Carbon dioxide use and removal

Prospects and policies

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Abstract

This report presents an overview of the current status of carbon capture, utilisation and storage (CCUS) and carbon dioxide removal (CDR), in terms of and main technologies, markets and policies, especially from the perspective of Finland. CDR refers to technologies and practices, which can remove carbon dioxide (CO_2) from the atmosphere and store it in a manner intended to be permanent. CCUS refers to permanent storage of captured CO_2 or to the utilisation of captured CO_2 as a feedstock for different products which also form short- or long-term storage over their life cycle. The products can range from fuels (short lifetime) to performance polymers (long lifetime) and to mineral products (often permanent storage).

The market assessment included also quantitative and qualitative estimates for future development in size and growing CCUS and CDR solutions. Finland’s export potential in the technologies and products was also investigated. The policy environment of the technologies was assessed in terms of greenhouse gas accounting and reporting rules under the UNFCC and EU legal frameworks. Moreover, an international benchmarking of national policies was carried out to survey good practices in peer jurisdictions. Taking note of the assessed main technology options, the policy overview was used to identify policy development needs and to provide recommendations accordingly.

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Keywords research, research activities, carbon dioxide, carbon capture, utilisation and storage, carbon dioxide removal, policies

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Tiivistelmä

Tämä raportti antaa yleiskatsauksen hiilidioksidin talteenoton, hyötykäytön ja varastoinnin (CCUS) sekä hiilidioksidin poiston (CDR) nykytilasta, käsittäen pääteknologiat, markkinat ja ohjauspolitiikat Suomen näkökulmasta. CDR:llä tarkoitetaan teknologioita ja menetelmiä, joilla voidaan poistaa hiilidioksidia (CO_2) ilmakehästä ja varastoida sitä pysyväksi tarkoitetulla tavalla. CCUS:llä tarkoitetaan CO_2:n talteenottoa ja pysyvää varastointia tai hyötykäyttöä tuotteiden valmistuksessa, joka voi myös toimia lyhyt tai pitkäaikaisena varastona tuotteen elinkaaren yli. Tuotteet voivat vaihdella polttoaineista (lyhyt ikä) teknisiin polymeereihin (pitkä ikä) ja mineraalituotteisiin (usein pysyvä varasto).

Selvitys sisälsi myös määrällisen ja laadullisen tarkastelun CCUS ja CDR-ratkaisujen markkinoiden kehittymisestä sekä ratkaisujen kasvupotentiaaleista. Suomen vientipotentiaali teknologioiden ja tuotteiden osalta otettiin myös huomioon. Teknologioiden lainsäädännöllistä toimintaympäristöä tarkasteltiin UNFCC:n kansallisten kasvihuonekaasuinventaarioiden sekä EU:n lainsäädännön osalta. Tämän lisäksi suoritettiin kansainvälinen vertailu ohjauskeinoista muissa valtioissa. Huomioiden keskeisimmät teknologiavaihtoehdot, politiikkakartoitusta hyödynnettiin tunnistamaan lainsäädännön ja ohjaustoimien kehitystarpeita sekä toimenpidesuosituksia.

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Referat

Denna rapport ger en översikt av det nuvarande läget av avskiljning, användning och lagring av koldioxid (CCUS) och koldioxidupptag (CDR), angående huvudteknologier, marknader och politik, särskilt ur Finlands perspektiv. CDR hänvisar till teknologier och metoder som kan avskilja koldioxid (CO_2) från atmosfären och lagra den på ett sätt som är avsett att vara permanent. CCUS avser permanent lagring eller utnyttjande av avskild CO_2 som råvara för olika produkter som också kan tjäna som kort- eller långtidslagring under sin livscykel. Produkterna kan sträcka sig från bränslen (kort livslängd) till prestandapolymerer (lång livslängd) och mineralprodukter (ofta permanent lagring).

Marknadsbedömningen inkluderade också kvantitativa och kvalitativa uppskattningar av den framtida utvecklingen i storlek samt de växande CCUS- och CDR-lösningarna. Även Finlands exportpotential inom teknologi och produkter undersöktes. Teknologiernas politikmiljö bedömdes angående redovisning av växthusgaser och rapporteringsregler enligt UNFCC och EU:s rättsliga ramar. Ytterligare genomfördes en internationell jämförelse av nationell politik för att kartlägga god praxis i andra länder. Vid beaktning av de bedömda huvudsakliga teknologiska alternativen, användes politiköversikten för att identifiera behov av politikutveckling och för att ge rekommendationer i enlighet därmed.

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Contents

ABBREVIATIONS AND SYMBOLS

BECCS	Bioenergy carbon capture and storage
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CDR	Carbon Dioxide Removal
CO_2	Carbon dioxide
DACSS	Direct air carbon capture and storage
EOR	Enhanced oil recovery
ESR	Effort sharing regulation
ETS	Emission trading sector
EU	European Union
EW	Enhanced weathering
H_2	Hydrogen
HWP	Harvested wood product
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land-use change and forestry
PtX	Power-to-X
RED	Renewable Energy Directive
UNFCCC	United Nations Framework Convention on Climate Change
VTT	VTT Technical Research Centre of Finland Ltd.
WtE	Waste-to-Energy

DEFINITIONS

Carbon dioxide removal (CDR)

Within this report, we define CDR as the removal of carbon from the carbon cycle, with sufficient permanence. To generate CDR, carbon (dioxide) must be captured from air directly, indirectly from oceans, or through biomass growth and conversion process, such as production of electricity, heat, fuels and/or chemicals, followed by a storage in a manner intended to be permanent. The total quantity of atmospheric CO_2 removed and permanently stored must be greater than the total upstream and downstream GHG emissions from the conversion, capture and storage processes.

Carbon capture, utilisation and storage (CCUS)

Within this report, CCUS refers to Carbon Capture and Utilisation or Carbon Capture, Utilisation and Storage. CCU refers to the utilisation of captured CO_2 as a feedstock for different products which can also form temporary storage for CO_2 over their life cycle. The products can range from fuels (short lifetime) to performance polymers (long lifetime) and to mineral products (often permanent storage). CCS refers to carbon capture and storage (permanent storage).

Technological sink

CDR can be generated by technology or nature-based means. Within this report, 'technological sink' refers to technology-based CDR, such as direct air capture of CO_2 (DACCS) or bioenergy with CO_2 capture (BECCS) in contrast to nature-based CDR such as land or forest management for enhanced CO_2 uptake and storage. The focus of this report is on technological sinks.

PREFACE

This is the final report of the research project "Carbon use and removal: prospects and policies", funded by the Government of Finland, as part of its analysis, assessment and research activities. The purpose of the project has been to assess the current and up-coming technologies, markets and policies regarding carbon dioxide capture, use and storage (CCUS). Special focus has been given on the technologies for carbon dioxide removal (CDR) from the nature's carbon cycle, allowing negative emissions.

We hope the results will enable consideration of policy measures and incentives needed in Finland and help defining Finland's positions at EU level. The project was divided into the following four sub-goals:

1. Increase knowledge about the technologies for utilisation and storage of re-covered carbon dioxide, with special focus on technological sinks and CCU technologies with products providing long-term storages. Consider carbon capture, its use in products or processes, geological and non-geological storage, and storage in products or processes.
2. Investigate the overall configuration, development and sectors of the relevant markets of CCUS and technological sinks. Study possibilities for growing business operations, expanding the carbon handprint and contributing to achieve Finland's climate targets.
3. Assess the relevant legal, regulatory and policy frameworks for CCUS in the multi-level (i.e. especially EU and national) regime context, considering the reasonable certainty of generating emissions reductions and technological sinks. Identify the possibilities to regulate CCUS and technological sinks through the existing climate and energy regulatory frameworks.
4. Make sure the findings reach key audiences. Present project results in a policy-relevant and widely understandable manner.

The partner organisations in the project are VTT Technical Research Centre of Finland Ltd., the Finnish Environment Institute and Tyrsky Consulting, VTT acting in the coordinating role. The project has had an active steering group formed by three Finnish ministries: Ministry of Economic Affairs and Employment, Ministry of the Environment and Ministry of Agriculture and Forestry of Finland.

The report does not include or represent the official positions of the Finnish Government.

Lauri Kujanpää[1], project coordinator, March 2023

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[1] VTT Technical Research Centre of Finland Ltd.

1 Introduction

Carbon dioxide removal (CDR) and Carbon Capture, Utilisation and Storage (CCUS) are becoming increasingly relevant in the discussions on how to reach the Paris Agreement targets for climate change mitigation. CDR refers to technologies and practices, which can physically remove carbon dioxide (CO_2) from the atmosphere and store it permanently to underground storages or other storages intended to be permanent. When more CO_2 is stored than caused by the process of CDR, the activity is serving as a negative emission. CCU refers to the utilisation of captured CO_2 as a feedstock for different products which can also form temporary storage for CO_2 over their life cycle. The products can range from fuels (short lifetime) to performance polymers (long lifetime) and to mineral products (often permanent storage). CCS refers to carbon capture and storage.

CO_2 can be captured using different technologies from various sources, and utilised (CCU) or stored (CCS). The ability of CCUS technologies to act as technological sinks depends on the source of CO_2 captured and permanency of stored CO_2. Common definitions on this are still missing[2]

Figure 1 presents the influence on atmospheric carbon dioxide balance of CCUS depending on different possible sources for captured CO_2 and utilisation and storage options with varying permanence.

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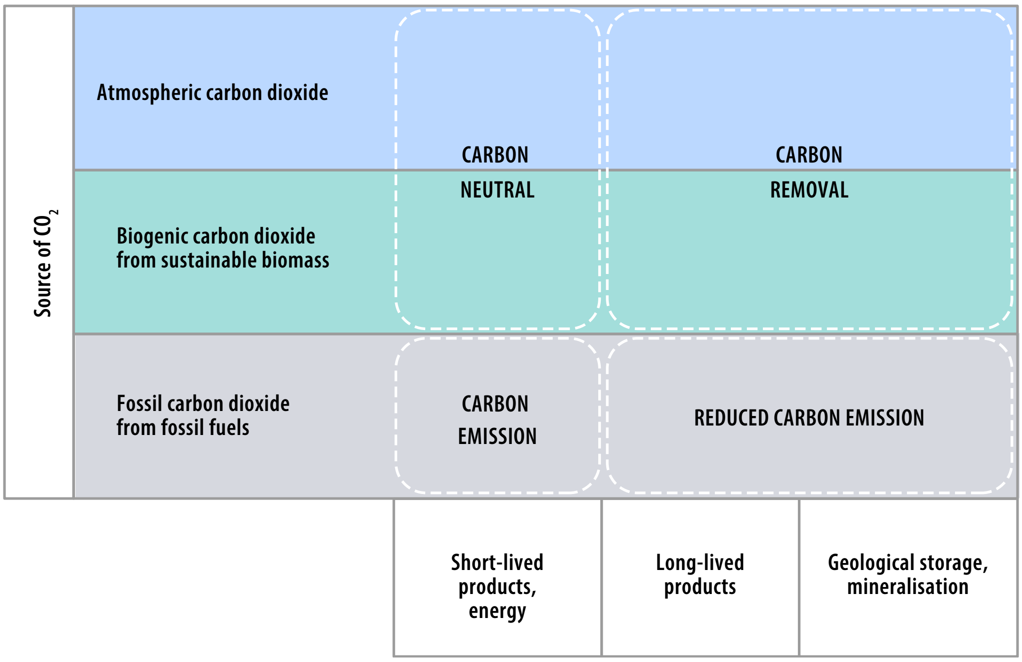
[2] There is no scientifically agreed definition for “permanent storage”, and the definitions vary from minimum storage length of decades to centuries, some considering only geological storage of thousands of years as permanent.

Figure 1. Rough categorisation of sources of carbon dioxide and its utilisation and storage options with varying permanence and influence on atmospheric carbon dioxide balance.



CCUS technologies may help to either avoid CO_2 emissions or remove CO_2 from the atmosphere, and in some cases do both. By recycling CO_2 into products in CCU, fossil-based CO_2 emissions can be avoided when replacing products with higher life cycle CO_2 emissions. In addition, if long-living products are produced from captured CO_2, release of CO_2 is postponed, and part of the captured carbon remains unreleased in this product pool, resulting in lowered CO_2 emissions compared to immediate release (Figure 1). Consequently, with the help of CCU, generation of CO_2 emissions may be avoided. However, CO_2 removal from the atmosphere requires 1) that CO_2 is captured from the atmosphere directly, through biomass growth or by increasing the carbon sink of the hydrosphere and 2) permanently stored in some carbon pool (Figure 1).

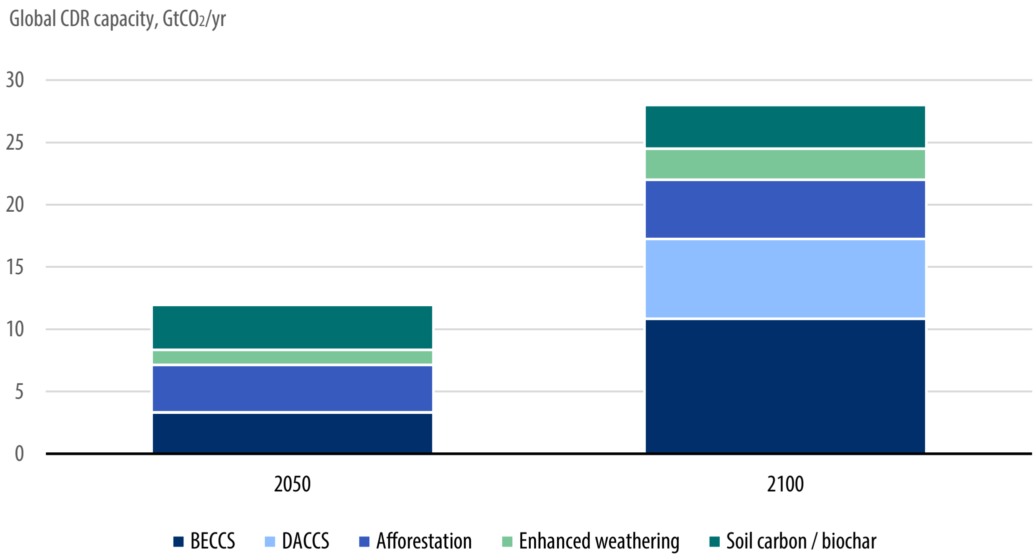
CDR can be produced by several technological and nature-based solutions. While assessing the prospects of CDR in Finland, this report has a focus on technological solutions applicable to industrial CO_2 emissions and direct air capture (DAC). These solutions may also be referred to as technological sinks. CDR can include, for example:

- Afforestation and reforestation
- Bioenergy combined with carbon capture and storage (BECCS)
- Direct air capture of CO_2 combined with carbon storage (DACCS)
- Biochar
- Enhanced weathering
- Ocean alkalinisation
- Long-lived harvested wood products (HWP)
- Long-lived products from CO_2 (CCU products) captured from the atmosphere (directly or through biomass growth).

In the Working Group III contribution to the IPCC Sixth Assessment report (IPCC 2022), CDR was reported with high confidence as a key element in all scenarios where global warming is reduced below 1.5°C or 2°C by 2100. IPCC WG3 reports CO_2 removal on managed land, BECCS and DACCS as three predominant CDR methods. According to their Summary for Policymakers (IPCC 2022), to limit warming to 1.5 °C, global cumulative CDR during 2020–2100 in total should be 190–960 $GtCO_2$ (from BECCS 30–780 $GtCO_2$ and from DACCS 0–310 $GtCO_2$). To limit warming to 2 °C, the total CDR between 190–900 $GtCO_2$ is needed (from BECCS 170–650 $GtCO_2$ and from DACCS 0–250 $GtCO_2$).

Figure 2 shows the global scale of CDR deployment in 1.5 °C IPCC scenarios by mid- and end of the century.

Figure 2. Scale of CDR deployment per year in the IAMC (Integrated Assessment Model Consortium) 1.5°C Scenarios Database, as median values over all scenarios having each CDR option active in the results. (Koljonen et al. 2021)



Finland is set to be carbon neutral by 2035, as stated in the reformed Climate Act (Act 423/2022). The Climate Act also includes emission reduction targets for 2030, 2040 and 2050. The most recent Finnish scenarios for "Carbon neutral Finland 2035 – measures and impacts of the climate and energy policies" (Koljonen et al. 2021a) aimed to assess how Finland could sustainably achieve the climate and energy targets from 2030 to 2050 set nationally and by the European Union. These scenarios indicated a need for around 8.3 Mt CO_2 removal with BECCS in 2050. Earlier scenarios from Finland's long-term low greenhouse gas emission development strategy indicated a need for 7 Mt CO_2 removals by 2040 and 14 Mt CO_2 by 2050 (PITKO scenarios 2019). The reduction in use of BECCS in HIISI scenarios stems e.g. from limitations in forest residue use in energy production. Nordic scenarios for BECCS in Finland see potential of 6.5–6.9 Mt CO_2, by 2035, reduced to 4 Mt if storage cost is assumed high. The potential for other CDR technologies, or potential for CCU products to act as sinks in Finland has not yet been studied in the scenarios. As the carbon sink by land use sector (LULUCF) in Finland has significantly reduced (Statistics Finland 2022), the need for additional CDR may be significantly higher than analysed in former scenarios.

To give an example on the scale of implementation needed, Fuss and Johnsson (2021) studied the upscaling of BECCS in Sweden and concluded that in order to achieve e.g. 6.4 Mt CO_2 removal target by year 2045, 7 pulp and paper mills and 7 CHP units utilising biomass should be converted to BECCS plants, meaning a new investment on both every 2.5 years, starting from 2025. This shows the possible speed of implementation needed, the current gap in implementation and incentives for CDR, and the urgency to develop guiding policies and regulations.

CCU products are produced from captured CO_2, often together with hydrogen produced with electrolysis. EU has recently adopted ambitious strategies on renewable hydrogen production, which will for one's part facilitate the increased production of CCU products. Several CCU and green hydrogen projects have been recently announced in Finland. A news article from January 2023 mapped 23 green hydrogen projects in various development phases around Finland, of which 10 were planning to produce synthetic fuels (Yle 2023). There are also Finnish start-up companies developing CO_2 capture in buildings (Soletair Power 2023) and technology for the production of edible proteins from CO_2 (Solar Foods 2022a).

Finland has several research activities ongoing related to CCU technologies, including production of polymeric materials and e-fuels (VTT 2022a, 2023a, 2023b; LUT 2022a, 2022b). In some of these projects, the focus is on biogenic CO_2 sources. Furthermore, the use of CO_2 for concrete curing and mineralization is studied (VTT 2022b). Technologies developed in these projects are in technology readiness level (TRL) 3–6, so currently in technology development phase. In some projects, small scale demonstrations connected to an industrial CO_2 have been performed.

Aside other technologies to utilise and store captured CO_2, biochar as a CDR solution has also been extensively studied in Finland for at least a decade, and scientific publications are rapidly increasing. In addition, various Finnish research organizations have invested in biochar research infrastructure and are actively developing and expanding it. Over 30 Finnish municipalities or cities have already participated in biochar projects (including all ten largest Finnish cities by population) and applied biochar for various purposes, such as soil amendment (urban trees and other vegetation) and stormwater management (Salo E. 2018). The City of Helsinki, for instance, is currently scaling the use and application of biochar (Aalto, 2022).

GHG emissions are reported to the United Nations Framework Convention on Climate Change (UNFCC) applying methods and guidelines of the Intergovernmental Panel on Climate Change (IPCC). In GHG reporting CO_2 flows or carbon stock changes related to CDR and CCUS technologies are considered differently depending on technology. In the EU, GHG emissions are accounted towards binding targets at the EU level under EU Emissions Trading Scheme (EU ETS) and Member State specifically under effort sharing and LULUCF regulations. GHG reporting creates basis for GHG accounting.

However, direct EU level regulation to promote the use of CDR have not been introduced. Consequently, the promotion has mainly depended on national policies. CCU is indirectly promoted in the EU through carbon price in the EU ETS and mandates for renewable fuels in the Renewable Energy Directive. The Commission Communication on Sustainable Carbon Cycles (EC, 2021a) and the proposal establishing a Union certification framework for carbon removals (EC, 2022f) indicates a will to promote the use of CDR and CCU in the EU.. EU also offers funding through e.g., Horizon Europe, Innovation Fund and Connecting Europe Facility.

Apart from the EU, a number of jurisdictions have introduced policies and measures to promote CDR, especially in the past couple of years. Measures include RDI funding (e.g., for DACCS in the US); infrastructure funding (e.g., the Carbon Capture and Storage Infrastructure Fund in the UK and the Longship hub in Norway); tax credits (e.g. investment tax credit for CCUS in Canada); reverse auctions (e.g. auction for CDR in Sweden); and integration into regulatory requirements (e.g. the Low Carbon Fuel Standard in California, proposal on MRV rules on CDR in UK).

This report has the following structure: First we present an overview of CCUS and especially CDR technologies in the section 2: "Overview of CCUS and CDR technologies". Second, we assess the current status of commercial plans and demonstrations, the volumes of voluntary and compliance carbon markets focusing on the EU and Finland in the section 3: "Market for CCUS and CDR". The relevant adopted policies in the EU and the proposals by the Commission are assessed in the section 4: "CCUS and CDR in GHG reporting and accounting and in policies and measures in selected countries". We further discuss the needs and proposals for new policies in the fifth section. Finally, we present the conclusions and a summary of policy recommendations in the section 6.

2 Overview of CCUS and CDR technologies

Carbon capture, utilization, and storage (CCUS) refers to value chains where carbon dioxide (CO_2) is captured from the atmosphere or from emission point sources and utilized as feedstock or permanently stored to avoid releasing it to the atmosphere. CCUS can be used to mitigate emissions of hard-to-abate industries, to create value by providing feedstock for CO_2 utilization, or to create negative emissions by permanently removing carbon from its natural cycle. CCUS and CDR are expected to have a significant complementary role in the portfolio of actions for climate change mitigation, with several climate scenarios acknowledging the importance of these technologies to meet the climate goals set to abate global warming.

Methods to remove CO_2 from the atmosphere contain at least two components: (1) CO_2 capture and (2) CO_2 storage. CO_2 is naturally captured by the growth of biomass like forests and seaweed and by dissolving into oceans. By using carbon capture technologies CO_2 can be captured directly from the atmosphere or from industrial emission point sources deriving either from biogenic or fossil-based sources. CO_2 captured via technological pathways can be utilized as feedstock in products or processes (CCU) or permanently stored to avoid the climate-warming greenhouse effect of CO_2 in the atmosphere (CCS).

In CCU, the CO_2 is temporarily stored into carbon-containing materials, like synthetic chemicals, fuels and materials. The CO_2 is often released at the end of the products life cycle commonly via combustion or decomposition. However, CCU can indirectly provide emission reductions if used to replace unsustainable fossil-based production with higher life cycle emissions. In manufacturing of CCU-based products, hydrogen is often needed, which can be sustainably produced via water electrolysis powered by renewable electricity. Therefore, the role of renewable energy is especially critical, when aiming for CO_2 emission reductions with non-permanent CCU products by replacing fossil-based counterparts, e.g., chemical and fuels.

CO_2 can be stored permanently either in geological storage reservoirs or as minerals or stable carbon-containing products. Some techniques avoid the conversion of captured carbon back to CO_2 and store it as biochar or bio-oils pumped underground. However, sometimes the stored bio-based product might have replaced a fossil-based one. Other techniques aim at increasing the rate of CO_2 dissolving into the ocean (ocean alkalinity enhancement, enhanced weathering on the coasts and CO_2 stripping from seawater), where CO_2 is stored as ions – unless major disturbances occur in the chemistry of the oceans.

2.1 Carbon dioxide capture technologies

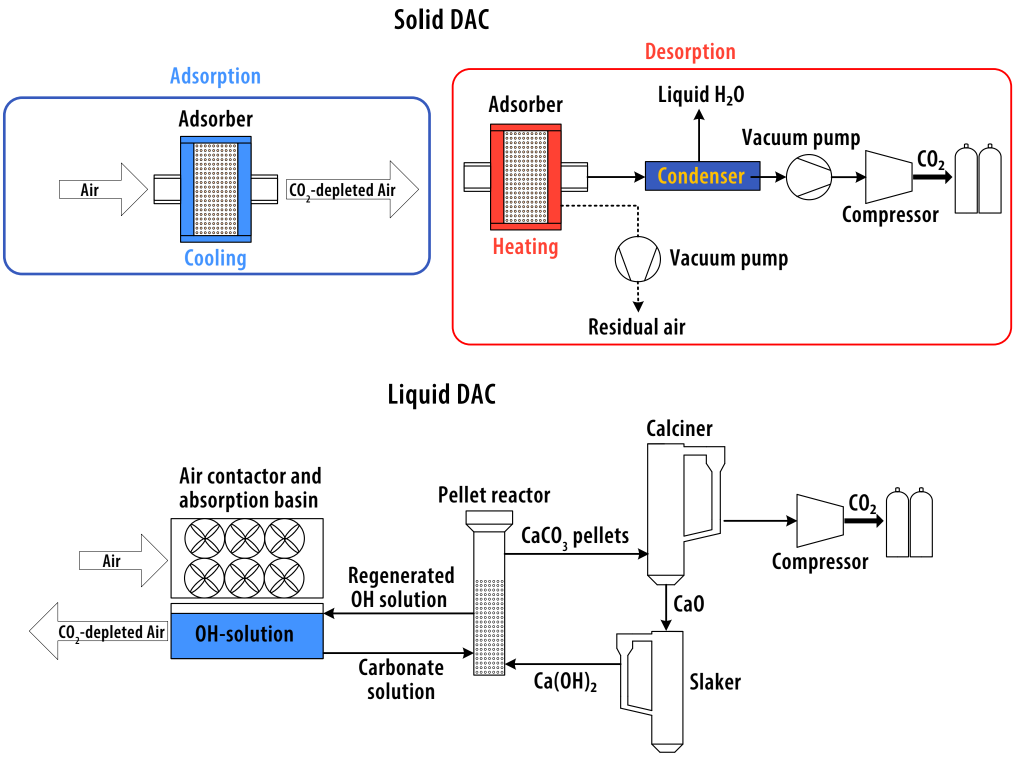
2.1.1 Direct air capture

Direct air capture (DAC) refers to technologies developed to capture CO_2 directly from the atmosphere. As atmospheric CO_2 is part of the natural carbon cycle, negative emissions can be achieved via DACCS, where CO_2 captured directly from the atmosphere is permanently stored, and life-cycle emissions from capture and storage process are smaller than the amount of CO_2 stored. However, the first applications for DAC have been to provide CO_2 as feedstock for utilization, e.g., power-to-X products (fuels, chemicals, materials), greenhouse fertilization, or the food and beverage industry.

Mainstream DAC technologies are based on cyclic processes where atmospheric air is led in contact with a substance selectively binding CO_2 via chemical or physical forces (Figure 3). Primarily solid adsorbent materials or liquid solvents are used as CO_2-binding substances – referred to as solid-DAC (S-DAC) and liquid-DAC (L-DAC), respectively. After the capture step, the saturated, CO_2-rich substance is regenerated commonly via temperature elevation, pressure reduction/vacuum or a combination of both, releasing a concentrated stream of CO_2. Depending on the capture technology in use, purity of the captured CO_2 ranges from mildly concentrated streams to near 100 %.

DAC benefits from high capture potential that is estimated around 5–40 $GtCO_2$/yr globally (IPCC 2022), flexibility regarding site location, relatively low environmental impacts, and simplicity of operation and monitoring. Solid-DAC processes are modular in nature with potential for mass production, therefore yielding high capital cost reduction potential. Liquid-DAC systems have higher potential for large CO_2 capture capacities, benefitting from economy of scale derived from large-scale operation. In contrast, as atmospheric air has a very low CO_2 concentration (~0.04 vol-%), separation of CO_2 is highly energy-intensive, yielding high cost per captured CO_2-tonne. Therefore, regarding economics, the greatest potential for the energy-intensive DAC processes lies in areas with high supply of low-cost renewable energy available. Furthermore, DAC facilities require high capital investment in relation to the CO_2 capture capacity.

Figure 3. Simplified process configurations of solid-DAC and liquid-DAC systems – the two most common technologies for direct air capture. (IEA 2022a)



Capture cost estimates for DAC currently range around 250–600 USD/tCO_2 (Ozkan et al. 2022). Capture cost could fall below 100 USD/tCO_2 as full-scale operation is reached (Keith et al. 2018). Some estimates state that sub-100 USD/tCO_2 capture cost could be reached by 2030 in areas with high renewable energy potential, although this would require strong public and private support for technology scale-up and deployment (Renforth & Kruger 2013). Although much of the infrastructure costs relating to CO_2 transport can be avoided in the case of DAC, the above-mentioned costs do not include any downstream costs of CO_2 transport, storage or utilisation.

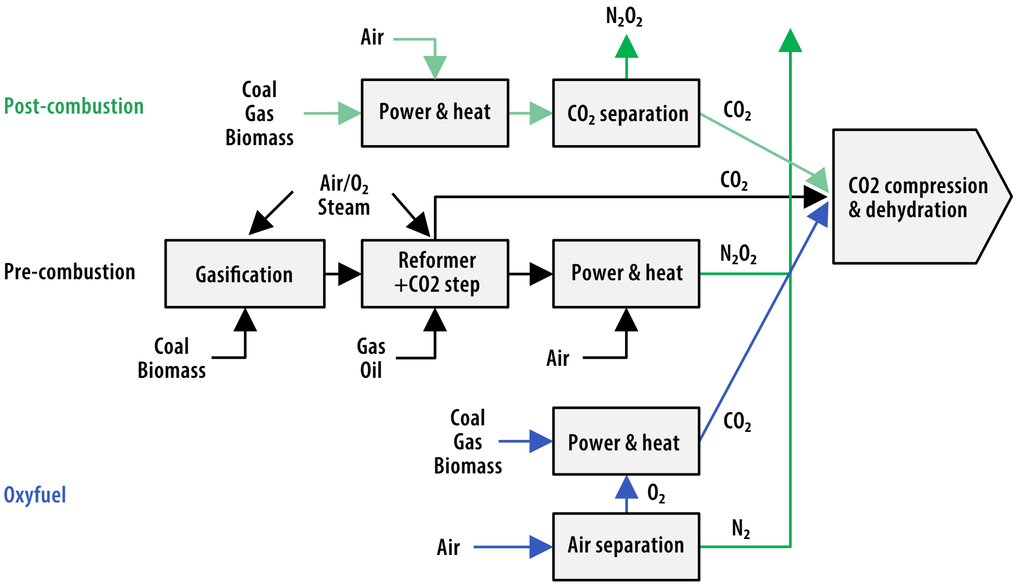
DAC technologies are currently at pilot and demonstration scale, with commercial facilities expected to be commissioned in mid-2020's. Capacity of DAC installations is low, totalling globally only around 0.01 MtCO_2/yr (IEA 2022a). The largest operational facility, the Iceland-based Orca industrial demonstration plant by Climeworks commissioned in 2021, has a capture capacity of 4,000 tCO_2/a. As DAC is still a novel technology, basic research is essential, for instance, in developing durable and high-performance sorbent materials and efficient process configurations. Further demonstrations are still needed to show the technology can reach large-scale deployment at reasonable costs.

2.1.2 Point source carbon capture

Point source carbon capture refers to capturing CO_2 from emission point sources such as combustion flue gases or other exhaust and process streams containing CO_2. Point source capture can be implemented into various CO_2-emitting processes of energy production and energy-intensive industries, e.g., power plants, pulp mills, refineries, and steel, cement, or chemicals production. Depending on the natural origin of the captured CO_2 and its end-use application (utilization or storage), point source capture can be used to mitigate fossil-based emissions, to produce negative emissions, or to supply CO_2 as feedstock for utilization. Negative emissions can be achieved via BECCS (bioenergy with carbon capture and storage), in which CO_2 of sustainable biogenic origin is captured and permanently stored, thus removing carbon from its natural cycle between growing biomass and the atmosphere. To produce negative emissions, the life cycle emissions of biomass procurement and BECCS process need to be lower than the amount of CO_2 stored.

Point source carbon capture technologies are generally categorized into post-combustion capture, pre-combustion capture and oxyfuel combustion (Figure 4). Post-combustion capture, that is the most common technology for point source carbon capture, refers to capturing CO_2 from combustion flue gases or other gases of similar nature typically with near-atmospheric pressure and low CO_2 concentration (<20 vol-%). Post-combustion capture technologies are generally end-of-pipe technologies that can be retrofitted into existing processes without major modifications on the original process. In pre-combustion capture, CO_2 is separated from the fuel prior to combustion or other utilization, e.g., by using gasification or pyrolysis to decompose carbonaceous matter into gas or liquid form from which the CO_2 is separated. Oxyfuel combustion refers to using oxygen-rich combustion conditions to obtain flue gas with high CO_2 concentration to facilitate separation of CO_2. Additionally, inherent capture can be included to point source carbon capture. It refers to applications like fermentation facilities producing ethanol, where CO_2 concentration of the emission point source is so high that a specific capture technology is not needed. As only some treatment (e.g., drying or purification), if any, is required to produce high-purity CO_2, capture costs in inherent capture applications are typically the lowest among all carbon capture applications.

Figure 4. The primary routes for point source carbon capture are post-combustion capture, pre-combustion capture and oxyfuel combustion (modified from IPCC 2005). Additionally, inherent capture, i.e., capturing CO_2 directly from high purity sources, can be included to point source carbon capture.



Several types of technologies have been developed for point source carbon capture, where depending on the process many types of conditions and feed gas streams with different characteristics may occur. Technologies developed for point source capture include, e.g., liquid solvents, solid adsorbents, membranes, fuel cell systems, chemical looping, cryogenic distillation and various hybrid systems combining multiple technologies. CO_2 absorption using liquid solvents is the most mature technology, with amine absorbents representing the state-of-the-art with high performance and commercial maturity. However, due to challenges of amines such as energy-intensive regeneration and hazardous amine-based emissions, interest for alternative technology options has increased as CCUS has become more relevant. In recent years several emerging technologies, such as solvents based on inorganic salts, solid sorbents, and membranes, have reached the scale of industrial demonstration, being on the brink of commercialization. Due to the large number of technologies available for carbon capture, identifying suitable technology options for a specific carbon capture project is a case-by-case matter determined by several factors such as desired capture performance (capture efficiency and product CO_2 purity), characteristics of the feed gas stream (e.g., composition, impurities, pressure, and temperature), and process integration factors (e.g., energy availability at the site, utility needs, and equipment size limitations).

Cost of capturing CO_2 from emission point sources depends on several factors, e.g., characteristics of the feed gas stream, operating conditions, capture technology in use, and the scale of operation. Capture from high CO_2 concentration sources (e.g., fermentation and natural gas processing) yields capture costs around 15–35 USD per captured CO_2-tonne (incl. CO_2 compression), whereas post-combustion capture from dilute streams is generally more expensive, yielding costs around 40–120 USD/tCO_2 (IEA 2019a). Although capture is generally the most influential factor on cost of CCUS, additional costs derive from other stages of the value chain like conditioning, logistics and storage of CO_2, and therefore the total cost of CCUS is higher.

Carbon capture from point sources has reached commercial scale, but there is large variance on maturity between different technology types. Although there are commercially available technologies on the market, deployment of carbon capture has been slow due to weak economics and lack of incentives. The global carbon capture capacity from energy production and industrial facilities is currently around 44 MtCO_2/yr (IEA 2021c). Most operational point source carbon capture projects at large-scale (>1 MtCO_2/yr) are located in the US where the captured CO_2 is primarily utilized in enhanced oil recovery (EOR), which makes carbon capture profitable by increasing oil production capacity.

