frontiers | Frontiers in Climate

TYPE Policy and Practice Reviews
PUBLISHED 20 October 2022
DOI 10.3389/fclim.2022.943387

Check for updates

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Negative Emission Technologies, a section of the journal Frontiers in Climate

RECEIVED 13 May 2022
ACCEPTED 26 September 2022
PUBLISHED 20 October 2022

CITATION
Thielges S, Olfe-Kräutlein B, Rees A, Jahn J, Sick V and Quitzow R (2022) Committed to implementing CCU? A comparison of the policy mix in the US and the EU. *Front. Clim.* 4:943387. doi: 10.3389/fclim.2022.943387



# Committed to implementing CCU? A comparison of the policy mix in the US and the EU

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Carbon capture and utilization (CCU) technologies aim to use carbon dioxide ($CO_2$), either captured from industrial point sources or from the atmosphere, instead of fossil carbon in the production of a variety of valuable goods. CCU has the potential to contribute to emission reductions and to lower raw material consumption as well to foster transitional processes toward a circular economy. To enable societies to take full advantage of this potential, policy support is needed in overcoming current barriers and fostering CCU implementation as a feasible option for the industry. Based on a literature and online investigation, this paper identifies and compares the current policy mixes for CCU in the US and the EU, focusing on policy strategies and existing and proposed policy instruments. The analysis shows that US strategy documents, with very few exceptions, do not mention CCU specifically in the context of the country's 2030 or 2050 climate targets. In the EU, in contrast, the future role of CCU is clearly linked to achieving climate-neutrality by 2050. The main policy instruments to incentivize the implementation of CCU in the US are tax credits (45Q). Moreover, funding exists for research and development efforts. In the EU, many reform proposals are currently underway that could benefit CCU technologies. At present, policy support, for instance through the Renewable Energy Directive, mainly aims at renewable fuels of non-biological origin while in other areas CCU support remains at odds with principles such as "energy efficiency first". The EU does, however, have a broad range of funding opportunities available for research, development and demonstration projects. The paper uses the cross-regional comparison of policy mixes to formulate policy recommendations to improve policy mixes for CCU. A clearer strategic commitment to CCU, its incorporation into green public procurement guidelines, incorporating CCU across different funding schemes for sustainable energy transition, and ambitious new targets for renewable electricity and green hydrogen, for instance, could help develop the policy mixes further to provide a supportive framework for CCU.

KEYWORDS

**CCU, CCUS, carbon capture and utilization, policy mix, US, EU**

## Introduction

In order to address the challenge of climate change and achieve the internationally agreed goal of achieving net-zero emissions by 2050 at the latest, a diversity of political and technological approaches will be necessary to quickly halt any further release of carbon dioxide ($CO_2$). Transitioning the energy system toward sustainable energy alone will not suffice to tackle this challenge. There is also a need for strategies for heavy industry and transport, among others (Sick, 2021). In this context, carbon capture and utilization (CCU) technologies are the subject of growing interest in politics, industry, and science and have become widely discussed as a concept for industrial and transport transformation toward sustainability (Group of Chief Scientific Advisors, 2018; Schlögl et al., 2018; Hepburn et al., 2019). CCU technologies aim to use $CO_2$ captured from different sources instead of fossil carbon in the production of a variety of valuable goods, thus reducing emissions and the use of fossil resources as well as addressing a continued need for carbon in the creation of products such as chemicals and polymers (e.g., Olfe-Kräutlein et al., 2016; IEA, 2019; North and Styring, 2019; Sick, 2021; de Kleijne et al., 2022). This sets it apart from Carbon Capture and Sequestration (CCS), which captures $CO_2$ in order to store it permanently through injection in geological sites. The $CO_2$ can be captured directly from industrial point sources or the from atmosphere via direct air capture (DAC).

Today, $CO_2$ is mainly used in the fertilizer industry (urea manufacturing) as well as the oil and gas industry for a process called enhanced oil recovery (EOR). In EOR, $CO_2$ is injected into oil reservoirs to maximize oil recovery and then permanently stored in the reservoirs (Hepburn et al., 2019). $CO_2$ is often used directly in these established CCU processes. Captured $CO_2$ can, however, also be transformed into other products: It can be used to produce e-fuels for the transport or aviation sector via a carbon-based conversion of green hydrogen. In chemicals and plastics, $CO_2$ can be used as a raw material which replaces fossil fuels. These pathways for $CO_2$ are all highly energy-intensive. A less energy-intensive pathway is the reaction of $CO_2$ with minerals ("mineralization"), for instance, to produce building materials (for an overview of all potential pathways for the captures $CO_2$, see for example: Global CO2 Initiative, 2016; IEA, 2019; Turnau et al., 2019). Furthermore, as a biological capture approach, algae can capture $CO_2$ in large facilities and can be used as feedstock or, for instance, for the production of ethanol (Sudhakar and Soni, 2017).

Given the versatile applications of $CO_2$ utilization technologies, the expected positive climate effects vary greatly depending on the application and many other factors, such as the electricity mix used in the production. Thus, CCU technologies need to be monitored and assessed individually to determine their respective contribution to climate protection (de Kleijne et al., 2022). In most cases, the captured $CO_2$ is not stored permanently. Instead, it is released again at the end of the life-cycle which can be after a few days or even years. Under certain circumstances, CCU technologies have the potential to foster transitional processes toward a circular economy. If CCU-based fuels or chemicals, for instance, are produced from atmospheric $CO_2$ via DAC through renewable energy only, this could create a closed carbon cycle, i.e., it enables the reuse of $CO_2$ and avoids additional $CO_2$ emissions (UBA, 2021). Few CCU pathways hold the promise of enabling permanent $CO_2$ storage thus creating negative emissions. Among these technologies is $CO_2$ in mineralization (Sick, 2021). This pathway could, under specific conditions, create carbon neutrality or, if combined with additional $CO_2$ uptake through DAC, carbon negativity (Ostovari et al., 2021).

The exact potential of CCU as a building block in climate mitigation strategies is difficult to gauge since the amount of $CO_2$ that can actually be used is still unclear. Current estimates rank between 330 megatons by 2060 (IEA, 2019) to 500 by 2050 (Hepburn et al., 2019) or up to 8 gigatons of $CO_2$ by 2030 (Global CO2 Initiative, 2016) per year. Next to the different time frames, this difference roots, amongst other things, in the definitions of what is considered a CCU technology. The inclusion of EOR into the definition of CCU, in particular, has been subject to debate as it does not contribute to sustainability transformation efforts that seek to phase-out fossil fuel use and can also be considered carbon storage rather than utilization (Olfe-Kräutlein, 2022). Also, it needs to be taken into consideration that the amount of $CO_2$ used is not equivalent to the amount of $CO_2$ avoided, since the new processes might require additional, carbon-positive energy or might cause additional emissions, while the availability of carbon-free electricity is still building up. Nevertheless, it is apparent that CCU technologies have the potential to make a positive contribution in the fight against climate change.

Today, many CCU applications are considered by university research to be technically feasible but are now facing other obstacles in the upscaling and market implementation. So far, only a few products achieved market entry, including construction materials, chemicals and fuels (e.g., Covestro, 2019; Carbon8, 2020; Aircompany, 2022; CarbonCure, 2022; Lanzatech, 2022). Interest from industrial actors and investors to scale up CCU would, however, require a higher technology readiness level for many technologies, which, in turn, would require significant financial support. Furthermore, accelerated deployment is inhibited by high costs of carbon capture, higher costs compared with conventional products, high demand for energy from renewable resources for many applications, and in some cases the need for green hydrogen (Group of Chief Scientific Advisors, 2018; Sick, 2021).

