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OPPORTUNITIES PROVIDED BY TECHNOLOGICAL CARBON SINKS AND THE MEANS FOR THEIR ADVANCEMENT IN FINLAND

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The Finnish Climate Change Panel promotes dialogue between science and policy-making in matters related to the climate. It provides advice for the government's policy-making involving the climate and reinforces interdisciplinary insight in the climate sciences. The Finnish Climate Change Panel's analyses and opinions are science-based.

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FOREWORD BY THE FINNISH CLIMATE CHANGE PANEL AND KEY MESSAGES

Technological carbon sinks have gained a lot of interest in public debate in Finland, and they also involve financial opportunities for the Finnish actors. The Finnish Climate Change Panel has drawn up this report to support climate related policymaking and planning activities by actors in the field in cooperation with the experts from VTT Technical Research Centre of Finland. The report discusses carbon dioxide removal and generation of negative emissions by capturing and permanently storing biogenic carbon dioxide flue gas streams from existing industrial point sources. In addition, it discusses the utilisation of carbon dioxide and related costs. Other carbon dioxide removal practices, such as production of biochar, are excluded from this report and deserve their own analyses.

Based on the results from the report, the Finnish Climate Change Panel wishes to emphasise the following:

In the Paris Agreement, countries have agreed to limit the increase in global average temperatures to clearly below two degrees Celsius, while aiming at activities that would help to achieve the goal of 1.5 °C. According to the 1.5 °C report by the Intergovernmental Panel on Climate Change (IPCC), the detrimental impacts of climate change will be substantially smaller if global warming is limited to 1.5 °C. This target has later been adopted as the starting point for climate policy in several countries as well as within the EU. In its latest report concerning emission reductions (IPCC AR6, WG3, 2022), the IPCC has brought up the need for dramatic and immediate emission reductions in order to make it possible to reach the 1.5 °C target for global warming. Achieving this requires that, by the middle of the current century, anthropogenic carbon dioxide (CO_2) emissions and carbon dioxide removal (CDR) must be equal in volume. Following this, during the latter half of the century, the removals should be higher than the emissions (IPCC 2022). Therefore, in addition to the reduction of fossil emissions and process emissions, negative emissions are required; they can be generated by removing CO_2 from the air, either by reinforcing natural carbon sinks or by technological means. Technological carbon sinks refer to the permanent removal of CO_2 from the atmosphere by technological means.

As the report states, technological carbon sinks may refer to several different technological solutions for permanently removing CO_2 from the atmosphere. The most feasible option for Finland in the medium term, from the points of view of the scale of emission reductions and technical feasibility, is the capture of biogenic CO_2 originating from combustion of forests or other biomass, combined with permanent geological or mineral-based storage of CO_2 (bioenergy with carbon capture and storage, BECCS). During its growth, biomass has captured CO_2 from the atmosphere, and the same amount of CO_2 is released when the biomass is combusted. By capturing the biogenic CO_2 released during the combustion of biomass, liquifying it and transporting it to permanent storage facilities, such as underwater geological formations, carbon that is part of the biological circulation can be permanently removed from the atmosphere, thereby achieving negative emissions. The captured CO_2 may also be utilised in various products (carbon capture and utilisation, CCU). However, short-lived CCU products cannot act as technological carbon sinks, as the CO_2 contained in them will be quickly released back into the atmosphere. The climate benefits of CCU products come from substitution of fossil counterfactual products with higher life cycle emissions. Furthermore, the capture and storage of CO_2 released from fossil fuels does not create technological carbon sinks, as this does not remove CO_2 from the atmosphere; it only prevents CO_2 from entering it.

All CO_2 removal technologies and practices involve various risks and uncertainties, due to which it is important to strengthen both natural and technological carbon sinks. In terms of natural carbon sinks, the uncertainty is related to the permanence of the carbon sink as climate change progresses. By default, BECCS generates a permanent carbon sink, but the possibility of a leak risk in the CO_2 storage cannot be fully excluded. Attention should also be paid to the origins, sustainability and alternative purposes of the biomass that acts as the source of the biogenic CO_2 being used for the BECCS technology.

Key conclusions in terms of the planning and implementation for climate policy-making:

Starting points for technological carbon sinks based on BECCS in Finland:

- Currently, approximately 44Mt of biogenic CO_2 emissions are generated in Finland each year, of which 28 Mt in installations with over 0.1Mt emission. The most significant sources of biogenic CO_2 are the forest industry (19.6 Mt_{bio}), thermal power stations (8.0 Mt_{bio}) and waste incineration (0.6 Mt_{bio}). However, the anticipated technological and financial potential is significantly lower than this.
- Finland has no geological formations suitable for the permanent storage of CO_2, such as deep saline water layers or porous bedrock sealed by dense deposits. The storage areas with the highest potential will likely be found in the North Sea region. Therefore, the CO_2 to be stored should first be transported to a port, from where it is transported by ship either directly to the storage area or a receiving port that has a pipe connection to the storage area.