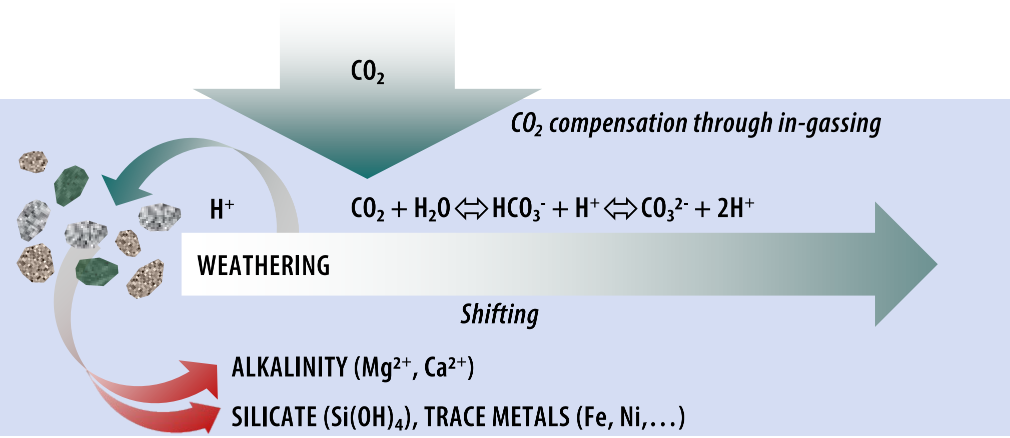
2.1.3 CO_2 capture by biomass growth

The sustainable growing of biomass plays an essential role in many of the CDR in two aspects: growing plants capture CO_2 from the atmosphere, but carbon is also stored in ecosystems within living and dead organisms and their surroundings (soil carbon, seashells). For biomass growing on land, sustainable practices are being developed for forest management, the utilization of agricultural wastes, forest, pulp and paper industry residues and crops for areas unsuitable for the cultivation of food crops. In marine environments, similar efforts consider the growing of algae or seaweed, as well as a broad spectrum of novel ideas.

2.1.4 CO_2 capture and dissolution into the oceans

Of all the CO_2 that is emitted into the atmosphere, the oceans absorb about 30 %, lowering the pH towards more acidic. The phenomenon is known as ocean acidification, and it threatens marine ecosystems, especially species building their shells from calcium carbonate ($CaCO_3$) (NOAA 2020). To hinder this and enable higher CO_2 absorption into the ocean, the pH may be increased toward the alkaline direction with different technologies, such as spreading ground minerals either directly into the oceans (known as *ocean* *alkalinisation* or *ocean alkalinity enhancement*) or at the coasts (known as *enhanced weathering* – also applicable on land) (Figure 5). Studied minerals include for instance quick lime (CaO) and olivine. (Bach et al. 2019)

Figure 5. Oceanic carbon balance can be influenced by ocean alkalinisation and enhanced weathering (redrawn based on Bach et al. 2019).



The benefit of ocean alkalinisation is, that whereas one mole of dry CaO could bind one mole of CO_2 and form limestone ($CaCO_3$), when dissolved into the ocean the same one mole of CaO can result into about 1.7 moles (Renforth and Kruger 2013) of CO_2 being absorbed from the atmosphere. These concepts would require the spreading of gigatons (~1 000 000 000 t) of minerals to achieve a substantial global impact, and the side effects of e.g., other dissolved elements to the marine ecosystem are largely unknown but are currently being studied. (Bach et al. 2019) Another option is to directly strip CO_2 from seawater, while the carbon could be bound into minerals in the process. (La Plante et al. 2021)

2.2 CO_2 utilization technologies

The carbon captured from the atmosphere or from point sources can be stored temporarily or permanently in products and materials. Once the carbon is in the gaseous carbon dioxide form, its utilization includes direct use of CO_2 as well as chemical conversion of carbon dioxide to other chemical products. Typical direct uses of CO_2 are enhanced oil recovery, uses in food industry, production of special gases and other industrial use e.g. in forest industry. Conversion of CO_2 can be based on chemical, catalytic or biochemical routes and the products can be either organic or inorganic chemicals. CCU can be either provide a permanent, long-term or short-term storage of carbon. Examples of permanent storages are some inorganic mineralization applications whereas long term storages can be e.g. some organic polymeric materials used in application with tens of years applications. Fuel and direct uses are typically considered as short-term storages.

2.2.1 Direct use

The technical, so-called direct uses of carbon dioxide have a roughly 20–30 $MtCO_2$/yr global market, although this value is quite difficult to estimate (Aresta, 2003 & IEA, 2019b). These technologies involve, for example, using carbon dioxide as an additive to beverages, food packaging, and cereal preservation. For instance, beer is typically canned under pressure of CO_2, while coffee, fruits, vegetables, and cereals can be transported under CO_2 (Topham et al. 2014). Other uses include water treatment, extraction of fragrances and caffeine, dry-washing, fumigant, fire extinguishers, shielding gases, enhanced oil recovery (EOR), and as a solvent in chemical processes (Aresta et al. 2014). Promoting plant growth is another interesting application and it is particularly used in the UK and Netherlands, where some farmers introduce CO_2 into their greenhouses (~3x ambient level). Yields typically increase between 15 to 20 %. The carbon dioxide applied in direct use is usually ending up in the atmosphere after the use, and the reduction to carbon dioxide emissions will derive from the replacement of other more potent greenhouse gases such as chlorofluorocarbons (CFCs). One notable exception is enhanced oil recovery, where significant part of CO_2 can remain in the oil or gas reservoir. Usually, the carbon dioxide is sourced from adjacent wells, but it can come from anthropogenic sources as well. In 2015, use of CO_2 in EOR greatly surpassed other direct uses, which is discussed in more detail in the Section 3.1.1.

2.2.2 Mineral products

CO_2 can be used to create new stable minerals – in a way, the CO_2 is turned into stone. With sufficient heating or chemical agitation, the CO_2 can also be released from minerals, like in the case of cement manufacturing from natural limestone or the combustion of paper containing a calcium carbonate filler. Examples of these carbon-binding compounds are magnesium and calcium carbonates, which are present in the nature as magnesite ($MgCO_3$) and limestone ($CaCO_3$) formed by natural weathering of rock during millions of years.

There are several man-made approaches mimicking this natural weathering phenomenon. The goals in such approaches may be to accelerate the process from millions of years to hours or days, to utilise secondary instead of virgin raw materials or to create valuable products in the process. (IEAGHG 2022) Examples of such processes include the manufacturing of artificial aggregates to replace natural crushed stone aggregate, the curing of concrete with carbon dioxide and cement alternatives to replace conventional cement to some extent or the production of precipitated calcium carbonate (PCC) from industrial wastes.

Some technologies could provide additional negative emissions, given that the raw materials do not form carbonates quickly in atmospheric conditions (as e.g. many ashes do), the energy consumption is low, and the product is used in a way that keeps the formed carbonate intact. One such technology has been developed to commercial scale: the production of artificial aggregates from thermal residues and industrial wastes (O.C.O Technology 2023), while other construction products are in the piloting and demonstration phases (Orbix 2023; VTT 2022b; Fortera 2023).

2.2.3 Organic products from CO_2 and hydrogen (PtX products)

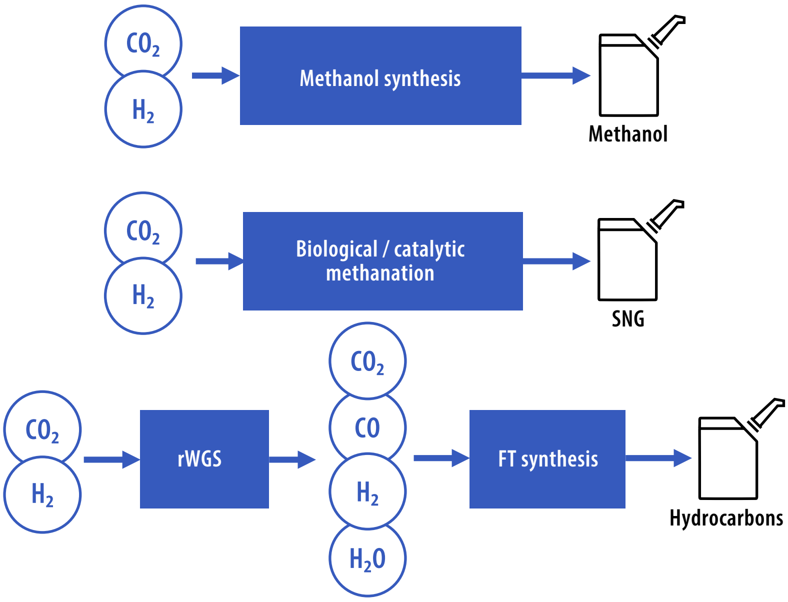
CO_2 is a low energetic combustion product and therefore another high energetic molecule, such as hydrogen, is typically needed when producing other products by chemical conversion from carbon dioxide. Other such molecules are e.g. epoxides and strong bases like hydroxides. Conversion processes of CO_2 and H_2 can either be catalytic or bioprocesses and the final products either fuels, chemicals or polymeric materials. Production of such final products is typically based on some key intermediates such as methanol or olefins. These intermediates can be further upgraded to various chemicals or monomers for polymer production.

2.2.3.1 Fuels

Gaseous or liquid fuels produced from carbon dioxide and hydrogen are called electro-fuels or simply e-fuels (also PtX fuel or synthetic fuels) referring to the origin of the energy through electrolytically produced hydrogen. Fuels are short lifetime products where carbon is typically stored less than one year. Furthermore, because the transportation fuels are used i.e. combusted in engines of different vehicles, it is difficult to further capture CO_2 from transportation use. The rationale of producing e-fuels for the transportation is to provide second life for the carbon captured from fossil CO_2 emissions. However, carbon dioxide for fuel production can also be captured from the air or from biogenic sources.

The most typical carbon-containing e-fuels are methane (synthetic natural gas, SNG), methanol and paraffinic hydrocarbons produced trough Fischer-Tropsch synthesis that could be used as alternatives to conventional hydrocarbon fuels like diesel, gasoline, and kerosene. Their production processes are presented in Figure 6.

Figure 6. Main pathways to carbon containing e-fuels.



Other carbon-containing e-fuels listed in the literature are e.g. dimethyl ether (DME) and oxymethylene ethers (OMEs) originating both from methanol. Methanol can also be upgraded to hydrocarbons such as gasoline according to standard EN228 and aviation jet fuel according to standard ASTM D7566. Recently, ammonia has also been considered as potential e-fuel, however, not containing carbon (Concawe 2019).

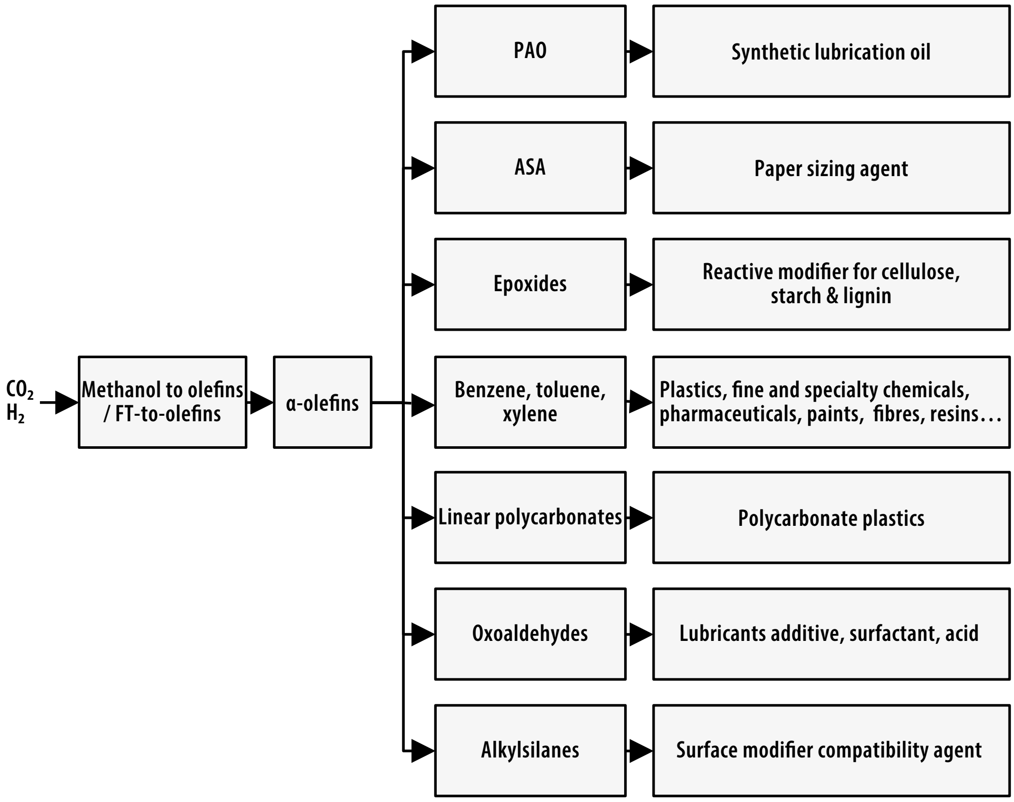
2.2.3.2 Chemicals and polymeric materials

Production of organic chemicals from CO_2 and H_2 can be based on the production of some key intermediates. Such intermediates are e.g. methanol and olefins (alkenes). From these intermediates, many important platform chemicals and monomers for polymers can be produced.

Production of methanol for the chemical use does not differ from the production of methanol for fuel use. Methanol is an important intermediate and the largest applications in chemicals are formaldehyde and acetic acid. Methanol can also be further converted into olefins by methanol-to-olefins technology (Methanol Institute 2023).

Olefins are versatile intermediates for many chemicals and monomers for polymers. Some main applications of olefins are given in Figure 7. Especially, light olefins (ethylene, propylene) are high volume olefins with many significant applications including polyolefins plastics (polyethylenes, polypropylenes), acrylic acid and acrylate polymers and epoxides (ethylene oxide, propylene oxide).

Figure 7. Some products from CCU-based olefins and their applications.

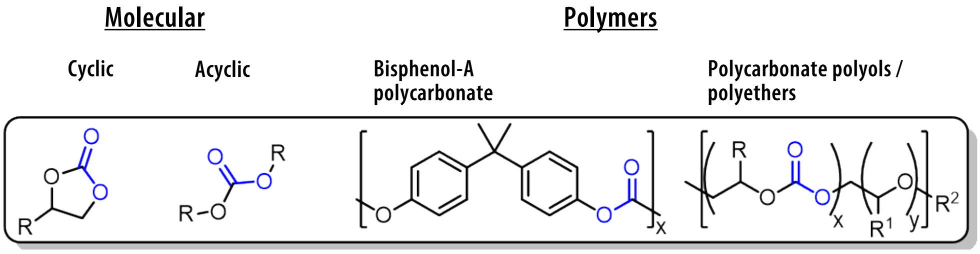


2.2.4 Other organic products from CO_2

Other organic products cover the products which can be manufactured from carbon dioxide without hydrogen. There are several such chemicals and intermediates, and an example of those chemicals is given below.

One class of compounds is the so-called organic carbonates that can be used either as molecular components or as a polymeric material in many different end-applications. For example, polycarbonate polyols / polyethers (Figure 8) could replace polyether polyols (i.e., polymer without carbon dioxide) in significant amounts in polyurethane applications. Another interesting application for CCU is in the synthesis of bisphenol-A polycarbonates which are widely used in clear polycarbonate plastics in applications such as in bottles, CD:s, food packaging, bullet proof glasses etc.

Figure 8. Different molecular and polymeric carbonates.



2.2.5 Wood products

In Europe, wood is used in many product sectors, including solid wood products, engineered wood products, products from bark and branches, veneer products and wood panels (CEPI 2021). The change in the Finland's carbon stock in wood products is calculated annually as part of the LULUCF sector emissions in the national greenhouse gas inventory. In 2021, the carbon stock in wood products increased 3.1 $MtCO_2$ (Statistics Finland, 2023), also including paper and cardboards products.

The gross production value of wood products industries in Finland, excluding the pulp and paper product sector, was 8.9 billion Euros in 2021 (Luke n.d.). Lintunen et al. (2023), presented technology pathway options to double the added value from forest industries in Finland. Although most of the additional potential would seem to be in the new products from pulp, lignin and side streams, the study presented significant potential for more added value in the manufacturing of cross laminated timber (CLT) and similar mechanical wood products. Below in Table 1 is a list of end-use application for the mechanical wood product sectors.

Table 1. Wood product sectors and typical applications.

Wood product sector	Typical applications
Solid wood products	Musical instruments, furniture, doors and windows, wood flooring, dishes and cutlery, toys, wood packaging, barrels, construction timber, roof shingles, railroad ties, pallets, matchsticks, wood pellets, mouldings, I-joists, garden products, poles and log houses.
Engineered wood products	Laminated veneer lumber (LVL), laminated strand lumber (LSL), timber-concrete composite (TCC), dowel laminated timber (DLT) and cross laminated timber (CLT).
Products from bark, branches and leaves (excl. power and heat)	Cosmetics, perfumes, mulch and cork production, essential oils and natural fabric dies.
Veneer products	Sports equipment, wood flooring, ceilings, furniture insulation boxes for liquefied natural gas carriers, vehicle body interior, packages and boxes and high-end loudspeakers.
Wood panel products	Medium-density particle board / high density particle board (MDP/ HDP), medium-density fibreboard / high density fibreboard (MDF/ HDF), laminate flooring, hard fibre board and oriented strand board (OSB).

Looking more closely on the chemical composition of wood, the main components are cellulose, hemicelluloses and lignin (Table 2).

Table 2. Typical products refined from chemical components in wood.

Chemical component in wood	Typical refined products
Cellulose (incl. nanocellulose products)	Synthetic viscose fibre, cellulosic ethanol, texturizers and emulsifiers, textile fibres, edible excipients, personal hygiene products, bio-plastics, medications and cosmetics, drilling fluids, cellulose foams, flexible and LCD screens, anti-caking agents and texture stabilizers, reinforcement agent, barrier film, newsprint paper, tissue paper, papers for printing and graphics, specialty paper, card stock, carton board, corrugated board, honeycomb structures and nitrocellulose.
Lignin	Flavourings, carbon fibre for e.g. electric car batteries, drilling fluids, thermoplastics, paints and dyes, phenols for plastic production, bitumen, disinfectants and deter-gents, medication and cosmetics and from hemicellulose gelling agent (food industry), food storage, medication, platform chemicals, barriers.
Other, involving several chemical components in wood	Resins, disinfectants, detergent and paint, flavourings, turpentine, sap and syrup (from wood sap), pyroligneous extracts including tar and preservatives, tall oil and other bio-oils.

2.2.6 Biochar

Biochar is a porous and carbonaceous material produced by a thermochemical conversion process called pyrolysis. Biochar can be produced from various feedstocks, including but not limited to forestry and agricultural side streams such as wood processing side streams, demolition and waste wood, municipal green waste, crop residues, sludges, manures, and food processing residues. During pyrolysis, the feedstock is heated in an oxygen-limited environment, ranging from 350 to 1,000 °C (EBC 2022). The pyrolysis process requires external energy during the start-up phase. Once the reactor is heated, the process becomes self-sustaining and produces a considerable amount of excess energy that can be utilized, for example, in district heating.

In addition, the pyrolysis process can also be used to produce pyrolysis liquids such as bio-oil. The main products of pyrolysis depend on feedstock, pyrolysis reactor, and business model/strategy and can vary significantly between companies. There are various types and scales of pyrolysis reactors available that can enable micro (household), small (e.g. farms), medium (e.g. sawmills), and large-scale (e.g. biorefineries) biochar production.

Biochar has numerous agricultural, urban, and industrial applications. Biochar can also be further processed into high-value carbons, such as activated carbon. Activated carbon is used across multiple purification applications such as water, air, and gas treatment.

Permanent carbon removal is achieved when biochar is produced and applied in applications such as soil amendment and additive in construction materials. There are already existing methodologies for measuring and accounting for carbon removal based on biochar production and application (Puro.Earth 2023). Biochar can be distributed by utilizing existing infrastructure, processes, and machinery. When biochar is used in short-term products, such as hard carbon in batteries or as an ingredient in biocomposites, it replaces fossil-based carbon. It acts as carbon storage during the product's lifetime.

2.3 CO_2 storage

2.3.1 Geological storage

Geological storage means injecting the CO_2 into a suitable geological formation, such as saline aquifers, unmineable coal seams or exhausted oil and gas fields deep under the earth's surface, where it would remain permanently. Their suitability for CO_2 storage and storage potential is determined by several factors, including but not limited to structure, porosity, pore pressure, permeability, and depth (Mortensen & Sopher 2021). Ideally, the storage formation has a high porosity and permeability to allow the flow of the CO_2 plume and is structured so that it traps the CO_2 and prevents its flow towards the surface. Moreover, the formation needs to be in sufficient depth of over 800 m (Halland et al. 2011), where the CO_2 stays in supercritical state.

According to EU GeoCapacity (2006) estimates, total CO_2 storage capacity in Europe is 360 Gt of with 326 Gt exist in deep saline aquifers, 32 Gt in depleted hydrocarbon fields and 2 Gt in un-mineable coal beds. The CO_2Stop project estimated a total storage capacity of 482 Gt in Europe's saline aquifers, and a total capacity of 31 to 54 Gt in identified storage reservoirs within these aquifers (Anthonsen & Christensen, 2021). The largest storage potential in the North Sea basin is in the deep saline aquifers and in depleted oil and gas fields (Halland et al. 2011). It is estimated that the theoretical storage capacity in both saline aquifers and depleted gas field in the North Sea only would be over 250 Gt. The difference between theoretical storage potential and effective potential is typically large, however. The difference can be indicated as the storage efficiency. The safe and effective storage potential reported in the Norwegian North Sea Storage Atlas in 2011 was 1.1 Gt, of which 1.0 Gt was in the aquifers of Utsira and Skade reservoir (Halland et al. 2011). The storage efficiencies ranged from below 1 % to over 5 % in the region.

The potential to geologically store CO_2 within the borders of Finland has been studied in the past (Teir et al. 2016), concluding that no known storage potential exists, and the geology of Finland is very unlikely to provide suitable conditions for viable CO_2 storage potential. Due to the lack of storage potential, Finland has banned the geological storage of CO_2 for other than purposes of research and development, as part of the implementation of the European Union's CCS Directive. Similar bans are in force in Estonia, Latvia and Lithuania and onshore storage bans in general are common practice in Europe (CO_2GeoNet 2021). Within the Nordic and Baltic Sea region, offshore storage of CO_2 is allowed in Sweden, Norway and Denmark.

From the viewpoint of Finland, the currently most attractive storage potential would seem to be off-shore in the North Sea (Teir et al. 2016), although less proven off-shore storage potential has been identified closer in saline aquifers under the southern Baltic Sea (Mortensen & Sopher 2021, Johnsson & Kjärstad, 2019). The effective storage capacity, estimated as 2 % of the theoretical capacity, of Faludden, När and Vikau storage formations are 1.7 Gt under the south-east Baltic Sea in the depths of 830–865 m. The aquifers reach across the economic areas of Sweden, Latvia, Lithuania, Russia and Poland. Another area where storage potential has been identified in the Baltic Sea region is in south-west Skåne. There, the estimated total effective capacity in five assessed saline aquifers is also close to 1.7 GtCO_2 in depths of 776–1 509 m (Mortensen & Sopher 2021).

The closest geological storage sites, which are in commercial operation, are two offshore locations in Norway, the Sleipner CO_2 storage in the North Sea and Snøhvit CO_2 storage in the Norwegian Sea. Both sites currently store CO_2 which is produced and separated from the natural gas on-site. Furthermore, Norway's national CCS initiative Longship, which develops open access infrastructure for the storage of CO_2, is planning to store CO_2 within the area south of the Troll field in the North Sea. The development project for the storage licence, the Nordic Lights, is a joint venture by Equinor, A/S Norske Shell and Total E&P Norge AS.

The costs associated with the geological storage of CO_2 depend on the case specific conditions and whether the CO_2 is injected into a saline aquifer or a depleted oil and gas field, on- or offshore. Furthermore, the availability of legacy wells that are suitable for re-opening and injecting CO_2, affects the geological storage costs. A study by European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP 2011) indicated a cost 14 €/tonne CO_2 stored (with a range of 6 to 20 €/tonne CO_2 stored) in offshore saline aquifers and 10 €/tonne CO_2 stored (with a range of 3 to 14 €/tonne CO_2 stored) in offshore depleted oil and gas fields without legacy injection wells available. Availability of useable legacy wells would lower the cost to 6 €/tonne CO_2 stored (2 to 9 €/tonne CO_2 stored), according to the study. Rubin et al (2015), in their review of onshore storage costs, observe that the highest typical costs are below 13 (US DOE 2014; GCCSI 2011) or 12 (IPPC 2005) 2013 USD/tonne CO_2. The widest range 2–18 2013 USD/tonne CO_2 was reported by ZEP (2011) for onshore storage sites. IEA (2021) report that although the storage costs vary, over half of the onshore storage capacity in US is estimated to be available at below 10 USD/tonne CO_2.

Transport of CO_2 to storage sites incurs further costs. Kujanpää et al. (2014) estimated that the post demonstration cost of transporting CO_2 by ships from Finland's coast would be 13–24 €/tCO_2 to the North Sea and 8–11 €/tCO_2 to Faludden aquifer under the Baltic Sea. Johnsson & Kjärstad (2019) estimates ship transport costs from Finland to Faludden would be 12–13 €/tCO_2. The cost of ship transport of CO_2 is not as sensitive to distance or transported CO_2 volume as transportation by pipeline. IEA (2020) reported a ship transport cost of 27 USD/tCO_2 (25 €/tCO_2), assuming a distance of 1 000 km and transport capacity of 2 MtCO_2/yr. Assuming the transport capacity of 2 MtCO_2/yr, the shipping costs were quite insensitive to the transport distance, and ship transport cost became more economic compared to pipelines with distances over 800 km (IEA 2020).

2.3.2 Storage via CO_2 mineralization

In addition to geological storage, it is possible to store CO_2 permanently as minerals. It has been estimated that there are enough suitable minerals, such as serpentinite, to store about 2,000–3,000 Mt of CO_2 in Finland (Teir et al. 2006). If these minerals were used steadily during the next 100 years, about 20–30 Mt of CO_2 might be stored annually. The bulk of the suitable minerals is located in the east and north of Finland and new mining operations would be needed for accessing it.

About 96 Mt of mining waste was produced in Finland in 2018. Globally, the annual production of mine tailings is about 10 000 Mt. (Vesa 2021) The amount of suitable mine tailings consisting of magnesium and calcium silicates, is much smaller but still in the millions of tonnes per year in Finland. However, there is great variation in the potential to bind CO_2, content of hazardous substances and distance to CO_2 source. Several tons of minerals are needed to bind one ton of CO_2, favouring the transportation of CO_2 to the mine over the transportation of minerals to the CO_2 source. The amount of minerals needed per ton of CO_2 depends greatly on the raw material and specifics of the process, but if valuable use for most of the mineral product is found, the transportation of minerals instead of CO_2 might come into question. Moreover, there are major differences in the distance to the closest CO_2 source and the availability of waste heat, which can have a drastic impact on the feasibility and environmental impacts of CO_2 storage by mineralisation (Zevenhoven et al. n.d.).

Even if some mines contain suitable materials and are located nearby a CO_2 source, the mine tailings may be very difficult to access, for instance due to landscaping after mine closure, environmental hazards or pile-up of non-suitable minerals on top of the suitable ones. Thus, the number of potential and easily accessible implementation sites is limited and recent mineralization projects in Finland have focused on Hitura and Kemi Elijärvi mines. When operating, a single mine of this size might be producing enough suitable mining wastes to bind in the order of ~0.1–1 Mt CO_2 per year. Therefore, when assigning environmental permits for new mining operations, it would be good to consider the CO_2 binding potential of the mining wastes and their accessibility during and after the mining operations. CO_2 mineralization technology for large-scale negative emissions is still in the development phase (TRL ~5–7) with one pilot plant operating in Australia (MCi 2022) and another one with a different process to be built in Finland in the PILCCU project (University of Oulu n.d.).

Taking into account the described limitations for the economic and technical feasibility, the CO_2 storage potential in the mineral wastes of Finland is in the order of about 0.5–2.0 $MtCO_2$/yr. The potential to store CO_2 in mineralized construction products, using for instance calcium containing wastes, is limited to plants of below 0.1 $MtCO_2$/a capacities.

2.4 Potential for CCUS and technical CO_2 sinks in Finland

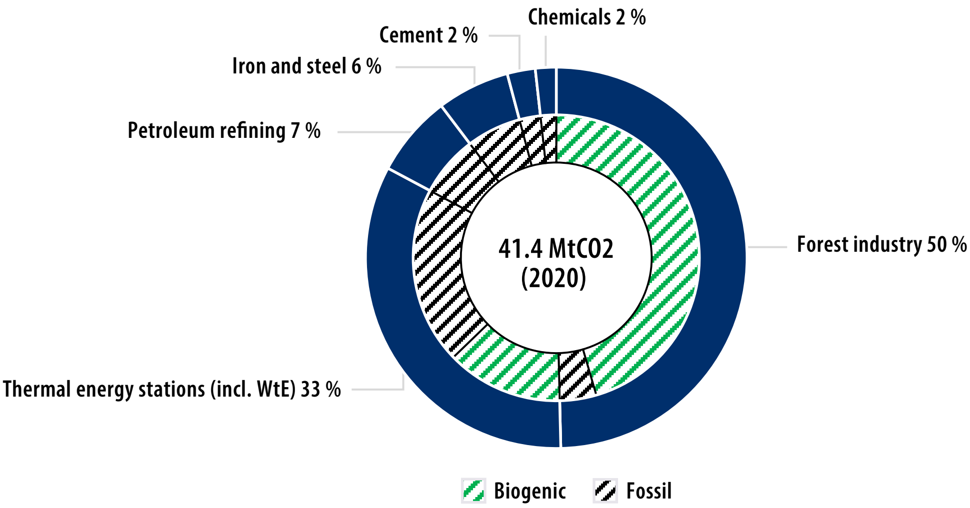
2.4.1 Point sources of CO_2 in Finland

In this section, we summarise reported CO_2 releases in Finland in order to assess the types of stationary processes the emissions are caused by and how much of the emissions are biogenic compared to fossil. Non-stationary and non-point source emissions, such as CO_2 emission from transport, work machines, and agriculture are not included. Furthermore, emissions from smaller facilities, such as emissions from heating of buildings (excluding large district heating plants), are not included in the assessment. In effort to set the following numbers into perspective, the total greenhouse gas emissions of Finland, excluding the LULUCF-sector, were 47.7 Mt CO_2 in 2021 (Statistics Finland 2023). In 2021, most of the emissions, 27.6 $MtCO_2$ eq. were from the effort sharing sector, while 20.3 $MtCO_2$ eq. were from the ETS sector (Statistics Finland 2021). In the effort sharing sector, 46 % of emissions come from traffic, transport and working machines, and 23 % from agriculture, including methane and nitrous oxide emissions. The share of greenhouse gases from stationary sources, including waste combustion, fuel use in industries, industrial processes and district heating plants outside the ETS sector amounted to 9 % of the effort sharing sector's emissions.

According to data collected from European Pollutant Release and Transfer Register (EEA 2023a), in 2020 there were 68 industrial facilities in Finland that need to report the annual amounts of pollutants released to air according to Directive 2008/1/EC concerning integrated pollution prevention and control (EEA 2023b). This means installations, which are likely to have significant negative environmental effects, e.g., combustion installations with a rated thermal input exceeding 50 MW. The number includes 7 industrial plants for the production of paper and board and other primary wood products, 13 industrial plants for the production of pulp from timber or similar fibrous materials, 2 installations for the incineration of non-hazardous waste, 1 installation for the recovery or disposal of hazardous waste, 36 thermal power stations and other combustion installations, 2 mineral oil and gas refineries, 2 installations for the production of pig iron or steel, 3 installation for the production of cement clinker and lime in rotary kilns, and 2 chemical installations for the production on an industrial scale of basic inorganic chemicals.

These industries produced altogether 41.4 MtCO$_2$, of which nearly 60 % was from biogenic source (see Figure 9). Forest industry accounted for approximately half of the reported emissions (20.6 MtCO$_2$). Most of the emissions (92 %) in the sector were from biogenic source. In thermal energy production, 40 % of the reported CO$_2$ emissions (13.7 MtCO$_2$ in total) were from biogenic source. The rest of the CO$_2$ emissions that are registered from Finland are fossil based (see the ETS sector's emissions in more detail in Figure 10). Largest CO$_2$ emissions were reported from Metsä Fibre Oy's Äänekoski Bioproduct Mill (2,040 ktCO$_2$), Neste Oyj's Porvoo Refinery (2,660 ktCO$_2$), and SSAB Europe Oy's Raahe Steel Plant (1,900 ktCO$_2$). In these industrial complexes the emissions originate from several point sources.

Figure 9. Fossil and biogenic CO_2 emission by industry sector in Finland as reported in E-PRTR. Data from EEA (2023a).

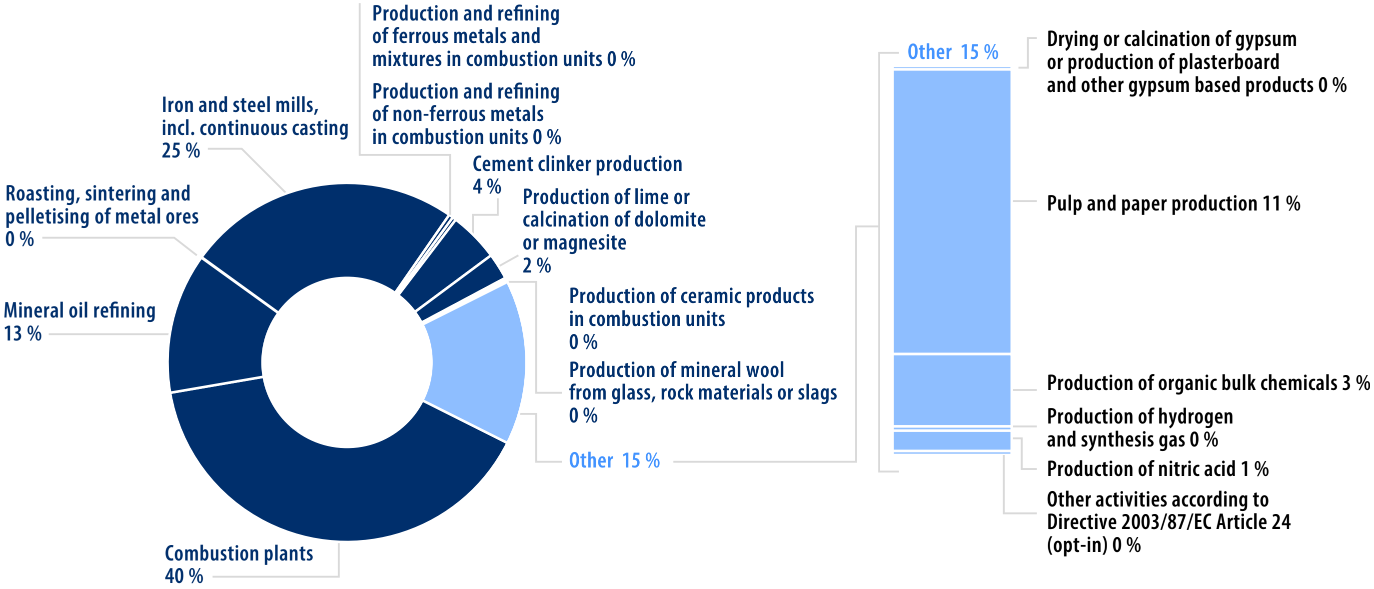


The total fossil CO_2 emissions from the Finnish ETS sector were 20.3 Mt in 2021 (see Figure 10). The majority of emissions, 40 %, came from combustion plants producing energy. The second largest share of emissions, 25 %, were produced in the iron and steel sector. Most of the remaining emissions were caused by the pulp and paper production, mineral oil refining, cement clinker production and production of organic bulk chemicals.

