reduce GHG emissions, rather than immediate market demand. To support this “technology-push”, the EU has established funding schemes such as the Innovation Fund and Horizon Europe to provide financial support for research, development, and demonstration, including for CCU activities.

Regarding “demand-pull” in CCU, efforts are certainly underway to develop solutions that meet the growing demand for sustainable and environmentally friendly practices. Governments and industries are, among others, recognizing the need to reduce carbon emissions and mitigate climate change. While the EU has set binding deployment targets for synthetic fuel production under ReFuelEU Aviation and FuelEU Maritime initiatives, the EU has not established similar targets for low-emission products to drive the demand for CCU products. Additionally, the EU has not instituted any procurement mandates to stimulate demand for CCU low-emission products.

Moreover, the analysis of the EU policy framework revealed certain observations regarding the comprehensiveness of the EU policy framework in addressing systematic concerns in developing CCU market.

Lack of unified CCU legislation: Despite the EU’s development of several policy strategies over the past years that directly or indirectly involve CCU, there is no unified legal framework specifically tailored for CCU. Various EU policy

strategies have acknowledged the need for a supportive regulatory environment, including the recently adopted Industrial Carbon Management Strategy in February 2024.

Absence of a comprehensive definition of CCU: Like the status of the CCU legislation, the EU lacks a clear definition of CCU within its policy framework. While the US, through the Bipartisan Budget Act of 2018, explicitly defines carbon utilization to include carbon dioxide alongside other carbon oxides, the EU primarily focuses on carbon dioxide in its respective policy frameworks. This discrepancy is particularly significant when considering the classification of CCU technologies, and to avoid ambiguity and inconsistency in the regulation and promotion of CCU technologies.

Overall, the analysis of the EU legal and policy framework regarding CCU, along with the discussion of its characteristics, reveals strengths in certain aspects, such as consistency within policy strategy documentation and credibility in political commitment. However, there are notable areas for improvement, particularly in developing a unified legislative framework specifically tailored for CCU. Therefore, the analysis suggests that while progress is underway, there remains a significant journey ahead to fully support the potential of different CCU technologies within the EU.

7.2 Bridging Gaps: Policy Recommendations

After analyzing the EU CCU framework and its various components, including policy strategies, legislative drivers, and existing cost reduction measures, alongside the comparison of the CCU frameworks in the EU - US, several policy recommendations could be drawn up to further support and develop the EU CCU market.

Improve regulatory clarity: The need for regulatory development is clear, and the EU Commission has acknowledged this in the Industrial Carbon Management Strategy. A crucial first step towards comprehensive CCU legislation is establishing a clear definition of CCU. The absence of such a definition leads to

ambiguity and inconsistency in regulating and promoting CCU technologies. Given that CCU includes various processes and applications beyond carbon dioxide utilization, such as carbon monoxide or methane conversion, a clearer and more inclusive definition is essential to guide regulatory efforts effectively and support innovation. Drawing from the US vision, the concept of CCU should extend beyond the traditional concept of CO2 capture and use to encompass novel and non-traditional CO2-derived products with Carbon-Carbon bonds, such as solid carbon, carbon nanotubes and carbon nano fibers. Naturally, the environmental impact of such products should be considered.

Design horizontal legislation: Instead of focusing on specific industries or sectors such as for synthetic fuel production under ReFuelEU Aviation and FuelEU Maritime initiatives, the legislation should be horizontally designed to include all possible CCU pathways to support innovative solutions, particularly that the technological development outpaces the development of the respective regulatory framework, and to avoid ex-post regulatory changes. To this end, the legislation should provide a clear methodology for what could be considered permanent and non-permanent CCU products storing carbon and provide incentives to develop the CCU market.

Include CCU in the proposed Net-zero Industry Act (NZIA): The NZIA was originally proposed with the EU aiming to maintain the competitiveness of the EU industry, especially given the growing global competition facilitated by ambitious support initiatives from other economies, such as the US Inflation Reduction Act. Given the EU's commitment to achieving net-zero emissions and fostering the competitiveness of its industry, it is important to reconsider the exclusion of CCU as a strategic net-zero technology.

Including CCU as a strategic net-zero technology under the NZIA would align EU's broader goals of promoting sustainable economic growth and unlocking opportunities for CCU development and deployment within the EU. This is already a low-hanging fruit that the EU could capitalize on ahead of developing a regulatory framework designed to establish a single market for CO2 within

Europe, as stated in the Industrial Cabon Management Strategy. Therefore, it is recommended that CCU be recognized as a strategic net-zero technology under the NZIA to stimulate the CCU market.

Promote market demand and commercialization: To stimulate the development of CCU market in the EU, it is important to establish binding deployment targets similar to those set for synthetic fuels. Specifically, making the aspirational objective outlined in the Sustainable Carbon Cycles EU strategy, of achieving a 20% share of sustainable non-fossil carbon in chemical and plastic products by 2030, a mandatory target would provide a clear signal for market players to invest in CCU technologies. By setting this - or any another specific target - as a binding target, the EU can send a strong signal to industries, encourage investments, and accelerate the commercialization of CCU technologies.

With the implementation of these policy recommendations, the EU could enhance its support for the development of the CCU market, drive innovation, and accelerate the transition to a low-carbon economy.