Research has shown the importance of political support as well as a conducive policy and regulatory environment to overcome these types of barriers CCU technologies are facing (Quitzow, 2015). In order to scale up CCU, policy and regulatory instruments need to address above named challenges by fostering CCU research, development and deployment and by creating competitive advantages for CCU products, for instance through taxes, subsidies and mandates (Sick, 2021). Yet, in contrast to policy research that focuses on CCS (see e.g., Romasheva and Illinova, 2019 for an overview), there is only a small body of academic literature so far that offers insights into how different countries and regions design CCU policy mixes. Jung et al. offer a brief overview of CCU policies and projects in the US, Germany, China and Korea (Jung et al., 2021). Tcvetkov (2021) takes one instrument supporting CCU in the US—the tax credit 45Q—into focus. Castillo-Castillo and Angelis-Dimakis (2019) offer an analysis of CCU policies, relevant stakeholders and institutions in the European Union (EU)—however due to the timing of the research, are not able to include the latest reform proposals under the EU Green Deal. With this paper, we seek to contribute to contribute to this small CCU policy literature by offering an in-depth comparative analysis of the state of the art of the CCU policy mix in the US and the EU, two major players in CCU technological development. We thus offer both an update to the insights provided by Castillo-Castillo and Angelis-Dimakis (2019) on the EU case as well as a current and more in-depth insight into the US case than exists in current literature. We add a novel aspect to the CCU policy research landscape by using an analytical framework developed by Rogge and Reichardt (2016).

The research questions guiding the paper are: What is the state of the art of the policy mixes for CCU in the EU and the US and what transatlantic learning opportunities exist? This paper identifies and analyses relevant strategies and policies that promote CCU as well as set the boundaries for research, development, and the implementation of $CO_2$ utilization technologies in the US and the EU. The purpose of this analysis is to compare the policy instruments and the related policy strategies and to develop insights into the challenges of the policy mixes as well as recommendations on how to strengthen them.

## Assessment of strategies and policies on CCU in the US and the EU

### Analytical framework and method

It is widely acknowledged in the literature on innovation and technological change that the development of emerging climate-friendly technologies requires active policy support (Quitzow, 2015). Policies and regulations are needed to overcome lock-ins in incumbent technologies and create an enabling environment for the development and diffusion of new technologies and related business models (EEA, 2016). Moreover, there is widespread consensus in the literature that so-called policy mixes are needed to support these processes of innovation and technological change (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016). A set of complimentary and mutually reinforcing policy interventions is needed to overcome a host of different challenges, ranging from skill development and R&D to questions of finance and the reform of institutions and market rules that frequently prevent new technologies from developing (Hekkert et al., 2007).

In order to allow for an in-depth analysis, this paper focuses on policy mixes in two case studies: The US and the EU. The rationale for this selection was their major role in CCU technology development and funding for research and development (R&D) in this field. Both jurisdictions do not always share political goals and agendas tied to climate protection. Moreover, the EU and the US represent different types of political entities, which needs to be factored in especially when formulating policy recommendations. They are, however, both currently committed to the UN Sustainable Development Goals (SDGs) and the target of the Paris Agreement of reducing emissions aiming to net-zero by 2050 (EC, 2019b; UNFCCC, 2021) and provide a highly relevant context to study policy mixes for CCU. The analysis focuses on EU-level policies and federal policy interventions within the US system, respectively. While it would be beneficial to supplement this with additional analysis at the level of the EU member states and the US states, this is beyond the scope of this paper but will be an interesting venue for further research.

To structure its analysis, the paper makes use of a subset of analytical categories developed for policy mixes by Rogge and Reichardt (2016). In their seminal article, Rogge and Reichardt (2016) present a comprehensive analytical framework for the study of policy mixes for sustainability transitions. The authors propose that fundamentally policy mixes are composed of policy strategies and a related instrument mix. Policy strategies are defined as key policy objectives and plans to achieve them and are seen as important in steering government decisions and company-level R&D activities for new technologies. The instrument mix comprises a set of policy interventions to achieve larger strategic goals. Rogge and Reichardt distinguish between three different instrument types: economic instruments (e.g., tax exemptions, R&D grants), regulation (e.g., market design, performance standards) and information (e.g., professional training, workshops). To make the last category more fitting for the CCU policy mix, the latter category is expanded to include "soft," voluntary instruments (e.g., recommendations or voluntary agreements) (Borrás and Edquist, 2013). As the instruments at times can be categorized as more than one type, we follow Rogge and Reichardt's lead in determining the *primary* type.

A major asset of the framework by Rogge and Reichardt is that it offers three concepts for assessing policy mixes studied, which was a main rational for choosing the framework in this paper. The first concept is consistency. A policy mix is considered consistent when its elements are aligned with each other, when it is free of contradictions and when its elements reinforce each other. The second concept is credibility. A policy mix is considered credible when there is a clear commitment from political leadership, and it is considered believable and reliable. The third concept is comprehensiveness. A policy mix is considered comprehensive when it is exhaustive, i.e., it does not exhibit significant gaps and addresses relevant barriers to innovation (Rogge and Reichardt, 2016). The paper makes use of these assessment categories as well as the cross-regional case comparison to develop policy recommendations.

Building on research done by Rogge and Reichardt and others, Ossenbrink et al. (2019) have highlighted the importance of delineating the specific scope of the policy mix under consideration. In this vein, they propose a so-called top-down and bottom-up perspective on policy mixes. While the former refers to clearly defined strategies with stated policy goals and corresponding policy measures, the latter takes a specific impact domain, for instance a field of technology, as its starting point. Based on the defined impact domain, the policy mix analysis seeks to identify and assess those policies and regulations that might affect this impact domain. As a research strategy, this article takes a bottom-up approach: It seeks to identify all the relevant policies and regulations in the EU and the US that have an explicit or implicit influence on enabling or constraining the development and deployment of CCU technologies.

To gather the relevant data on policy strategies for its policy mix analysis, the authors first conducted a search of current climate policy-related strategies in the EU and the US. For the US, this included mainly executive orders and for the EU, documents related to the Green Deal and the EU's 2030 climate targets. Strategy documents were finally selected for this paper that provide a relevant framing for CCU policy instruments—either because they mention CCU directly or because they are relevant to industrial decarbonization overall. In order to gather policy relevant instruments, the authors first relied on academic and gray literature that delineates instruments that are generally important for CCU development (e.g., Global CO2 Initiative, 2016; Bobeck et al., 2019; Turnau et al., 2019). The list of relevant policy instruments includes, for instance, carbon pricing, tax credits, instruments promoting carbon capture or DAC, instruments promoting synthetic fuels or instruments promoting recycling. Based on this, the authors conducted a web-based search to identify specific policies, programs, and legislation with implications for the development and deployment of CCU technologies. As the policy mix in the field of climate policy is currently developing at a fast pace, the analysis also alludes to select reform proposals that are not yet in place in the US and the EU but could be of high relevance to the CCU policy mix. Due to its contested status as a climate protection strategy and its categorization as both CCU and CCS, EOR is not included into the analysis. This search was conducted in the fall of 2021 with smaller updates added in 2022.

In the following sections, the paper first maps out the policy mixes in the US and the EU and then discusses them from a comparative perspective. The paper then develops policy recommendations based on the categories developed in Rogge and Reichardt (2016).

## The US policy mix on CCU

Despite the recent passage of the Inflation Reduction Act, which offers broad financial support for climate protection, the US lacks a comprehensive, legislation-based climate strategy at the federal level which, for instance, determines emission reduction targets. The climate agenda much depends on the respective president in office. Thus, CCU technologies have, in the past, not been a part of an evolving climate strategy. They are rather promoted through existing energy legislation as well as through regulatory efforts by the respective US executive or at the state level. This promotion, as the analysis of the following strategy documents and policy instruments shows, is often not explicit. The measures, nevertheless, improve the policy and financial environment for CCU technologies and value chains.

### Strategies in the US

The lack of a legislation-based climate strategy at the federal level makes it difficult to analyze how the various policies supporting CCU connect to an overarching agenda. There are, however, certain directives under which these policies can be examined, including executive orders, agency documents and the US Nationally Determined Contribution (NDC) to the Paris Agreement.