In addition to bioenergy plants, biogenic CO_2 emissions are formed in the production of biogas and ethanol. Furthermore, CO_2 concentrations are typically high in both fermentation and digestion. Depending on the feedstock, biogas typically consists of 25–50 % CO_2. In 2021, there were 33 landfill gas collection facilities and 79 bioreactor facilities. 25 of the biogas reactor plants were in farms and 9 were industrial plants. The number of co-treatment facilities for biowaste and sludges was 26, and there were additionally 19 sludge decomposing facilities. Altogether, the plants produced 156 GWh biomethane and 750 GWh biogas. Assuming the above given typical CO_2 content in biogas, these would indicate a biogenic CO_2 capture potential of 4–12 ktonCO$_2$/year from biomethane and biogas production. Most of the production was in the co-treatment facilities for biowaste and sludges (Statistics Finland 2022b).

Regarding ethanol, St1 produces bioethanol from sawdust in Kajaani, with an annual capacity of 10 million litres per year (IEA 2021b). Furthermore, Anora produces technical alcohols and alcohol beverages in Koskenkorva and Rajamäki facilities.

Figure 10. Verified fossil CO_2 emissions from the Finnish ETS sector in 2021. Unit tCO_2. (Energiavirasto, N.d.)



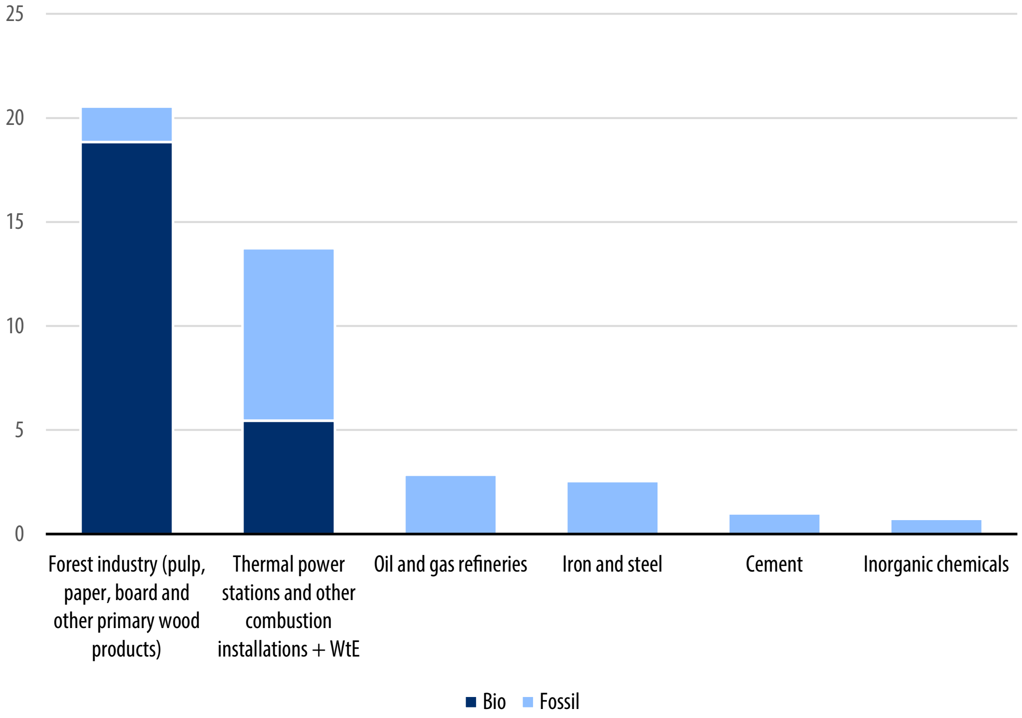
2.4.2 Most relevant technology pathways and applications

As presented in the previous section, industrial point sources of CO_2 play a significant role in the Finland's greenhouse gas emissions, and although considered climate neutral in emissions accounting, the biogenic CO_2 emissions surpass fossil emissions. Fossil CO_2 emissions from large industrial facilities, 17.1 $MtCO_2$ in 2020, cover roughly 36 % of total emissions not including the LULUCF sector. If we count in the biogenic CO_2 emissions, the amount of all CO_2 released by the large industrial facilities equals roughly 86 % of Finland's greenhouse gas emissions.

The most typical CO_2 emission in Finland is biogenic and originates from pulp and paper industry (Figure 11), where carbon is combusted in processes including recovery boilers, power and heat utilities and lime kilns. The emissions from the sector were over 20 $MtCO_2$ in 2020. The number of facilities within the sector in 2020 was 20, meaning one site produces roughly 1.0 $MtCO_2$ on average.

Together with the forest industries, thermal heat, power and waste-to-energy stations are the two most significant types of large emission point sources. Most of the emissions from the energy industry were fossil in 2020, however, although biogenic emissions were over 5 $MtCO_2$. The number of large combustion facilities was 39 in 2020, making them the most typical point source of CO_2 in Finland, one facility emitting 0.4 $MtCO_2$ per year on average.

Figure 11. Industrial CO_2 emissions from facilities in Finland 2020. Data from EEA (2023a).

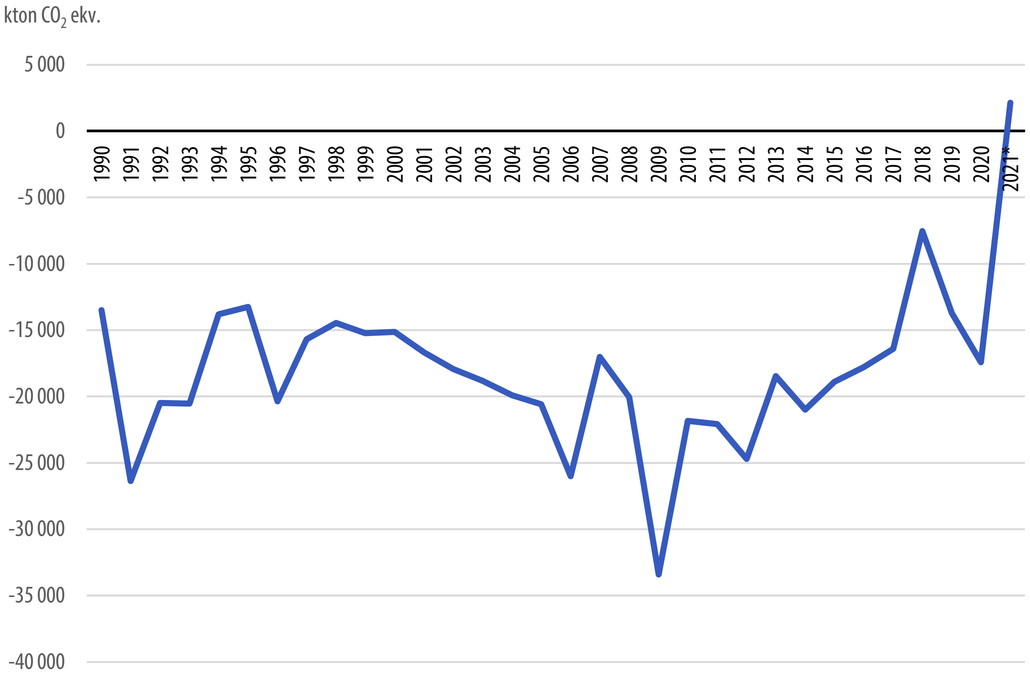


The point-source emissions from the remaining sectors i.e. oil and gas refineries, iron and steel factories, cement production facilities and production of inorganic chemicals are fossil. Although the sites are few, the highest site-specific CO_2 emissions come from oil and gas refineries (1.4 $MtCO_2$ per site on average) and iron and steel production sites (1.3 $MtCO_2$ per site on average). Refineries have various sources of CO_2 emissions, but the majority of the emissions are caused by the production of hydrogen, typically by reforming methane, and by the production of process heat. Steam methane reformers produce a CO_2 side stream, which can be captured at cost that is generally considered the lowest among industrial CO_2 emissions. At Neste Porvoo refinery, CO_2 from hydrogen production is currently captured for direct uses of CO_2. In steelmaking, CO_2 emissions are caused by blast furnace top gases and other combustion processes either directly associated with steel production or utilities.

For purposes of geological storage, captured CO_2 would need to be exported by ships from Finland, at least in the short to medium-term. Hence the most favorable locations for CO_2 capture facilities would be along the coastline, preferably close to existing harbor infrastructure. In the future, pipeline transportation could also be considered. In 2020, the combined fossil and biogenic emissions from such large industrial facilities amounted to roughly 24 MtCO$_2$, including over 8 MtCO$_2$ from forest industries. Of the emissions, over 7 MtCO$_2$ were biogenic.

Considering both the most favorable locations for capture of biogenic CO$_2$ and the total biogenic emissions 24.3 MtCO$_2$ from large point sources in 2020, the theoretical industrial carbon dioxide removal potential in Finland would be 5–20 MtCO$_2$/yr. Towards the theoretical upper limit of the potential, the technological sink would be of nearly the same size to the recommended level of LULUCF net sink for reaching the carbon neutrality target in 2035 (The Finnish Climate Change Panel 2022). There is a natural causality between the use of forest biomass and the forest carbon sink, however, and strengthening the forest carbon sink may result in reduced availability of forest biomass and lower biogenic CO$_2$ emissions from forest industries and combustion facilities. During the past decade, the forest carbon sinks have been declining, although with considerable annual fluctuation, and the LULUCF sector became a net emission for the first time in 2021 (Figure 12).

Figure 12. Net LULUCF sink in Finland 1990–2021. (Statistics Finland 2023)



Geological storage is currently the highest TRL technology for permanent storage of CO_2, but may be limited in the short-to-medium-terms by the availability of storage capacity in permitted and operational storage sites (IEA, 2022c). Regarding mineralization of CO_2, Mt-scale solutions are not yet commercially available (~TRL 5–7) (IEAGHG, 2022). As described in the previous section, the anticipated potential to store CO_2 in the most promising mining wastes (e.g. Kemi Elijärvi and Hitura mines) is about 0.5–2.0 $MtCO_2$/yr. The potential to store CO_2 in mineralized construction products, using for instance calcium-containing wastes, is limited to plants of below 0.1 $MtCO_2$/yr capacities.

Finland has potential to utilize CO_2 in long-lifespan polymer products. About 0.6 Mt of plastics is produced annually in Finland (Borealis, N.d.), which translates to a theoretical CO_2 utilization potential of approximately 2–3 $MtCO_2$. The technologies are current at low TRL, and the production costs remain high, although the latter can be alleviated by high product values. The permanence of CO_2 storage in polymer products depends on the targeted use. The permanence of the CO_2 storage would be improved by circular use of the materials, where the carbon would be recirculated into new polymers in the product end-of-life phase. It is not yet certain how monitoring rules in policy frameworks for certification of carbon removals or for EU ETS will allow for these considerations.

As an alternative for utilisation or storage of CO_2, there are various feedstocks that can be used for biochar production. Each feedstock type requires specific assessment for biochar potential as the amount of carbon content can vary significantly. There is limited amount of information available regarding biochar potential from different feedstock streams in Finland. In previous VTT studies, the biochar potential has been estimated from forest industry side streams such as bark, woodchips and sawdust. The estimates are presented below in Table 3.

Table 3. Biochar potential from forest industry side streams.

Feedstock	Total volume	Potential feedstock for biochar Mm^3	Biochar production potential Kt/a	CO_2 storage potential estimate Mt
Forest side streams Bark from spruce and pine Woodchips and sawdust from sawmills Forest woodchips	28.2 Mm^3	9.1	1 500	4.5

However, there are various other waste and side streams than can be used as feedstock for biochar production (see Table 4). Some examples of waste types and volumes that are potentially suitable for biochar production are presented below. The carbon content of each waste type varies significantly, but through pyrolysis around 50 % can be captured into biochar and stored permanently.

Table 4. Industrial waste potential for biochar. (Statistics Finland 2022c)

Waste type	Total volume 1 000 tons
Wood waste	3,135
Sludges	1,574
Animal and vegetal waste	1,139
Paper and cardboard waste	589

3 Market for CCUS and CDR

3.1 Current market status

3.1.1 CO_2 markets for direct use

CO_2 can be directly used in a wide range of applications. Globally the largest consumers are urea manufacturing (130 $MtCO_2$/yr, 57 % of global direct use) and enhanced oil recovery (70–80 $MtCO_2$/yr, 34 % of global direct use) followed by use in food and beverage production, the fabrication of metal, cooling, fire suppression and in greenhouses (IEA 2019b). According to the IEA (2019b), the global CO_2 demand in 2025 is estimated to be 272 $MtCO_2$/yr and demand in Europe in 2019 was 16 % of the global demand. If the share stays unaltered, Europe will directly use 43.5 $MtCO_2$/yr in 2025. Steady growth in the global demand is expected. In addition to these direct uses, novel technologies will enable using CO_2 as a feedstock to value-added products such as polymers, building materials, chemicals and synthetic fuels, which contributes to circular economy objectives, but these uses are still marginal compared to above-mentioned common uses.

3.1.2 Compliance carbon market (EU ETS)

The European Union’s Emission Trading Scheme has been operational since 2005. In 2021, the ETS market size was 683 billion €, which corresponded to around 90 % of global carbon market value (Reuters 2022). Other major emission trading systems are the schemes of China, New Zealand, South Korea, North America and UK (Refinitiv 2022). The market size has grown rapidly, caused mainly by the emission allowance price of the EU ETS, which roughly doubled during 2021, ending above €80/tonne. With a great deal of fluctuation, the price has continued climbing since, peaking at roughly €105/tonne in January 2023 (Trading Economics 2023). The emission allowance price is driven up by the increased level of ambition in the EU, aiming for climate neutrality by 2050 (EC 2020). Regarding CO_2 emissions, the sectors currently included under the EU ETS are electricity and heat generation, oil refineries and production of steel and metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals and finally commercial aviation within the European Economic Area. Other included emissions are nitrous oxide (N_2O) from the production of nitric, adipic and glyoxylic acids and glyoxal and perfluorocarbons (PFCs) from the production of aluminium (EC 2022a).

The CCS Directive was published in 2009, aiming to harmonize rules within EEA on the safe geological storage of CO_2. As the CCS Directive entered into force, the rules of the EU ETS were amended to make it possible for the operators of plants with an emission permit to not surrender emission allowances equal to the amount of fossil CO_2 captured for the purpose laid out in the CCS Directive. In other words, captured fossil CO_2 that is transported by pipelines and permanently stored in geological reservoirs can be deducted from the emissions of a facility within the scope of the EU ETS.

While the EU ETS provides value for geological storage of CO_2, the past price levels of emission allowances have not yet triggered operational CO_2 storages the within the ETS (CO_2GeoNet 2021).

3.1.3 Voluntary carbon offset market

In distinction to compliance CO_2 markets (section 3.1.2), there are voluntary markets for carbon offsets. Voluntary markets can be used by participants for voluntarily compensating their emissions, and thereby backing up carbon neutrality claims or reductions in net emissions, or towards national climate targets. Voluntary carbon markets can deal with reductions, i.e. the emission is avoided somewhere else, or removals. CO_2 removal from the atmosphere requires that CO_2 is captured from the atmosphere directly or through biomass growth, and is permanently stored in some carbon pool. Moreover, the impact must be measurable and additional, as well as preserve or contribute to sustainability. Traditionally, the avoidance or reduction market has been bigger. Markets specifically focused on carbon removals represent a core interest in this report, and they have emerged in the past 2–3 years. In the existing removal market efforts, natural solutions have been emphasized so far.

New voluntary market platforms and service providers specifically focussed on CDR units include Puro.earth (Finland), Nori (US), MoorFutures (Germany), and max.moor (Switzerland) (Honegger et al. 2021). Puro.earth is referred as the first specifically business-to-business oriented marketplace, (B2B), whereas Nori (US), Compensate (Finland), Carbon Engineering's direct air capture carbon dioxide removal via BeZero (Canada, Great Britain), offer services also for individual consumers (B2B/C) (Carbon Herald 2022). For example, marketplace Puro.earth currently offers biochar, soil amendment and wooden building elements as carbon removal methods available for purchasing of carbon removal certificates (CORC).

In Finland, the use of offsets corresponded to approximately 284,600 tCO_2 in 2019, and a little higher amount of 306,000 tCO_2 for 2020 (Laine et al. 2021). Estimates on the volume of global voluntary carbon markets differ. According to numbers from Ecosystem

Marketplace, internationally, voluntary offset markets have steered over 5 billion USD to voluntary projects during the last 20 years. Top value, 602 MUSD was reached in 2011, whereas the 2019 value was 320 MUSD and volume 104 $MtCO_2$. The fall in markets after 2011 can be explained by supply-demand disequilibrium and carbon price collapse observed under uncertainties on future climate regimes (e.g., continuation of Kyoto commitment period) and mitigation ambition (Michaelowa et al. 2019).

Internationally, during the last 10 years, majority of annually sold offset units have been based on renewable energy projects as well as afforestation and land use projects (esp. REDD+, Reducing emissions from deforestation and forest degradation in developing countries). Hence, the technological CDRs have not played a significant role so far.

Voluntary carbon markets already include several types of CDR project activities. According to Honegger et al. 2021, carbon dioxide removal types that have so far been adopted include, inter alia, afforestation and reforestation, biochar as soil amendment, enhanced soil carbon sequestration, wooden building elements, DAC, and enhanced weathering.

According to Tamme and Beck (2021), DACCS and BECCS have gained a lot of interest in the voluntary carbon markets since 2020. However, there are no methodologies for DACCS and BECCS projects under the current major voluntary market standards. Reportedly, the transactions take place outside the main standards.

3.2 European status of CCUS and CDR projects

CCUS and CDR projects in the EU have been listed by ZEP[3], CATF[4], SCCS[5], IOGP[6] and Global CCS Institute[7]. According to CATF (2022), today, there are more than 50 proposals for carbon capture and storage projects in Europe. They estimate that these projects could permanently store over 80 $MtCO_2$/yr. Most of the on-going CCS development projects in Europe are located on the coastal area of the Northern Sea; United Kingdom, Norway, and the Netherlands being the forerunners in the field.

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[3] Link to database: https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/

[4] Link to database: https://www.catf.us/ccsmapeurope/

[5] Link to database: https://www.sccs.org.uk/expertise/global-ccs-map

[6] Link to database: https://iogpeurope.org/resource/map-of-eu-ccus-projects/

[7] Link to database: https://www.globalccsinstitute.com/resources/global-status-of-ccs-2022/

In the above-mentioned sources, the CCUS projects have been categorized by type to those that develop either CO_2 storage, transport or capture or a combination of these. Capture projects are, furthermore, categorised by the source of the emissions to e.g., industrial capture, heat and power production and waste-to-energy.

3.2.1 Existing carbon storages coupled with capture

Today, there are three CCS facilities capturing and storing CO_2 permanently in operation in Europe (Table 5). Sleipner CCS project (ICE 2017) has been a pioneer in the field by successfully operating for more than 20 years in the North Sea, Norway. CO_2 is captured from the natural gas production with amine process. The project reports of storing 16 million tonnes of CO_2 in the Utsira sandstone formation by 2016 and are storing about 1 million tonnes each year (ZeroCO2 2016a). The Snøhvit field has been used to store CO_2 from Hammerfest LNG plant since 2008 (ZeroCO2 2016b). The project reports of storing more than 700,000 tonnes of CO_2 annually. However, a fire in September 2020 shut down the production at LNG terminal temporarily and successful start-up followed by repairs has not yet been announced.

In Iceland, basaltic rock formations are already exploited in CO_2 storage. A demonstration plant at Hellisheidi geothermal power plant has been capturing approximately 12,000 tonnes/yr of CO_2 since 2014 and received a grant from the EU Innovation Fund to scale-up the capacity to 34,000 tonnes/yr by 2025. Furthermore, Orca plant in Hellisheidi, Iceland, has been capturing and storing 4,000 tonnes/yr of CO_2 captured directly from air into reactive basaltic bedrock formations since 2020 exploiting Carbfix technology (Carbfix 2021). Carbfix has started a pre-design to extend the CO_2 storage to 500,000 tonnes/yr by 2026. Carbfix aim to establish a Coda Terminal and storage hub in Iceland for cross-border carbon transport (Carbfix 2022a). Carbfix estimates that the active rift zone in Iceland could store over 400 billion tonnes of CO_2 (Carbfix 2022b).

Table 5. CCS plants in operation.

	Project name	Description	Location	Year commissioned	Storage capacity existing, t/a	Status of project	Partners
Industrial CCS, natural gas production	Sleipner CCS	CO_2 capture from natural gas production, CO_2 transportation and storage in the North Sea	Norway	1996	1,000,000	Operational	Equinor Energy AS (operator), ExxonMobil
Industrial CCS, LNG facility	Snøhvit CCS	CCS-equipped LNG facility, CO_2 transportation and storage in the Barents Sea	Norway	2008	700,000	Unknown (in repair after fire)	Equinor Energy AS (operator), Total, Hess
DACCS	Orca	DACCS, CO_2 injected into nearby basaltic rock-formations to be permanently turned into stone	Hellisheidi, Iceland	2021	4,000	Operational	Carbfix, Climeworks, ON Power
Industrial CCS, power production	Project Silverstone	CO_2 and H_2S emissions from geothermal power plant are co-captured in a scrubbing tower and stored	Hellisheidi, Iceland	2014	12,000	Operational, scaling up to 34,000 tonnes by 2025 granted.	Carbfix, ON Power

3.2.2 CO_2 transport and storage hubs in Europe

Most of the carbon capture facilities in progress in Europe are connected to CO_2 transport and storage hubs that are also under development (Table 6). Such hubs are being developed e.g., by Northern Lights, Porthos, Antwerp@C, C4 Cluster, Greensand, NEP, Acorn, HyNet North West, South Wales Industrial Cluster, and Ravenna Hub. These hubs already connect several facilities planning or piloting CO_2 capture and are in most cases searching for more customers with CO_2 storage needs.

Northern Lights is developing and operating CO_2 transport and storage facilities in Norway (Northern Lights 2021). This partnership of Equinor, Shell and TotalEnergies aims at starting operations in 2024 to transport and store annually 1.5 million tonnes of CO_2 under the seabed in the North Sea from the Oygarden onshore receiving terminal on the Norwegian west coast. The ambition is to extend the operations to 5 million tonnes of CO_2/yr by 2026. Front-end engineering and design studies to capture CO_2 at the Norcem cement factory in Brevik and waste-to-energy plant Fortum Oslo Varme in Oslo has been completed. These two facilities would take half of the planned capacity at Northern Lights storage, both aiming to capture 400,000 t CO_2/yr (Fortum 2020, Aker 2022). Third party customers for remaining capacity have been searched for, and cooperation plans with seven companies (Air Liquide, Arcelor Mittal, Ervia, Fortum Oyj, HeidelbergCement AG, Preem, and Stockholm Exergi) have been announced (CCUS Project network 2022). Of these companies, Preem's goal is to reduce 500,000 t CO_2/yr at their refinery in Lysekil, Sweden, with a full-scale carbon capture plant and store that to the Northern Lights storage site (Cision 2020). So far, they have piloted the carbon capture in a project called "Preem CCS" from 2020 onwards (Offshore Energy 2020). Stockholm Exergi has received funding from the European Commission for their BECCS@STHLM-project to build a full scale BECCS-plant to the existing biomass CHP plant in central Stockholm (Stockholm Exergi 2022). The project aims at capturing 800,000 t CO_2/yr from 2025 onwards. The above-mentioned capture facilities would fulfil the capacity of storage planned in project's first phase.

Table 6. Northern lights storage hubs and plants allocating captured CO_2 to it.

	Project name	Location	Year commissioned	Storage capacity planned, t/a	Status of project	Partners
CO_2 transportation and storage hub	Northern Lights	Norway	2024	1,500,000	Design work finalized, positive final investment decision obtained 2020	Shell, Equinor Energy AS, Total
Carbon capture from waste-to-energy	Fortum Oslo Varme (with Northern Lights)	Oslo, Norway		400,000	Has applied funding from the EU Innovation Fund in March 2022. Funded also by the state (Norway) by 300 M€ as part of the national Longship project.	Fortum Oyj, City of Oslo
Carbon capture from cement production	Brevik Cement plant (with Northern Lights)	Norway	2024	400,000	In September 2019, a memorandum of understanding on the capture and storage of CO_2 was signed by HeidelbergCement and Equinor; project funding largely supported by the Norwegian government ('Longship' climate investment)	Aker Carbon Capture, Heidelberg Norcem
Carbon capture from a refinery	Preem CCS (with Northern Lights)	Lyselik, Sweden		500,000	Pilot study/pre-study done 2019–2021. The goal is a full-scale CCS plant in operation by 2025.	Sintef, Preem AB, Aker Solutions, Equinor, Chalmers University of Technology
Carbon capture from bioenergy production	BECCS@STHLM (with Northern Lights)	Stockholm, Sweden	2025	800,000	Funding received from the EC. Grant agreement preparation.	Stockholm Exergi

Porthos project is developing transportation and storage of CO_2 from industry in the Port of Rotterdam (Porthos 2022). The captured CO_2 is collected at Rotterdam port area, pressurised, and transported through an offshore pipeline in the North Sea, where it is pumped in an empty gas field. The start of construction was expected after the final investment decision in the second half of 2022. The start of operation was expected by 2024/2025. However, the construction has been delayed due to an appeal regarding the effect of nitrogen emissions from the construction and their effect on nearby natural areas (Porthos 2023). Porthos has signed a Joint Development Agreement with Air Liquide, Air Products, ExxonMobil and Shell (Porthos 2022). Yet, Porthos project has announced that no new companies can participate, since no storage capacity is available. Project Antwerp@C has investigated possibilities to cross-border CO_2 transport from the Port of Antwerp with pipeline to the Port of Rotterdam and/or by shipping to the Northern Lights project (Port of Antwerp 2022). Antwerp@C estimate that seven leading chemical and energy companies at the Port of Antwerp (Air Liquide, BASF, Borealis, ExxonMobil, INEOS, Fluxys, Port of Antwerp and Total) could capture and reduce CO_2 emissions approximately 9 Mt by 2030 by these means.

C4 cluster in Copenhagen metropolitan area develops utilisation, transport, and storage of locally captured CO_2 (SCCS 2021). The plans include joint infrastructure: a port in Prøvestenen for CO_2 shipping, onshore pipe network with offshore shipping to geological storage of offshore utilisation, and storage in depleted oil and gas fields. The plants that would capture CO_2 include the ARC Amager Bakke, Vestforbrænding and Argo waste-to-energy plants, the HOFOR biomass plant and the BIOFOS wastewater sludge incineration plant. ARC Amager Bakke planned to start a demonstration plant by the end of 2022 to capture 4 $ktCO_2$/year. Their goal is to capture 0.5 $MtCO_2$/yr by 2025 if national or EU funding is received. However, they did not receive the EU's Innovation fund on the first round (C4CPH 2021). Vestforbrænding develops capture/PtX solution with COWI (Vestforbrænding 2022). Furthermore, in Denmark, a consortium of 23 partners with project called Greenssand has received funding to demonstrate their value chain for transportation and geological CO_2 storage to an offshore sandstone reservoir at the North Sea in Denmark (Green Sand 2022). They aim to start with the capacity of 1 $MtCO_2$/yr by 2025 and extend the storage capacity to 8 $MtCO_2$/yr by 2030.

Several clusters in the UK have been investigating possibilities for CCUS due to the high availability of depleted gas reservoirs for carbon capture in coastal areas. In 2020, The Northern Endurance Partnership (NEP) was formed for the development of transportation and storage of industrial emitters across Teesside (Net Zero Teesside) and Humber (East Coast Cluster/Zero Carbon Humber) (NEP 2022). NEP will offer access to the Endurance carbon store in the southern North Sea with onshore and offshore infrastructure for transport. Projects in Teesside aim at capturing up to 10 $MtCO_2$/yr and those in the

Humber 17 $MtCO_2$/yr. The commercial scale BECCS project from at Drax Power Station belongs to the Zero Carbon Humber hub, aiming to capture 8 $MtCO_2$/yr by 2027. Their pilot scale plant capturing 300 $kgCO_2$/day started in 2020.

The Acorn CCS project is repurposing existing pipelines based on St Fergus gas terminal in North East Scotland to capture imported CO_2 from Grangemount industrial site and third parties (Acorn 2022). INEOS Chemicals Grangemouth, INEOS FPS and Petroineos estimate their investments at the Grangemount site to be able to capture approximately 1 $MtCO_2$/yr by 2027 (INEOS 2021). HyNet North West is repurposing existing natural gas pipelines for CO_2 to transport and store over 1 $MtCO_2$/yr in depleted gas reservoirs under the seabed in Liverpool Bay with Local Growth Fund (HyNET 2020). By 2025, they aim to capture 0.4 $MtCO_2$/yr from the local industrial sites. Also, The South Wales Industrial Cluster (SWIC) has received nearly £20 million funding to study industrial CCUS technologies along the South Wales coast as well as transportation and shipping of CO_2 (SWIC 2022).

Ravenna CCS expects an investment decision in 2022 for their phase 1 testing of full capture, transport and storage chain handling up to 100 $ktCO_2$/yr (CCUS Hub 2022). CO_2 from Ravenna District in Northeast Italy will be stored in offshore depleted gas reservoirs in the Adriatic Sea. The total storage is estimated to be 500 Mt and 10 $MtCO_2$/yr would be stored by 2030. The project is led by ENI (2020).

3.2.3 Progress towards e-fuel production

E-fuels are still more expensive than their fossil counterparts, and according to eFuel alliance, a political framework crediting e-fuels as a climate-neutral could significantly ramp up their implementation (Efuel Alliance 2022). The installed capacity of hydrogen projects has been increasing, with the IEA (IEA 2021e) estimating that the global capacity could reach 17 GW by 2026 and European Clean Hydrogen Alliance has listed over 750 hydrogen projects in pipeline (EC 2022d). However, so far only two industrial scale e-fuel plants have been announced in Europe, by Norsk e-Fuel and Project Air (Table 7).

Table 7. Funded commercial scale e-fuel production projects.

	Project name	Location	Year to be commissioned	Production capacity planned	CO_2 capture capacity planned, t/a	Status of project	Partners
Production of renewable aviation fuel	Norsk E-Fuel	Mo,sjøen, Norway	2026	25,000,000 (liters/yr)	n.a.	Funding under the SkatteFUNN tax incentive scheme received.	Norsk e-Fuel, Sunfire, Climeworks, Valinor, Paul Wurth
Production of methanol for chemical manufacturing	Project Air	Perstorp, Sweden	2025	200,000 (tonnes/yr)	500,000	Received funding from the Swedish Energy Agency.	Perstorp Group, Fortum, Uniper
Production of methanol	North-C-Methanol	North Sea Port, Belgium	2024	46,000 (tonnes/yr)	63,000	Under construction	North Sea Port, Provincie Oost-Vlaanderen, POM Oost-Blaanderen, Gent:, Oiltanking, Fluxys, Engie, Cargill, ArcelorMittal, Alco Biofuel, Universiteit Gent, Bio Base Europe, C-Capture, PMV, Mitsubishi Power, Proman
Production of methanol	Finnfjord e-methanol project	Finnmark, Norway	2025	100,000 t/yr	150,000	Investment decision expected in 2023	Carbon Recycling International, Statkraft, Finnfjord

Norsk e-Fuel has received funding under the SkatteFUNN tax incentive scheme to build Power-to-Liquid production plant with annual capacity of 25,000,000 liters at Mosjøen, Norway, by 2026 (Norsk e-Fuel 2022). The project will exploit Norwegian renewable electricity to produce hydrogen via alkaline electrolysis, DAC using Climeworks technology to produce CO_2, and FT-synthesis to produce hydrocarbons that will be refined to aviation fuels. The project is carried out in cooperation with Sunfire, Climeworks, Paul Wurth, Valinor and lux-Airport. Furthermore, project Westküste 100 in Schleswig-Holstein in Germany aims to start synthetic fuels production in smaller scale, starting with 30 MW electrolyser installation during this decade (Westküste 100, 2022).

Project Air aims at exploiting up to 500,000 tonnes of CO_2 from Perstorp operations to produce 200,000 tonnes of renewable methanol for chemicals such as formaldehyde and polyols production in Sweden (Project Air 2022). The hydrogen will be produced using purified wastewater and renewable electricity by Fortum and Uniper. The project has received funding from the Swedish Energy Agency and the goal is to start the production by 2025. Furthermore, project North-C-Methanol (North-CCU-Hub 2022) is building a large-scale demonstrator project to produce annually 46,000 tonnes of methanol utilising 63,000 tonnes of CO_2 and hydrogen from electrolysers with capacity of 63 MW at North Sea Port, Belgium. A goal is to increase electrolyser capacity for methanol production to 600 MW by 2030. Port of Antwerp has also demonstration plans in smaller scale (8,000 tonnes of methanol) (Power to Methanol 2022).

Furthermore, ArcelorMittal has started construction of a plant that converts carbon-containing gas from blast furnaces in production of ethanol at Ghent, Belgium, by 2024 (ArcelorMittal 2022). The installation will be commissioned by mid-2020 and will produce 80 million litres of ethanol.

Carbon Recycling International, an e-methanol producer since 2012 (Carbon Recycling International, 2023), has a new project in Norway with Finnfjord and Statkraft to produce 100,000 t/yr e-methanol (Carbon Recycling International, 2023b). The project is expected to start operations in 2025 and is going to utilise about 150,000 t CO_2/yr.

3.2.4 Carbon captured through mineralisation

From the novel mineralisation technologies, carbon-negative artificial aggregate production has reached commercial scale with three operational plants in the United Kingdom (O.C.O 2022a), one in France (AggNet 2020) and one to be built in Spain in 2024 (O.C.O 2021) (Table 8).

Table 8. Funded commercial scale CO_2 mineralisation plants.

	Plant name	Location	Status	Production capacity, t aggregates/a	CO_2 capture capacity, t/a	Partners
Production of artificial aggregates	Brandon, O.C.O Technology	Brandon, Suffolk, UK	Operational	~100,000 [a]	~3,700 [a]]	Preceding collaboration with: Carbon8 Systems, University of Greenwich [b]
Production of artificial aggregates	Avonmouth, O.C.O Technology	Avonmouth, UK	Operational	~100,000 [a]	~3,700 [a]	Preceding collaboration with: Carbon8 Systems, University of Greenwich [b]
Production of artificial aggregates	Leeds, O.C.O Technology	Leeds, UK	Operational	~150,000 (225,000 starting 2022) [a]	~5,500 [a]	Hooton Bio Power EfW, Coventa Europe. Preceding collaboration with: Carbon8 Systems, University of Greenwich [b]
Production of artificial aggregates	Montalieu cement plant of Vicat Group	Montalieu-Vercieu, (~Lyon), France	Operational	~30,000 tonnes/ year [c]	~1,200 [c]	Carbon8 Systems
Production of artificial aggregates	Repsol-Petronor EU Innovation Fund 2020: “AGGREGACO2”.	Petronor refinery, Spain	Funded, start-up in 2024	Planned ~56,000 tonnes/year [d]	Planned ~2,200 [e]	O.C.O Technology, EU Innovation Fund.