7.3 Relevance of the study to the development of CCU market in the EU

Without a supportive regulatory framework, the development of the CCU market will be slow and perhaps limited. The relevance of the study to the development of the CCU market in the EU lies in providing a comprehensive analysis of the EU CCU legal and policy framework. The study identified both strengths and areas for improvement within the EU's approach to CCU technologies. One noteworthy strength is the consistency within the EU's policy strategy documentation, exemplified by initiatives like "The Green Deal" and the "Industrial Carbon Management", which explicitly recognize CCU as pivotal in reducing GHG emissions across industries such as cement, steel, and chemicals. However, the study also identified gaps, such as the absence of unified legislative frameworks tailored specifically for CCU.

Furthermore, the results of this study highlight the need for regulatory clarity and comprehensive legislation to fully harness the potential of CCU technologies. By offering insights into these aspects of the EU's legal and policy framework, the study provides guidance for policymakers and stakeholders seeking to navigate and enhance the CCU market landscape within the EU and ultimately contributing to the EU's transition towards a sustainable, low-carbon economy.

7.4 Relevance of the study to the Commissioning Company (Hycamite) and Recommendations

The starting point for the scope of this study was driven Hycamite's interest in the CCU market both in the EU and US, as addressed in Section 1.3. The following are the key findings of the study relevant to Hycamite.

Thermo-catalytic decomposition of methane as a technology is not recognized as CCU:

A central finding of this study is that the concept and technology of thermo-catalytic decomposition of methane, which is used by Hycamite, is not recognized in the context of carbon capture and utilization within the existing EU legal and policy framework. The focus of the EU in these strategies is on the utilization of the captured CO2. In the case of the US, the concept of carbon capture is broader than in the EU and is applicable to CO2 (carbon dioxide), CO (carbon monoxide), and C3O2 (carbon suboxide). In the thermo-catalytic decomposition of methane, methane is split into hydrogen and solid carbon, without emitting any CO2, meaning that there are no emissions to be captured, but rather CO2 emissions are avoided.

This thermo-catalytic decomposition of methane conceptually achieves comparable results to the conventional concept of carbon capture and utilization. Consequently, there is a strong case for recognizing this process as a form of CCU. This demonstrates the importance of broadening the scope of policy considerations to include diverse carbon sources and innovative technologies to

ensure a comprehensive and inclusive approach to sustainable practices in the industry.

Based on this finding, Hycamite is not eligible for any support schemes under the CCU framework in either the EU or the US. Therefore, discussing the results of this study on the Hycamite's case is not relevant. However, the following recommendations could be proposed to further support of the solid carbon products produced by Hycamite:

Strategic Marketing Focus: the development of solid carbon products by Hycamite poses challenges due to the likely higher production costs compared to equivalent fossil-based products. In response, Hycamite could focus on emphasizing the competitive advantages of their solid carbon products, particularly their environmental friendliness.

To achieve this, conducting a comprehensive lifecycle assessment of the solid carbon products would be essential to compare the environmental impact with similar fossil-based products, including the environmental footprint throughout all stages, from production, utilization, to disposal. By having such data available, Hycamite can furnish its customers with transparent information, thus reinforcing the inherent value of its carbon product portfolio. Additionally, Hycamite could further emphasize the fact that their solid carbon products could be tailored to different applications, as emphasized by Hycamite's team in several meetings.

Value Proposition for Customers: Hycamite could conduct an in-depth analysis of the tangible benefits that its solid carbon products offer to potential customers. This analysis should highlight matters, including cost efficiencies, regulatory compliance advantages such as ESG reporting obligations, and sustainability benefits and sustainability reporting. By demonstrating how solid carbon products align with customers' sustainability goals and regulatory requirements, Hycamite can strengthen its value proposition and build long-term partnerships.

Certification framework for carbon removals: Hycamite should closely monitor the development of the proposed carbon removal certification framework in the EU and evaluate the eligibility of its process for such certification. Achieving EU carbon removal certification would validate the environmental credentials and potentially create opportunities for additional revenue stream through carbon credit trading or premium pricing for certified sustainable products.

7.5 Concluding remarks and proposals for future studies

In conclusion, the journey towards achieving climate neutrality by 2050 in the EU requires a comprehensive approach that includes not only the reduction of GHG emissions but also the utilization of captured carbon as a feedstock to substitute conventional fossil-based products. CCU technologies emerge as a pivotal component of the industrial carbon management strategy, along other pathways.

While measures such as incentives, policies, and supportive funding opportunities for research, development, demonstration, and deployment play an important role in accelerating CCU deployment, they are not standalone solutions. Regulatory frameworks are equally important to establish the necessary standards and certainty for successful and responsible technological deployment. Establishing clear guidelines and regulatory frameworks for CCU will help mitigate investment risks, enhance confidence among stakeholders, and thus facilitate the scaling up of CCU technologies. This, in turn, will further catalyze the transition towards a sustainable, low-carbon economy.

As a proposal for future research, the EU Industrial Carbon Management strategy of February 2024 (EC 2024) pointed out that the EU Member States have set different priorities for solutions to address their industrial carbon management. For instance, Finland and Luxembourg have prioritized CCU, whereas Denmark, Greece, France, Sweden, among others, have focused on CCS. Some EU Member States, such as Germany and Portugal, maintain a dual focus on CCS and CCU. Therefore, as a continuation of this study, it would be interesting to examine how different EU Member States have translated the EU strategies into

their national energy and climate plans. A relevant comparison of CCU policy and legal frameworks could be drawn between Finland, Luxembourg, and Germany.

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