Executive orders provide insight into the priorities of the current Administration, as well as their plans and strategies surrounding certain topics. They can be amended by future executive orders, and thus are frequently impermanent due to the changes in the presidential administration every 4–8 years, and commonly the different policy agenda of each president.

Since his inauguration in 2021, President Biden has signed several climate-related executive orders, the most relevant of which are discussed in the following. They provide a strategic framework for climate policy in line with the goal of the Paris Agreement to achieve net-zero greenhouse gas (GHG) emissions by 2050. The Executive Order on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis provides the base for all future orders surrounding the climate. It draws a connection between a science-based approach to policy making, public health and environmental protection. Reducing GHG emissions is one of the priorities mentioned (The White House, 2021a). The Executive Order on Tackling the Climate Crisis at Home and Abroad (The White House, 2021b) reaffirms the climate as a priority for the Administration, establishing new offices and groups to develop climate policy These two orders with a clear commitment to climate protection set a general conducive framework for emission reduction strategies. Both major orders do not mention CCU, however.

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The Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability (The White House, 2021d) calls for an increase in sustainability within federal supply chains through green procurement of low-carbon products, including within the construction sector ("buy clean"). It thus at least implicitly encourages CCU-related materials through government procurement. The Executive Order on America's Supply Chains (The White House, 2021c) calls for an increase in the resilience of domestic supply chains for the energy and industry sectors. As such, it devises a framework in which CCU is strongly encouraged as a technological approach to reducing emissions, enhancing the domestic raw material base through recycled $CO_2$, and promoting the creation of a circular economy with reuse and recycling front and center.

Beyond these executive orders from the US President, two executive institutions recently issued strategy documents that explicitly address CCU: In a report to Congress on CCUS from 2021, the Council on Environmental Quality (CEQ), an executive agency in the Office of the President, underlines the important role CCS and CCU will "likely" play in achieving global climate targets. The report states that the Biden Administration seeks to "accelerate the responsible development and deployment of CCUS", particularly in the hard to decarbonize industrial sector and the power sector. The report, moreover, frames CCUS as an "enabler of CDR [Carbon Dioxide Removal]" (CEQ, 2021). Early in 2022, the Department of Energy's Office of Fossil Energy and Carbon Management (FECM) published a Strategic Vision which outlines how FECM plans to contribute to the goals formulated in the Executive Order on Tackling the Climate Crisis at Home and Abroad. The Strategic Vision acknowledges the country's current dependence on fossil fuels and formulates three strategic directions to achieve the net-zero target as well as the Biden Administration's target of a carbon pollution-free power sector by 2035. One of them relates directly to CCU: The advancement of carbon management approaches. This includes the scale up of point source carbon capture; "$CO_2$ conversion," a term FECM introduces as an alternative to CCU; $CO_2$; removal; and Carbon storage and transportation. The strategic vision thus makes a clear reference to CCU and related technologies for carbon capture as a building block of the country's climate policy.

Biden's Executive Order on Tackling the Climate Crisis at Home and Abroad began the process of creating a new NDC to the Paris Agreement for the US after the country had rejoining the Agreement in early 2021. The NDC details the broad strokes of the US climate plan, its goals, and what pathways it plans to use to achieve it. The overall commitment of the US is to reduce its economy wide GHG emissions by 50–52% compared to 2005, by 2030. To achieve this, the NDC details six categories in which improvements will be made, including electricity, transportation, buildings, industry, agriculture and lands as well as non-$CO_2$-greenhouse gases (UNFCCC, 2021). While none of these categories explicitly mention carbon dioxide utilization, CCU pathways are represented in the proposed decarbonization solutions through carbon capture priorities in the electrical and industrial sectors and through the decarbonization of transportation: In order to generate 100 percent carbon pollution free electricity by 2035, the Biden Administration mentions carbon capture retrofitted fossil fuel plants as one building block. It, moreover, plans to increase research, development and demonstration (RD&D) efforts in carbon capture retrofits. This strengthens the role of capture technologies which are crucial for CCU technologies. Moreover, industry decarbonization overall is put front and center. Moreover, CCU is addressed implicitly in the strategy trough RD&D for low-carbon fuels for the transportation sector.

From this investigation of relevant government documents, it can be concluded that CCU's role in the climate policy effort envisioned by the federal government has been largely implicit and was only made more tangible in the recent FECM Strategic Vision as well as the CEQ report. In the executive orders, there is an emphasis on creating a decarbonized economy as well as promoting the practice of recycling and reuse for improved supply chains. This suggests that a transformation toward a circular economy is increasingly becoming a priority, as is exploring alternatives to the conventional raw material resource base both of which show the potential for the large role of carbon utilization in the overall climate strategy of the US.

## Policy instruments in the US

At the level of policy instruments, several pieces of relevant legislation and regulation can be identified in the US which support CCU (DOE, 2021a). Most support is indirect as the instruments concentrate rather on capture and storage technologies than on CCU. But there are some measures with an explicit focus on CCU, as well. The mix includes mainly two types of instruments: Economic instruments and regulation as well as one instance of a soft instrument.

### Economic instruments

Since 2008, the main instrument supporting CCU and CCS in the US has been paragraph 45Q of the US Tax Code ("Credit for Carbon Oxide Sequestration") (Tcvetkov, 2021). It underwent major reform in 2018. 45Q provides a tax credit for qualifying facilities that capture carbon monoxide (CO) and $CO_2$ (USC, 2020). It lowers taxes owed by a facility by a given amount per Metric ton, depending on the year and the end-use of the $CO_2$. The credit can be split into 2 sections: credits for facilities placed into service before and after the enactment of the Bipartisan Budget Act of 2018 (U.S. Congress, 2018). Within that split, there are three classifications based on the end-use of the $CO_2$: Enhanced Hydrocarbon Recovery (EHR), geological storage, and utilization. The utilization category is further specified into fixation through photo/chemosynthesis (such as algae to create biomass), chemical conversion to a

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material or chemical compound in which $CO_2$ is securely stored (such as plastics), and any purpose for which a commercial market exists. The $CO_2$ counted for utilization is determined by comparing the baseline emissions of a product to the emissions calculated by a life cycle assessment (LCA) of the CCU-based product, up to a maximum of what is measured at the source of capture. In order to qualify for this credit, minimum annual capture thresholds need to be achieved: 1. If a facility emits fewer than 5,00,000 tons of $CO_2$ per year and utilizes the $CO_2$, at least 25,000 tons must be utilized; 2. If an electricity generating facility emits >5,00,000 tons of $CO_2$ per year or is not utilizing the $CO_2$, at least 5,00,000 tons of $CO_2$ must be captured and stored; 3. In any other facility, including direct air capture facilities, at least 1,00,000 tons of $CO_2$ must be captured and stored.

The 45Q reform in 2018 was accompanied by considerable implementation difficulties. Investors had to wait for 2 years for specific accompanying guidelines from the Internal Revenue Service (IRS) which proved an obstacle for the announcement of new projects. Even after the guidelines were published, it was left unclear, for instance, what the existence of a commercial market means (Medina, 2020). A further increase of the 45Q tax credit was long hampered by partisan politics. The recent Inflation Reduction Act of 2022, however, finally implemented reforms. It increases the tax credit substantially for CCU from \$50 to \$130 per ton of $CO_2$ for credits from DAC. For point source CCU, the credit rises from \$35 to \$60 per ton of $CO_2$. The qualification threshold for DAC is lowered substantially from 1,00,000 tons to 1,000 tons. While previously, 45Q mainly incentivized big emitters to invest in CCU, the 2022 reform opens up opportunities for smaller firms and start-ups working on DAC (Bettenhausen, 2022; Moch et al., 2022; Obern, 2022). The 45Q tax credit strongly supports $CO_2$ emission reduction efforts, the development of a circular economy, and an increased in domestic raw material availability by decreasing the costs of CCU technology. This allows for the creation of more cost-competitive $CO_2$-based products, lowering the global warming potential of certain industries, while allowing for $CO_2$ recycling. It enables the $CO_2$, and the products created with it, to function as alternatives to raw materials newly introduced to the economy such as mined minerals.