[a] O.C.O Technology 2022b
[b] Carbon8 Systems 2022
[c] Estimate based on 12 000 t raw material and comparison to a similar plant in Spain, O.C.O Technology 2021
[d] O.C.O Technology 2021
[e] Orbix 2023

However, even in the commercial scale, these four plants combined bind only about 14 kt CO_2/year. Demonstration and pilot plants for precast concrete products cured with CO_2 exist in Belgium (Orbix 2023) and Finland (MTV 2022). In addition, a CO_2 mineralisation process based on using magnesium-rich serpentinite mine tailings is being developed in Finland (University of Oulu n.d.) with the commissioning of a pilot expected in 2025. In addition to the novel mineralisation technologies, the conventional production of precipitated calcium carbonate (PCC) is worth mentioning, as secondary raw material use (e.g. oil shale ashes or steel slags) may turn this process carbon negative.

3.2.5 Carbon storage in wood products

Pilli et al. (2015) estimated emissions and removals associated with harvested wood products (HWP) from 1990 to 2030 for EU-28. An estimated average HWP sink of 12.0 MtC/yr (reported as -44.0 $MtCO_2$/yr, for years 1990–2012) with about 10 percent of the sink in forest pools. In other European scenarios, the potential emissions savings by 2030 of using wood-based construction compared to conventional building materials ranges from approximately 18 Mt to 46 Mt CO_2 (Hildebrandt et al. 2017).

Product lifetimes estimation requires some effort for the HWP. HWP commodity classes of sawn wood, wood-based panels and paper and paperboard are used in the CO_2 emissions estimation in the National Greenhouse Gas Inventories. Member States are obliged to report on harvested biomass, depending on the type. In Finland, Statistics Finland collects the information of the carbon sink of wood products as part of National Greenhouse Gas Inventory data collection (Statistics Finland, 2023). HWP sink in Finland was 3,1 $MtCO_2$ in 2021. For HWP, the carbon storage period can vary according to the type (primarily paper, wood panels or sawn wood), whereas biomass for energy or designated as solid waste assumes immediate emissions (European Parliament 2023a). Half-time describes service lives of products. It is defined as the number of years it takes to lose one half of the material currently in the pool. 0-year half-life is common for household and sanitary paper products, a 2-year half-life for other paper and paper products. For wood-based panels and for sawn wood IPCC recommended (IPCC, 2006) a 25-year and 35-year half-lives. IPCC (2019) guidance includes the possibility of replacing default half-lives with country-specific half-lives provided there is verifiable and transparent information.

Globally production estimates indicated that construction, furniture manufacturing, other solid harvested wood product uses, household and sanitary paper, and paper products for other uses accounted for 23 %, 5 %, 28 %, 3 %, and 42 %, respectively (Zhang et al. 2020). In-use carbon stock (2015) was estimated to be about 10.8 Gt of CO_2. Short term carbon storage (0 to 2 years) represents 45 % of production. The carbon stored in wood products is reported as negative emission when growth in this stock happens. This follows the internationally agreed reporting measures of GHG inventories (EC 2022e).

3.3 CCUS and CDR demonstrations and projects in Finland

There is a diverse set of on-going commercialization and piloting activities related to carbon removal and utilisation by Finnish technology providers. Technologies have been patented by Finnish companies related to biocatalytic methanation, protein production, building-scale DAC, industrial carbon capture, carbonization of concrete, cement and alternative binders, and biochar production. The following chapters describe the on-going developments in more detail, and they are listed in Table 9.

Q Power has developed a biocatalytic methanation process that utilizes microbes to produce renewable methane from hydrogen and carbon dioxide (Q-Power 2022). Their bioreactors are modular and commercially available in scales from 50 kW to 20 MW. They have on-going pre-feasibility studies related to synthetic methane production with Tampereen sähkölaitos Oy and piloting with Keravan Energia Oy.

Solar Foods has developed product called Solein® that is a protein produced from air-captured CO_2, nitrogen, water and electricity. They are building a first production line close to Helsinki-Vantaa airport (Solar foods 2022a).

Soletair Power has patented a modular carbon capture solution to be installed at building premises or retrofitted with the existing HVAC system (Soletair Power 2022). One building HVAC integrated CO_2 capture unit (VIDAC 1.0) is capable of handling daily 47 kg of CO_2 and the estimate is that an average commercial building would be using 6 units. The technology was demonstrated at Expo 2020 Dubai in making fuel out of CO_2 captured from air.

CarbonReUse Finland Oy has patented a water scrubbing process based on CO_2-to-water physical absorption phenomenon (CarbonReuse Finland 2016). They have built a container size demonstration plant for carbon capture with the patented technology and have made tests at the customer's sites with it in several publicly funded projects since 2016.

CarbonAide is a VTT spin-off company commercializing a technology for carbon-negative concrete production (VTT 2022b). The company has piloted the technology in a marine container size and is moving towards industrial demonstrations and commercial production.

Carbofex has been producing biochar and district heating from wood chips since 2017. Today the company has relocated to Nokia (prev. Hiedanranta, Tampere) and produces annually 2,000 tonnes of biochar, which corresponds to 7000 tons of CO2. Carbofex's carbon removal is certified by Puro.earth.

Joensuu Biocoal is building a commercial scale plant for biochar production with torrefaction to Savon Voima Oyj's production site (Joensuu Biocoal n.d.). The plant would produce 60,000 tonnes of biochar from summer 2023 onwards. The company is still searching for the end-uses for the product but estimates significant emission's reduction potential if the product is used in replacing coal in heat and power production.

Carbo Culture uses pyrolysis of agricultural wastes to produce biochar and heat, while selling carbon credits at Puro.earth. The company has built a pilot plant in the USA in 2019 and improved its capacity in 2022. The next step is a 14,000 tonnes CO_2 pilot plant, planned to be built in Finland in 2024. (Carbo Culture 2021; Puro.earth 2021a.; Lappalainen 2021)

Helsinki Region Environmental Services HSY has built a wastewater treatment sludge pyrolysis char pilot plant in Ämmässuo, which has been in use since 2021 (HSY n.d.). The pilot project is a collaboration with Häme University of Applied Sciences and Aalto University (HSY n.d.).

Table 9. Projects by Finnish technology providers.

Name (project / main actor)	Keywords	Description	Partners	Scale	Schedule / status
Q Power	CCU, power-to-gas	Carbon-negative biomass-fired boiler plant exploiting CCS and CCU technologies	Tampereen sähkölaitos	n.a.	Inspection of the Q-Power's bioreactors' and PtX technology's applicability to Naistenlahti 3 biomass-fired power plant CCU is on-going. (Tampereen sähkölaitos 2022)
Q Power	CCU, power-to-gas	Carbon-negative bioenergy plant CCU	Keravan Energia	4–10 MW installation, up to 16,500 tonnes of CO_2 reduction annually	Pre-feasibility study conducted; small-scale piloting on-going. The goal is to start the commercial production of synthetic methane in 2024. (Keravan Energia 2021)
Factory 1, Solar Foods production facility	CCU, DAC, protein production	Growing protein out of microbes cultured with electricity and air.	Solar Foods	n.a.	Construction of the production facility has started in 2021 and production is estimated to start in the first half of 2023. The Pharmacy Pension Fund acknowledged the project with €10m investment and Solar Foods invests over €20m. (Solar Foods 2022b)
CarbonAide pilot plant	CO_2 capture in concrete production	Carbonization of binders and concrete products with CO_2	CarbonAide	n.a.	Piloting on-going in Hollola; Start-up company launching for technology commercialization. (MTV 2022)
Carbofex	Biochar, pyrolysis, wood chips	Commercial scale biochar production	Puro.earth	7,000 t CO_2/year	Hiedanranta demo plant has been operational since 2017, the production is currently being scaled-up and is expected to be finalized by summer 2023

Name (project / main actor)	Keywords	Description	Partners	Scale	Schedule / status
GRK	Biochar, pyrolysis, demolition wood, wood industry sidestreams, sludge and manure	Commercial scale biochar production	Carbon Balance	12,000 t CO_2/year	Full scale production start is estimated to start during spring 2023. Another plant is planned for 2024 doubling the current scale
PUHI	Biochar, pyrolysis, demolition wood and other woody wastes	Commercial scale biochar production		9 000 t CO_2/year	New plant under construction and production is estimated to start during autumn 2023
Joensuu Biocoal Oy	Biomass torrefaction to biocoal.	Commercial scale plant for biocoal production		60,000 tonnes of biocoal per year.	Received funding. Construction work at Savon Voima Oyj's powerplant site has started in spring 2022. Full scale production start is estimated at summer 2023.
Carbo Culture	Biochar, pyrolysis, agricultural waste	R&D pyrolysis plant in Kerava.		n.a.	New pilot plant under construction and production estimated to start during summer 2023.
HSY Ämmässuo pilot	Biochar, pyrolysis, wastewater treatment sludge	Pyrolysis pilot plant in Ämmässuo using sludge and forest residues and producing biochar.	Häme University of Applied Sciences, Aalto University	n.a.	Pilot plant operational since 2021.

Furthermore, Puro.earth offers Soilfood’s soil improvement fibres (Puro.earth 2021b), LapWall LEKO wooden elements (Puro.earth 2021c) and Ekovilla insulation (Puro.earth 2021d) for carbon removals.

CCUS projects with major actors in the Finnish energy and process industry have been listed in Table 10. Currently, the single largest known project on CCUS in Finland is the SHARC project by Neste, which has been funded with 88 M€ by the EU Innovation Fund. The aim of the project is to develop the Porvoo refinery by implementing hydrogen production and CCS (Neste 2021). Other CO_2 storage projects, although in research or feasibility study phases, are the joint efforts of Helen and the Norwegian company Horisont Energi (Helen 2021); Westenergy and AFRY (Westenergy n.d.; Afry n.d.); as well as Tampereen Sähkölaitos and Q-Power (Tampereen sähkölaitos 2022). These could lead into carbon-negative BECCS or waste-to-energy (WtE) plants, while some of the projects also explore CO_2 utilisation options. Fortum has launched its own CCU project aiming at better plastics recycling, CO_2 utilisation from WtE plants and eventually carbon-negative materials (Fortum 2022).

Table 10. CCUS projects in the energy and process industries.

Name (project / main actor)	Keywords	Description	Partners	Planned scale	Schedule / status
Neste – SHARC project	CCS, CCU, hydrogen	88 M€ from the EU Innovation Fund to implement CCS and hydrogen production at the Porvoo oil refinery.	n.a.	4 Mt CO_2 in first 10 years, ~400 000 t CO_2/a	Grant agreement in Q1/2022. Transform refinery by 2030
Helen	BECCS, CCU, hydrogen	Joint effort to study CCU and BECCS; aim at carbon-negativity by 2040.	Horisont Energi	n.a.	Memorandum of understanding signed in 2021
Tampereen sähkölaitos	BECCS, CCU	Research on CCUS alternatives for a biomass-fired CHP plant in Tampere, focus on CCS.	Q Power (see also Table 9).	n.a.	Research phase
Westenergy	CCS, CCU, WtE	Feasibility study on CCUS for a WtE plant; aim at being a carbon sink.	AFRY	Capture of 20 000 t CO_2/a.	Planned start-up in 2025
Fortum	CCU, WtE, plastics recycling	Research on plastics CCU using CO_2 from WtE plants, aiming to provide net carbon-negative products.	n.a.	n.a.	Research phase
Keravan Energia Oy	Power-to-gas, bio-CO_2	Piloting and feasibility of power-to-gas in a biomass-fired power plant.	Q Power	4–10 MW electrolyser, up to 16 500 t CO_2/a	Piloting in 2021. Planned start-up in 2024.
Turun Seudun energiantuotanto Oy	Hydrogen, power-to-X	Feasibility of a hydrogen and power-to-X plant to produce fuel for heavy road and marine transport in Naantali.	Elomatic, Green H2UB Oy, Green Industry Park	n.a.	Construction earliest in 2023
Vantaan Energia	Power-to-gas, WtE	Feasibility of a power-to-gas plant in Vantaa.	n.a.	n.a.	Planned start-up in 2025.
Etelä-Savon Energia Oy	Power-to-gas	Feasibility of a power-to-gas plant in Mikkeli.	Nordic Ren-Gas Oy	20 MW electrolyser, 19 000 t CO_2/a	Feasibility study. Earliest start-up in 2026.

Name (project / main actor)	Keywords	Description	Partners	Planned scale	Schedule / status
Kotkan Energia Oy	Power-to-gas	Feasibility of a power-to-gas plant in Kotka.	Nordic Ren-Gas Oy	40 MW electrolyser.	Feasibility study. Earliest start-up in 2026.
Lahti Energia Oy	Power-to-gas	Feasibility of a power-to-gas plant in Lahti, Kymijärvi power plant.	Nordic Ren-Gas Oy	120 MW electrolyser, > 100 000 t CO_2/a (2nd phase).	Feasibility study. Earliest start-up in 2025, 2nd phase in 2030.
Porin Prosessivoima	Power-to-gas	Feasibility of a power-to-gas plant in Pori.	Nordic Ren-Gas Oy	20 MW electrolyser, 20 000 t CO_2/a	Feasibility study. Earliest start-up in 2026.
Tampereen sähkölaitos	CCU, power-to-gas	Feasibility of a power-to-gas plant in Tampere, Tarastenjärvi.	Nordic Ren-Gas Oy	60 MW electrolyser.	Earliest start-up in 2026
Finnsementti	CCU, power-to-X, CO_2 capture from cement manufacturing	Feasibility of power-to-X plant in Joutseno and CO_2 capture from an electric cement pre-calciner kiln.	LUT, VTT	n.a.	n.a.

There has been rapid development in the past few years in announcing new plans for power-to-gas plants in Finland. In addition to the power-to-gas piloting collaboration between Q Power and Keravan Energia (2021); a joint effort between Turun Seudun Energiantuotanto and Elomatic (2021); and a plant planned by Vantaan Energia (2022), a number of municipal energy providers have partnered with Nordic Ren-Gas Oy to plan future power-to-gas installations. The implementation sites studied with Nordic Ren-Gas Oy include power plants from Etelä-Savon Energia in Mikkeli (ESE 2022), Kotkan Energia (n.d.), Lahti Energia (2022), Porin Prosessivoima (Nordic Ren-Gas 2022) and Tampereen sähkölaitos (n.d.). Moreover, there are plans to capture CO_2 from cement manufacturing in Lappeenranta and utilize the CO_2 in power-to-X processes (Finnsementti 2021; Rakennuslehti 2021). St1 is planning an e-methanol plant with capacity of 25 kt/yr in Lappeenranta utilizing carbon dioxide from Finnsementti cement factory (St1 2022). The focus of these projects is to provide carbon-neutral fuels to heavy road transport.

Research and development on CCUS, and in some cases enabling carbon-negative processes, has been and continues to be funded by the Academy of Finland, for instance in nine projects of the C1 Value programme (Academy of Finland n.d.), Climate-Synergy programme (Academy of Finland n.d.) and the MAGNEX project (University of Oulu n.d.). Research on methods enhancing the carbon sinks in Finland in the LULUCF sector has been funded by the Ministry of Agriculture and Forestry (Finnish Government 2021) and developed for instance by Carbon Action (n.d.) platform, in the Carbocity project (UH n.d.) and in the Biosykli project (LAB n.d.). Although this report focuses on technical carbon sinks, some of these LULUCF-sector focused projects share common grounds with technical carbon sinks – for instance when considering biochar, biogenic CO_2 utilisation or CO_2 capture.

Business Finland has supported creating a pathway towards CO_2 utilisation and related technology exports. The Smart Energy Finland program 2017–2021 (Business Finland n.d.) funded testbeds related to the power-to-X technologies. E.g., projects BECCU (n.d.), E-Fuel (n.d.) and P2Xenable (2023) were funded in the program. In addition, the on-going Bio and Circular Finland program (Business Finland 2022) has funded and is funding projects related to CO_2 utilisation such as CarbonAide (VTT 2022b) and Synjet (ÅA 2022). Most of the listed projects have multiple objectives related to the power-to-X technologies and are developing several technologies along the production value chain. In BECCU project, biobased CO_2 is turned into polyurethanes, the E-fuel project will demonstrate an integrated concept for the synthetic fuel production exploiting CO_2, the P2Xenable project developed CO_2 capture and modular methanol synthesis from H2 and CO_2, CarbonAide carbon negative concrete production, and the Synjet project sustainable aviation fuels production exploiting fatty alcohol and isosynthesis routes. The work of BECCU project is continued in Forest CUMP project where production of large-scale polymers polyethylene and polypropylene is targeted from CO_2 of forest industry and waste incineration plants

(VTT 2022a). The project is funded by Business Finland. Furthermore, in PILCCU project (University of Oulu, n.d.), CO$_2$ mineralization to turn magnesium together with CO$_2$ into durable building materials is studied and will be piloted in 2024–2025.

3.4 Global outlook for CCUS and CDR

3.4.1 Implementation of CCUS and CDR based on scenario modelling

According to scenarios in IEA Net Zero by 2050 Roadmap (IEA 2021d), global CO$_2$ capture volumes increase steadily from today's around 40 Mt/a, to 1.6 Gt/a by 2030, and to 7.6 Gt/a by 2050. This estimate is higher than most of the scenarios presented by *IPCC WG3* (Babiker et al. 2022). IPCC WG3 reports CO$_2$ removal on managed land, BECCS and DACCS as three predominant CDR methods. According to their Summary for Policymakers (IPCC 2022), to limit warming to 1.5 °C, global cumulative CDR during 2020–2100 in total should be 190–960 GtCO$_2$ (from BECCS 30–780 GtCO$_2$ and from DACCS 0–310 GtCO$_2$). To limit warming to 2 °C, the total CDR between 190–900 GtCO$_2$ is needed (from BECCS 170–650 GtCO$_2$ and from DACCS 0–250 GtCO$_2$).

In European strategic long-term vision "A Clean Planet for all" (EC 2018), CCS is seen as an option to tackle remaining CO$_2$ emissions especially in the power sector and energy intensive industries in the transition phase towards climate-neutrality, to produce carbon-free hydrogen, and to create negative emissions from biomass-based energy and industrial plants. There is a concern that since CCS has not yet reached the commercialisation stage and economic viability, significantly larger research, innovation, and demonstration effort will be needed. Also, regulatory barriers and limited public acceptance in some Member States need to be tackled. In Commission's Communication "Sustainable Carbon Cycles" (EC 2021a), it is stated that 5 MtCO$_2$ should be annually removed in the EU from the atmosphere and permanently stored through technological solutions by 2030. According to estimates of European Commission (EC 2021b), the climate-neutrality objective of the EU will require an amount between 300–500 MtCO$_2$ of industrial carbon capture by 2050 from various sources (fossil fuels, industrial processes, biogenic carbon, DAC) for storage or to supply innovative routes to produce materials and fuels. To restore sustainable carbon cycles, the CO$_2$ should be sourced mostly from the air and from biogenic sources.

The Carbon Neutral Nordic (CNN) scenario of the Nordic Clean Energy Scenarios (Wråke et al. 2021) which seeks the least-cost pathway in the framework of current national plans, strategies, and targets predicts that Nordic region captures and stores ~25 Mt/a of CO$_2$ in 2050 of which 90 % is from biogenic sources and municipal waste. This is about 12 % of needed reductions from 2020 levels. The scenario is reasoned by long experience with the CCS, coupled with offshore energy industries and large storage potentials in Norway and large presence of bio-based sectors, such as pulp and paper and bioenergy in district heating, which offers opportunities to achieve negative emissions through BECCS. BECCS is also predicted to become revenue stream for the plant operators once markets for negative emissions are developed. Barriers to the CCS technologies foreseen are unbearable costs (due to only few benefits beyond emissions reduction), large infrastructure needs, need for new value chains, and the drawback of preserving the dependence on fossil fuels.

In Nordic Clean Energy Scenarios (Wråke et al. 2021), combining biorefineries with the production of PtX fuels for transportation (heavy-duty road transport, fishing and other maritime application and aviation) is seen as an interesting option since Nordic countries possess leading international expertise in the bioenergy and chemical sector. Also, opportunity for adding flexibility to the energy system via electrolyser production is highlighted. However, it is stated that use of captured CO_2 would not necessarily eliminate the emissions but rather delay them depending on the end-product. Also, the significant energy penalty of hydrogen production is seen as a drawback as a typical efficiency of commercial electrolyser is 60–80 %. The Nordic Clean Energy Scenarios (Wråke et al. 2021) estimate that the demand for PtX fuels (including H_2) will be modest (below 50 TWh in 2050) in Nordic countries, although the EU is pursuing an aggressive hydrogen strategy and PtX is competitive with direct electrification in some cases. This is due to demand concentrated on sectors that are not suited for direct electrification and since competition with biofuels and CCS exists. It is estimated that that PtX lowers CO_2 emissions in Nordic countries by approximately 7.4 Mt/a by 2050.

In Finland, WAM (With Additional Measures) scenario in Hiilineutraali Suomi 2035 (Koljonen et al. 2021a) estimates that the annual reduction of CO_2 with CCS by 2050 would be about 9 Mt. According to Nordic Clean Energy Scenarios project funded by Nordic Energy Research, main CCS option utilised in Finland until 2050 would be BECCS.

3.4.2 Costs and global capacities of CCUS and CDR

To estimate the future development of CDR and CCUS markets, the current and estimated future capacities in Mt CO_2/yr of the most relevant CCUS and CDR methods were collected in Table 11. In addition, the cost and future cost estimate of CO_2 removal in €/t CO_2 is also given, where applicable. In some cases, such as harvested wood products, a price range for €/t product is given to indicate market volumes, even if the additional cost of CO_2 removal could not be determined.

Table 11. Global capacity and cost estimates of studied CDR and CCUS technologies and methods.

Technology/Method	Global capacity today [Mt/yr]	Cost [€/t CO_2] (Price* [€/t]) today	Global capacity estimate 2030 [Mt/yr]	Cost [€/t CO_2] (Price* [€/t]) estimate 2030	Global capacity potential 2050 [Mt/yr]
Afforestation, reforestation and peatland restoration	500–1 500 [a]	<100 [b,c]	1 000–2 000	<100 [b,c]	3 000–4 000 [b,c]
Soil carbon sequestration and agroforestry	500–1 500 [a]	<100 [b,c]	1 000–2 000	<100 [b,c]	2 000–5 000 [b,c]
Harvested wood products	220–335 [a,d]	300–1 500 [e,f]*	441 [d]	300–1500 [e,f]*	440–560 [d]
Biochar	~ 0.32 [g]	110–150 [b,g,h]*	300–6 600 [c]	60–80 [g] *	300–6 600 [c]
Restoring blue carbon ecosystems	< 0.01 [a]	200–6 000 [i,j]	not enough data	200–6 000 [i,j]	230–1 200 [i,k]
Ocean alkalinisation	< 0.01[a]	40–240 [c]	not enough data	40–240 [c]	1 000–100 000 [c]
Enhanced weathering	< 0.01 [a]	~ 20–550 [b]	not enough data	~ 20–550 [b]	2 000–4 000 [b,c]
DACCS	~ 0.01 [l]]	250–600 [m]	~ 60 [l]	110–330 [c]	500–40 000 [b,c]
Biogenic CO_2: capture only	~ 2 [n]	25–90 [c,o]	~ 40 [n]	25–90 [o]	500–11 000 [b,c]
Fossil CO_2: capture only	~ 41 [n,p]	15–120 [o]	~ 240 [n,p]	15–120 [o]	4 000–10 000 [q]
Geological storage (total costs for full chain fossil CCS and BECCS)	9 (~1 bio) [n,p,r]	20–200 (fossil) [c,o] 30–350 (bio) [b,c]	184 [p]	20–200 (fossil) [c,o] 30–350 (bio) [b,c]	320 000–10 000 000 in total [b]
CO_2 mineralisation	0.01–0.02 [s]	<100 [s,t]	not enough data	<100 [s,t]	2300–3300 [u]
Long-lifespan CCU products (e.g. plastic pipes)	< 0.05 [v]	2500–6000 (vs. fossil 1500–3000) [w]*	10 [v]	2500–6000 (vs. fossil 1500–3000) [w]*	200–1200 [v]
Short lifespan CCU products (prices for e-Fuels)	~150 [x]	120–270 €/MWh [x] (vs. Fossil 15–200 [y]*	~200 [x]	50–120 €/MWh [x]*	500–2500 [v,x]

Dark green = largest capacities and lowest costs; light green and yellow = medium capacities and costs; red = smallest capacities and highest costs. Grey = not enough data or value is not comparable (does not cover the entire value chain; or price of product, not cost of CDR).

[a] Smith et al. 2023. ~2 Gt CO_2/yr in total for CDR on managed land.
[b] Fuss et al. 2018. Managed land options Capacity potential in 2050 estimates for <100 USD/tCO_2. Total cost for entire BECCS ~30–400 USD/tCO_2 depending on the CO_2 point source. 1 USD ~ 0.92 EUR.
[c] Nabuurs et al. 2022. 1–100 Gt CO_2/yr for all ocean-based methods. Ocean alkalinization 40–260 USD/tCO_2., DAC 100–300 USD/tCO_2. Managed land options Capacity potential in 2050 estimates for <100 USD/tCO_2. p.642: Fossil-CCS: 33–106 USD/t. 1 USD ~ 0.92 EUR.
[d] Johnston & Radeloff 2019
[e] PTT 2022. Sawn wood export price statistics 2014–2022 ranging between 170–420 €/m^3. Plywood export price statistics 2014–2022 ranging between 510–750 €/m^3.
[f] Metsäteollisuus 2001. Plywood average density ranging between 400–680 kg/m^3.
[g] Kalra et al. 2022. Cost estimates for high-quality certified biochar. 1 USD ~ 0.92 EUR.
[h] Nasdaq, 2023.
[i] Claes et al. 2022. Restoring blue carbon ecosystems: estimate for restoration, not including conser-vation.
[j] Taillardat et al. 2020
[k] Gattuso et al. 2021
[l] IEA 2022a
[m] Lebling et al. 2022. Lowest cost estimate 250 USD/tCO_2 did not include storage, a minimum cost of 20 €/t was added to the lower range.
[n] IEA 2022b
[o] IEA 2019a
[p] BloombergNEF 2022. CO_2 captured 43 Mt/a, minus biogenic CO_2 capture ~2 Mt results in 41 Mt captured fossil CO_2/yr. Endpoint of the 43 MtCO_2 capture capacity in 2021: 20 % to dedicated storage sites (8.6 Mt), 73 % to EOR (31.2 Mt), 2 % to utilization (0.86 Mt) and 5 % undetermined (2.15 Mt).
[q] Biniek et al. 2022
[r] GCCSI 2021
[s] See Table 8. Funded commercial scale CO_2 mineralisation production plants. Profitable production, i.e., negative costs.
[t] IPCC 2005. Storage costs of feasible options 50–100 USD/tCO_2.
[u] Renforth 2019. Storage potential in waste materials.
[v] Expert estimate based on Bazzanella & Krämer (DECHEMA) 2017.
[w] Expert estimate based on market prices of polyethylene, polypropene, polycarbonate and polyurethane.
[x] IEA 2019b. CO_2 use for urea ~130 Mt CO2/yr. CO_2 used for EOR excluded. Prices of CO_2-derived fuels on p. 44. Net-Zero-Emission scenario for 2030: total CO_2 utilisation 1286 Mt CO_2/yr.
[y] Trading Economics, EU Natural Gas. Typical price range during the past 5 years.

Globally, the vast majority of current CO_2 removals are based on actions in the LULUCF sector (*Afforestation, reforestation and peatland restoration* and *Soil carbon sequestration and agroforestry*) with a total volume about 2 000 Mt CO_2/yr. In addition to that, harvested wood products are a significant carbon sink binding annually about 220–335 Mt CO_2. These methods are well-established and while there is potential to roughly double these carbon sinks by 2050, the growth and export potential are limited. The IPCC estimates that the global potential for CDR on managed land – including biochar – is in total about 8 000–14 000 Mt CO_2/yr between 2020–2050, when costs up to 100 USD/tCO_2 are considered, although about one third could be achieved with costs lower than 20 USD/t CO_2. (Nabuurs et al., 2022 p.776).

CO_2 capture from industrial point sources has reached commercial scale from both fossil and biogenic CO_2 sources, while fossil CO_2 capture is dominant. While the CCS project pipeline is increasing, deployment of CO_2 capture and especially storage is lagging far behind the net-zero emission scenario (IEA 2019b). By 2030, the global CO_2 capture capacity from biogenic sources is expected to grow 20-fold to reach 40 Mt CO_2/yr and 6-fold from fossil CO_2 to reach 240 Mt CO_2/yr. The global CO_2 use is about 230 Mt, most of which is used for urea production (~130 Mt/yr), enhanced oil recovery (EOR, ~70–80 Mt/yr) and food and beverages (~30 Mt/yr), whereas e-Fuels or polymer feedstocks play only a minor role. About 9 Mt/yr is stored annually, of which about 1 Mt/yr is BECCS. The expected trend is to have more dedicated CO_2 storage projects, totalling about 184 Mt CO_2/yr by 2030.

Biochar production, DAC, CO_2 mineralisation and novel CCU products are emerging with global CO_2 storage or use capacities of about 0.32 Mt CO_2/yr (including only certifiable biochar in Europe and North America), 0.01 Mt CO_2/yr, 0.01–0.02 Mt CO_2/yr and <0.05 Mt CO_2/yr, respectively. The estimated growth trends for these options are exponential, reaching 500 -fold or up to 6 000 -fold increases in global capacity by 2030. Of these technologies, biochar production is perhaps the most mature, with barriers related to finding large volumes of suitable waste biomass streams. There are large investments made for developing DACCS, for instance a 0.5 Mt CO_2/yr facility is already under construction in the USA and front-end planning and engineering for a 30 Mt CO_2/yr site has begun (Carbon Engineering 2022). CO_2 mineralisation products, like artificial aggregates are already commercial, but the stored CO_2 volume is relatively small. Likewise the CO_2 uses for polymers are just emerging, while the project pipeline for short-lifetime CCU-products like synthetic methane is increasing, which can also be seen in Finland (see Chapters 3.2.3 and 3.3).

Of the studied CDR alternatives, restoring blue carbon ecosystems, ocean alkalinisation and enhanced weathering are still in their early stages of development. It is suggested (Taillardat et al., 2020) that in managing the blue carbon ecosystems such as inland wetlands, the focus in the future should be on conservation, not restoration, due to high costs.

While there is great uncertainty in the estimates for the potential global capacity in 2050, most of the studied methods might have Gt-scale CO_2 removal capacity. Somewhat smaller potential is seen for long-lifespan CCU products, wood products and restoring blue carbon ecosystems, while ocean alkalinisation and geological CO_2 storage from DAC or point sources show significantly larger potential, at least theoretically.

The cost and income structure of the studied CDR and CCUS methods are vastly different, which in turn means that the numbers in the Table 11 cannot be directly compared. This is resulting from the fundamental differences in these methods regarding the products, goods and other benefits beside the removal of CO_2 from the atmosphere. The CDR methods of the LULUCF sector are characterised by low technology requirements but require large areas of land; low costs, but less room for growth. Methods that produce physical products are finding niche markets already, but large-scale impact is yet to be seen. CO_2 capture for dedicated storage requires separate funding schemes such as the EU ETS for fossil CO_2 emissions, because from the plant operator’s perspective it is an additional cost or a loss in energy production.

A common aspect for the CDR technologies that manufacture physical products is the dependency on the product market price. On one hand, this can ease the implementation, due to the income from the products, but on the other hand, market price fluctuations can produce significant uncertainties. The market value of harvested wood products is already driving the industry and more like a side effect is storing CO_2 for years to decades. The case is similar for CO_2 mineralisation products, where some amount of CO_2 is stored into the construction products. However, the main business drivers are increasing landfilling costs and market demand of low carbon footprint products.

The biochar market has started to emerge only during the past few years and has significant annual growth rates such as 75 % CAGR in Europe (EBI 2022). The price of biochar removal per tonne of CO_2 varies significantly between $10 and $345 (Fuss et al. 2018). However, the average cost currently is estimated to be $120/t$CO_2$ (~110€/tCO_2) (Kalra et al. 2022). Despite the rapid development, the biochar market is still early stages and can significantly benefit from the economy of scale. In principle the market is somewhat similar for other CCU products as well, but the costs of CO_2-derived products are higher and more sensitive toward renewable electricity price due to the need of hydrogen produced with electrolysers. Where short-lifespan products do not gain benefit from voluntary CO_2 removal markets, EU’s Renewable Energy Directive is supporting the implementation of e-fuels.

In CCS pathways (i.e., fossil CCS, BECCS and DACCS) costs are derived from CO_2 capture, conditioning, transportation, storage and monitoring. Cost of CO_2 capture is case-specific and mainly affected by CO_2 concentration of the source stream. The lowest capture costs can generally be achieved in high CO_2 concentration sources where little effort is needed to recover a pure CO_2 stream (e.g. natural gas processing and ethanol fermentation), whereas in low CO_2 concentration sources (e.g. power production and atmospheric air) capture costs are significantly higher as more work is required to separate CO_2 from the other gas compounds.

Other factors affecting capture cost include the capture technology in use, scale of operation and operating conditions regarding heat integration and utility demands. Capture costs for DAC is around 230–550 €/tCO_2 and 15–120 €/tCO_2 in point source capture. Transport costs depend significantly on the mode of transportation as well as on distance and the volume of CO_2 transported. In DACCS capture location can be chosen based on availability of cheap renewable energy and storage site access and therefore transportation is not necessary.

In fossil-CCS the cheapest pathways often occur in enhanced oil recovery (EOR), where CO_2 captured from oil refining processes is stored at the same site to increase production capacity of the oil reservoir. Also, natural gas processing and CO_2 storage into depleted gas reservoirs is a low-cost application of CCS due to low capture cost, little logistical demands and existing storage infrastructure.

In BECCS lowest costs lie in processes with high CO_2 concentration exhaust streams like ethanol fermentation (20–175 USD/tCO_2 captured) (Fuss et al. 2018), although the quantitative capture potential is low as the capacity of such facilities is often small. Instead, pulp and paper mills and biomass-fired power plants and combined-heat-and-power plants offer greater BECCS potential with higher capture capacities at moderate costs (20–70 USD/tCO_2 from pulp mill black liquor, 88–288 USD/tCO_2 from power production). The most promising facilities for CCS implementation have suitable location regarding CO_2 logistics, e.g., coastline industrial hubs near potential CO_2 storage sites.

The total cost of DACCS is estimated to decrease from 250–600 €/tCO_2 to 110–330 €/tCO_2 in the long term. To achieve this, technical development in sorbent materials and energy efficiency is needed in addition to scale-up. In BECCS the total cost ranges around 30–350 €/tCO_2 and in fossil-CCS around 20–200 €/tCO_2. As technologies used in CCS and BECCS are already at commercial level, the costs are likely to remain in the similar range in the foreseeable future although slight decrease in the average cost is expected over time due to technology development.