In addition to 45Q, paragraphs 48A (USC, 2005a), 48B (USC, 2005b) and 48C (USC, 2009) of the US Tax Code provide tax credits for companies who invest in carbon capture technology, giving a tax refund up to a given percentage of their investment ranging from 15 to 30%. 48A aims at increasing coal plant efficiencies through advanced techniques or gasification, with carbon capture additions receiving high priority. 48B requires a 75% capture and sequestration rate for qualifying gasification projects. 48C is largely used to promote investment in renewable energy. However, CCU is also mentioned as eligible explicitly, as is renewable fuel blending equipment. The certification period for each of the credits that were introduced between 2005 and 2009 has passed. Its renewal is on the Biden Administration's political agenda. While not as directly applicable to CCU technology as 45Q, these tax credits encourage the use of carbon capture on coal and gasification plants or just the equipment in general.

Various legislative acts have further supported carbon utilization throughout the previous two decades by increasing national funding for CCU technologies. The DOE Office of Fossil Energy and Carbon Management receives much of this funding (DOE, 2021b). But some of it also goes to the Department of Defense.

More recent legislation such as the USE IT Act and the Energy Act of 2020 (passed as divisions of the Consolidated Appropriations Act of 2021) (U.S. Congress, 2021b) provide funding with an increased utilization focus as opposed to previous legislation that tended to focus primarily on capture and storage. More specifically, these laws provide R&D funding for pathways such as chemicals, plastics, building materials (specifying concrete), fuels, coal-utilization products, and other novel technologies. These acts also promote the growth and expansion of a $CO_2$ transportation infrastructure, funding more pipelines, sequestration sites, and carbon capture/DAC projects, as well as commissioning studies on various economic and environmental impacts of the potential infrastructure and CCU technology pathways. The SCALE Act (U.S. Congress, 2021a) also provides R&D funding for carbon capture pilots and DAC hubs, all of which strengthen the investment and infrastructure necessary for the utilization side of the CCU field to thrive.

Overall, this funding supports investment in the development and commercialization of CCU-based products and the necessary surrounding infrastructure. While initially one of the main goals was to promote fossil fuel resources in the US, the focus increasingly also includes the promotion of the idea of a circular economy with $CO_2$ and its products as raw materials, thus also linking CCU with climate goals.

### Regulation

The Renewable Fuel Standard (EPA, 2021b) was created through the Energy Policy Act of 2005 (U.S. Congress, 2005) and expanded on by the Energy Independence and Security Act of 2007 (U.S. Congress, 2007) to create a national policy requiring certain volumes of renewable fuels to replace conventional fossil fuels. Specifically, these required volumes can be realized through the replacement of petroleum-based transportation fuels, heating oil, and jet fuels. The four renewable fuels categories are biomass-based diesel, cellulosic biofuel, advanced biofuel, and total renewable fuel. Each of these categories has a specific volume requirement associated with it, which is scaled up every year, as well as an associated lifecycle-GHG reduction minimum in comparison to a 2005 petroleum baseline. The EPA can adjust the requirements through its waiver authority if it determines that they cause severe economic or environmental harm or an inadequate domestic supply. Citing an underproduction of advanced biofuels, the EPA has made use of this waiver frequently: The statutory target has not been met since 2014 and thus renewable fuels have only slowly been able to replace conventional fuels (Congressional Research Service, 2022). While this standard does not directly mention carbon utilization, it indirectly supports it by encouraging the production of biofuels as a replacement for petroleum as a transportation fuel. Biofuels often have high purity $CO_2$ streams, making them ideal for carbon capture as the purification process is much easier as compared to other sources such as industrial natural gas waste streams (Jiang et al., 2019; Pace and Sheehan, 2021). Biofuels thus provide less expensive feedstocks for utilization lowering the costs of $CO_2$ recycling.

Another regulatory instrument which indirectly supports CCU is the EPA's Underground Injection Control Regulations. They set requirements for $CO_2$ injection in EHR and geological sequestration (see 40 CFR §§146.21–146.24 and 40 CFR §§146.81–146.95 in EPA, 2010). Though not its focus, this regulation provides support for utilization as the development of these adjacent technologies creates, among other things, a $CO_2$ transportation infrastructure, which are necessary and beneficial for carbon utilization as well. Moreover, it broadens the relevant knowledge base.

Finally, the Storing $CO_2$ and Lowering Emissions (SCALE) Act, passed within the Infrastructure Investment and Jobs Act of 2021 (U.S. Congress, 2021a) encourages state-level regulation by providing grant funding for state and local governments to create standards and certifications to facilitate the commercialization of CCU products.

### Soft instruments

Under the Biden administration, green public procurement has emerged as an important climate strategy and the federal government is directed per executive order to use its purchasing power to meet zero-emission goals. The U.S. Environmental Protection Agency (EPA) has issued a series of recommendations to guide federal purchasers toward procuring more environmentally friendly products and services in line with the federal sustainability strategy (EPA, 2021a). The recommendations identify some 40 different already existing private sector sustainability standards and ecolabels in 30 different purchase categories which are to serve as guidelines for purchase. Preference is given to multi-attribute- and lifecycle-based approaches in large impact areas. $CO_2$ utilization is not explicitly mentioned in these recommendations. However, the categories that are covered align with common $CO_2$ utilization pathways such as low-carbon construction materials. Given the immense buying power of the US federal government these recommendations could assist with the strategies outlined in the executive orders and NDC, both in terms of creating a circular economy with $CO_2$ as a raw material, and overall GHG emission mitigation efforts. The SCALE Act (U.S. Congress, 2021a) takes a step further by providing grant funding for state and local governments to procure CCU products.

## The European policy mix on CCU

The European regulatory framework for CCU technologies is a complex system of complementary strategies and policies in the areas entrusted to EU authority by the member states under the EU treaties. These include, among others, trade, environment, energy, innovation, and, to some extent, industry policies (EC, 2021b). All of them are relevant in the context of CCU technologies and the related value chains. Due EU's current efforts to speed up climate protection, the policy framework is currently in flux. The following sections, nevertheless, seek to offer a comprehensive overview of the status quo of relevant strategies, policy instruments and reform proposals.

### Strategies in the EU

In November 2018, the EU submitted its long-term vision for achieving economy-wide net-zero emissions by 2050 (EC, 2018e). It mentions CCU as one strategy to reduce industrial emissions and underlines the importance of RD&D activities for the coming decade. The background vision for the long-term strategy elaborates more on the role of CCU and states that both CCS and CCU will be necessary to achieve necessary emission reductions in hard to abate sectors such as cement and chemicals. The documentation points out the potential application of CCU in materials and e-fuels. It links CCU closely to the circular economy approach as a supplement to reusing and recycling materials (EC, 2018f).

In December 2019 the EC released the European Green Deal (EC, 2019b). It is a comprehensive strategy for the EU, with the objectives to become climate neutral by 2050, decouple economic growth from resource use, and reduce inequalities between the member states of the EU. It also resulted in raising GHG emission reduction targets from 40 percent to at least 55 percent by 2030 (EC, 2020a,g). This new goal is reflected in the EU Climate Law of 2021, as is the target of becoming climate neutral by 2050 (EC, 2021k), putting a strong emphasis on emission avoidance, CCS as well as CCU (EC, 2022e). As a strategy to reach its 2030 targets, the EC presented the corresponding "Fit for 55" package. It consists of Commission Communications as well as 15 different legislative proposals that, once they proceed through the legislative process, will revise climate-related policy instruments, including the Emissions Trading System (EU ETS) the EU's cap-and trade system which establishes a carbon market, and the Energy Taxation Directive which includes among others, tax exemptions on aviation and shipping (EC, 2021e,h).