3.5 Finnish outlook for CCUS and CDR

In Finland, the role of bio-based industries is greater than on the global average. This affects the amount of carbon stored in harvested wood products and other biomass products, the availability of biomass waste streams for biochar and the volume of biogenic CO_2 emissions. The volume of carbon stored in all biobased products may increase by the development of new materials and more efficient material use of the biomass resources, for example as lignin-based materials, replacing plastics in packaging or biobased composites. Even if the use of biomass in energy production would change, the CO_2 emissions of the pulp and paper industry are significant, offering MtCO_2/yr-scale potential for BECCS. There are currently no operating CCS plants in Finland. In the scenarios it is estimated that BECCS will play a more significant role for Finland than fossil CCS, but as there is no financial security in investing in BECCS, the technology has not yet been deployed. The voluntary carbon offset market is boosting the biochar market and the production capacity is increasing beyond 80 kt biochar/yr in the short term (see Table 9. *Projects by Finnish technology providers*), making Finland a major actor in Europe in the biochar sector.

As there are no suitable geological storage sites in Finland, implementing BECCS or DACCS with the currently available technology would require international collaboration for transporting and storing the CO_2 elsewhere, such as into geological storage sites in the North Sea. However, the number of active CO_2 storage actors and sites is limited and might form at least a temporary bottleneck in the implementation of CCS.

Direct air capture (DAC) technology is being developed in Finland by at least two start-up companies, as well as LUT and VTT. As there is the possibility to locate DAC next to the CO_2 storage site and avoid CO_2 transportation, it may be that DACCS would be implemented in another country, even if it was developed and installed by Finnish actors. In some applications, like in conjunction with air conditioning or with CO_2 storage by mineralisation, the installation site could be in Finland. Despite the lack of geological storage, the expected up to 6 000-fold increase in DAC capacity during this decade and $GtCO_2$/yr-scale potential in 2050 makes DAC a huge opportunity for Finnish technology exports.

Finland stands out having the most waste generated per capita in the EU – more than 20 000 kg/yr and over 75 % is major mineral waste from the quarrying of minerals (Eurostat 2020). In Finland the total mining waste in 2018 was 96 Mt/yr (Vesa 2021) and a part of it could be used for storing CO_2 as carbonates in $MtCO_2$/yr scale. However, the technology applicable in the large-scale is still in TRL 5–7, and development is also needed when changing from one mineral resource to another. The combination of DAC and CO_2 mineralisation could yield a negative emission process applicable in Finland in the $MtCO_2$/yr scale, which would be independent of the use of biomass resources. Another alternative to utilise the mineral wastes could be enhanced weathering on land, but for ocean alkalinisation the environmental risks would be significant.

New possibilities for the storage of CO_2 may be offered by the manufacturing of long-lifespan products for example for the construction industry. These could include aggregates for construction, structural materials, wall elements, plastic piping, biobased insulation materials and paints. While there may be many benefits from the economic or circular economy point of view, the total volume of CO_2 that could be used in the production of these material is limited. For instance, in Finland about 0.6 Mt/yr of plastics (FPIF n.d.), about 1.5 Mt/yr of cement (Finnsementti 2022) and about 8–10 Mt/yr of concrete aggregates (gravel and sand) is used. An exception is the use of aggregates for earth construction, which is about 90 Mt/yr (Betoni n.d.), but the value per ton is low making the economical transportation problematic and the high compressive strength of natural aggregates is tough to compete against. These material volumes give an upper limit or an indication of the order of magnitude, how much CO_2 might be used for the production of these materials. In practise, the volume of CO_2 that could be captured by producing these materials is only a fraction, because CO_2 would form only a part of the raw materials used for the product, not all products in these categories can be manufactured using CO_2 and the properties of the CO_2-derived product may be different.

There is a lot of activity around CCU in Finland, which can be seen for instance in the number of power-to-X projects (see Table 10. *CCUS projects in the energy and process industries*). The Renewable Energy Directive and the inclusion of 'renewable liquid and gaseous transport fuels of non-biological origin' in addition to the detaching from natural gas imports can be seen as drivers for this development. Power-to-X processes can reduce the GHG emissions in Finland, but not produce permanent CO_2 removals. Nevertheless, there might be some technological synergies to developing other CO_2-based products, such as polymers. Also the market value of these products is significant, offering good export potential.

4 CCUS and CDR in GHG reporting and accounting and in policies and measures in selected countries

In this chapter, a synthesis on how carbon dioxide captured and used or stored is considered in greenhouse gas reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and accounting under EU legislation. In addition, the links from the sustainability criteria of the EU Renewable Energy Directive on the GHG accounting are discussed.

4.1 Greenhouse gas emission reporting to the UNFCCC

4.1.1 General requirements for the reporting

Annex I Parties of the United Nations Framework Convention on Climate Change (UNFCCC) are required to report their anthropogenic, territorial greenhouse gas emissions and removals to the convention each year. GHG emissions and removals covered include direct carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) from five sectors, namely energy; industrial processes and product use; agriculture; land use, land-use change and forestry (LULUCF); and waste. The reporting period covers all years from the base year (or period) to two years before the inventory is due (e.g. the inventories due 15 April 2016 cover emissions and removals for all years from the base year to 2014). (UNFCCC 2022a)

4.1.2 IPCC rules for greenhouse gas reporting

The IPCC defines internationally agreed methodologies intended for use by countries to estimate greenhouse gas inventories to report to the UNFCCC. These methodologies are presented in IPCC guidelines. The *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* provide a technically sound methodological basis of national greenhouse gas inventories (IPCC 2006). The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* provides certain refinements required to maintain the scientific validity of the 2006 IPCC Guidelines (IPCC 2019).

According to the IPCC rules, CO_2 emissions from fossil fuel and peat combustion are reported as such in a particular *Energy* or *Industrial processes and product use (IPPU)* sector where they take place. However, CO_2 emissions from biomass combustion for energy are reported in the energy sector as a memo item and estimated and reported in the LULUCF sector as part of net changes in carbon stocks. Therefore, these emissions are not included in the Energy sector total to avoid double counting in the reporting (IPCC 2023).

According to the IPCC rules, reporting of CO_2 captured, used or stored depends on data availability and reporting method (Tier) applied by a reporting country. It is good practice to consider CO_2 captured and stored in reporting countries' GHG inventories, but this requires that appropriate data is available for Tier 3 method. The capture of biogenic CO_2 emissions from biomass combustion, or other processes, should be treated consistently with CO_2 capture from fossil fuel combustion and reported in the Energy and/or IPPU Sectors (IPCC 2006, 2019). In case CO_2 is permanently stored, emissions can be fully deducted (IPCC 2006). In case biomass-based CO_2 is captured, negative emissions should be reported as such (IPCC 2006). In case CO_2 captured for later use and short-term storage, the quantity of CO_2 captured should not be deducted from CO_2 emissions except when the CO_2 emissions are accounted for elsewhere in the inventory (IPCC 2006). Basically, it is not appropriate to report CO_2 capture and release in short-term use separately in GHG inventory but might be relevant in case long-living products would be made from CO_2 captured. For example, Finland has decided not to report CO_2 quantities in capture unless CO_2 captured is permanently stored. As in Finland precipitated calcium carbonate (PCC) is currently the only available permanent (long-term) storage applied for captured CO_2, CO_2 emissions in case PCC is burned are accounted in the relevant sector where the CO_2 emissions take place (Statistics Finland 2022a).

In CO_2 transportation, fugitive emissions may arise for example from pipeline breaks, seals and valves, intermediate compressor stations on pipelines, intermediate storage facilities, ships transporting low temperature liquefied CO_2, and ship loading and offloading facilities. According to the IPCC guidelines, emissions from transport of captured CO_2 are reported under Energy sector balance (IPCC 2006).

Carbon sequestered in vegetation and soil and harvested wood products are reported in the LULUCF sector. The way carbon stock changes are considered in the reporting depends on the data and methods applied by the reporting country. Consequently, the quantity of carbon sequestered by a certain measure is considered in the reporting if it is recognised in the data and methods applied by a reporting country. For harvested wood products (HWPs), there are a number of approaches to dealing with the related carbon stock changes in the IPCC guidelines. The UNFCCC has not yet decided which approach to use (Q4–14, FAQs – IPCC-TFI (iges.or.jp)). For example, Finland applies the so-called *production* approach for HWPs (Statistics Finland 2022a).

The IPCC guidelines do not refer to carbon captured directly form the atmosphere. This can be interpreted either that such carbon is excluded in the reporting or that the IPCC rules do not make any difference in the treatment of captured CO_2 regardless of the origin. The latter interpretation is supported by the statement provided in both IPCC 2006 and 2019 guidelines: "*Once captured, and added to the carbon capture and storage process there is no differentiated treatment between biogenic carbon and fossil carbon*". Thus, it can be expected that it would be good practice, when DACCS process is applied, to report the quantity of CO_2 captured and stored as negative emission, regardless of the fact that it is not mentioned in the guidelines. However, it is unclear under which sector such negative emissions would be reported.

The IPCC guidelines do not refer to imports and exports of captured CO_2 between reporting countries. For CO_2 captured and stored this is not an issue, as it is clearly determined that "*emissions (and reductions) associated with CO2 capture should be reported under the IPCC sector in which capture takes place*". Thus, the quantity of CO_2 captured for storage is deducted from the GHG inventory of a reporting country where CO_2 capture takes place regardless of whether the CO_2 is stored outside that country. However, for CO_2 captured in one reporting country and exported to use in another country, a potential issue is encountered if not reported consistently to avoid double-counting or zero-counting. Such an issue takes place if a reporting country in which CO_2 is captured deducts the particular quantity of CO_2 from its GHG inventory, and a country where the particular CO_2 is released reports the emissions as zero. This issue could be solved only if all relevant countries apply consistent methods in GHG reporting which might be difficult to ensure. It should be noted that this adjustment would make the CO_2 release from these products similar to CO_2 from fossil origin. Consequently, although such an adjustment, in principle allowed by the IPCC guidelines, might make sense in some cases where CO_2 is captured and used within one country, it is not necessarily appropriate to be applied generally for CCU.

The IPCC guidelines do not refer to temporary carbon stock changes except those in HWPs. Basically, similar methods that are applied to HWPs could also be applied to other long-living products produced from captured CO_2 regardless of its source. The requirement is that appropriate data for life-time of products would be available and such method would otherwise be considered appropriate. In such a case, the amount of carbon dioxide captured and stored temporarily into a product is deducted from a sector where capture takes place and added as a delayed emission into a sector where a product releases its carbon (likely in energy sector). Such products should then be considered like any fossil materials, i.e. carbon dioxide emissions from releasing the carbon content of a product are reported when and where they take place. In case the amount of carbon dioxide captured in a product is not deducted from a sector where capture takes place, such products should then be considered similarly with the biomass-based products, i.e. carbon dioxide emissions from releasing the carbon content of a product are reported as zero, and the storage time of carbon is not taken into account. Applying such methods for short-living products from GHG inventory point of view is basically meaningless, thus, there must be evidence that such products are long-living enough in order to propose changes in GHG inventory methods applied.

The IPCC guidelines do not mention CO_2 captured in enhanced weathering, ocean fertilization or ocean alkalinization. However, the IPCC guidelines define that "*in the context of national GHG inventories, carbon dioxide capture and storage (CCS) means geological carbon sequestration.*" Thus, it can be concluded that CCS technologies other than those relying on geological carbon sequestration are not considered.

4.2 Paris agreement article 6

Paris agreement article 6 provides principles for how countries can "pursue voluntary cooperation" to reach their climate targets. Countries are allowed to trade emission reductions and removals with one another through bilateral or multilateral agreements. The traded emission reductions and removals shall be based on robust accounting to ensure the avoidance of double counting, and this should be authorized by participating Parties. The article 6 forms the general frames for the traded emission reductions and removals, including CCUS and CDR. In the 27th Conference of the Parties (COP27), carbon removals emerged as a critical discussion point emphasising the essentiality, urgency and large volumes required (UNFCCC 2022b). However, as funding remain one of the most important issues in the climate negotiations, no concrete decisions related to these points have been made yet.

4.3 EU legal framework

4.3.1 EU Emissions Trading System (ETS)

EU Emissions Trading System (EU ETS) sets the carbon market and mandatory cap to the overall GHG emissions from the power plants, industry factories and aviation sector covered. The EU ETS regulation is set first in the Directive 2003/87/EC and currently in the Directive 2018/410. In July 2021, the European Commission published a legislative proposal for a revision of the EU ETS. In February 2023, the Council and the European Parliament reached a provisional political agreement on the proposal (Council of the European Union 2023). The EU ETS directive aims to enhance cost-effective emission reductions and low-carbon investments, including environmentally safe carbon capture and utilisation that contributes substantially to mitigating climate change like its former version 2003/87/EC.

In the categories to which the EU ETS Directive apply, "*Capture of greenhouse gases from installations covered by this Directive for the purpose of transport and geological storage in a storage site permitted under Directive 2009/31/EC*" is mentioned. More detailed rules for CCS are determined in Emission monitoring regulation (2018/2066) and in CCS directive (2009/31/EC).

The agreed amendment to the EU ETS directive does not make changes to the existing EU ETS directive as regards to CDR. CO_2 removals through CDR are not considered in the proposal which is also the case in the existing EU ETS directive. Regarding CCUS, the amendment establishes that *"An obligation to surrender allowances shall not arise for emissions of CO_2 that end up permanently chemically bound in a product so that they do not enter the atmosphere under normal use, including any normal activity taking place after the end of life of the product*." Concerning the requirement to be permanently chemically bound in products the Commission shall adopt delegated acts. This is an extension from precipitated calcium carbonate (PCC) determined in the EU ETS directive in force to any product with the particular property.

With a special relevance for Finland, the agreed amendment to the EU ETS enables also other methods besides pipelines for transport of captured CO_2. This removes finally the regulatory barrier to transport captured CO_2 by ships from Finland to storage sites or other importing terminals for the purpose of CCUS within the ETS framework. The ETS frameworks has not been the only regulatory barrier to transport of CO_2 from Finland, however, as the International Maritime Organization (IMO) London Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 prohibited the export of CO_2 to off-shore geological storage sites until 2009 Article 6 amendment. But as the slow ratification pace of the Article 6 amendment by the Contracting Parties to the protocol inhibited the entry into force of the amendment, the regulatory barrier remained in effect. Finally in the 14th meeting of the parties to the protocol in 2019, an agreement was made to allow a provisional application of the amendment. This requires the Contracting Parties involved in an arrangement where CO_2 is transboundary shipped for geological storage under the seabed to make a declaration to IMO on the provisional application of the amended Article 6.

The complete, consistent, transparent and accurate monitoring and reporting of greenhouse gas emissions applied for the emission trading system is set in the EU regulation 2018/2066. In its Article 49, 1 it is defined that: "*The operator shall subtract from the emissions of the installation any amount of CO_2 originating from* fossil *carbon in activities covered by Annex I to Directive 2003/87/EC that is not emitted from the installation, but: (a) transferred out of the installation to any of the following: (i) a capture installation for the purpose of transport and long-term geological storage in a storage site permitted under Directive 2009/31/EC; (ii) a transport network with the purpose of long-term geological storage in a storage site permitted under Directive 2009/31/EC; (iii) a storage site permitted under Directive 2009/31/EC for the purpose of long-term geological storage; (b) transferred out of the installation and used to produce precipitated calcium carbonate, in which the used CO2 is chemically bound.*".

The EU's CCS Directive (2009/31/EC) provides regulatory framework and guidelines for the safe geological storage of CO_2. Extensive requirements for selecting sites for CO_2 storage are laid down in the CCS Directive. Geological storage of CO_2 is not allowed without a storage permit. According to the CCS Directive, there must not be significant risk of leakage or damage to human health or the environment, in order a site can be selected for storage.

4.3.2 Effort sharing regulation

EU Effort sharing regulation (ESR) (EU 2018/842) sets binding, Member-state-specific, annual greenhouse gas emission targets for 2021–2030 for those sectors of the economy that fall outside the scope of the EU Emissions Trading System. In July 2021, the European Commission proposed to amend the binding annual emissions reductions by Member States from 2021 to 2030. In November 2022, the Council and the European Parliament reached a provisional political agreement on the proposal (Council of the European Union 2022a). The sectors covered by ESR include transport, buildings, agriculture, non-ETS industry and waste.

In the GHG inventory the GHG emissions are reported for the sectors covered by the ESR in accordance with the rules provided by the IPCC (EU 525/2013). Consequently, CO_2 captured and stored or used is considered for these sectors in line with the methods a Member State applies in its GHG emission reporting to the UNFCCC.

The accounting of the GHG emissions under the effort sharing regulation (non-ETS) is carried out towards the target set. The non-ETS GHG emissions are calculated as the total national emissions without LULUCF as reported in the GHG inventory minus the national emissions in EU Emissions Trading System for that Member State (EU 2018/842).

This means that in case CO_2 removals are considered in the GHG inventory, they reduce the total national GHG emissions, thus also GHG emissions reported for ESR sectors. Consequently, CO_2 removals generated by ,for example, BECCS, are accounted as CO_2 removals under the effort sharing regulation. In addition, limited amount of excess net removals (determined in Annex III of the Effort sharing regulation) generated in afforested land, deforested land, managed cropland and managed grassland in Member States' LULUCF sector according to the Article 4 of the LULUCF regulation may be taken into account for that year when fulfilling the target set in the ESR.

4.3.3 LULUCF regulation

The LULUCF regulation (2018/841) determines the inclusion of the land use, land-use change and forestry (LULUCF) sector into the EU climate policy framework, as of 2021. In July 2021, the European Commission proposed to amend the LULUCF regulation. In November 2022, the Council and the European Parliament reached a provisional political agreement on the proposal (Council of the European Union 2022b).

Land use and forestry include the use of soils, trees, plants, biomass and timber and land-use changes cover the change of land status from one class (e.g. forest) to another class (e.g. crop land). The current LULUCF regulation (2018/841) sets accounting basis towards the actual GHG emission balance of the LULUCF sector in each Member State is compared with. According to the 'no debit rule', the LULUCF sector in each member State should cause no net emissions. These net emissions are determined 1) for deforestation and afforestation as they occur, 2) for crop lands, grass lands and wetlands in comparison to the average between 2005 and 2009, and 3) for forest land and harvested wood products in comparison to a reference level verified as delegated act by the EC. According to the agreed amendment of the LULUCF regulation, these rules will be applied for the period 2021–2025, while these will be replaced by Member State specific GHG emission targets for the whole LULUCF sector for the period 2026–2030.

The actual GHG balance is calculated based on the IPCC rules applied by a Member State in its GHG emission reporting to the UNFCCC. Each unit of GHG emissions reported in the LULUCF sector of a Member State are fully taken into account when accounting the overall LULUCF balance, except for managed forest land in the period 2021–2025 for which the net removals exceeding the reference level is limited. Limited amount of surplus removals (i.e. removals exceeding the LULUCF targets) can be taken into account when fulfilling the target set in the Effort sharing regulation (see section 4.3.2) or transferred to some other Member State. If a Member State does not reach the LULUCF targets, considering the flexibilities and penalties determined in the LULUCF regulation, a Member State should show corresponding additional measures in its compliance reports to be submitted to the European Commission by 2027 for the period 2021–2025 and 2032 for the period 2026–2030.

4.3.4 EU Renewable Energy Directive (RED)

EU Directive 2018/2001 sets binding targets for the use of renewable energy in the EU and sustainability criteria that must be fulfilled in order for renewable energy to be accounted towards the targets and to be able to be subsidized. According to the EU regulation on emission monitoring and verification (EU 2018/2066), for bioliquids that do *not* meet the sustainability criteria, CO_2 emissions from the combustion of bioliquids must be treated as fossil emissions in the EU ETS.

In the Directive 2018/2001, "*'renewable liquid and gaseous transport fuels of non-biological origin' means liquid or gaseous fuels which are used in transport other than biofuels whose energy content comes from renewable energy sources other than biomass*". According to set sustainability criteria, "*the greenhouse gas emission savings from the use of renewable liquid and gaseous transport fuels of non-biological origin excluding recycled carbon fuels shall be at least 70 % as of 1 January 2021*". In addition, "*the gross final consumption of energy from renewable sources in transport shall be calculated as the sum of all biofuels, biomass fuels and renewable liquid and gaseous transport fuels of non-biological origin consumed in the transport sector*". Consequently, liquid and gaseous transport fuels produced applying CCU technologies are considered in the binding targets if they fulfil the sustainability criteria set in the Directive.

CCS is not considered in the targets set in the Directive 2018/2001, but it is considered in the sustainability criteria for renewable energy. The GHG emission reductions achieved when applying CCS are considered in calculation of actual GHG emissions of renewable fuels.

The Commission's proposal for a revised RED was published in July 2021. At the moment trilogue negotiations between the Parliament, the Council and the Commission are ongoing. The key changes in the proposal compared to the existing RED Directive are the increase in the binding EU minimum share of renewable energy sources in final energy consumption, strengthening of sustainability criteria for biofuels and bioenergy installations (European Parliament 2023b).

4.4 Summary on GHG reporting and accounting

Consideration of CO_2 flows or carbon stock changes related to CDR and CCUS in GHG reporting and accounting vary depending on technology. For technologies based on carbon sequestration in vegetation or soil (AR and SCSs), CO_2 removed is reported under LULUCF sector given that methods applied in the reporting are validated and reliable data is available. CO_2 removals through BECCS are reported under energy sector given that reliable case specific data is available. In case there are both fossil and biomass-based CO_2 captured and stored in the same plant, the fossil and non-fossil fraction of the fuel should be established and the emission factors applied to the appropriate fractions, i.e. appropriate negative CO_2 emission factor for biomass-based fuel and positive CO_2 emission factor for fossil fuel. Currently, there are not methods provided for biochar. In addition, DACCS, EW, OA and OF are not mentioned in the IPCC reporting guidelines. (Table 12)

CO_2 removed by those CDR technologies which are recognized in the GHG reporting to the UNFCCC are also recognized in the GHG accounting under EU legislation. In such a case CO_2 removed by land-based measures is accounted under LULUCF regulation and by BECCS is accounted under effort sharing regulation. (Table 12)

CO_2 captured and released in use can be classified based on the origin of CO_2 that are fossil (CCU), biomass (BECCU) and direct air capture (DACCU). The basic principle applied in the GHG reporting to the UNFCCC related to CCU and BECCU is that captured CO_2 is reported as an instant emission in relevant energy or IPPU sector in which the capture takes place, unless CO_2 in product is permanently stored. CO_2 related to DACCU is not reported. Fossil CO_2 captured and permanently stored is deducted from the balance of relevant energy or IPPU sector where capture takes place in case reliable case specific data is available. (Table 13)

CO_2 flows related to CCU and fossil CCS technologies which are recognized in the GHG reporting to the UNFCCC are also recognized in the GHG accounting under EU legislation. The particular CO_2 flows are accounted either under the ETS or effort sharing regulation (ESR) depending on the sector where CO_2 is released. Fossil CO_2 permanently stored in products can be deducted from the GHG balance of both ETS and ESR sectors which one is relevant. In case biomass-based CO_2 captured is permanently stored in products (BECCU), it is accounted under ESR. Temporary carbon storage of CCU products is not considered but instant oxidation assumption is applied (Table 13).

Table 12. Greenhouse gas (GHG) reporting to the United Nation's Framework Convention on Climate Change (UNFCCC) and accounting under EU regulation as regards to various carbon dioxide removal (CDR) technologies and the related CO_2 removals.

CDR technologies (Nemet et al. 2018, Griscom et al. 2018, Smith et al. 2023)	Sector where CO_2 is reported	Notes on reporting	EU Regulation where CO_2 is considered	Notes on accounting
Afforestation/ reforestation (AR)	LULUCF (forest land)	reported as part of relevant land use category	LULUCF (deforestation/ afforestation)	accounted in full carbon basis in LULUCF regulation; application under ESR limited due to MS specific gaps on LULUCF credits
Enhanced forest management (vegetation and soil carbon sequestration) (SCS)	LULUCF (forest land)	considered in reporting if methods validated and reliable data available; not necessarily the case	-/LULUCF (managed forest land + HWP)	if recognized in GHG reporting, accounted against forest reference level under LULUCF regulation; application under ESR limited due to MS specific gaps on LULUCF credits
Harvested wood products (HWP)	LULUCF	different approaches for reporting provided; IPCC provides default decay rates for sawn wood, wood panels and pulp and paper products	LULUCF (managed forest land + HWP)	accounted against forest reference level under LULUCF regulation; application under ESR limited due to MS specific gaps on LULUCF credits
Enhanced agricultural and livestock practices (soil carbon sequestration) (SCS)	LULUCF (agricultural land, grassland)	considered in reporting if methods validated and reliable data available; not necessarily the case	-/LULUCF (cropland, grassland)	if recognized in GHG reporting, accounted against reference years under LULUCF regulation; application under ESR limited due to MS specific gaps on LULUCF credits
Biochar	-	currently no guidelines provided by the IPCC on how to report. If guidelines become available, reported likely under LULUCF	-	not accounted due to lacking GHG reporting methods
Direct air carbon capture and storage (DACCS)	-/?	Not mentioned in the IPCC guidelines; unclear if and where in the inventory to be taken into account	-/ESR	if considered in GHG reporting, then accounted under ESR

CDR technologies (Nemet et al. 2018, Griscom et al. 2018, Smith et al. 2023)	Sector where CO_2 is reported	Notes on reporting	EU Regulation where CO_2 is considered	Notes on accounting
Bioenergy with carbon capture and storage (BECCS)	Energy	in case reliable case specific data available	-/ESR	if considered in GHG reporting, then accounted under ESR
Enhanced weathering (EW)	-	not mentioned in the IPCC guidelines which only rely on geological storage due to permanency issues	-	not accounted due to lacking GHG reporting methods
Ocean alkalinisation (OA)	-	see above	-	not accounted due to lacking GHG reporting methods
Ocean fertilisation (OF)	-	see above	-	not accounted due to lacking GHG reporting methods

Table 13. Greenhouse gas (GHG) reporting to the United Nation’s Framework Convention on Climate Change (UNFCCC) and accounting under EU regulation as regards to various carbon dioxide capture and use (possibly including storage) and fossil carbon dioxide capture and storage technologies and the related CO_2 captured and released.

CCUS technologies	Sector where CO_2 is reported	Notes on reporting	EU Regulation where CO_2 is considered	Notes on accounting
Fossil carbon capture and use (CCU/CCUS)	Energy / IPPU	capture not deducted unless CO_2 in product is permanently stored → CO_2 in product use is considered carbon neutral; (if capture would be deducted, CO_2 from product use needs to be reported, which is meaningless from the national/global inventory point of view)	ETS/ESR	capture and release of CO_2 from CCU product are accounted as zero, unless CO_2 in product is permanently stored (under ETS in PCC); instant oxidation considered for temporary carbon stocks
Biomass carbon capture and use (BECCU/BECCS)	-	biomass CO_2 released not reported; Capture not deducted unless CO_2 in product is permanently stored → CO_2 released in product use is considered carbon neutral; (if capture would be deducted, CO_2 from product use needs to be reported, which is meaningless from the national/global inventory point of view)	-/ESR	capture and release of CO_2 from CCU product are accounted as zero, unless CO_2 in product is permanently stored in which case removals are accounted under effort sharing regulation; instant oxidation considered for temporary carbon stocks
Direct air capture and use (DACCU/ DACCS)	-	direct air capture not mentioned in the IPCC guidelines;	-	capture and release of CO_2 from CCU product are accounted as zero, unless CO_2 in product is permanently stored; instant oxidation considered for temporary carbon stocks
Fossil carbon capture and storage (CCS)	Energy / IPPU	in case reliable case specific data available, deducted from the balance of relevant energy/IPPU sector	ETS, ESR	in case verifiable, CO_2 emissions captured under ETS or ESR depending on in which plant CO_2 capture takes place

4.5 International benchmarking of policies and measures

The benchmarking covered eight countries that were considered particularly relevant for Finland either because of their proximity in terms of circumstances or their relevance in terms of policy development. The countries included were Sweden, Denmark, Norway, the Netherlands, the United Kingdom, the United States, Canada and Japan.

The benchmarking was based on a review of publicly available documents in English. The analysis focused on documents released in the past couple of years. For the full benchmarking results including references, please see Annex 1.

All countries in the benchmarking have a range of policies and measures to promote carbon dioxide use and removal. Federal jurisdictions (the United States, Canada and the United Kingdom) have large variety between regional units of governance, with some showing significant initiative. Many of the policies in the analysed countries are relatively recent or still under process, which indicates that this is a rapidly evolving field.

All covered EU countries have national policies going beyond EU measures. Significantly for Finland, all covered countries have policies and measures that are more advanced or ambitious than the ones currently in use in Finland.

4.5.1 Findings by policy type

Looking at direct **regulation**, the benchmarking identified basic regulation covering transport, storage and monitoring in all eight countries. In the EU countries (and the United Kingdom), the regulation is based on the transposition of the EU CCS directive. Norway has mandated the use of CCS in the Snøhvit oil and gas project. California and Canada allow for using CCS projects to meet the commitments under their clean fuel standards for transport. Denmark has introduced lighter licensing requirements for small pilot storage projects.

The use of dedicated **pricing mechanisms** (emissions trading, taxes, auctions) divides the covered countries, with half of them having some mechanisms in place. Norway has a carbon tax on the oil and gas industry in addition to the EU emissions trading scheme. Norway also applies carbon pricing equal to the ETS on carbon captured in Longship, including biogenic carbon. The United States, Canada and the province of Saskatchewan have tax credits for CCS. Sweden has decided to introduce a reverse auction for BECCS.

All countries in the benchmarking provide **funding** for relevant solutions, with variation in the distribution between RDI and deployment. On the RDI side, Norway and the Netherlands have dedicated research programmes on CCS. The United States have research centres on CCS. The United Kingdom and the United States have CDR technology competitions. Scotland, the United States and Japan have funding programmes for CCU. The United States funds four regional DAC hubs.

On the deployment side, all countries have climate or innovation funding mechanisms that also cover implementing CCUS solutions. The United Kingdom has a dedicated CCS Infrastructure Fund. Norway has established a technology centre for testing CCS. Norway also provides extensive funding for the Longship project at high rates of subsidy. Sweden's broader Industry Leap funds also BECCS and CDR.

When it comes to **information and other measures**, all covered countries have climate and energy strategies relevant for CCUS, with Norway, the United Kingdom, Canada and Denmark having specific CC(U)S strategies. Sweden has specified the role of BECCS in the national emission targets. Norway has a state-owned enterprise dedicated for CCS. Norway has also published a CO_2 storage atlas. The United Kingdom has established a CCUS Council. The United States has online tools like the Carbon Matchmaker.

4.5.2 Findings by country

Looking at the countries, **Sweden** is noteworthy for its policies on BECCS. The national emission targets have certain carveouts for BECCS and the reverse BECCS auction is first of its kind internationally. The Industrial Leap mechanism (Industriklivet), established to support the broader decarbonisation of industries, provides significant funding for BECCS.

In **Denmark**, CCUS is covered both in the national climate roadmap and in the climate agreement for energy and industry. There is both research and demonstration funding available. Small-scale storage pilot projects have a lighter licensing system.

Of all the countries, **Norway** is likely to have the longest and broadest track record in CCS policies and measures. The country has used both CO_2 pricing and mandatory obligations to promote CCS in the oil and gas industry. Norway has extensive investment in RDI and information, including a CO_2 storage atlas and a technology centre for testing CCS. Also public funding for the seminal Longship project is considerable.

The Netherlands initially planned a notably large role for CCUS in the national climate strategy, but toned it down based on feedback. The country has funding available both for RDI and deployment. Public funding for CCS will be provided until 2035, after which only CDR can be supported.

The United Kingdom has a notably large number of strategies referring to CCUS. The country also has various financing mechanisms, such as the CCS Infrastructure Fund and the CCUS Innovation Programme. Within the United Kingdom, Scotland is active regionally with the Emerging Energy Technologies Fund and the CO_2 Utilisation Challenge Fund.

The United States has a number of policies both at the federal and state level. A key federal policy is the CCS tax credit (45Q), recently extended and broadened in the Inflation Reduction Act. There are significant investments in RDI, including on DAC. Active states include climate leaders like California, but also fossil fuel producers like Wyoming and Louisiana have introduced state laws to regulate CCS.

In **Canada**, CCUS is largely seen in the context of the oil and gas industry. At the federal level, CCUS is supported through a tax credit. There is funding available for deployment both at the federal and provincial level. Alberta and Saskatchewan are particularly active provinces.

Finally **Japan** has significant activity in RDI. The regulatory framework is still in a draft stage. Japan does not seem to have any pricing incentives or funding available for deployment.

5 Policy development proposals and needs

5.1 International level

Although the important role of CDR is recognized in the Paris agreement and in the IPCC mitigation scenarios, this has not yet been reflected in the UNFCCC decisions on the global need for large-scale CDR. However, recent developments in the context of implementing the Paris Agreement's Article 6 on international cooperation indicate that the UNFCCC could play a more active role in the near term. An important step would be developing methodologies for monitoring, reporting and verification (MRV) of carbon flows related to CDR. (Smith et al. 2023)

The IPCC guidelines for CDR technologies could be improved. To improve clarity, various types of CDR technologies should be explicitly mentioned in the IPCC guidelines. In addition, reasoning to exclude certain technologies could be improved. This relates especially to biochar, DACCS, enhanced weathering (EW), ocean alkalinization (OA) and ocean fertilization (OF) (Table 12). In addition, the possibility to produce long-living CCU products from captured CO_2 should be recognized (Table 13). Such products could create new carbon pool which could store carbon dioxide similarly to HWP. At least, reasoning to omit such carbon pool should be provided.

5.2 EU policies

The Article 1 of the EU Climate law determines that "*This Regulation sets out a binding objective of climate neutrality in the Union by 2050 in pursuit of the long-term temperature goal set out in point (a) of Article 2(1) of the Paris Agreement, and provides a framework for achieving progress in pursuit of the global adaptation goal established in Article 7 of the Paris Agreement. This Regulation also sets out a binding Union target of a net domestic reduction in greenhouse gas emissions for 2030. This Regulation applies to anthropogenic emissions by sources and removals by sinks of the greenhouse gases listed in Part 2 of Annex V to Regulation (EU) 2018/1999.*" The EU Climate law also recognizes the key role of the EU ETS and emphasizes the role of all the economic sectors regulated under the EU ETS, effort sharing regulation and LULUCF regulation in achieving climate neutrality.

In the communication on Sustainable Carbon Cycles (EC, 2021a) the EU recognizes the need to integrate CDR into the regulatory and compliance frameworks. The communication separates four different key areas where to proceed. First, in order to reverse the decline of forest carbon sinks detected during the past years, the EC has proposed the amendment for the LULUCF regulation. Second, the need to create business models for carbon farming is recognized. This includes concepts, funding possibilities and monitoring and verification to be developed and agreed. Third, industrial, capture, use and storage of carbon would need to be increased to a level between 300 and 500 Mt CO_2 by 2050 through creating an internal market and other policy measures. Forth, a regulatory framework for the certification of carbon removals is proposed.

In this subsection 5.2, the following questions are reflected:

- What changes in EU climate and energy law would provide reasonable certainty of the generation and permanence of emissions reductions and enable expansion in the deployment of CCUS and technological sink solutions?
- What or what types of products should be included in emissions trading regulation?
- How could verification and validation be implemented in terms of technological sinks?
- How to avoid double accounting or other accounting inconsistencies between sectors (ETS, non-ETS, LULUCF)?

5.2.1 Development of emission trading system

Overall, the EU ETS incentivizes CCU through carbon price but does not incentivize CDR except through the Innovation Fund which is financed by the EU ETS revenues. By 31 July 2026, the Commission shall report to the European Parliament and to the Council on “how negative emissions resulting from greenhouse gases that are removed from the atmosphere and safely and permanently stored could be accounted for and how these negative emissions could be covered by emissions trading”.

The amendment of the EU ETS provides a perspective on what or what types of products should be included in emissions trading regulation by determining the permanence criteria for carbon storage in products. Consequently, any products with temporary carbon storage are excluded. This is reasonable as it is very difficult to verify and monitor the use of products and release of carbon from them in practice unless an appropriate and reliable tracking system is developed and launched. If products with temporary carbon storage would be included in the EU ETS, this issue related to the release of carbon from products should be solved somehow. In principle, temporary carbon storage in products might be handled similarly to HWP applying agreed default values to estimate the release of carbon from products.

5.2.2 Development of regulation concerning effort sharing and LULUCF sectors

The effort sharing regulation and LULUCF regulation set binding national GHG emission targets for non-ETS sector and LULUCF sector but don't provide incentives for any specific technologies. Consequently, although those CDR and CCUS technologies recognized by the GHG reporting carried out in line with the IPCC guidelines to the UNFCCC are considered in the accounting of GHGs under ESR and LULUCF, the incentives to deploy such CDR and CCUS technologies mainly depend on national policies. Furthermore, the ambition to implement national policies is influenced by the GHG emission reduction commitments and caps for flexibilities set in the effort sharing and LULUCF regulations.

5.2.3 Verification and validation in terms of technological sinks

In November 2022, the European Commission published its proposal for a regulation on certification of carbon removals (EC 2022f). The particular initiative is "*a first EU-wide voluntary certification framework for carbon removals*" which aims to *"expand sustainable carbon removals and encourage the use of innovative solutions to capture, recycle and store CO2 by farmers, foresters and industries"*. Carbon removals, under this proposal, must bring clear benefits for the climate, as well as preserving or strengthening other environmental objectives. Thus, certified carbon removals must meet four different quality criteria related to quantification, additionality, long-term storage and other environmental effects (sustainability). To operationalize the legislation, the EC will adopt "*delegated acts establishing technical certification methodologies for the different carbon removal activities*", and "*implementing acts setting out harmonized rules on the certification modalities and procedures and on the recognition of certification schemes*". Most of the details related to the operationalization are left open, and the EC will consult the Expert Group set up to help translating the quality criteria into detailed certification methodologies.

According to the EC proposal, carbon removal certificates can be used for result-based rewards by private or public sources as financing criteria or for carbon removal claims. However, "*it will not be possible to use the certified carbon removals for compliance with the EU Emission Trading System*". The operationalization of the legislation will influence not only on how the certificates can be used in voluntary carbon market but likely also on the related climate effects, other environmental effects and volume of market generated through the regulation.

5.2.4 Avoidance of double accounting or other accounting inconsistencies between sectors

The ETS directive, effort sharing regulation and LULUCF regulation both currently in force and the amendments proposed and agreed to be implemented generates a framework to account GHG emissions in full economy basis in line with the GHG reporting to the UNFCCC. Consequently, as far as GHG accounting is based on the methods applied in GHG reporting to the UNFCCC and all the GHG emissions are appropriately accounted in the ETS, non-ETS or LULUCF sector, there is no double counting or other accounting inconsistencies between these sectors. The key point is that each unit of emissions or removals is accounted once in one of these sectors. Any violation in this would create an accounting inconsistency between GHG accounting and reporting which is not the case with the current and proposed accounting rules.

Within the EU, double-counting issues may arise between carbon crediting in voluntary carbon market and accounting under EU regulation or national commitments. Double-counting between voluntary carbon market and accounting under EU regulation can be avoided either by enabling and making corresponding adjustments to GHG emission reduction bookkeeping or by ensuring that the GHG emissions in question are not reported and accounted towards EU regulation.

For GHG emissions detected in GHG reporting, avoiding double-counting between a state and non-governmental actor would require that a particular CDR (or GHG emission reduction) would not be accounted as a part of GHG emission reduction target of a Member State. This would require that a Member State makes corresponding adjustment to its bookkeeping of GHG emission reductions (i.e. tighten its GHG emission reduction target correspondingly. Avoiding double-counting is very important to make voluntary carbon market reliable and successful in GHG emission reductions. However, the current EU legislation does not enable corresponding adjustments by its Member States (Laine et al. 2023) as the EU has joint commitment under the Paris Agreement, and that target has not fully shared among the EU Member States (Laininen et al. 2022). It would be possible for Finland to make corresponding adjustments in the context of national climate targets, but this would *not* remove the double-counting issue in the global context unless corresponding adjustments are made at the EU level (Laininen et al. 2022).

Double-counting issue is not arisen between voluntary carbon market and accounting under EU regulation or national targets if the CDR (or GHG emission reduction) is not detected by GHG inventories. Although this might be the real case, it should be noted that the IPCC guidelines aims to detect the anthropogenic GHG emissions as reliable as appropriate. Consequently, a measure not detected by the GHG inventories means that there are certain concerns related to the reliability of associated GHG emissions. In case such concerns are avoided through deploying enhanced GHG emission reporting methods or data, a particular measure will likely become part of GHG inventories in the future.

In voluntary carbon market, climate actions are connected to various types of claims. In case carbon units sold in voluntary carbon market are accounted in EU regulation, double counting can be avoided by adjusting the related claims from "*offsetting claim*" to "*impact claim*". In contrast to "*offsetting claim*" that is related to GHG emission reduction or carbon sequestration increase, "*impact claim*" is related to helping in achieving climate targets. (Laine et al. 2023)

5.3 Options for national policies and measures

5.3.1 Key issues to be considered

As discussed in section 5.2, the EU regulation leaves room for national policies to promote the deployment of CDR and CCUS. Carbon dioxide capture and use is included in the concept of climate change mitigation in the national Climate Act (Article 6, HE 27/2022vp) which provides aims and frames for planning and monitoring the implementation of national climate policy. Specific policies and measures are not determined in the national Climate Act.

There are various policy options that can be implemented to boost the deployment of CDR and CCUS. These include direct regulation, economic instruments such as incentives and taxes, and information. Table 14 lists certain key issues to be considered when creating a national framework for CDR and CCUS (Table 14).

First, the question of the type of regulation and its appropriateness can be raised. The consistency with the EU and international legislation needs to be ensured. When assessing the appropriateness of national regulation, it is worth recognising the rapidly developing regulatory landscape both within the EU and internationally. It can be expected that carbon removals will be integrated into the EU regulatory and compliance frameworks post-2030 (EC 2021a).

The EU and international regulation beyond the climate regime may also influence the national regulatory framework. For example, the proposal for Nature Restoration Law sets a list of indicators to assess the improvement of agricultural ecosystems and forest ecosystems, and "*once defined and developed, these indicators could be taken as a basis* *for the disclosure of co-benefits of carbon removal activities."* In addition, "*The Taxonomy Do No Significant Harm criteria can inspire a general approach to exclude (carbon removal) activities with a significant negative impact on sustainability."*

Second, the consistency with the national legislation needs to be ensured. For example, Environmental Protection Act, Waste Act, Mining Act, Emission Trading Act and Act on separation and storage of carbon dioxide might be relevant to consider in this context. (Table 14)

Third, there are several specific aspects related to the type of regulation and instruments applied. These include questions related to the aim of regulation in terms of technology deployment, technology neutrality, cost-efficiency, as well as climate, environmental and social impacts. (Table 14)

Table 14. Key questions and aspects to be considered when implementing a national framework for CDR and CCUS.

Question	Aspects
What type of regulation is considered?	Direct regulation, economic incentives or information; Instruments may include norms (e.g. use mandates, standards, emission caps), economic instruments (taxes, fees, subsidies, emissions trading) and information
How regulation relates to the EU and international legislation?	Consistency with the EU and international legislation; Appropriateness concerning rapidly developing regulatory landscape both within EU and internationally
How consistent regulation is with other national legislation?	For example, with Environmental Protection Act, Act on Environmental Impact Assessment, Waste Act, Mining Act and Emission Trading Act, Act on separation and storage of carbon dioxide, Chemicals Act
What technologies regulation aims to promote?	A specific technology, a group of technologies or all technologies in general? Depending on the type of regulation and instruments applied, they may or may not be technology neutral.
How effective regulation is in CDR or CCUS deployment?	The effectiveness of deploying CDR or CCUS may vary significantly depending on the type of regulation and instruments applied. For example, use mandates might be powerful instruments to increase deployment of certain technologies to a certain level, while the effectiveness of e.g. subsidies, taxes and fees significantly depend on the rates applied and their effect on relative competitiveness. Effectiveness of information tends to remain marginal.

Question	Aspects
How cost-efficient regulation is in terms of CO_2 removals or emission reductions?	Cost-efficiency of CO_2 removed or reduced may vary a lot between technologies and compared to other measures. Non-flexible regulation boosting a limited number of technologies does not necessarily support cost-efficiency in general but might improve cost-efficiency of specific technologies.
In which sector are carbon removals and reductions recognised in reporting to the UNFCCC?	This influences the development of the GHG balance of a particular sector and furthermore the achievement of national climate targets. In case removals are not recognised in reporting, they do not affect the national GHG balance.
How are carbon removals and reductions accounted under the EU regulation?	Are the removals generated accounted under the effort sharing regulation, LULUCF regulation or are they not detected in accounting; are there gaps related to the use of removals when achieving the EU commitments? Emissions avoided by CCU affect the GHG emissions in the ESR or ETS sectors depending on where emissions are reduced.
What are the overall climate impacts related to the regulation?	Emissions are also generated in the value chain of CDR and CCUS solutions due to the consumption of energy, land, biomass or other resources. The emissions generated might take place under the EU ETS in which case CO_2 emission allowances are consumed, outside the EU ETS (i.e. under non-ETS or LULUCF sector) in which case emissions outside the EU ETS are increased or outside the borders of the EU in which case they might increase unregulated emissions. In some cases the emissions generated in the value chain of a CDR or CCUS solution may be significant compared to the CO_2 removed or reduced, increasing the risk for perverse incentives. Additionality of CO_2 removed or avoided and permanence of CO_2 removed as well as the risk of carbon leakage and double counting varies between technologies and the type of regulation applied.
What are other environmental impacts related to regulation?	Deployment of CDR or CCUS may cause other environmental impacts, such as those on biodiversity, water or air. Significance and direction of these impacts depend on the technology concerned. It is important that regulation does not generate unacceptable harmful impacts.
What are social impacts related to regulation?	Deployment of CDR or CCUS may cause various types of social impacts through resource needs (e.g. energy, land, biomass, money) and the related price effects. Also, environmental impacts especially at the local level may amplify social impacts. The acceptance of CDR or CCUS deployment may be very different between different groups of people, technologies and levels of deployment.

Based on the international benchmarking, literature, current policy landscape and expert judgement, the project identified various policy options for Finland to consider. The measures could be implemented nationally; for a discussion on EU policies, see chapter 5.2.

The policy options cover a wide range of possible tools. For instance, some of the options would be relatively quick and easy to implement, whereas some would require more time and effort. Some would only require minimal investments, whereas some might incur significant costs. Some address the full spectrum of CCUS and CDR solutions, whereas some focus on particular technologies or use cases. The full list of policy options is included as Annex 2.

The list is neither exhaustive nor prescriptive. There may be additional policies implemented or considered in other countries that Finland could also learn from. Many of the options overlap and are as such alternatives. For a proposal on the suitable policy package for Finland, see chapter 6.4.

5.3.2 Possible options for direct regulation

There are various regulatory options to consider. They can be broadly grouped into foundational and deployment categories.

Foundational measures would create an enabling framework for CCUS and CDR solutions. The current **national legislation** on the implementation of the CCS and ETS directives could be reviewed and consequently updated to include current best practice, to the extent necessary. The goal would be to provide regulatory clarity and enable the use of the full range of CCUS and CDR options.

At least for the time being, **bilateral governmental agreements** are required to transport carbon dioxide for storage outside of Finland, e.g. to Norway or Denmark. While the issue may be solved in the future at the EU level (EC 2022c), Finland could already follow the example of Belgium and Sweden and sign bilateral agreements with the most potential storing countries (Danish Ministry of Climate, Energy and Utilities 2022). This would give a signal to the market that capturing carbon dioxide for storage is also possible in Finland.

There is a broad agreement in literature and expert discussions that negative emissions should have **separate targets** to provide policy certainty and avoid using removals as a substitute for vital emission reductions (McLaren et al. 2019). The current emission reduction targets for the years 2040 and 2050 as well as the net carbon neutrality target for 2035 in the Finnish climate act could be complemented with additional targets for negative emissions. Whether the targets should cover removals both in the LULUCF sector and through technological solutions and how much removals should be allocated to each is an issue that requires further consideration.

A less well-known option for storing carbon lies in **mining wastes** (Craig 2022). Legislation could be updated to require mining operators to estimate the storage potential of wastes in the environmental impact assessments or applications for environmental permits. The requirement could be complemented with recommendations to separate wastes suitable for storage from other wastes.

In the deployment category, **companies could be mandated** to use CCUS in at least two different ways. The first is to legally require point sources above a certain size to capture carbon dioxide and either store it (CCS) or use it in products (CCU). The second focuses on the use side, requiring blending a certain, and possibly gradually growing, fraction of captured carbon in products. While both policy options can be considered feasible at a conceptual level, much depends on key design choices, such as the time of introduction, point source size limits and required share of recycled carbon content.

A variation of these mandates is setting an **end date for releasing fossil carbon** to the atmosphere from large point sources. Modelled after the existing coal phase-out law, the end date would provide policy certainty and a push for addressing the emissions from hard-to-abate industrial sources. The phase-out requirement is technology neutral as it can be met by either cutting fossil emissions to zero, replacing fossil carbon with biogenic carbon or capturing the carbon for storage or use. Again, the effectiveness, costs and feasibility of the measure depend to a large extent on key policy design choices.

5.3.3 Possible options for pricing and funding instruments

Some of the solutions are likely to require financial support through pricing mechanisms, at least in the initial stage. There are various options to consider which can complement direct regulation.

To establish markets for first movers, the state could **auction negative emissions** (Lundberg & Fridahl 2022). This could remove a key bottleneck in the deployment of CDR requiring large investments. Auctions have been used before to allocate support for renewable energy sources in a cost-effective fashion. A question to be resolved later is whether the auction should be technology neutral, have dedicated carveouts for specific technologies or focus on just one option, like the BECCS auction in Sweden (Regeringskansliet 2022).

The EU emissions trading system already creates an incentive to capture carbon dioxide, but at times the price has been too low and volatile to trigger investments in CCS. Setting a **national price floor**, like in the United Kingdom (Hirst 2018), could provide the additional incentive required. However, depending on the scope and level of the price floor, the measure could spark concerns about carbon leakage.

Tax credits have been used fairly widely in the United States to incentivise negative emissions (Congressional Research Service 2021). A similar measure could be considered in Finland, although the tax systems and political contexts of the two countries are quite different. Compared to direct subsidies, tax credits or rebates tend to have lower administrative costs, but higher chances of being allocated inefficiently (Työ- ja elinkeinoministeriö 2022).

As many of the technologies considered are at relatively low levels of maturity, support should be targeted to the earlier stages of the innovation chain. That is why **funding programmes** should be considered for RDI as well as demonstration and piloting, like in Denmark. Dedicated programmes have the benefit of sending a stronger signal about the importance of the emerging field. However, for ease of implementation and synergies, separate windows or carveouts in existing mechanisms (e.g. Business Finland, the Climate Fund) should be considered.

5.3.4 Possible options for information and other instruments

Information and miscellaneous other measures can help complement direct regulatory and financial options. The project identified two possible measures with an information focus and five others with a miscellaneous character.

Similarly to hydrogen, Finland would benefit from a **strategy for carbon dioxide use and removal**. A dedicated strategy raises the political importance and provides direction for policy and markets alike. If a separate strategy is not considered justified at first, it could be integrated into the national climate and energy strategy, as long as the scope and ambition are sufficient.

Also similarly to other emerging fields, it would be helpful to bring experts and stakeholders together in a **roundtable on carbon dioxide use and removal**. A dedicated roundtable allows policymakers to interact with key stakeholders, facilitating mutual understanding and minimising risks. The roundtable could also contribute to the national strategy.

Other possible measures include a **Green Deal to harness public procurement for CCU**. Finland has a long tradition of voluntary agreements with the private sector, with relatively high acceptance from businesses. A Green Deal could facilitate first mover markets for CCU products, such as construction materials.

Some countries, such as Norway, have established **state-owned enterprises** to address the bottlenecks in the nascent industry (Gassnova 2023). Establishing a state-owned enterprise for infrastructure to transport carbon, modelled after Fingrid and Gasgrid, could enable the creation of private markets. Alternatively, the task could be allocated to one of the existing state-owned infrastructure companies.

The **IPCC guidelines** form the foundation for measuring and reporting both emissions and removals, but they do not currently address many of the emerging technologies, such as enhanced weathering (Smith et al. 2023). Explicitly addressing emerging solutions in the guidelines would provide clarity and encourages deployment. As the IPCC is an intergovernmental process, Finland could take the lead in calling for an update of the guidelines, either by itself or under the EU.

Policy guidance on voluntary carbon markets has developed recently, both at the national and the EU level. Further guidelines, information and possibly regulation could encourage gradually shifting the voluntary compensation markets towards permanent removals.

Finally, Finland could play a more active role in **international initiatives** on carbon dioxide use and removal. Many initiatives already exist, such as the CDR Launchpad. Finland may have much both to offer and gain, but more active participation would also require some additional resources in the involved ministries and agencies. (Tynkkynen 2018)

6 Conclusions

This report has compiled the "Carbon use and removal: prospects and policies" project's results, including an overview of the market status, policies and main technologies in the field of CCUS and CDR, especially from the perspective of Finland.

The Finnish and international markets for CCUS and CDR solutions were assessed both in terms of current state and quantitative and qualitative estimates for future development in size and growing solutions. The solutions, technologies and products in which Finland has export potential were also assessed.

As a general conclusion, CDR applied to industrial biogenic CO_2 emissions has significant potential to reduce the effort sharing sector's emissions and contribute to Finland's carbon neutrality target. The significance is further heightened by the decreasing trend of the net carbon sink in Finland's LULUCF sector, visible over the past decade. The industrial point sources of biogenic CO_2 in Finland provide an interesting opportunity for large-scale CDR.

CCUS and CDR are being promoted and regulated under separate EU policy frameworks, and both are evolving. Policy framework regarding CCS of fossil CO_2 emissions within the ETS sector has been in place since 2009, and the recent provisional agreement to amend the ETS Directive provides that CCU in products where CO_2 is bound permanently will be allowed. In addition, ship transport of CO_2 will be allowed, which is highly relevant for Finland. It is up to future delegated acts, which CCU products will be allowed within the ETS, however. Once defined, this can mean that for instance the mineralization of fossil CO_2 permanently into construction products has a financial incentive based on the emission allowance price in the EU ETS. The recent emission allowance prices have risen to levels within or close to costs of full chain CCS.

CDR solutions are not within the scope of the ETS framework, and they are currently operated in the voluntary carbon removal and off-set markets. The recent EU proposal of a CDR certification framework is a significant step for establishing a regulated voluntary market for CDR. However, the monitoring rules and which CDR solutions will be eligible for the certification is not yet certain, nor is the expected market potential of the voluntary scheme. CDR solutions that are detected in GHG inventory can, however, be accounted in the effort sharing sector's emissions and thus help reach national emission reduction targets. National policies would be needed to provide the operational incentive for the CDR activities.

The above-mentioned lack of direct operational incentive for CDR, along with missing greenhouse gas accounting guidelines for technologies including DACCS and biochar, present some of the main regulatory hurdles for CCUS and CDR. There is also a risk that future rules regarding CCU products within ETS and carbon removal certification framework exclude relevant solutions. Most significantly, these hurdles may limit in the medium-term the capture and storage of industrial biogenic emissions and production of biochar.

We elaborate on the above general conclusions in the following sub-sections, where we provide the main conclusions regarding the technologies and markets for CCUS and CDR, policy framework and key CDR options for Finland. Finally, we recommend options to consider in the national policy making.

6.1 Technologies and markets for CCUS and CDR

Based on the market assessment, the EU ETS or the voluntary CDR markets have so far not provided sufficient incentive for sustainable investments to and operation of CCUS or CDR technologies. The market environment for CCUS and CDR is evolving, however, along with developments in the policy framework, the rising level of emission allowance prices and the decreasing cost of renewable wind and solar energy. Furthermore, future inclusion of maritime transport to the EU ETS, and requirements to cut down traffic emissions in the effort sharing sector are creating new market pull for e-fuels, a trend which may be further contributed by the restructuring of fossil hydrocarbon markets after the Russian invasion to Ukraine in 2022.

The current global market size for the use of CO_2 consists mainly of urea production and enhanced oil recovery, 130 $MtCO_2$/yr (57 % of total use) and 70–80 $MtCO_2$/yr (34 % of total use), respectively. Novel uses of CO_2 like PtX or CO_2 mineralization have only a minor role so far, and the costs are generally higher than similar fossil-intensive products. Globally, about 9 Mt/yr of fossil CO_2 and about 1 Mt of biogenic CO_2 is captured for dedicated storage, whereas the first 1 $MtCO_2$/yr DACCS plant is in construction. Thus, the development of CCS is lagging compared to scenarios meeting the climate goals. The costs for CCS depend on the source CO_2 volume and concentration, the facility and site in question, CO_2 capture technology, logistics and the storage method. Cost ranges of 20–200 €/tCO_2, 30–350 €/tCO_2 and 250–600 €/tCO_2 have been estimated for fossil CCS, BECCS and DACCS, respectively. Of these technologies, the cost for DACCS has been estimated to decrease significantly in the coming decades due to technology development, reaching even ~100€/t$CO_{2.}$ The respective cost ranges for fossil CCS and BECCS might remain similar in the future, but the average cost could decrease over time.

The interest towards CCS is growing rapidly with rising EU ETS emission allowance prices over 100 €/tCO_2, and a handful of European CCS projects with CO_2 capture capacities of 0.4–1.5 MtCO_2/yr each, are commissioning in the next couple of years. EU ETS is the largest carbon market globally with a size of 683 000 M€ in 2021 and a market share of about 90 % of global carbon market value. For instance, the global voluntary markets were 320 M$ in 2019 providing offsets for 104 MtCO_2e, and the voluntary carbon markets of Finnish service providers provided offsets for ~0.3 MtCO_2e/yr in 2020.

The vast majority of global CDR includes activities on managed land, like forest management. These activities provide total removals of about 2,000 MtCO_2/yr, whereas increase in carbon stock in harvested wood products is about 220–335 MtCO_2/yr. Novel technologies like BECCS or biochar play only a minor part in comparison. Despite the current state of deployment, a number of options exist with CO_2 removal potential in the GtCO_2/yr-scale. The cost of CDR activities on managed land is mostly below 100 €/tCO_2 and significant potential exists with costs below 20 €/tCO_2. Price of CO_2 removal via biochar production is currently on average about 110–150 €/tCO_2, but cost reductions to a level of 60–80 €/tCO_2 might be realized. In the case of harvested wood products, it is difficult to separate the value of increased carbon stock from the product value.

Driven by the inclusion of 'renewable liquid and gaseous transport fuels of non-biological origin' into the Renewable Energy Directive, and the abandoning of Russian natural gas imports, several commercial PtX projects are currently either in the planning, permitting or construction phases in Finland. While most of the current projects aim for synthetic fuel production from hydrogen and CO_2, one facility under construction will utilize CO_2 captured from air in production of edible proteins. Starting from the near-term, e-fuel projects, technology development and e-fuel production can offer significant export potential for Finland. Other CO_2-derived products, like proteins and polymers, can offer very large export potential in the medium- to long-term.

Although most of the assessed projects in Finland aim for CCU without permanent sequestration of CO_2, a number of technology demonstrations and projects are producing biochar on voluntary carbon markets. From the European perspective, Finland is a major actor on the biochar market and biochar is one of the few products that is already significantly benefiting from the current voluntary CDR market. In this case the export potential might be in the form of certified CO_2 removal service, not always the physical product. In the long term, there may be additional potential in developing high-value biochar products, such as active carbon or materials for batteries.

The overview of CCUS and CDR projects in the EU shows that several commercial facilities are utilizing and storing CO_2 into mineral products, such as artificial aggregates or precast concrete products. The total storage capacity of these CO_2 mineralization projects is so far modest, however. One Finnish company is aiming to commercialize concrete curing technology where CO_2 is permanently bound in the precast concrete products. There is currently a high pressure in the European cement industry to lower their CO_2 emissions rapidly, as the CO_2 emission allowance price is already high compared to the price of the produced cement. The interest towards carbon-neutral concrete is high not only in the EU, but also globally. This creates a large market opportunity for technology exports, but the price per ton of cement or concrete is often too low to make it financially sound to transport over long distances. The cost of CO_2 storage by mineralization has been estimated at 50–100 \$/tCO_2 for large-scale operations, but in the currently commercialized applications, economically feasible operation is already achieved as a net result from savings in landfill costs of utilized industrial wastes, sold products with improved value as low-carbon products.

Besides production of biochar or the utilization of CO_2 in products that would provide adequate permanence, the two main technology options for CO_2 storage are mineralization or geological storage. In the EU ETS, only geological storage has been acknowledged, but this will change as CO_2 bound permanently in products will be accounted for. Finland has large theoretical storage potential in binding CO_2 to magnesium silicate minerals, such as serpentinite. A smaller potential exists in binding CO_2 to calcium containing mineral wastes. The practical storage potential is likely reduced strongly by the quality, accessibility and locations of the minerals, but is considered to be altogether in Mt-scale per year in Finland. However, more research, piloting and demonstration are needed to commercialize the technology, and further policies can be considered to improve the accessibility of suitable mine tailings. The global mineral reserves and even the alkaline industrial wastes offer potential for Gt-scale CO_2-storage, and thus a good opportunity for technology export. However, the mineral resources vary significantly from one site to another, and foundational changes may be needed when expanding production to new sites. This may slow down the broader adoption of CO_2 mineralization. On the other hand, Finland has significant mining industry on the European scale, and thus even the domestic applications can be significant.

Except for biochar, most of the studied CCUS and CDR technologies involve the capturing of CO_2 from a gas stream using separation technology. While there is some CO_2 capture technology development in Finland, on the European level actors in other Scandinavian countries that have large financial support for implementing CCS, and large economies like Germany or the UK with significant PtX development seem to be leading also in CO_2 capture technologies. Therefore, the CO_2 capture technology export potential in the near-term at least, is more modest. As for DAC, there are not yet that many commercial actors and the market is estimated to grow exponentially in the next decades. This creates a huge technology export potential in the long-term, although the facilities themselves might be installed nearby the suitable CO_2 storage locations and less often in Finland.

Based on the TRL level and project outlook, we conclude that CO_2 transport and geological storage is the most viable large-scale storage option in Europe in the medium-term. The economic area of Finland does not have a suitable geology for CO_2 storage, such as hydrocarbon fields or saline aquifers at required depth, but CO_2 can be transported by ships to hubs at closest storage sites. The assessed storage projects that are furthest towards becoming commercial are focused on storage formations under the North Sea and Norwegian Sea. For instance, the Northern Lights project aims to start transporting and storing CO_2 in Mt scale in near future. Closer to Finland, relevant practical storage potential has been identified under the southern Baltic Sea. Developing CCS projects rapidly with CO_2 capture from Finnish industrial facilities offers large potential in the medium-term large fossil CO_2 emission reductions and CO_2 removals from biogenic CO_2 sources. Building on the gained know-how and technology, this could create export potential in the long-term for fossil CCS, while the global export potential for BECCS might be lower.

6.2 Policy framework

The IPCC provides guidelines for GHG reporting which creates a basis for GHG accounting under the EU legislation. Basically, GHG emissions are considered in GHG accounting if they are detected in GHG reporting. In case reliable information is available and specific requirements are fulfilled, CCS and BECCS are considered in GHG reporting and accounting. In principle, CO_2 content in and release from CCU products are not considered (except for harvested wood products (HWP)) and not detected from the GHG balance of a sector where capture takes place, unless CO_2 is permanently stored. For afforestation, reforestation, vegetation and soil management the detection of carbon stock changes depends on the methods applied in GHG reporting.

Although GHG reporting practices are sound and reasoned, they could be clarified and developed further. To improve clarity, various types of CDR technologies should be explicitly mentioned in the IPCC guidelines. In addition, reasoning to exclude certain technologies could be improved, in particular for biochar, DACCS, enhanced weathering (EW), ocean alkalinization (OA) and ocean fertilization (OF). Furthermore, the possibility to report CO_2 captured in temporary carbon stock of long-lived CCU products from captured CO_2 should be recognized. Such products could create a new carbon pool which could store carbon dioxide similarly to HWP. At least, reasoning to omit such a carbon pool should be provided, and the possibility to produce long-lived CCU products from captured CO_2 should be recognized.

The EU ETS creates incentive to reduce regulated GHG emissions through carbon price which may promote the use of CCU and CCS. Appropriately verified fossil CCS and products with permanent fossil carbon storage shall be detected from the CO_2 emissions regulated under the EU ETS. In addition, CCU might be economically viable option to replace fossil fuels if the price of CO_2 is high enough. However, carbon price in the EU ETS does not affect the economic viability of CDR technologies which may hinder the development and deployment of CDR technologies.

Appropriately verified BECCS (i.e. detected in GHG inventory) is considered under the ESR of a Member State where CO_2 capture takes place. Carbon stock changes related to land use, land-use change and forestry including HWP are accounted under the LULUCF regulation. CO_2 content in CCUS products is accounted as reported, i.e. CO_2 flows are not accounted in case of temporary carbon storage except for HWP which are accounted under LULUCF regulation.

The EU accounting framework creates indirect incentives for those CDR technologies which are detected in GHG reporting. For example, appropriately verified BECCS can be applied to achieve GHG emission commitments of ESR or to compensate possible shortfall in LULUCF commitments. As ESR and LULUCF regulation affects EU Member states, they do not create direct incentives for economic operators. **It is recommended that the EU clarifies targets for CDR deployment, how the targets are to be achieved, and what is the role of the EU level and national level policies in achieving the targets.**

6.3 Key CDR options for Finland

In terms of current industrial activities, the fossil and biogenic CO_2 emissions (41.4 Mt CO_2 in 2020) from large point sources such as power and heat production plants and other industrial facilities equal to approximately 80 % of Finland’s greenhouse gas emissions LULUCF-sector excluded. Moreover, roughly half of the CO_2 emissions (24.3 Mt CO_2 in 2020) are biogenic. Of the point source emissions, some 14 Mt fossil CO_2 and 10 Mt biogenic CO_2 is emitted from facilities on the coastline, from where CO_2 could be transported cost efficiently by ships to storage sites already in the medium-term. Majority of these costal biogenic CO_2 emissions are emitted by pulp mills (7.4 Mt CO_2 in 2020). Therefore, theoretical potential for CCUS and CDR is high and relevant for reaching our medium to long-term climate targets. In the case of biochar, the production potential is limited by the availability and other uses of biomass waste, such as wood waste (3.1 Mt/yr), sludges (1.6 Mt/yr), animal and vegetal waste (1.1 Mt/yr) and paper and cardboard waste (0.6 Mt/yr). The potential for CCUS products is limited by the market volume of the products: for instance, about 0.6 Mt of plastics, about 1.5 Mt of cement and 8–10 Mt of sand and gravel for concrete is used annually in Finland. About 90 Mt/yr of aggregates are used for earth construction, but these are low in value per ton and usually sourced locally. In addition, the price and availability of low-carbon electricity around the year limits the market penetration of more energy-intensive products in competition with fossil alternatives.

The strengths, weaknesses, opportunities and threats of the key carbon dioxide removal options for Finland were identified and summarized in Table 15. These options included direct air carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS), and biochar. These categories include the utilization of CO_2 in long-lifespan products and CO_2 mineralization; not as separate technologies, but as an alternative for a part of the value chain. CDR methods with little technological contribution were excluded due to the focus of the study, and harvested wood products because the market is well established. Ocean alkalinization involves severe environmental risks, measuring the impact is difficult and international regulatory framework is not favorable. In conclusion, we see that the selected technologies currently offer the best potential for Finland in additional CO_2 removals.

Table 15. SWOT analysis of key CDR options for Finland with significant technology involved.

CDR method	Strengths	Weaknesses	Opportunities	Threats
DACCS	• Does not compete with arable land use • Independent of biomass use • Independent of industrial CO_2 emissions • Can avoid CO_2 transportation, when deployed by the storage (in Finland e.g. by a suitable mining waste) • Finnish technology development (DAC start-ups, LUT, VTT)	• Limited implementation potential within Finland (CO_2-based products e.g. for construction and CO_2 mineralisation) • High cost • Significant technology development needed • Underdeveloped regulatory framework; unclear how considered in GHG reporting and accounting	• Vast global potential (export, carbon handprint) • Co-benefits: can be applied to improve indoor air, sustainable carbon source • Utilise some of the ~96 Mt/yr mining wastes produced in Finland by CO_2 mineralisation	• High energy consumption, thus also high life cycle GHG emissions unless low emission intensive energy available • If major DAC implementation only by the CO_2 storage site, can Finland count the removals towards own climate goals? • Risk of amine or other chemical emissions CO_2 capture
BECCS	• Commercial technology available • Large biogenic CO_2 capture potential in Finland without additional biomass use, especially pulp & paper industry • Energy-efficient capture from CO_2 point sources	• Limited full-chain implementation potential within Finland (CO_2-based products e.g. for construction and CO_2 mineralisation). Large potential if CO_2 is exported for geological storage, however. • Harmful climate and biodiversity effects related to biomass production and harvest may be significant	• CO_2 capture technology development to reduce costs and increase technology export • Utilise some of the ~96 Mt/yr mining wastes produced in Finland by CO_2 mineralisation • Cheap CO_2 capture from one medium-sized source and utilisation in various products to improve economic feasibility	• CO_2 transportation may be complex and expensive for inland facilities • Uncertain future of large biogenic CO_2 sources of the energy sector
Biochar	• Mature technology • Entire value chain in Finland possible • Active companies and market development in Finland; Finland is a major actor on the European level • Cheapest available option for Finland at the moment.	• Competing uses of biomass residues (e.g. bioenergy) • Not currently considered in GHG reporting or accounting	• Enhanced soil quality • High-value product development (active carbon, battery materials)	• Future availability of biomass waste streams

The lowest costs for CDR within the industrial scale applications are found in biochar (~120$/t$CO_2$) and BECCS (30–350 €/t$CO_2$). The lowest CO_2 avoidance costs for BECCS are found in ethanol and biogas production or from pulp mill black liquor, and the higher end of the costs from power production flue gases.

BECCS in collaboration with international partners could enable MtCO_2/yr-scale removals for Finland in the medium-term. However, there are risks and linkages related to carbon sinks in standing forests and biodiversity. The biogenic CO_2 emissions from the pulp mills along the Finnish coast could be the lowest hanging fruits for BECCS in Finland. The costs could be decreased by developing the CO_2 capture technologies and preparing joint efforts to optimize logistics. Smaller scale BECCS could be realized for high-CO_2-concentration alternatives like biogas, pulp mill lime kilns or ethanol fermentation, where the CO_2 could be used for various purposes, like CO_2 storage by mineralization, CO_2-based polymers and e-fuels production.