The EC's Communication on the European Green Deal directly addresses the role of CCU technologies. The EU and its member states should, accordingly, "foster the deployment of innovative technologies and infrastructure, such as smart grids, hydrogen networks or carbon capture, storage and utilization, energy storage, also enabling sector integration."

The role the EC sees for CCU is to ensure "the supply of sustainable raw materials, in particular of critical raw materials necessary for clean technologies, digital, space and defense applications, by diversifying supply from both primary and secondary sources" (EC, 2019b). The 2030 Target Plan addresses the role of CCU technologies, as well (EC, 2021a). They are framed as an instrument to decarbonize the industrial sector after the year 2030, especially for sectors with limited alternative decarbonization options, like aviation and maritime navigation. A major part of the planned emission reductions in the industrial sector is supposed to be "due to technologies such as clean gases and carbon capture and storage and carbon removals, including CCUS technologies and $CO_2$ storage in materials" (EC, 2020c). The EC has introduced several legislative proposals to revise CCU-relevant policy instruments to achieve its new 2030 goal. This includes the EU ETS, the Renewable Energy Directive II (REDII) and the creation of a new European terminology and certification system for all renewable and low-carbon fuels (EC, 2020i).

Through the Green Deal, CCU technologies have thus gained significant momentum as part of the climate policy strategy when compared to the previous EU climate and energy policy frameworks (Turnau et al., 2019). Other recent strategy documents enrich the Green Deal strategy. They focus, among other things, on promoting a circular and hydrogen economy

The EU Strategy for Energy System Integration (EC, 2020f) aims to integrate different energy carriers, infrastructures, and consumption sectors. The main pillars of the strategy are sector coupling, direct electrification, and clean fuel promotion, including renewable hydrogen and derivatives, i.e., synthetic fuels based on carbon neutral $CO_{2,}$ as elaborated in the Hydrogen Strategy (EC, 2020d) and sustainable biofuels and biogas. The energy system integration strategy affirms the importance of properly monitoring, reporting, and accounting for the emissions and removals of $CO_2$ associated with the production of synthetic fuels to correctly reflect their actual carbon footprint (Turnau et al., 2019).

The EU Circular Economy Action Plan (CEAP), adopted in March 2020 (EC, 2020e), announces policy initiatives along the entire life cycle of products to reduce waste and generate additional value at the same time. It outlines the development of a sustainable product policy framework from 2021 on, scoping the development of further EU-wide end-of-waste and by-product criteria, and the inclusion of circular economy practices in the upcoming Best Available Techniques (BAT) Reference[1] and Industrial Emissions Directive (EC, 2022a). Of particular importance for CCU technologies is that the CEAP includes a plan to adopt a regulatory framework for the certification of carbon removals, based on carbon accounting to monitor and verify the authenticity of carbon removals, by 2022. This will directly apply to CCU technologies in the context of decarbonisation as well as circular economy aspects.

The EU's latest Strategic Energy Technologies (SET) Plan (EC, 2018d) elaborates in detail on CCU technologies. The SET Plan's aim is to support technological development, innovation, and research for a climate neutral energy system. Action 9 of the SET-Plan is the "CCS and CCU Implementation Plan", which is divided into ten targets for research and innovation in the fields of CCS and CCU. Within this, two targets address CCU technologies. The revised Target 8 is to establish several operating large-scale commercial plants in Europe for each of the main $CO_2$ valorization routes, which are carbonation, transformation into methanol, fuels and chemicals, and production of polymers. Target 9 proposes the integration of CCU in upcoming Important Projects of Common European Interest (IPCEI) on hydrogen or low $CO_2$-emission industries, to foster the demonstration of different applications of industrial CCU (CCUS SET-PLAN, 2020). This emphasizes the strategic weight the SET Plan gives CCU as IPCEI projects are of high strategic importance: They allow member states to support industrial actors in the development of large-scale transnational projects in Strategic Value Chains (SVC) in ways that would otherwise not be possible due to State Aid regulation.

One year prior to the US, the European Union submitted an updated version of its NDC to the UNFCCC in 2020. It reflects the new Green Deal targets for emissions reductions in 2030 and mentions policy instruments that will help the EU achieve this target. There is no direct or indirect mention of CCU, however (EC, 2020j).

## Policy instruments in the EU

Various policy instruments exist in the EU that support CCU implicitly or explicitly. They are mostly part of larger frameworks on climate and energy as well as environmental pollution and are discussed as such, below.

### Regulation

CCU technologies can contribute to the defossilization of industrial processes, meaning the shift away from fossil fuels. They are therefore subject to the European policy framework on climate and energy. Only one specific CCU pathway is, however, included as a carbon reduction measure in the current EU Emission Trading Scheme (ETS) Directive (EC, 2020h). This minor exception is the transfer of $CO_2$ out of the installation used to produce precipitated calcium carbonate, in which the used $CO_2$ is chemically bound. This exception is based on the ruling of the European Court of Justice in the Schäfer-Kalk-case (Turnau et al., 2019). The exclusion of CCU technologies stems from the GHG accounting approach used for the EU ETS, which seeks avoid double counting emissions in sectors

1 Best Available Techniques References (BREFs) collect information on Best Available Techniques (BAT) to provide reference information for regulators to use when determining permit conditions, as in the Industrial Emissions Directive.

that fall under different EU legislations, like the Effort Sharing Regulation (ESR) (EC, 2021c). CCU has, however, made its way into the Commission's reform proposal for the ETS at part of the Fit for 55 package. $CO_2$ emissions, accordingly, would not count toward a company's emission allowance if the $CO_2$ is "permanently chemically bound in a product", i.e., does not enter the atmosphere "under normal use" (EC, 2021m). This therefore offers an incentive for products such as plastics rather than CCU-based fuels, which immediately release $CO_2$ upon usage.

The ESR sets binding annual GHG emission reduction targets for member states for the period 2021 to 2030 for most sectors not included in the EU ETS Directive such as the transport sector, buildings, and small industries (EC, 2018c). While the ESR does not address CCU directly, CCU technologies can potentially contribute to emission reductions in the sectors under the regulation. Therefore, the ESR can be considered an indirect incentive for the development of CCU technologies.

The Renewable Energy Directive (RED II), last updated in 2018 and currently under revision once again in the context of Fit for 55, is a framework for the promotion of energy from renewable sources (EC, 2018b). CCU technologies that produce recycled carbon fuels and renewable fuels of non-biological origin (RFNBOs) are considered eligible pathways to meet the 2030 climate targets. Fuels must reduce GHG emissions by 70% to be counted as renewables, and renewable electricity for CCU must not consume electricity that could otherwise be used for more energy efficient alternative applications, and therefore not challenge the Energy Efficiency Directive (EED) and its 'energy efficiency first' principle (EC, 2021d). This currently limits possible CCU pathways but will become more relevant in fostering CCU when more carbon-free electricity becomes available in the future. Currently, RED II remains an incentive for CCU only in energy-intensive, difficult to defossilize sectors and rather acts as a disincentive for other applications. As part of the ongoing deliberations on RED III, the EC proposed that by 2030 at least 2.6 percent of the energy supplied to transport and 50 percent of the use of hydrogen in industry shall be covered by RFNBOs, providing a clearer incentive for CCU.

The Fuel Quality Directive (FQD) requires a reduction of life cycle GHG emissions by up to 10 percent (minimum 6%) per unit of energy from fuel and energy supplied, compared to the EU-average level of life cycle GHG emissions per unit of energy from fossil fuels in 2010. This is to be achieved mainly through RFNBOs (EC, 2018a). Two proposals are discussed to supplement FQD: The ReFuelEU Aviation Regulation (EC, 2021h), which sets binding targets of minimum shares of 0.7 percent of RFNBOs by 2025, 8 percent by 2040 and 28 percent by 2050 as well as the FuelEU Maritime Regulation (EC, 2021i), which sets binding reduction targets for GHG emitted by ships of 2 percent in 2025, 6 percent in 2030, 26 percent in 2040 and 75 percent in 2050. These instruments are directly linked to the strategies for CCU in the future and serve as an incentive for the development of CCU technologies, needed to produce RFNBOs.