Biochar production is a mature technology that can remove and store CO_2 within Finland. The biomass waste streams offer potential for MtCO_2/yr-scale removals. The costs are relatively small and by the rise of voluntary carbon removal markets, the business is developing quickly, and Finland has already a significant role in the European biochar market. The future availability and competing uses of biomass are the major downsides of biochar technology deployment.

DACCS is a technology that offers CO_2 removal capacity independent of biomass use. It can be deployed directly at the CO_2 storage site, saving costs from CO_2 transportation. Of the selected alternatives, DACCS currently has the highest costs, mainly due to the low CO_2 concentration compared to industrial point sources. DACCS may be deployed in other countries, where there is geological storage capacity, but still providing the technology could offer major technology export potential for Finland. Alternatively, the captured CO_2 could be used in some of the construction products manufactured in Finland, but products with MtCO_2/yr-scale impacts may be challenging to achieve.

From the risk management perspective, all of these technologies should be developed in parallel to ensure we have enough CO_2 removal capacity by 2035.

6.4 Recommendations for national policy

To seize the full potential of CCUS and CDR solutions, a step change in policy is required. Finland needs to lay the foundation, introduce financial incentives and improve the knowledge base. The measures should constitute a balanced and mutually reinforcing policy package, including regulatory, financial and informational measures.

6.4.1 Lay the foundation

Foundational measures provide the overall framework for developing and deploying CCUS and CDR solutions. They can help in forging a joint vision, raising awareness and increasing policy certainty, among others.

To set the direction for policy and investments, Finland should define **targets for negative emissions in the Climate Act**. The targets should cover key years both before and after carbon neutrality in 2035. Whether the targets should cover removals both in the land-use sector and through technological solutions and what would be the role for each are subjects for further discussion.

Complementing the targets, **a strategy on carbon dioxide use and removal** is required. The topic would merit a dedicated strategy, but it could also be incorporated into the national climate and energy strategy – at least at first. The strategy should identify the policy package and investment needs necessary to reach the targets. The strategy should also be aligned with other relevant strategies and goals, such as the sustainable use of biomass.

Reviewing and updating laws would help make sure the national regulatory framework is fit for purpose. Legislation (including laws on CCS and emissions trading as well as the Climate Act) should recognise the role of CCUS and CDR, provide transparent and predictable rules and encourage (and not discourage) innovation.

To inform both writing the strategy and reviewing legislation, **a roundtable on carbon dioxide use and removal should be established**. The roundtable could bring together experts, stakeholders and policy makers, establishing a regular dialogue and ensuring the flow of information on various relevant aspects. These include links to international, EU and national legislation and environmental, economic and social impacts and risks. The roundtable could also increase the acceptability of public policies and improve the effectiveness of their implementation.

A key enabling factor is **signing agreements with countries storing carbon dioxide**. Current international law requires bilateral agreements to export carbon dioxide for storage, although in the future this could be addressed at the EU level. Finland should follow the example of, for example, Belgium and sign agreements with countries such as Norway that has an advanced capability to receive carbon dioxide for storage.

While preparing financial incentives (see below), Finland could **support voluntary markets** as one of the key drivers for CDR. Finland could facilitate the growth of voluntary markets, help ensure their quality and nudge them towards permanent removals.

Concrete tools could include information, guidelines, registries and, possibly, regulation. A key challenge is to create robust and functioning voluntary carbon market that would be attractive in boosting deployment of CDR resulting in additional mitigation impacts.

Finally, Finland can **play a more active role in international initiatives**. This can help in both bringing state-of-the-art knowledge to Finland and introducing Finnish perspectives to international discussions. As various initiatives already exist (e.g. the CDR Launchpad under Mission Innovation), Finland should primarily latch on to them. However, in emerging areas (such as enhanced weathering) also establishing new initiatives should be considered.

6.4.2 Introduce financial incentives

There is a clear need to introduce financial incentives for CCUS and CDR solutions. The measures can be grouped in two baskets depending on whether they focus on development or deployment. In addition to national measures, EU funding windows (e.g. the Innovation Fund) should be used to the maximum extent.

Based on the examples of peer countries such as Denmark, Sweden and Norway, **dedicated funding programmes** should be introduced for the full RDI chain from research to piloting. Existing mechanisms (such as Business Finland and the Climate Fund) provide platforms that would make providing funding faster and cut administrative costs. To have a meaningful impact, the funding should be large and long-term enough.

There is also a clear need to introduce **financial incentives for deploying the solutions**, most notably technological CDR. The incentives should provide enough visibility and stability for investors, so that large and possibly risky investment decisions can be made. However, it is not yet clear which policy mechanism to choose and how to design it to achieve maximum impact and efficiency. Therefore, a study should be commissioned about financial incentives, such as reverse auctions and tax credits. Based on the findings, decisions to introduce incentives should be made. Timewise, deciding on the financial incentives should be a key priority, since the uncertainty of future business is the main identified bottleneck for deploying CDR technologies in a large-scale.

6.4.3 Commission further studies to inform policy making

There is a wide range of policy options available and emerging to promote CCUS and CDR solutions. However, for many of them, further studies are needed to inform the choices of policy makers. The studies should address issues such as impact, costs, business opportunities, strategic planning of CO_2 transportation infrastructure, material property requirements of long-lifespan CCU products, product standard revision possibilities, political feasibility and policy design.

Additional policy options that require further information include mandating either capturing carbon or blending it as a raw material; setting a national emission price floor; requiring mining companies to estimate the storage potential of mining wastes; signing a Green Deal to use public procurement for CCU; and setting an end date for releasing fossil carbon from large point sources. A study could cover these and other potential policy options, comparing their benefits, challenges and design choices.

Studies relevant for a CCUS and CDR strategy and road map include identification of strategically important technology demonstrations and needs to prioritise certain technologies or sectors. The study should consider multiple criteria and their trade-offs, including sustainability and biodiversity effects, impact on national economy and the greenhouse gas reduction potential.

Further research is also required on **CCUS and CDR solutions that are less technologically mature or have a less robust evidence base**. These include, for example, enhanced weathering and solutions relying on sea ecosystems.

Annexes

Annex 1: Policy benchmarking

Norway

Regulation:

- CCS regulation. CCS Directive 2009/31/EC was implemented through 1) the CO_2 Storage Regulations, 2) a new chapter in the Pollution Control Regulations, and 3) a new chapter in the Petroleum Regulations. Together with the CO_2 Safety Regulations, these make up a comprehensive regulatory framework. Norwegian Ministry of Petroleum and Energy (2020). https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/en-gb/pdfs/stm201920200033000engpdfs.pdf
- Transferring storage responsibilities. Following closure of a storage site, obligations on monitoring and corrective measures are transferred to the state if four conditions are met: 1) information indicates that the CO_2 will remain completely and permanently contained, 2) a minimum period no shorter than 20 years has elapsed, 3) financial obligations have been fulfilled, 4) the storage site has been prudently abandoned and the injection facilities removed. Norwegian Ministry of Petroleum and Energy (2020). https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/en-gb/pdfs/stm201920200033000engpdfs.pdf
- Monitoring obligations. The storage operator shall make a financial contribution available to the State. The contribution shall, as a minimum, cover anticipated monitoring costs for a period of 30 years. Norwegian Ministry of Petroleum and Energy (2020). https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/en-gb/pdfs/stm201920200033000engpdfs.pdf
- CCS obligation. Snoehvit project had a mandatory requirement for CCS. Global CCS Insittute (2020) https://cdrlaw.org/wp-content/uploads/2020/10/Overview-of-Organisations-and-Policies-Supporting-the-Deployement-of-Large-Scale-CCS-Facilities-2.pdf

Trading and taxation:

- Carbon tax. The tax applies to the oil and gas industry on top of the ETS, creating an incentive for CCS. Global CCS Insittute (2020) https://cdrlaw.org/wp-content/uploads/2020/10/Overview-of-Organisations-and-Policies-Supporting-the-Deployement-of-Large-Scale-CCS-Facilities-2.pdf
- CO_2 pricing for Longship. For CO_2 outside of the ETS, the companies in Longship receive funding equal to the allowance price for CO_2 captured. If the emissions are subject to a tax, the value of the carbon tax will be subtracted from the allowance price. The funding applies also to biogenic CO_2. Norwegian Ministry of Petroleum and Energy (2020). https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/en-gb/pdfs/stm201920200033000engpdfs.pdf

Funding (deployment)

- Technology Centre Mongstad 2012–23. TCM calls itself the world’s largest and most flexible test centre for developing CO_2 capture technologies and a leading competence centre for carbon capture. The largest owner of TCM is Gassnova, a state-owned enterprise. https://tcmda.com/
- Longship funding: capture. The state covers all investment and operating costs for CO_2 capture in the Longship project up to a threshold and 75 % of the costs above it for ten years from the start of operations. The maximum cost is capped. Norwegian Ministry of Petroleum and Energy (2020). https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/en-gb/pdfs/stm201920200033000engpdfs.pdf
- Longship funding: storage. The state covers 80 % of the investment costs and companies 20 %. In the operational phase, the state covers 95 % for the first year, 90 % the second year, 85 % the third year and then 80 % from the fourth year and the remainder of the funding period (ten years from the start of operations). If a second well or third ship is needed, the state covers 50 % of costs, with the max amount of funding limited to NOK 830 M. The state will also bear a share of the cost risk for unexpected incidents. The max cost is capped. Norwegian Ministry of Petroleum and Energy (2020). https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/en-gb/pdfs/stm201920200033000engpdfs.pdf

Funding (RDI)

- National research programme for CCS technologies (CLIMIT). CLIMIT's objective is to contribute to the development of technology and solutions for CCS by providing financial support to projects that will: 1) Develop knowledge, expertise, technology and solutions that can contribute towards cost reductions and international deployment of CCS; 2) Leverage national advantages and develop new technology and service concepts with commercial and international potential. https://climit.no/en/
- Norwegian CCS Research Centre (NCCS). NCCS is an international research cooperation on CCS, co-financed by the Research Council of Norway, industry and research partners. NCCS is financed by the Norwegian government through the Research Council of Norway's Centres for Environment-friendly Energy Research (FME) programme. The Centre will operate for eight years (2016–2024). https://nccs.no/

Other (strategies, guidelines etc.)

- Gassnova SF. Established in 2008, the state-owned enterprise promotes CCS development, including through CLIMIT and TCM. According to the IEA, Gassnova has played a pivotal role in co-ordinating the full-scale CCS feasibility studies at industrial sites. https://gassnova.no/en/
- CO_2 Storage Atlas. The Atlas of the Norwegian part of the North Sea has been prepared by the Petroleum Directorate, on request by the Ministry of Petroleum and Energy. One key objective is to provide input on where it is possible to implement safe long-term storage of CO_2, and how much capacity there is for geological storage. Norwegian Petroleum Directorate. https://www.npd.no/globalassets/1-npd/publikasjoner/atlas-eng/co2-atlas-north-sea.pdf

United Kingdom

Regulation:

- The Energy Act 2008. Provides for a licensing regime that governs the offshore storage of CO_2. It forms part of the transposition into UK law of EU Directive 2009/31/EC on the geological storage of CO_2. UK Public General Acts (2008). https://www.legislation.gov.uk/ukpga/2008/32/contents
- Energy Security Bill (in progress). A Bill to make provision about, e.g. energy production and security and the regulation of the energy market, including provision about the licensing of CO_2 transport and storage; commercial arrangements for industrial CCS and for hydrogen production. Bill will introduce state of the art business models for CCUS and hydrogen, attracting private investment by providing long-term revenue certainty. The Bill will establish the economic regulation and licensing framework to ensure successful deployment. UK Parliament (2022). https://bills.parliament.uk/bills/3311
- The Storage of Carbon Dioxide (Licensing etc.) Regulations (2010). Regulates the issuance of CO_2 appraisal and storage licenses (each, a CS License) and storage permits and set out a number of requirements for CCUS operations. UK Statutory Instruments (2010). https://www.legislation.gov.uk/uksi/2010/2221/contents/made
- The Storage of Carbon Dioxide (Termination of Licences) Regulations (2011). Regulates the liability for a closed CCUS site upon termination of a CS License. UK Statutory Instruments (2011). https://www.legislation.gov.uk/uksi/2011/1483/contents/made
- The Environmental Permitting (England and Wales) (Amendment) Regulations (2011). Regulates the permitting regime for CO_2 capture and discharges to groundwater. UK Statutory Instruments (2011). https://www.legislation.gov.uk/uksi/2011/2043/contents/made

Trading and taxation:

- Dispatchable Power Agreement (DPA) proposal. The government has consulted stakeholders on a proposal to introduce a contract for difference for power production using CCS. Natural gas fired power plants using CCS would get an availability payment and a variable payment. Department of Business, Energy & Industrial Strategy (2022). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1117566/ccus-dispatchable-power-agreement-business-model-summary.pdf

Funding (deployment):

- CCS Infrastructure Fund (2021). The government has committed to deploy CCUS in 4 industrial clusters, aiming to capture 10MtCO$_2$ a year by 2030. The CCS Infrastructure Fund, announced in 2020, will support capital expenditure on transport and storage (T&S) networks and industrial carbon capture (ICC) projects. Department of Business, Energy & Industrial Strategy (2021). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/984001/ccs-infrastructure-fund-cif-design.pdf
- Cluster sequencing for CCUS deployment: Phase-1 (2021). Phase-1 of the cluster sequencing process will identify and sequence CCUS clusters which are suited to deployment in the mid-2020s. These clusters will have the first opportunity to negotiate for support from the government's CCUS programme. Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2021). https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-deployment-phase-1-expressions-of-interest
- Cluster sequencing for CCUS deployment: Phase-2 (2021). Phase-2 was open to Power, Industrial Carbon Capture and Hydrogen production projects which meet the technology specific eligibility criteria. Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2021). https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-deployment-phase-2
- Industrial Decarbonization and Hydrogen Revenue Support (2021). The government will invest £140 million to fund new hydrogen and industrial carbon capture business models, which includes up to £100 million to award contracts of up to 250MW of electrolytic hydrogen production capacity in 2023, with further allocations in 2024. Department of Business, Energy & Industrial Strategy (2022). https://www.gov.uk/government/publications/beis-government-major-projects-portfolio-accounting-officer-assessments/industrial-decarbonisation-and-hydrogen-revenue-support-accounting-officer-assessment-2022-html
- Scotland: Emerging Energy Technologies Fund (2020). £180 million fund to support the development of the hydrogen sector and CCS, including NETs in Scotland. Cabinet Secretary for Net Zero, Energy and Transport (2020). https://www.gov.scot/policies/renewable-and-low-carbon-energy/emerging-energy-technologies-fund/#:~:text=The%20Climate%20Change%20Plan%20Update,Technologies%20(NETs)%20in%20Scotland
- Acorn CCS Project. Acorn CCS is a carbon capture and storage project specifically designed to overcome one of the acknowledged blockers to CCS deployment in the UK. The project is funded and supported by industry partners (Storegga, Shell, Harbour Energy and NSMP), the UK and Scottish Governments and the EU. https://www.theacornproject.uk/about-acorn

Funding (RDI):

- DAC and other Greenhouse Gas Removal technologies competition (2020). This competition will provide funding for developing technologies that enable the removal of greenhouse gases from the atmosphere in the UK. Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2020). https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition
- Hydrogen BECCS Innovation Programme (2022). BEIS is providing £5 million in funding to support innovation in hydrogen BECCS technologies. Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2022). https://www.gov.uk/government/publications/hydrogen-beccs-innovation-programme
- Carbon Capture, Usage and Storage (CCUS) Innovation 2.0 programme (2022). Up to £20 million grant funding is available over 2 calls to: support innovation in novel CCUS technology increasing its technology and commercial readiness level (TRL & CRL) demonstrate and de-risk next generation CCUS technologies to allow it to deploy commercially from 2025 reduce the cost of deploying CCUS and create competitive pressure on current available technology. Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2022). https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-innovation-20-competition-call-2
- CCUS Innovation Programme (2018). BEIS launched a call for CCUS Innovation in July 2018 to offer grant funding (Up to £24 million) for world-leading research and innovation projects that offer: a significant reduction in the cost of CCS; and/or a quicker, more widespread deployment of CCUS in the UK and internationally. Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2018). https://www.gov.uk/government/publications/call-for-ccus-innovation
- Scotland: CO_2 Utilisation Challenge Fund (2022). £5 million fund will help businesses and organisations develop and commercialise the technology, which involves harnessing and converting CO_2 and using it to produce valuable products such as synthetic fuels and proteins for use in aquaculture. Scottish Government (2022). https://www.gov.scot/news/gbp-5-million-to-develop-carbon-dioxide-utilisation-technology/

Other (strategies, guidelines etc.)

- National Infrastructure Strategy (2020). The Government will: Invest £1 billion to bring forward four CCS clusters by the end of the decade, with two to begin construction by the mid 2020s; Set an ambition to capture 10 megatons of carbon dioxide per year by 2030; and Outline further details in 2021 on a revenue mechanism to bring through private sector investment into transport and storage, power and industry CCS and hydrogen projects via new business models to support these projects. HM Treasury (2022). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/938539/NIS_Report_Web_Accessible.pdf

- The UK carbon capture usage and storage deployment pathway: an action plan (2018). The next steps government and industry should take in partnership in order to achieve the government's ambition of having the option to deploy CCUS at scale during the 2030s, subject to costs coming down sufficiently. Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2018). https://www.gov.uk/government/publications/the-uk-carbon-capture-usage-and-storage-ccus-deployment-pathway-an-action-plan
- CCUS Council. The purpose of the CCUS Council is to review progress and priorities on CCUS. It is also the primary forum for engaging the CCUS sector on CCUS issues. https://www.gov.uk/government/groups/ccus-council
- A Carbon Capture, Utilisation, and Storage Network for Wales (2021). The Welsh Government has a statutory target to reduce emissions by at least 100 % (net zero) in 2050 compared to 1990. This report outlines how CCUS could help meet the net zero goal in Wales. It considers a range of different CCUS uptake levels, in order to model a range of decarbonisation pathways driving varying technology needs, CO_2 export options and associated costs. Welsh Government (2021). https://www.gov.wales/sites/default/files/publications/2021-10/a-carbon-capture-utilisation-and-storage-network-for-wales-report.pdf
- Net Zero Strategy: Build Back Greener (2021). This strategy sets out policies and proposals for decarbonising all sectors of the UK economy to meet the net zero target by 2050. Includes commitments for different sectors including carbon capture. Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2021). https://www.gov.uk/government/publications/net-zero-strategy
- The ten point plan for a green industrial revolution (2020). The ten point plan sets out the approach government will take to build back better, support green jobs, and accelerate the path to net zero. Point 8: Investing in CCUS, including Commitment for two industrial clusters by mid 2020s, and an aim for four sites by 2030, capturing up to 10Mt CO_2 per year & £1 billion CCUS Infrastructure Fund. Department of Business, Energy & Industrial Strategy, Prime Minister's Office , 10 Downing Street & Department of Energy Security & Net Zero (2021). https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

- Biomass Policy Statement (2021). A strategic view on the role of biomass across the economy in the medium- to long-term. Key principles include: biomass to be used with CCUS where feasible, otherwise used only in hard-to-decarbonise sectors with limited or no low carbon alternatives. Department of Business, Energy & Industrial Strategy (2021). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1031057/biomass-policy-statement.pdf
- UK's carbon storage licensing round by The North Sea Transition Authority (2022). UK's first-ever carbon storage licensing round with 13 areas of potential available. The North Sea Transition Authority (2022). https://www.nstauthority.co.uk/news-publications/news/2022/bids-invited-in-uk-s-first-ever-carbon-storage-licensing-round/
- Carbon capture, usage and storage (CCUS): investor roadmap (2022). Outlines key opportunities to invest in CCUS in the UK. Outlines joint government and industry commitments to the deployment of CCUS in the UK and sets out the approach to delivering 4 CCUS low carbon industrial clusters, capturing 20–30 $MtCO_2$ per year across the economy by 2030 to help meet the UK's 2050 net zero target. . Department of Business, Energy & Industrial Strategy & Department of Energy Security & Net Zero (2022). https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-investor-roadmap

United States of America

Regulation:

- California low-carbon fuel standard (LCFS): CCS protocol. Describes the requirements that CCS projects must meet in order to generate LCFS credits.) Post-injection monitoring requirement is 100 years (whereas in most of the USA the rquirement is 50 years). International Energy Agency. https://iea.blob.core.windows.net/assets/bda8c2b2-2b9c-4010-ab56-b941dc8d0635/LegalandRegulatoryFrameworksforCCUS-AnIEACCUSHandbook.pdf
- Federal Carbon Dioxide Removal Leadership Act of 2022 (Bill). An act to amend the environmental conservation law, in relation to enacting the CO_2 removal leadership act; and to repeal certain provisions of the tax law relating to taxes on CO_2. The Act would Direct the Department of Energy (DOE) to use technology-based approaches to annually remove an increasing amount of CO_2, culminating in removal of 10 M net metric tons of CO_2 on a lifecycle basis starting in fiscal year 2035; support a diverse portfolio of viable CDR projects – including a special carve-out for small-scale projects; instruct DOE to ensure that best practices for monitoring, reporting and verifying carbon removals

are applied to any funded projects. 117th Congress (2021–2022). https://www.congress.gov/bill/117th-congress/senate-bill/4280/text

- Indiana HOUSE ENROLLED ACT No. 1209. (2022). Carbon sequestration projects. Provides for the mechanism for underground storage of carbon dioxide in Indiana. Indiana General Assembly (2022). https://iga.in.gov/legislative/2022/bills/house/1209#document-4ce28005
- Wyoming's carbon storage and sequestration-liability. An act relating to geologic sequestration of CO_2; clarifying ownership of CO_2 injected into geologic sequestration sites; specifying the transfer of title and liability of injected CO_2; providing definitions; renumbering current statutes; making conforming amendments; specifying applicability; requiring rulemaking; and providing for effective dates. State of Wyoming (2022) https://wyoleg.gov/Legislation/2022/SF0047
- Louisiana's long-term CO_2 liability law. Provides a process for the state to take title to sequestered CO_2 ten years after injections cease. Louisiana State Legislature. http://www.legis.la.gov/legis/Law.aspx?d=670795
- Montana Code Annotated 2021. Certificate of completion -- department of environmental quality participation -- transfer of liability. (1) Pursuant to subsection (3), after carbon dioxide injections into a reservoir end and upon completion of the certification requirements pursuant to subsections (4) and (5), the board shall issue the geologic storage operator a certificate of project completion. Board of Oil and Gas Conservation (2021). https://leg.mt.gov/bills/mca/title_0820/chapter_0110/part_0010/section_0830/0820-0110-0010-0830.html
- Regulations for Carbon Sequestration on the Outer Continental Shelf (In progress). Infrastructure Investment and Jobs Act was signed into law in Nov 2021 and gave the Secretary of the Interior the authority to grant a lease, easement, or right-of-way on the Outer Continental Shelf (OCS) for long-term sequestration of carbon dioxide that would otherwise go into the atmosphere and contribute to further climate change. The Act sets out a one-year timeframe for DOI to promulgate regulations. Bureau of Ocean Energy Management (2022). https://www.boem.gov/about-boem/regulations-guidance/carbon-sequestration
- Louisiana Geologic Sequestration of Carbon Dioxide Act (2009, updated 2022), storage trust fund. The storage operator must pay a fee into a storage trust fund for a minimum of 10 years, up to a maximum of USD 5 M for each operator. International Energy Agency (2022). https://www.iea.org/data-and-statistics/data-tools/ccus-legal-and-regulatory-database?Issue=Financial+assurances+of+long-term+site+stewardship&Regulation=Louisiana+Geologic+Sequestration+of+Carbon+Dioxide+Act&Region=Louisiana+%28United+States%29

- Kansas: The Carbon Dioxide Reduction Act (2022), "carbon dioxide injection well and underground storage fund". This bill directs the Kansas Corporation Commission to establish regulations for permitting CO_2 storage facilities and creates a CO_2 storage fund to cover expenses related to permitting, enforcement, long-term monitoring, and post-closure remediation. International Energy Agency (2022). https://iea.blob.core.windows.net/assets/bda8c2b2-2b9c-4010-ab56-b941dc8d0635/LegalandRegulatoryFrameworksforCCUS-AnIEACCUSHandbook.pdf
- Wyoming: Geologic sequestration special revenue account (Base law: HB 17). Special fund has been established to fund the measurement, monitoring and verification of storage sites following site closure certification. CO_2 storage permit holders pay into this fund either via a lump sum closure fee or as a fee per tonne of CO_2 injected (which has yet to be determined). International Energy Agency (2022). https://www.iea.org/data-and-statistics/data-tools/ccus-legal-and-regulatory-database?Issue=Financial+assurances+of+long-term+site+stewardship&Regulation=HB+17&Region=Wyoming+%28United+States%29
- Montana: An Act Regulating Carbon Sequestration (SB 498), Geologic storage reservoir administrative fee -- account established (2022). The operator has the option of setting up a fund for long-term site management. If the operator opts to hand liability to the state 30 years after well closure, then the operator must pay into a storage fund account during the injection period. However, if the operator opts not to set up a fund, then the operator is liable forthe project indefinitely. Legislative Services Division (2022), https://leg.mt.gov/content/Bills/Primers/Energy/Climate%20Change-Carbon.pdf
- SECURE Act 2022. This bill would increase the authorization of appropriations by $50 million for a state underground injection control program to permit Class VI wells, which store CO_2.

Trading and taxation:

- Tax credits (45Q) (2021). Intended to incentivize investment in CCS. Computed per metric ton of qualified CO_2 captured and sequestered. The amount of the credit, as well as various features of the credit, depend on when the qualifying capture equipment is placed in service. Congressional Research Service (2021). https://sgp.fas.org/crs/misc/IF11455.pdf
- Carbon Capture, Utilization, and Storage Tax Credit Amendments Act of 2021 (Bill). The Act extends the window for projects to begin construction and qualify for the 45Q tax credit to the end of 2030. It establishes a direct pay option for the 45Q and 48A tax credits, allowing recipients to receive the full value of the credits as an estimated payment on their tax return, in lieu of needing to apply the credit to their tax liability. Increases the 45Q credit

value from $50 to $120 per metric ton for direct air capture facilities that capture and securely store carbon dioxide (CO_2) in saline geologic formations. Increases the credit value from $35 to $75 per ton for such facilities that store captured CO_2 in oil and gas fields, or for beneficial utilization as fuels, chemicals and useful products. 117th Congress (2021) https://www.congress.gov/bill/117th-congress/senate-bill/986, Carbon Capture Coalition (2021) https://carboncapturecoalition.org/carbon-capture-coalition-applauds-introduction-of-bipartisan-senate-carbon-capture-utilization-and-storage-tax-credit-amendments-act/

- The Inflation Reduction Act (2022). Under the bill, any carbon capture, direct air capture or carbon utilization project beginning construction before 1.1.2033 will qualify for the federal 45Q tax credit. Legislation boosts credit values to accelerate project deployment and emissions reductions in key sectors, increasing the value of 45Q for industrial facilities and power plants that capture their carbon emissions to $85/t$CO_2$ stored in secure geologic formations, $60/t for the utilization of captured carbon and $60/t stored in oil and gas fields. Includes increased credit values for DAC technologies at $180/t for those projects storing CO_2 in secure geologic formations, $130/t for carbon utilization and $130/t for CO_2 stored in oil and gas fields. Carbon Capture Coalition (2021). https://carboncapturecoalition.org/inflation-reduction-act-of-2022-makes-monumental-enhancements-to-the-foundational-45q-tax-credit/
- Energy Sector Innovation Credit Act of 2021. This bill would establish a flexible tax credit for carbon capture equipment investors and producers. The credit would be available to direct air capture facilities that meet an annual carbon capture requirement of 5,000 metric tons. The investment tax credit for DAC would be eligible to stack with a 45Q credit for non–enhanced oil recovery geologic storage projects. The legislation intends to phase out subsidy support for these technologies as they scale their physical and market impact. 117th Congress (2021) https://www.congress.gov/bill/117th-congress/senate-bill/2475#:~:text=Introduced%20in%20Senate%20(07 %2F27 %2F2021)&text=This%20bill%20adds%20new%20tax,electricity%20from%20emerging%20energy%20technology
- Clean Energy for America Act (2021). This bill would modify the Section 45Q CO_2 sequestration tax credit by authorizing the direct payment of credits and removing minimum carbon capture thresholds to incentivize smaller projects. The bill would also make enhanced oil recovery ineligible after 2026, increase the credit amount for DAC facilities to $175 per ton for secure geologic storage and $150 for utilization, set a minimum wage requirement based on Department of Labor standards, and require that 15 % of total labor for constructing a credit-eligible facility be performed by qualified

apprentices. 117th Congress (2021) https://www.congress.gov/bill/117th-congress/senate-bill/1298?q=%7B%22search%22 %3A%5B%22Clean+Energy+-for+America+Act%22 %5D%7D&s=1&r=1#:~:text=Introduced%20in%20Senate%20(04 %2F22 %2F2021)&text=This%20bill%20provides%20tax%20incentives,requirements%20for%20the%20energy%20sector

Funding (deployment):

- Infrastructure Investment and Jobs Act (2021). Provides new funding for infrastructure projects. TITLE III--FUELS AND TECHNOLOGY INFRASTRUCTURE INVESTMENTS: This title reauthorizes, expands, and establishes programs that support infrastructure or technology for capturing, utilizing, storing, transporting, or removing carbon dioxide; TITLE IV--BOND PROVISIONS: This title adds broadband as an allowable use for private activity bonds and allows carbon capture and direct air capture technologies to be eligible for private activity bond financing. Department of Energy (2021). https://www.energy.gov/articles/biden-harris-administration-announces-over-23-billion-investment-cut-us-carbon-pollution
- CarbonSAFE: Phase II – Storage Complex Feasibility Funding Opportunity (2022). This Funding Opportunity will accelerate wide-scale deployment of CCS by potentially awarding additional projects to support the CarbonSAFE Initiative, DOE's flagship effort to move carbon storage technologies into geographically widespread commercial practice. Department of Energy (2022). https://www.fedconnect.net/FedConnect/default.aspx?ReturnUrl=%2FFedConnect%2F%3Fdoc%3DDE-FOA-0002610 %26agency%3DDOE&doc=DE-FOA-0002610&agency=DOE
- Consolidated Appropriations Act, 2022. Building on the Infrastructure Investment and Jobs Act, this omnibus legislation will direct $2 billion towards the deployment or improvement of existing and new fossil-fueled electric generating plants that utilize CCUS systems. Until September 30, 2023, $825 M will be allocated to the Department of Energy's Office of Fossil Energy and Carbon Management (FECM) for the advancement of carbon reduction and mitigation pathways and technologies. This amount is dedicated to the R&D of a number of carbon capture and removal pathways, including oceans-based CDR, BECCS, carbon-neutral methanol, and carbon utilization. 117th Congress (2022). https://www.congress.gov/bill/117th-congress/house-bill/2471
- The Utilizing Significant Emissions with Innovative Technologies (USE IT) Act (2019). Amends the US Clean Air Act to support CCU and DAC research, as well as the construction and development of CCUS facilities and CO_2 pipelines. International Energy Agency (2019). https://www.iea.

org/policies/11669-the-utilizing-significant-emissions-with-innovative-technologies-use-it-act

- Bipartisan Infrastructure Law (2022). $3.5 billion program to capture and store CO_2 pollution directly from the air. Department of Energy (2022). https://www.energy.gov/articles/biden-harris-administration-announces-over-23-billion-investment-cut-us-carbon-pollution
- American Jobs in Energy Manufacturing Act of 2021. This bill would invest $8 billion in American clean energy manufacturing and industry, creating jobs that draw on existing skilled workforces from manufacturing, coal mining, or retired coal power plants. The bill would support building or retrofitting facilities to recycle or produce clean energy products, including products from carbon capture, utilization, and storage. The bill would also amend the Internal Revenue Code to qualify projects that remove, use, and sequester carbon for advanced energy production tax credits. . Mancin, Bill (2021). https://www.manchin.senate.gov/imo/media/doc/AJEM%20one-pager_NATIONAL_final.pdf?cb
- The Carbon Removal and Emissions Storage Technologies (CREST) Act of 2022. This bill would build upon previously authorized carbon removal research and development programs across land-based solutions that lead to permanent storage or utilization. The bill would also creates a five-year pilot carbon removal purchasing program that uses reverse auction procedures to accelerate the deployment and commercialization of carbon removal pathways and carbontech products. Collins, Susan (2022). https://www.collins.senate.gov/imo/media/doc/crest_act_summary.pdf

Funding (RDI):

- Carbon Negative Shot. Carbon Negative Shot is an all-hands-on-deck call for innovation in CDR pathways that will capture CO_2 from the atmosphere and durably store it at gigaton scales for less than $100/net metric ton of CO_2-equivalent. Office of Fossil Energy and Carbon Management. https://www.energy.gov/fecm/carbon-negative-shot
- DoE DAC funding: Four Regional Clean Direct Air Capture Hubs. Program under which the Secretary shall provide funding for eligible projects that contribute to the development of 4 regional direct air capture hubs. A regional direct air capture hub that-- (i) facilitates the deployment of direct air capture projects; (ii) has the capacity to capture and sequester, utilize, or sequester and utilize at least 1,000,000 metric tons of carbon dioxide from the atmosphere annually from a single unit or multiple interconnected units; (iii) demonstrates the capture, processing, delivery, and sequestration or end-use of captured carbon; and (iv) could be developed into a regional or interregional carbon network to facilitate sequestration or carbon utilization.

$700,000,000 annually for the period of fiscal years 2022 through 2026. Office of Clean Energy Demonstrations (2022). https://www.energy.gov/oced/regional-direct-air-capture-hubs

- Commercial Direct Air Capture Technology Prize Competition (2022). The Secretary shall award prizes under the prize competition to qualified direct air capture facilities for metric tons of qualified carbon dioxide captured and verified at the point of disposal, injection, or utilization. Funding amount: $100,000,000. Office of Fossil Energy and Carbon Management (2022). https://www.energy.gov/fecm/commercial-direct-air-capture-technology-prize-competition
- Carbon Dioxide Transportation Infrastructure Finance and Innovation Program (2022). To establish and carry out a carbon dioxide transportation infrastructure finance and innovation program. Eligible projects: 1. are large-capacity, common carrier infrastructure; 2. have demonstrated demand for use of the infrastructure by associated projects that capture CO_2 from anthropogenic sources or ambient air; 3. enable geographical diversity in associated projects that capture CO_2 from anthropogenic sources or ambient air, with the goal of enabling projects in all major CO_2-emitting regions of the US. Loan Programs Office (2022). https://www.energy.gov/lpo/carbon-dioxide-transportation-infrastructure-finance-and-innovation-program
- Carbon Management Funding Opportunity (2022). This funding opportunity aims to expand the Department of Energy, Office of Fossil Energy and Carbon Management's carbon management portfolio through support for R&D projects in the programmatic areas of Carbon Conversion, Carbon Dioxide Removal, Point Source Carbon Capture, and Carbon Storage. Department of Energy (2022). https://www.fedconnect.net/FedConnect/default.aspx?ReturnUrl=%2Ffedconnect%3Fdoc%3DDE-FOA-0002614 %26agency%3DDOE&doc=DE-FOA-0002614&agency=DOE
- Carbon Utilization Program (2022). Eligible entities (state; local government; public utility or agency) shall use a grant to procure and use commercial or industrial products that (i) use or are derived from anthropogenic carbon oxides; and (ii) demonstrate significant net reductions in lifecycle GHG emissions compared to incumbent technologies, processes, and products. Secretary of Labor (2022). https://uscode.house.gov/view.xhtml?req=(title:42 %20section:16298a%20edition:prelim)
- American Recovery and Reinvestment Act (2009). Provided $3.4 billion for CCS projects and activities at DOE. The large infusion of funding was intended to help develop technologies that would allow for commercial-scale demonstration of CCS in both new and retrofitted power plants and industrial facilities by 2020. Nine individual projects garnered approximately $2.65

billion of the $3.4 billion–about 78 %. Congressional Research Service (2016). https://crsreports.congress.gov/product/pdf/R/R44387

- Energy Act 2020 (CCUS provisions). The Act includes almost USD 7 billion in authorization for various carbon management and removal programs over 5 years. E.g. large-scale pilot projects and commercial-scale demonstrations in key sectors such as heavy industry, development of large scale storage projects, establishment of a carbon removal program including a DAC technology prize competition, a carbon utilization programme. International Energy Association (2020). https://www.iea.org/policies/13192-energy-act-of-2020-ccus-provisions
- The National Carbon Capture Center. A research facility working to accelerate the commercialization of advanced technologies to reduce GHG emissions. Scope includes carbon capture for point sources such as natural gas power generation, carbon utilization and conversion, and NETs such as DAC. Sponsored by by DoE (and actors in energy industry). https://www.nationalcarboncapturecenter.com/our-mission
- Federal Carbon Dioxide Removal Leadership Act of 2022.This bill would require the federal government to procure carbon removal on a yearly basis starting in 2024. The first of its kind, the bill incrementally increases the quantity of carbon removed each year, requiring at least 10 million metric tons per year beginning in 2035. The bill gauges economic feasibility at different year milestones, aiming for a cost per ton of $150 by 2035. This feasibility framework takes into account the costs associated with the monitoring, reporting, and verification (MRV) of removal and storage.117th Congress (2022). https://www.congress.gov/bill/117th-congress/senate-bill/4280/text#:~:text=Introduced%20in%20Senate%20(05 %2F19 %2F2022)&text=To%20require%20the%20Secretary%20of,seawater%2C%20and%20for%20other%20purposes.&text=To%20require%20the%20Secretary%20of,seawater%2C%20and%20for%20other%20purposes
- Department of Energy Science for the Future Act of 2022. This bill would strengthen investment in scientific research to understand physical, chemical, and biological processes to transform, immobilize, remove, transport, and sequester CO_2 and other energy production derived contaminants. 117th Congress (2022). https://www.congress.gov/bill/117th-congress/house-bill/3593

Other (strategies, guidelines etc.)

- THE LONG-TERM STRATEGY OF THE UNITED STATES: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. United States Department of State and the United States Executive Office of the President, Washington DC (2021).

https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

- Carbon Capture, Utilization, and Sequestration Guidance (2022, in progress). Assists Federal agencies with the regulation and permitting of CCUS activities in the US. Council of Environmental Quality (2022). https://www.federalregister.gov/documents/2022/02/16/2022-03205/carbon-capture-utilization-and-sequestration-guidance
- Regional Carbon Sequestration Partnertships (RCSP) Initiative. Network of seven Regional Carbon Sequestration Partnerships (RCSPs). Created by DoE to support the development of regional infrastructure for CCS. https://netl.doe.gov/carbon-management/carbon-storage/RCSP
- An Interactive Diagram for Carbon Management Provisions. An interactive online tool that highlights carbon management provisions in Bipartisan Infrastructure Law and through other DOE funding opportunities. Office of Fossil Energy and Carbon Management. https://www.energy.gov/fecm/interactive-diagram-carbon-management-provisions
- Biochar Research Network Act of 2022. This bill would establish a national biochar research network of 20 sites dedicated to testing biochar across diverse soil types, soil conditions, application methods, climates, and agronomic contexts. The network would aim to assess the carbon removal potential of biochar solutions, understand how to use biochar for climate, productivity, and resilience goals, and deliver practical information on sustainable biochar to producers. 117th Congress (2022). https://www.grassley.senate.gov/imo/media/doc/biochar_research_network_act_of_2022.pdf
- Clean Energy Jobs Act of 2022. This bill would promote a 21st century energy workforce through a suite of workforce development, education, and outreach programs, primarily at the Department of Energy. The bill’s programs prioritize outreach and training for underrepresented groups and workers transitioning from fossil energy jobs. The bill includes carbon removal as a key industry for developing a clean energy workforce and directly calls out geologic storage, direct air capture, carbon conversion and use, and long-term biological pools like agriculture and forestry. 117th Congress (2022). https://www.congress.gov/bill/117th-congress/senate-bill/4640?s=1&r=23#:~:text=This%20bill%20directs%20the%20Department,the%20number%20of%20skilled%20individuals
- Carbon Sequestration Collaboration Act 2022. This bill would establish a coordinated interagency Carbon Seqeuestration Research Initiative across the Departments of Energy, the Interior, and Agriculture. Research under the initiative would seek to enhance understanding of carbon sequestration through land management and geologic storage, specifically to understand

permanence, environmental impacts, risk management, and baseline data for future research, development, and demonstration. 117th Congress (2022). https://www.congress.gov/bill/117th-congress/house-bill/8337?s=1&r=8

- REMOVE Act of 2022. This bill would establish a Committee on Large-Scale Carbon Management in the Department of Energy to develop a strategic plan for federal experimentation, modeling, and production of carbon removal technologies. This work would include establishing interagency working groups, budgeting for and evaluating carbon removal activities, and monitoring their community impacts. The bill directs federal agencies to include the development of carbon removal as part of their annual budget request and ensure coordination across the federal government. World Resources Institute (2022). https://www.wri.org/update/remove-act-carbon-removal

Canada

Regulation:

- Clean Fuel Standard (2021). Requires producers and importers to reduce the carbon intensity of liquid fossil fuels used in Canada from 2016 levels. To drive innovation at the lowest cost, the CFS establishes a credit market. One way to earn credits: Compliance category 1: undertaking projects that reduce the lifecycle carbon intensity of fossil fuels (e.g. CCS). Government of Canada (2021). https://laws-lois.justice.gc.ca/eng/acts/c-19.3/FullText.html

Trading and taxation:

- CCUS Tax Credit (2022) Incentive to companies that invest in carbon-capture technologies and will set aside as much as C$3.8 billion ($3 billion) over eight years to accelerate critical mineral exploration, extraction and processing as it seeks to cut carbon emissions. 60 % tax credit for equipment used to capture carbon from the air, and 50 % for all other capture equipment, plus a 37.5 % credit for transportation and storage equipment. Reuters (2021). https://www.reuters.com/business/sustainable-business/canada-creates-carbon-capture-incentives-critical-mineral-plan-cut-emissions-2022-04-07/
- Saskatchewan: Oil and Gas Processing Investment Incentive (OGPII). Offers transferable oil and gas royalty/freehold production tax credits for qualified greenfield or brownfield value-added projects at a rate of 15 per cent of eligible program costs. Eligible projects include: Carbon capture, utilization, and storage for enhanced oil recovery. Saskatchewan Regulations (2019). https://www.

saskatchewan.ca/business/agriculture-natural-resources-and-industry/oil-and-gas/oil-and-gas-incentives-crown-royalties-and-taxes/oil-and-gas-processing-investment-incentive

Funding (deployment):

- Energy Innovation Program (EIP). EIP advances clean energy technologies that help Canada meet its climate targets, while supporting the transition to a low-carbon economy. It funds RD&D projects, and other related scientific activities. Funding stream 2: Carbon capture, utilization and storage stream. Government of Canada (2022). https://natural-resources.canada.ca/science-and-data/funding-partnerships/funding-opportunities/funding-grants-incentives/energy-innovation-program/energy-innovation-program-carbon-capture-utilization-and-storage-stream/23815
- Net Zero Accelerator Initiative (2022). Provides up to $8 billion in support of projects that will enable Canada to reduce its emissions. The initiative will support projects that promote: Decarbonisation of large emitters. Examples could include, but are not limited to: adoption of CCUS. Government of Canada (2022). https://ised-isde.canada.ca/site/strategic-innovation-fund/en/net-zero-accelerator-initiative
- Alberta: Industrial Energy Efficiency, Carbon Capture Utilization and Storage Grant Program. The Program offers funding support for industrial energy efficiency and CCUS projects. https://www.alberta.ca/carbon-capture-utilization-and-storage-development-and-innovation.aspx
- Low Carbon Economy Fund. Supports projects that help to reduce Canada’s emissions, generate clean growth, build resilient communities, and create good jobs for Canadians. CCU & CCS are included. Government of Canada (2022). https://www.canada.ca/en/environment-climate-change/services/climate-change/low-carbon-economy-fund/challenge/champions-stream-summarized-2022-applicant-guide.html#toc6

Funding (RDI):

- CCUS RD&D. Canada is investing $319 million over seven years, into research, development, and demonstrations to advance the commercial viability of CCUS technologies. These funds will bring together businesses, academia, non-profits, industry, and governments on the path to net-zero emissions by 2050. Government of Canada (2022). https://natural-resources.canada.ca/our-natural-resources/energy-sources-distribution/carbon-management/4275

Other (strategies, guidelines etc.)

- 2030 EMISSIONS REDUCTION PLAN Canada's Next Steps for Clean Air and a Strong Economy (2022). Helping industries develop and adopt clean technology in their journey to net-zero emissions. Canada is positioning its industries to be green and competitive. This includes developing a CCUS strategy, introducing an investment tax credit to incentivize the development and adoption of this important technology. Environment and Climate Change Canada (2022). https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/erp/Canada-2030-Emissions-Reduction-Plan-eng.pdf
- CCUS strategy (in progress). Recognizing that CCUS can play an essential role in the transition to a prosperous net-zero economy, we are leading the development of a federal CCUS Strategy that will enable the Canadian CCUS industry to realize its GHG reduction and commercial potential. Government of Canada (2022). https://natural-resources.canada.ca/climate-change/canadas-green-future/carbon-capture-utilization-and-storage-strategy/23721
- Saskatchewan: Carbon Capture Utilization and Storage Priorities (2021). With this strategy, Saskatchewan will aim to e.g. Work with the energy sector to evaluate the EOR royalty regime to ensure that CO_2 injection projects remain highly competitive; Explore opportunities for CCUS infrastructure hubs and distribution models; Advance the development of a CCUS GHG credit generation program. Saskatchewan (2021). https://www.saskatchewan.ca/government/news-and-media/2021/september/07/saskatchewan-announces-carbon-capture-utilization-and-storage-priorities

Japan

Regulation:

- Draft legal framework for carbon transport and storage. Japan's industry ministry plans to create a legal framework for carbon capture and storage (CCS) to enable companies to start storing carbon underground or under the seabed by 2030. The ministry plans to submit a draft bill to the Diet in 2023 to establish a new right to store CO_2 in Japan and limit liability of operators in the event of a leak or other events. Reuters (2022). https://www.reuters.com/business/sustainable-business/japan-plans-set-legal-framework-carbon-storage-2022-04-21/

Funding (RDI):

- BECCS pilot. The MoE has awarded funding to the Toshiba 50 MW Mikawa BECCS plant through Demonstration of Sustainable CCS Technology. The pilot will capture 50 % of CO_2 from the plant. Toshiba (2020). https://www.global.toshiba/ww/news/energy/2020/10/news-20201031-01.html
- Storage pilot. Japan CCS Co. was commissioned by the government to test injecting 300,000 t of CO_2 in Tomakomai. https://www.japanccs.com/en/business/demonstration/index.php
- Storage and transport studies. Studies into the geological storage potential and transport by shipping have been commissioned by the government. https://www.japanccs.com/en/business/research/index.php
- Research Institute of Innovative Technology for the Earth (RITE). The state-funded RITE has two CCS-related research areas (capture and storage) out of five. https://www.rite.or.jp/en/
- Moonshot R&D programme. The Moonshot Research and Development Program, coordinated by the Cabinet Office of Japan, was established to promote ambitious R&D based on bold ideas, with the aim of stimulating disruptive innovation. Under the programme, run by NEDO, one of the projects develops technologies to recover GHGs and convert them into valuable materials. New Energy and Industrial Technology Development Organization. https://www.nedo.go.jp/english/news/ZZCA_100007.html?from=b
- Green Innovation Fund. The NEDO-run Fund has carbon recycling and materials industry as one topic out of 14. New Energy and Industrial Technology Development Organization. https://green-innovation.nedo.go.jp/en/about/
- Osaki RD&D base. A facility, supported by NEDO, to demonstrate carbon recycling technologies. Suzuki Kyoichi, New Energy and Industrial Technology Development Organization (2021). https://jcoal-ccd2022.com/file/program/program_suzuki.pdf

Other (strategies, guidelines etc.)

- CCUS in the Long-Term Strategy (LTS). The LTS has a significant focus on CCUS, including synthetic fuels and materials, BECCS and DAC RD&D, cost reductions, transport and storage infrastructure. The Government of Japan (2021). https://unfccc.int/sites/default/files/resource/Japan_LTS2021.pdf
- Technology roadmap. Japan has a separate Roadmap for Carbon Recycling Technologies. It looks at chemicals, liquid fuels and concrete products in three phases: current, until 2030 and beyond 2030. Ministry of Economy, Trade and Industry (2021). https://www.meti.go.jp/english/press/2021/pdf/0726_003a.pdf

- CCS roadmap. The roadmap sets a target of 6-12 Mt/a of storage capacity by 2030. Reuters (2023). https://www.reuters.com/business/energy/japan-sets-carbon-capture-roadmap-with-6-12-mln-tonneyear-target-by-2030-2023-01-26/

Sweden

Regulation:

- Transport and storage agreement with Norway. Sweden is preparing a bilateral agreement with Norway about transporting and storing carbon. An agreement between the countries is required under the London Protocol to allow carbon dioxide to be transported across their land border. Government offices of Sweden (2022). https://www.government.se/articles/2022/04/norway-and-sweden-agree-to-intensify-cooperation-on-carbon-capture-and-storage/
- Storage regulation. CO_2 storage in the Baltic Sea is regulated through the Directive on Geological Storage of CO_2, the Continental Shelf Law, the Environmental Code and the Law on Certain Pipelines. Fridahl, M., Bellamy, R., Hansson, A. & Haikola, S. (2020). https://www.frontiersin.org/articles/10.3389/fclim.2020.604787/full#:~:text=Sweden%20shall%20also%20achieve%20net,the%20option%20to%20use%20BECCS

Trading and taxation:

- BECCS auction. The government has decided to introduce a reverse auction for BECCS. The Energy Agency has proposed 0.6 Mt auctioned in 2022 and another 0.6 and 1.0 Mt auctioned before 2030. Lowest bids win, the winners get contracts for 15 yrs and they are also responsible for transport and storage, either directly or by contracting others. (1) The Energy Authority can purchase removals worth 1.7 bn SEK per year in 2023, with a second auction planned for 2026 at the latest. (2) The design of the measure has been criticised for being limited and ineffective. (3). Fridahl, M. & Lundberg, L. (2022). https://link.springer.com/article/10.1007/s43937-022-00008-8

Funding (deployment):

- Industrial Leap (Industriklivet). A mechanism for 2018–2040 to fund the low-carbon transition in process industries. It covers the full range from research and preliminary trials to planning and investment and can be granted to both companies and research institutions. (1) For 2022, the full allocation for all solutions is 909 M SEK. (2) The mechanism has an allocation for negative emissions of 100 M SEK in 2019–22 and 50 M SEK in 2023–27.

(3) Granted funding has covered e.g. piloting BECCS at three CHP facilities. (4). (1) Government of Sweden, Ministry of the Environment (2020). https://unfccc.int/sites/default/files/resource/LTS1_Sweden.pdf, (2) Swedish Energy Agency (2023). https://www.energimyndigheten.se/en/innovations-r--d/energyintensive-industry/the-industrial-leap/, (3) Fridahl, M., Bellamy, R., Hansson, A. & Haikola, S. (2020). https://www.frontiersin.org/articles/10.3389/fclim.2020.604787/full#:~:text=Sweden%20shall%20also%20achieve%20net,the%20option%20to%20use%20BECCS

- Green credits. A general credit guarantee system has been introduced for green industrial investments, administered by the National Debt Office. The loans must be at least 500 M SEK. The total scope was originally 10 bn SEK in 2021, proposed to be raised to 50 bn in 2022, 65 bn in 2023 and 80 bn in 2024. (1) The guarantee can cover up to 80 % of the loan. (2). (1) Swedish National Debt Office (2021). https://www.riksgalden.se/fi/our-operations/guarantee-and-lending/credit-guarantees-for-green-investments/, (2) Swedish National Debt Office (2021). https://www.riksgalden.se/fi/our-operations/guarantee-and-lending/credit-guarantees-for-green-investments/questions-and-answers-about-credit-guarantees-for-green-investments/

Other (strategies, guidelines etc.)

- National emission targets. To achieve the targets of net-zero emissions in 2045 and net-negative emissions therafter, CCS for fossil fuels may be used where no viable alternatives exist. Part of the target can be met with supplementary measures which include BECCS as one of three options. (1) Supplementary measures can in total cover 8 % and 2 % of 2030 and 2040 targets respectively. If BECCS was the only supplementary measure used, this would cap its application at 3.7 Mt and 0.9 Mt respectively. (2). (1) Government of Sweden, Ministry of the Environment (2020). https://unfccc.int/sites/default/files/resource/LTS1_Sweden.pdf, (2) Fridahl, M., Bellamy, R., Hansson, A. & Haikola, S. (2020). https://www.frontiersin.org/articles/10.3389/fclim.2020.604787/full#:~:text=Sweden%20shall%20also%20achieve%20net,the%20option%20to%20use%20BECCS
- Tentative BECCS targets. A public inquiry proposed BECCS targets of 1.8 Mt by 2030 and 3–10 Mt by 2045. Fridahl, M. & Lundberg, L. (2022). https://link.springer.com/article/10.1007/s43937-022-00008-8
- National Centre for CCS. Swedish Energy Agency has been designated as the National Centre for CCS, in charge of promoting CCS. Swedish Energy Agency (2022). https://www.energimyndigheten.se/en/sustainability/carbon-capture-and-storage/national-centre-for-ccs/
- Studying possible storage locations. The government has given the Geological Survey of Sweden the task to study

possible storage locations in Sweden. Regeringkansliet (2022). https://www.regeringen.se/pressmeddelanden/2022/11/stor-satsning-gors-pa-infangning-av-biogen-koldioxid/

Denmark

Regulation:

- Separate licensing for CO_2 storage pilot projects. In 2022, Denmark adopted an amendment to the Subsoil Act (undergrundsloven) according to which a separate license scheme may be set up for CO_2 storage pilot and demonstration projects of less than 100 kt CO_2. An opportunity was also introduced for governmental participation in carbon storage licenses. In the implementation of the CCS directive in 2011 and subsequently in the CCS Order, Denmark chose not to distinguish between geological storage of CO_2 of less than 100 kt for the purpose of research, development or testing of new products and processes and other geological storage of CO_2. World Law Group (2022). https://www.theworldlawgroup.com/news/denmark-co2-storage-licenses
- Exempting CO_2 storage from the prohibition of dumping in the sea. The Marine Environment Act was amended so that storage of CO_2 may be exempted from the prohiibition of dumping. The amendment entered into force 1 January 2022. The Danish Marine Environment Act has since its inception in 1981 prohibited dumping of materials and substances in the sea, in the seabed and under the seabed, and the transport of materials and substances for dumping. The bans also included geological storage of CO_2 under the seabed. WSCO Advokatpartnerselskab (2021). https://uploads-ssl.webflow.com/6183d750c2a4a2d74e966763/6234496d3d8d9d691f51ec2c_CCS%20-%20the%20Danish%20Perspective%2C%20March%202022.pdf

Funding (deployment):

- Energy Technology Development and Demonstration Program (EUDP). The program supports companies and universities to develop and demonstrate new energy technologies, including CCS. About DKK 400 M available during the two application rounds in 2022. In 2021, the Danish Government approved funding for two CCS projects using the existing oil and gas infrastructure in the North Sea: DKK 197 M for the Greensand project led by Inios and DKK 75 M for the Bifrost project led by the Danish Underground Consortium. Danish Energy Agency https://ens.dk/en/our-responsibilities/research-development/eudp, EUDP https://www.

eudp.dk/en, Offshore Energy (2021) https://www.offshore-energy.biz/danish-govt-bankrolls-two-projects-for-co2-storage-in-north-sea/

Funding (RDI):

- Funding for Green Research Missions. DKK 700 million in 2021 for green research missions, including two CCUS missions, as well as an additional DKK 295 million in 2023. WSCO Advokatpartnerselskab (2021). https://uploads-ssl.webflow.com/6183d750c2a4a2d74e966763/6234496d3d8d9d691f51ec2c_CCS%20-%20the%20Danish%20Perspective%2C%20March%202022.pdf

Other (strategies, guidelines etc.)

- National Climate Road Map. Inclusion of CCUS in the national climate road-map KEFM 2020. Identifies between 4–9 Mt of CO_2 suitable for carbon capture. Klimaprogram (2020). https://kefm.dk/Media/6/4/Klimaprogram_2020 %20(2).pdf
- Danish Climate Agreement for energy and industry 2020. The agreement includes investments in the carbon capture and storage. Danish Ministry of Climate, Energy and Utilities (2022). https://kefm.dk/Media/C/B/faktaark-klimaaftale%20(English%20august%2014).pdf
- A road map for capture, transportation and storage of CO_2. A political agreement: road map for capture, transportation and storage of CO_2 December 2021. It includes initiatives intended to ensure that the first Danish CCS facilities will be operational in 2025. Bech Bruun (2021). https://www.bechbruun.com/en/news/2021/ccs-strategy-political-agreement-to-ensure-clarity-about-important-regulatory-framework
- Agreement on state co-ownership in CCS licences in the North Sea. In June 2022, the Danish government signed a new political agreement with eight political parties which implies that it will have a 20 % co-ownership in future carbon storage licenses in the North Sea. With the co-ownership, the government removes part of the risk from the private companies, which should help start a new business sector. At the same time, it gets a share of the profits if carbon storage becomes a good business. Offshore Energy (2022). https://www.offshore-energy.biz/danish-govt-to-hold-co-ownership-in-future-co2-storage-licenses-under-new-political-deal/.
- Bilateral arrangement on transport of CO_2. Denmark, Flanders and Belgium signed on September 13th 2022 an arrangement, which allows transport of CO_2 between the countries for permanent geological storage. The arrangement is the first in the world. Danish Ministry of Climate, Energy and Utilities (2022). https://en.kefm.dk/news/news-archive/2022/sep/denmark-flanders-and-belgium-sign-groundbreaking-arrangement-on-cross-border-transportation-of-co2-for-geological-storage-

Netherlands

Regulation:

- Geological storage rules in the Mining Act (2011). The Mining Act already contained a (general) permit obligation for the storage of substances, including CO_2. With the implementation of the CCS Directive provisions specifically pertaining to the storage of CO_2 have been included. This includes requirements in relation to the contents of the permit (application) and regulations pertaining to the transfer to the State of the responsibility for stored CO_2 after it has been established that this substance has been safely and permanently stored. CMS https://cms.law/en/nld/publication/implementation-of-the-ccs-directive-into-the-dutch-mining-legislation-co2-storage
- CCS Restrictions: Sieve (2019). Restriction through the sieve will ensure that CCS is only subsidised at sites where no demonstrably cost-effective alternatives are available at the time. The objective is to find a balance between preventing clean technologies from being crowded out and using the reduction potential that CCS offers to achieve the reduction target. The Climate Agreement (2019). https://www.government.nl/documents/reports/2019/06/28/climate-agreement
- CCS Restrictions: Cap (2019). The CCS cap in industry in the expanded SDE+ scheme up to 2030 will facilitate a cost-effective transition up to 2030. The level of the cap will be determined in such a way that CCS will be subsidised for a maximum of 7.2 Mt of the total 14.3 Mt of emissions reductions in the industry sector by 2030. The Climate Agreement (2019). https://www.government.nl/documents/reports/2019/06/28/climate-agreement
- CCS Restrictions: Horizon (2019). By eventually no longer granting new subsidy decisions for CCS (with the exception of CCS for negative emissions), a time limit is imposed that will provide a necessary incentive for the development of alternatives to CCS in places where this is currently not yet cost-effective. No more SDE+ decisions will be granted for CCS applications beyond 2035 (with the exception of negative emissions) The Climate Agreement (2019). https://www.government.nl/documents/reports/2019/06/28/climate-agreement

Funding (deployment):

- Sustainable energy transition subsidy scheme (SDE++). Subsidy for producing renewable energy or applying CO_2-reducing techniques is intended for companies and organisations (non-profit and otherwise) in sectors such as industry, mobility, electricity, agriculture and the built environment. €13 billion is available for the SDE++ 2022. Netherlands Enterprise

Agency (2022). https://business.gov.nl/subsidy/sustainable-energy-production/#:~:text=You%20can%20apply%20for%20a,on%20the%20technology%20you%20use, https://english.rvo.nl/subsidies-programmes/sde

- SDE++ Subsidy Fund for Porthos Project (CCS projects) 2021. Dutch government allocated 2.1 billion euros (USD 2.56 billion) in grant money for Porthos' four customers: Air Liquide, Air Products, ExxonMobil and Shell. The Porthos project aims to capture and store carbon emissions from Rotterdam Port as a joint venture between the Port of Rotterdam Authority, Gasunie, and EBN, along with Porthos' customers. Offshore Energy (2021). https://www.offshore-energy.biz/porthos-ccs-project-industry-targets-e2-billion-in-dutch-subsidies/

Funding (RDI):

- Subsidy Demonstration Energy Innovation (DEI+). Subsidy for innovative projects that focuses on saving energy, generating sustainable energy or stimulating the use of sustainable energy, covering number of topics, including CCUS. Netherlands Enterprise Agency (2022). https://business.gov.nl/subsidy/demonstration-energy-innovation-dei-subsidy/
- CATO – CO_2 capture, transport and storage programme. The CATO programme is the Dutch CCS research programme. CATO is an abbreviation for CO_2 Afvang, Transport en Opslag (CO_2 capture, transport and storage). Major funding partners of the program are the Dutch Government as well as leading industrial partners. https://www.co2-cato.org/

Other (strategies, guidelines etc.)

- Dutch Integrated National Energy and Climate Plan (NECP) 2021–2030. Contains the main priorities of the climate and energy policy for the next 10 years. The aim is also to use CCS in a cost-effective way, to ensure that sustainable hydrogen production is on its way to implementation and to make bio-based raw materials the norm. The following five sub-programmes have been established to achieve this: 1. Circular plastics; 2. Bio-based raw materials for products and transport fuels; 3. CCU; 4. Circular non-ferrous metals; 5. CCS. Ministry of Economic Affairs and Climate Policy (2020). https://energy.ec.europa.eu/system/files/2020-03/nl_final_necp_main_en_0.pdf
- Climate Agreement (2019). Dutch industry carbon dioxide reduction target is 14.3 Mt by 2030. Dutch industry will be able to shape the transition through measures such as process efficiency, energy savings, CCS, electrification, use of blue and green hydrogen and acceleration of circularity. Capture, transport and storage of carbon dioxide produced by industry is regarded by the sector and by the national government as a crucial activity to achieving the 2030 target. In addition, capture and transport can serve as a prelude to the reuse of carbon (CCU). The Climate Agreement (2019). https://www.government.nl/documents/reports/2019/06/28/climate-agreement

Annex 2: List of policy options

Policy type	Policy	Description	Relevant solutions	International benchmarks	Feasibility and evidence base	Climate potential	Business potential	Costs	Recommendation	Questions	Sources
Regulation	Reviewing and updating CCS regulation	The current national CCS and ETS laws should be reviewed and, if necessary, updated to include current best practice	CCS		***/***	e	e	*	implement during the next government period	How should the laws be updated more concretely?	*[a]*
	Bilateral agreements with storing countries	To transport CO_2 for storage outside of Finland to e.g. Norway, bilateral governmental agreements are required, although this could be possibly solved at the EU level	CCS	Denmark, Sweden	***/**	e	e	*	implement	Should other countries than Norway be considered at this stage?	*[b], [c]*
	Setting targets for negative emissions in the climate act	Defining a separate target for negative emissions in a law would provide necessary clarity for both policy and markets	CDR	Sweden, the Netherlands	***/**	e	e	*	implement during the next government period	How soon should this realistically happen as the act has been recently revised twice?	*[d], [e]*
	Requiring estimating the storage potential of mining wastes	Estimating the CO_2 storage potential of mining wastes could be required as part of normal processes either under environmental impact assessments or environmental permits, with recommendations to separate it from other wastes	CCS		***/*	e	e	*	commission a study	Are there benchmarks in other countries?	*[f]*
	End date for releasing fossil carbon	Releasing fossil carbon from point sources above certain size could be phased out with a legal ban similar to the coal phase-out law	CCS		**/*	***		***	commission a study	What could be the end date – 2035? What could be the size limit?	*[g]*

Policy type	Policy	Description	Relevant solutions	International benchmarks	Feasibility and evidence base	Climate potential	Business potential	Costs	Recommendation	Questions	Sources
	Carbon capture mandate	A legal mandate could require the biggest point sources to capture carbon and either store it or use it for products	CCS	Norway	**/**	***	+	***	commission a study	How to define the mandate? Which sources and technologies to cover?	*[h]*
	Carbon blending mandate	Requiring to use a gradually growing share of recycled carbon for selected products	CCU		*/**	*		***	commission a study	Can a mandate be introduced on the national level or would this have to be EU-wide?	*[i]*
Pricing incentives	Auctions for negative emissions	To establish markets for first movers, the state could auction negative emissions from various technologies, such as BECCS, biochar and DACCS	CDR	Sweden	**/**	**	+	**	commission a study and introduce incentives based on that during the next government period	What should be the scope? Should there be different technology windows in the auctions?	*[j]*
	National emission price floor	A high enough national emission price floor to complement the EU ETS could incentivise CCS	CCS	the UK, Norway	**/**	**		***	commission a study	Which price level would be sufficient? What can we learn from the UK price floor?	*[k]*
	Tax credits for negative emissions	Tax credits could incentivise companies to produce negative emissions	CDR	the USA, Canada	**/**	**	+	**	commission a study and introduce incentives based on that during the next government period	Which tax would the credit be based on? Is this feasible in the Finnish tax system?	*[l], [m]*
Funding	Dedicated funding programme for RDI into CO_2 use and removal	CO2 use and removal RDI could benefit from a dedicated programme with significant funding	CCUS	Denmark, Norway, the UK, the USA, Japan	***/***	*		**	implement	Should this be split into reseach (e.g. STN) and development (e.g. Business Finland)?	*[n], [o], [p], [q]*
	Dedicated funding programme for demonstrating and piloting CO_2 use and removal	CO_2 use and removal demonstration and pilot projects could benefit from a dedicated programme with significant funding	CCUS	Denmark, Sweden, the UK, the USA	**/***	**	+	**	implement	How would this funding window relate to existing mechanisms (e.g. energy aid)?	*[r], [s], [t], [u]*

Policy type	Policy	Description	Relevant solutions	International benchmarks	Feasibility and evidence base	Climate potential	Business potential	Costs	Recommendation	Questions	Sources
Information	Strategy on CO_2 use and removal	Dedicated strategy would raise the political importance and provide direction for policy and markets	CCUS	Denmark, the UK	***/***	e	e	*	implement in the beginning of the next government period	How would the strategy relate to existing strategies, in particular the climate and energy strategy?	*[v]*, *[x]*
	Roundtable on CO_2 use and removal	Roundtable would allow policymakers to interact with key stakeholders, facilitating mutual understanding and minimising risks	CCUS	the UK	***/***	e	e	*	implement	Which existing roundtables could this use as a model?	*[y]*
Other	Green deal to use public procurement for CCU	Voluntary agreement could facilitate first mover markets for CCU products, such as construction materials	CCU		***/*	*	+	**	commission a study	Do we know enough to set procurement criteria for CCU products? Which products should be covered in the beginning?	*[z]*
	State-owned carbon transport enterprise	Establishing a state-owned enterprise for infrastructure to transport carbon, modelled after Fingrid and Gasgrid, could enable the creation of private markets	CCS	Norway	**/**	**		**	dialogue with stakeholders	What would the company focus on? What would be the main benefit compared to private operators? Could an existing SOE (e.g. Gasgrid) take the new role?	*[a1]*
	Taking initiative in updating IPCC guidelines	Explicitly addressing emerging solutions such as enhanced weathering and ocean-based options in the IPCC guidelines could provide clarity and encourage deployment	DAC, EW, oceans		**/*	e	e	*	discuss with the EU	Who would be the main operator here? Statistics Finland? Should some of the solutions be ineligible as too premature or risky?	*[b1]*
	Supporting voluntary markets for carbon removals	Guidelines, information and possibly regulation could encourage shifting the voluntary compensation markets towards removals	CDR		***/**	e	e	*	implement	What should this mean more concretely?	*[c1]*

Policy type	Policy	Description	Relevant solutions	International benchmarks	Feasibility and evidence base	Climate potential	Business potential	Costs	Recommendation	Questions	Sources
	Playing an active role in international initiatives on CO_2 use and removal	Finland could play a more active role in various international initiatives promoting CO_2 use and removal, such as the CDR Launchpad	CCUS		***/**	e	e	*	implement	Which initiatives could be mentioned here as examples?	*[d1]*
Explanation	Policy	Short description of the policy	Solutions that the measure would apply to	Jurisdictions where similar policies have been introduced	Feasibility: how implementable the policy is Evidence base: how solid the evidence for the policy is Based on expert judgement	Estimated positive climate impact with the proposed policies, based on expert judgement	Estimated positive business impact with the proposed policies, based on expert judgement	Estimated costs for both policy and implementation, based on expert judgement	Recommended action to take regarding the policy	Questions about the policy and its presentation	Selected sources
Rating					From small (*) to large (***)	From small (*) to large (***) – e = enabling measure	Considerable potential (+)	From large (*) to small (***)			
Colour					Total = 6*	***	+	*	Implement		
					Total = 5*	**		**	Study, then implement		
					Total = 4*	*		***	Study, then decide		
					Total < 4*						

[a] IEA 2022d [b] EC 2022g [c] Danish Ministry of Climate, Energy and Utilities 2022 [d] McLaren et al. 2019 [e] Government of the Netherlands 2019 [f] IEAGHG 2022
[g] Act 416/2019 [h] Global CCS Institute 2020 [i] Thielges et al. 2022 [j] Lundberg & Fridahl 2022 [k] Hirst 2018 [l] Congressional Research Service 2021
[m] EY Global 2022 [n] Gov.UK 2022 [o] Gov.UK 2018 [p] US DOE 2022 [q] WSCO 2022 [r] Swedish Energy Agency N.d. [s] National Carbon Capture Centre 2023
[t] Danish Energy Agency N.d. [u] Offshore Energy 2021 [v] Gov.UK 2018a [x] Bech-Bruun Law Firm P/S 2021 [y] Gov.UK 2018b [z] Thielges et al. 2022
[a1] Gassnova 2023 [b1] Smith et al. 2023 [c1] Honegger et al. 2021 [d1] Tynkkynen 2018

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