One of the central instruments for industrial decarbonization so far excludes CCU: Within the Environmental Pollution Policy Framework, the Industrial Emissions Directive (IED) imposes the use of Best Available Techniques (BAT) in the industrial sector to achieve set emission limit values (EC, 2011a). CCU is currently not, however, considered a BAT. CCU has more potential in other instruments under the Environmental Pollution Policy Framework: Some CCU routes potentially fall under the Regulation on Persistent Organic Pollutants (POPs) (EC, 2011b) and the Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) (EC, 2020b). The prior mandates that waste containing POPs must be destroyed or irreversibly transformed so that the remaining waste and releases do not exhibit the characteristics of POPs. Recovery, recycling, and reclamation are prohibited. The latter regulates chemical additives which are used for CCU processes. These regulations pose a framework for CCU rather than an incentive or obstacle (Turnau et al., 2019).

Although the EU's waste and circular economy policies are of particular importance for the development of CCU technologies, as the use of $CO_2$ from emissions has the potential to create an industrial carbon cycle, the current Waste Framework Directive (WFD) (EC, 2008) does not address $CO_2$. The regulatory framework for the certification of carbon removals, which is expected for late 2022, could facilitate the handling of captured $CO_2$ in the future. Similarly, through its Circular Economy Action Plan, the Commission has proposed rules for sustainable products in the EU. One element is the revision of the Construction Products Regulation which puts an emphasis on sustainable building materials. CCU is mentioned explicitly here (EC, 2022e).

### Economic instruments

RFNBOs are further incentivized through (proposals for) economic instruments. A current proposal by the Commission is the revision of the Energy Taxation Directive, to set taxation rates to zero for a transitional period of 10 years (2023–2033) for RFNBOs and other sustainable and low carbon fuels for specific types of air and maritime navigation (EC, 2021g).

The EU's Seven-Year Budget 2021-2028 comprises €1.8 trillion, one third of which is earmarked to finance the European Green Deal. For each fiscal year, the budget is then specified in more detail (EC, 2021f). The budget funds the EU's major research and innovation funding program Horizon Europe, which receives a total of €95.5 billion for the period 2021–2028. Its work program on climate, energy and mobility explicitly states the establishment of an infrastructure for CCUS hubs and clusters as a strategic goal (EC, 2021l). Through 2020, its predecessor program Horizon 2020 was instrumental in funding R&D projects on $CO_2$-based fuels (methanol and

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ethanol), chemicals (polymers) and microalgae. Other funding opportunities for CCU projects include the Research for Coal and Steel Fund (RCSF), the LIFE Circular Economy sub-program, the European Fund for Strategic Investments (EFSI), and the European Structural and Investment Funds (ESI).

The Innovation Fund, established in 2018, supports demonstration projects for technologies to decarbonize the energy and industry sectors. It has a budget of €10 billion which is funded through revenues from the EU ETS. CCU is one of the Fund's explicit focus areas. The Innovation Fund Regulation sets two important qualifications for projects to be eligible for funding: They need to contribute substantially to mitigating climate change and deliver a net reduction in emissions and ensure avoidance or permanent storage of CO2 (EC, 2019a). Almost 70% of the proposed projects for the first large-scale call of the Innovation Fund in 2020 were projects for energy intensive industries, and out of these one third included CCUS technologies, often in combination with hydrogen projects to produce synthetic fuels (EC, 2021j). Out of the seven proposals that were finally selected for a grant, one includes CCU as a technology pathway (EC, 2022c). The first small-scale call of the Innovation Fund yielded more than 50 percent applications projects for energy intensive industries which includes CCUS as a technological pathway. Here, only one out of the 30 projects, which finally received funding however, included CCU (EC, 2022d). The Commission's current proposal for ETS reform emphasizes the importance of directing Innovation Fund financing to projects in sectors covered under the proposed Carbon Border Adjustment Mechanism (CBAM), i.e., industries with high emissions and/or a high risk of carbon leakage. This includes, for instance, CCU pathways in the cement and chemicals sectors (EC, 2021n). This could also encourage other countries which export their products to the EU, including the US, to incentivize the production of CCU-based products domestically in order to avoid the EU's proposed future border tax. Overall, CCU R&D projects in the EU are becoming more prominent and receive more funding than in the past. Most are R&D projects that range from early-stage technology development to market-ready projects (ZEP, 2021).

Among others, the Commission proposal for ETS reform seeks to direct funds from the Innovation Fund to carbon contracts for difference (CCDs) that protect investments in innovative climate-friendly technologies. CCDs guarantee investors a fixed price for investments that are above the carbon price level of the ETS (EC, 2021m). For cost intensive CCU technologies, this would offer an important new incentive for investments.

Another EU funding initiative which aims at creating an integrated European energy network is the Connecting Europe Facility (CEF). The current CEF work program runs from 2021 to 2027. For projects under CEF—Energy, the budget is €5.84 (IEA, 2022). CEF funds large cross-border infrastructure projects. Among the Projects of Common Interest funded are also cross-border $CO_2$ transport networks. Six projects are currently funded in this context (CCUS Projects Network, 2022).

## Cross-regional comparison

The analysis of relevant strategies, laws, programs, and regulations shows that CCU plays a role in reaching the declared emission reduction goals for 2030 as well as the longer-term net-zero targets for 2050 in both the US and the EU.

### The envisioned future role of CCU technologies

In the US, CCU is only plays a major role in one of the strategic documents if the executive: FECM's Strategic vision. It is not mentioned explicitly in any of the major strategy documents of the Biden Administration for reaching the country's 2030 or 2050 climate targets. The strategy documents, nevertheless, devise a framework in which climate-friendly solutions are strongly encouraged. For instance, CCU pathways are represented in the carbon capture priorities for the electrical and industrial sectors. The strategy documents further determine a focus on low-carbon fuels and green public procurement. Moreover, the development of a circular economy has become a more prominent theme with an emphasis on broadening the US resource base by finding alternatives to the conventional raw material resources as well as reuse and recycling (e.g., DOE, 2021b). The strategy documents thus set up an environment in which CCU technologies are more likely to succeed.

In contrast to the US, CCU is mentioned much more explicitly in the EU Green Deal framework. It is envisaged in the context of industrial and transport sector decarbonation—especially aviation and maritime transport—for the period after 2030. A focus is on the production of energy carriers made with $CO_2$ and RFNBOs, as stated in the RED II and the SET-Plan (EC, 2018b,d; CCUS SET-PLAN, 2020). Among the envisioned valorization routes for CCU technologies are carbonation, transformation into fuels, methanol, other chemicals, and the production of polymers. The "Stepping up Europe's 2030 climate ambition" communication states that a "major part of the reductions in 2050 is due to technologies such as clean gases and carbon capture and storage and carbon removals, including CCUS technologies and $CO_2$ storage in materials" (EC, 2020c). The EU explicitly recognizes the potential of CCU to ensure a supply of sustainable raw materials such as those necessary for clean energy technologies (EC, 2019b). CCU is also an element of the EU's circular economy approach in the context of reducing waste. Finally, the EU links CCU technologies to its ambitious approach to clean hydrogen and further processing into synthetic fuels through the addition of carbon oxides. Fuels therefore play an important role but CCU mineralization technologies are recognized as well.

Comparing the policy strategies of the EC and the US federal government, CCU is mentioned in the same context as CCS technologies in both cases and it is seen as an instrument to reach climate targets in the long-term. However, in current EU strategy documents, CCU finds more explicit mention than in the US. This may be because there is currently no overarching detailed climate strategy in the US, whereas the EC has explicitly focused on climate and green technology topics in the Green Deal. The Biden Administration recently passed the Inflation Reduction Act, which contains major financial incentives for climate protection technologies including CCU. There is, however, no explicit climate law. Despite the Administration's focus on climate protection and clean energy technologies, the country therefore still follows a piecemeal approach through individual executive orders and regulations.

Regarding the envisioned role of CCU technologies in the future, the US and EU strategies differ to some extent. Both the US and the EU documents suggest a role for decarbonizing the electrical and the industry sector, creating a circular economy and discovering alternative resource bases. Beyond these broader points, the EU strategy, however, has a clear focus on supporting the transition to climate-neutrality by producing climate-neutral synthetic hydrocarbon fuels in combination with green hydrogen. CCU technologies are interlinked with the ambitious hydrogen production targets in the EU and the ambition to build a hydrogen economy in Europe (EC, 2020d).

## The policy instrument mix on CCU

Overall, the US instrument mix can be characterized as technology-open and market-oriented. Tax credits, mainly "45Q" (USC, 2020), are the most important instrument for upscaling and market implementation of CCU products. They are awarded based on the amount of captured $CO_2$, independently from technology or end-use (Rodgers and Dubov, 2021). This technology-open approach which comes with advantages such as the flexibility to adapt to market developments and room for innovation. The Federal Renewable Fuels Standard currently does not include fuels that include CCU in the production process (CEQ, 2021). It rather creates infrastructure that enables the development of CCU technologies.

Next to tax incentives, funding instruments play an important role in the US instrument mix. Most of the R&D funding for CCU technologies comes from the Office of Fossil Energy and Carbon Management of the DOE. Overall, funding is still concentrated more on promoting CCS technologies than on CCU and was originally aimed at ensuring a cleaner future for the use of US fossil fuel resources (DOE, 2021b). However, funding provided through the USE IT Act and the Energy Act of 2020 shows an increased focus on CCU technologies, more specifically calling out pathways such as chemicals, plastics, building materials (specifying cement), fuels, coal-utilization products, and new novel technologies (U.S. Congress, 2021b). The Infrastructure Investment and Jobs Act similarly provides additional funding, largely for $CO_2$ transportation infrastructure and carbon capture. But it also includes grants for the procurement of CCU products and the creation of standards and certifications for those products.

In the EU, there is no comparable technology-open approach. Only one very specific CCU pathway (preproduction of precipitated calcium carbonate, added to the EU ETS after the Schäfer-Kalk-ruling) is considered "permanently stored" $CO_2$ and therefore applicable to the EU ETS, one of the EU's main policy instruments for decarbonization. The current reform proposal for the ETS does include CCU, for instance through mineralization, however. In the other major climate policy instrument, the ESR, CCU us not included. Existing quotas for renewable fuels, regulated in the RED II currently also do not support CCU pathways as the EU electricity mix remains highly fossil-fuel intensive and CCU processes are energy-intensive. This is set to change as electricity decarbonization progresses, however, RED II rather poses a disincentive for CCU technologies. The RED reform proposal could, however, provide more support by incentivizing RFNBOs.

The FQD and the proposed new quotas in the aviation and maritime transport sectors explicitly consider CCU technologies, mainly to produce recycled-carbon fuels and RFNBOs. Here, CCU technologies are benefitting from the strong political and financial commitment to synthetic fuels for the transport sector and hydrogen technologies in the EU, as $CO_2$ is a carbon source for synthetic fuels produced from hydrogen. They could further benefit from a proposed major tax cut under the Energy Taxation Directive for RNFBO production and other sustainable and low carbon fuels.

In the EU's funding mechanisms, particularly Horizon Europe (and its predecessor Horizon 2020) and the Innovation Fund, CCU projects play a prominent role. Horizon Europe has declared the establishment of CCUS hubs and clusters a strategic goal, building on the work of Horizon 2020, which funded, among other things, R&D on $CO_2$ -based fuels and chemicals. The Innovation Fund provides funding opportunities for CCU as well. Initial proposals under the Fund underline the above-mentioned cross-fertilization in terms of the EU's focus on industrial decarbonization and the development of a hydrogen economy. Many proposed projects combine CCUS and hydrogen to produce synthetic fuels.

Table 1 compares the existing policy instruments in the EU and the US. The table points to some potentials for strengthening the instrument mix. For instance, government procurement for CCU products is not used as an instrument in the EU yet and is at its infancy in the US. The same applies to CCU related universal standards and labels. Existing labels for climate-friendly products and processes do not address CCU on either side of the Atlantic. Funding instruments in the US and EU have been highly focused on R&D, due to the immaturity of many CCU technologies (Fortunato et al., 2018; Tcvetkov, 2021).

TABLE 1 Comparison of policy instruments addressing CCU in the US and EU.

| Policy instrument | US | Instrument type | EU | Instrument type |
|---|---|---|---|---|
| (Blending) Quota | **No**, only for biomass-based fuels | / | **Yes**, for GHG emissions reductions and RFNBOs in the industry and transport sectors (Renewable Energy Directive II, Fuel Quality Directive) | Regulation |
| Tax credits | **Yes**, when a minimum capture threshold of $CO_2$ is achieved (45Q) | Economic Instrument | **Yes**, but only for production of clean fuels for specific types of air and maritime navigation (Energy Taxation Directive—reform proposal) | Economic Instrument |
| $CO_2$ prices | **No**, not on federal level | / | **Yes** (ETS directive—application currently only in the Schäfer-Kalk-Case, broader application in Fit for 55 reform proposal) | Economic Instrument |
| Government procurement | **Yes** (SCALE Act, EPA recommendations) | Soft Instrument; Regulation in process | **No** | / |
| Standardization/Labeling | **In process** (funded through SCALE Act) | Regulation | **No** | / |
| R&D Funding | **Yes**, for pathways as chemicals, plastics, building materials, fuels, coal-utilization products, and new novel technologies (e.g., SCALE Act, USE IT Act) | Economic Instrument | **Yes** (e.g., Innovation Fund; Horizon Europe) | Economic Instrument |
| Support in infrastructure | **Yes**, $CO_2$ transportation infrastructure (USE IT Act, Energy Act of 2020, SCALE Act) | Economic Instrument | **Yes**, $CO_2$ transportation infrastructure (Connecting Europe Facility) | Economic Instrument |
| Support for Upscaling | **No** | / | **Yes** (Innovation Fund) | Economic Instrument |

## Discussion

A supportive policy mix which takes societal interests into account is particularly important for a growing field such as CCU to fulfill environmental potentials and be economically successful (Olfe-Kräutlein et al., 2021). In this final section, the paper evaluates the policy mixes based on the characteristics defined by Rogge and Reichardt (2016).

Accordingly, the first characteristic of a policy mix that fosters sustainability transitions is *consistency* of the strategies, the instruments, and the mix thereof. In the US, policy mix consistency must be considered low: In terms of strategy, the country has no specified climate targets for industry and transport decarbonization. More specifically, there is no strategy for CCU—CCU plays a role only in executive agency documents, not in executive orders. In the EU, in contrast, there are specific climate targets for all sectors for 2030. There are no specific CCU targets, however there is an explicit strategic commitment to CCU. The analysis further shows some contradictions in EU and US policy instruments. On the US side, the instrument mix generally supports CCU mostly indirectly, for instance by supporting capture technologies or establishing a $CO_2$ transport infrastructure. CCU is, for instance not included in federal guidelines for procuring more environmentally friendly products, posing an obstacle for investments in CCU technologies. Moreover, the Renewable Fuel Standard does not include CCU. The EU ETS so far largely excludes CCU. The ETS reform proposal, however, includes CCU. The EED and the EU's energy efficiency first principle pose a considerable obstacle for energy-intensive CCU technologies. The same is true for the EU's waste policy framework which is currently not conducive to CCU—once again, reform proposals are underway, however. Furthermore, although the Union considers CCU an industrial decarbonization strategy, CCU technologies currently are not in the scope of the Industrial Emissions Directive as they are not included in the EU Best Available Techniques reference documents (BREFs) (Turnau et al., 2019).

The second characteristic of policy mixes is their *credibility*. From the US perspective, a major weakness of the policy mix in this regard is the lack of clear commitment from political leadership. CCU is hardly mentioned at all in strategy documents of the Biden Administration. As the Trump Administration demonstrated, there is no clear support for decarbonization efforts across the political aisle. This creates uncertainty as to the role of CCU technologies in the future. This is particularly problematic given the necessity to take into consideration the long industrial innovation and planning cycles and thus provide industrial actors better predictability and reliability for investment decisions. Credibility of the policy mix is much higher in the EU where there has been a long-term commitment to climate protection among most political groups with specific near-term and long-term climate targets and where CCU is mentioned explicitly in the analyzed Green Deal strategy documents. The fact that the instruments on how to achieve the EU's new ambitious climate targets are currently in the process of being revised in the legislative process limits the EU's credibility somewhat and creates a certain degree of uncertainty. The successful passing of the proposals initiated in Fit for 55 will strengthen the EU's credibility in this regard.

The final characteristic of policy mixes is their *comprehensiveness*. The first criteria here is the existence of a policy strategy. Once again, since the US policy mix suffers from a lack of high-level strategic commitment to CCU. Instruments, however, exist. They are largely focused on CCS and CCU only benefits indirectly. But the major economic instrument, 45Q, includes CCU as one of three technological pathways in focus. In the EU case, the policy mix is more comprehensive as both strategy and instruments exist, and they address some of the barriers to the large-scale uptake of CCU identified above. One is the high costs associated with CCU technologies. CCU has little support under current regulatory instruments in the EU. The EU ETS currently only includes CCU in a very limited pathway. Nevertheless, it puts a price on $CO_2$ emissions for industries with high emissions thus creating a more level playing field for some of the CCU applications. Most regulatory support for CCU currently comes from regulation of fuels for the transport sector. The EU, moreover, has various funding instruments that support CCU directly, including the Innovation Fund and Horizon Europe. Especially in its instrument mix, the EU is therefore more comprehensive than the US.

## Actionable recommendations

In summary, the analysis of the EU and the US CCU policy mix shows that strategies and policy instruments are in place, at least to some extent. What they lack at times are, however, consistency, credibility, and comprehensiveness. Based on this assessment, these final paragraphs develop recommendations which take into account cross-regional learning opportunities as well as opportunities to raise the consistency, credibility, and comprehensiveness of the policy mixes.

In the US, a first step toward enhancing the credibility of the policy mix on CCU could be the explicit mention of CCU in White House strategy documents or even a high-level CCU strategy. Such a public commitment to CCU could, as suggested in Rogge and Reichardt (2016), provide clarity on the longer-term contribution of CCU to industrial decarbonization strategies in the US incentivize related R&D investments at the firm-level. In the US case, however, the caveat here is that any political strategy could be altered significantly as the next president enters office. A more feasible solution, therefore, are CCU strategies in relevant large, climate ambitious states such as California or New York. Moreover, updating some of the policy instruments in place could enhance the consistency and comprehensiveness of the policy mix. One approach would be to adjust the Federal Renewable Fuel Standard to include CCU-based fuels, including ones that use biological processing pathways in their production, such as photo/chemosynthesis using algae or bacteria as specified in 45Q. This would also align these two instruments better with the Biden Administration's circular economy approach, allowing for the emissions of fuels to feed the creation of the next fuels to an even greater extent than the current biomass-exclusive pathways supported in the standard, assuming future emissions are paired with carbon capture or DAC. The CEQ Report to Congress on CCUS also calls out this connection as a future incentive for CCUS (CEQ, 2021). For 45Q, the tax credit could be even further expanded even further to enhance this major instrument for CCU promotion in the US, especially in the absence of a carbon price, which is currently not feasible.

At the EU level, policy mix consistency could be enhanced by adjusting some of the existing policy instruments. While the EU Innovation Fund explicitly supports RD&D for different CCU pathways, the Modernization Fund (EC, 2020a) so far does not explicitly mention the eligibility of CCU technologies for industry decarbonization in the eligible lower income member states (EC, 2020c). Creating instrument consistency here, by incorporating CCU across different funding schemes in the EU could send a clearer market signal for investments in CCU technologies and could clarify the role the EU envisions for CCU. Another step in the direction of a more consistent policy mix could be the already planned reform of the waste framework

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under the Circular Economy Action Plan as well as the addition of selected CCU technologies to the BREFs (Turnau et al., 2019). Including CCU in the ETS, moreover, might become critical support in the upcoming years, as many research efforts result in products and production pathways that approach market readiness and high production costs remain a major barrier to the deployment of CCU (Moch et al., 2022).

For both regions, including CCU in public procurement guidelines and standards would enhance the consistency and comprehensiveness of the policy mixes: Green public procurement is an important instrument in the Biden Administration's climate policy approach. Including CCU technologies more explicitly in the EPA recommendations of Specifications, Standards, and Ecolabels for Federal Purchasing is an untapped potential to support CCU with the US federal government being "the single largest consumer in the world" (EPA, 2022). "Buy clean" legislation in California and Colorado which promotes green public procurement and includes CCU could be used as models and frameworks to develop this further at a national scale (State of California, 2017; Colorado General Assembly, 2021). On the EU side, such public procurement guidelines could also greatly enhance CCU (Olfe-Kräutlein et al., 2021).

Finally, another opportunity to increase the comprehensiveness of the policy mixes in both EU and US would be to address some of the barriers of CCU uptake more clearly and ambitiously. These barriers include a high demand for clean electricity or green hydrogen (Group of Chief Scientific Advisors, 2018; Olfe-Kräutlein, 2020). A comprehensive policy mix for CCU must therefore go hand in hand with highly ambitious electricity decarbonization and clean hydrogen production targets and means to increase renewable energy and electrolyzer capacity (Bhardwaj et al., 2021). Through Fit for 55, the EU is currently in the process of increasing its targets for renewables and clean hydrogen through 2030. In May 2022, The EC in its REPowerEU plan set the target of speeding up permitting processes which are slowing down renewable energy projects. Moreover, it has specified targets for renewable hydrogen production and imports (EC, 2022b). The US government has chosen a different route for increasing clean hydrogen production, introducing its Hydrogen Shot which aims, through government support for RD&D to reduce the price of clean hydrogen to one US-Dollar per kilogram of hydrogen by 2031 (DOE, 2021c). A recent Supreme Court ruling which limits the power of the EPA to regulate the electricity sector ("West Virginia v. EPA"), however, has made it more difficult for the Biden Administration to regulate a clean electricity supply. Creating a net-zero electricity sector and ramping up clean hydrogen must progress much more quickly in the coming years in both EU and US, however, to create needed incentives for CCU investments.

Finally, the paper hints to venues for future research. Empirical data is missing, for instance, on the impact of these policies and strategies, for instance on investment decisions of firms. Second, expanding the analysis to individual country studies within the EU or cases such as China would be interesting in future projects.

## Author contributions

BO-K and VS developed the framework for the research and contributed to the introduction, case studies, discussion, and recommendations. ST put the final draft of the manuscript together, developed the policy recommendations further, updated the empirical chapters, and drafted tables. ST and RQ wrote the analytical framework and methods chapter. AR contributed the US case study and JJ contributed the EU case study. All authors contributed to the article and approved the submitted version.

## Funding

Funding for this work was provided by the Global CO2 Initiative at the University of Michigan within the Project CO2nsistent—Techno-Economic and Life Cycle Assessment Guidelines for CO2 Utilization.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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