Costs for the capture and storage of CO_2:

- According to current estimates, the unit cost for BECCS from Finland's industrial biogenic CO_2 sources varies between approximately €120 and €240 per tCO_2, when a commercial facility is used around the year 2030. The cost covers the capture, compression, transport and geological storage of CO_2. The cost estimates set forth in this report contain uncertainties, and are only meant to be indicative.
- Based on the analysis presented in this report, the specific emissions reduction cost of the capture and storage of biogenic CO_2 is lower than the cost for the recovery and reuse of CO_2 in the manufacture of synthetic fuels, for example.
- However, the business profitability of reuse is also affected by the price of the commodity being produced. This depends on the demand for the commodity, which is mostly driven by the strictness of climate policy across the various usage sectors, that is, the price of CO_2 emissions.

A strategy and incentives must be urgently created for promoting the capture, storage and reuse of CO_2.

- The limited volume of geological storage capacity may form a significant bottleneck; in order to eliminate this, preparations for projects related to the capture and storage of CO_2 should be started in Finland much more actively than is being done at present. It would benefit Finnish actors in the field and the implementation of technological carbon sinks if the government made strategic initiatives and combined separate actions into one united front.
- At the moment, Finland has no direct financial incentives for producing technological carbon sinks, aside from the voluntary carbon market. An investigation into reverse auctions (competitive bidding) or other financial incentive mechanisms should be started soon if projects are to be implemented in the early 2030s.
- Project development for carbon dioxide capture, transport and storage, including the planning, licensing and construction and commissioning stages, has been estimated to take at least 6 to 7 years. Due to the long preparation time, projects should be launched quickly.

There are many uncertainties related to the technological development, costs, and policy involving technological sinks.

- The combustion of biomass in the forest industry plays a key role in the estimated potential for biogenic CO_2. The biomass shortage will increase while the possibilities of using forest industry side streams to create new products instead of biomass combustion will grow. The choices made by the forest industry going forward will have a significant impact on the amount of biogenic CO_2 available.
- The reported costs are estimates of costs after the demonstration stage. They involve a high level of uncertainty. Technology and know-how may develop more quickly or more slowly.

- The lower limit for reported costs in 2030 is close to the level of emission reduction costs presently estimated for the Effort Sharing Regulation (ESR) sector. It should be noted that the costs clearly exceed the emission reduction costs of the least expensive actions on the land use sector (such as the rewetting of areas used for peat extraction). In other words, many climate actions already identified are clearly less expensive today than the production of technological sinks in the future.

Technological sinks offer an additional means of achieving Finland's climate targets after 2030, but they shall not displace or slow down other climate actions.

- Finland is falling clearly behind the EU's 2030 targets for the ESR and land use sectors. In order to achieve these targets, the actions that have already been identified must be significantly boosted. Technological sinks will not provide assistance in reaching these targets.
- Boosting climate action is necessary in order to reach Finland's target of carbon neutrality in 2035. This target can be reached by taking determined and efficient actions in the ESR and land use sectors, but these actions must be taken immediately.
- As was stated in the Finnish Climate Change Panel's memorandum Guidelines for boosting Finland's climate actions (2023), in order to ensure the meeting of the 2035 carbon neutrality target defined in the Climate Act and to reach net negative emissions after that, it would be beneficial for Finland to generate 5–6 Mt negative emissions through competitive bidding or other policy instruments.
- This report states that, the CO_2 captured and stored from Finland's top 2 or 3 facilities producing biogenic CO_2 would provide a technological carbon sink of approximately 5 Mt. These facilities are pulp, paper and bioproduct mills. If the national operating subsidy were to cover the entire cost of the capture, compression, transport and storage of CO_2, funding a technological carbon sink of 5 $MtCO_2$ would require €605–705 million per year.

The Finnish Climate Change Panel, 12 December 2023.

SUMMARY

This study examines the potential, costs and realistic scale of technological carbon sinks in Finland over the medium term more closely than in the previous publicly available literature. Technological carbon sinks can refer to various technological solutions for permanently removing carbon dioxide from the atmosphere. This study looks solely at the capture and geological storage of biogenic carbon dioxide from energy production and industrial facilities in Finland. This selection is based on the assumption that these methods can be used to achieve the largest technological sink in Finland over the medium term.

Up-to-date information has been compiled on biogenic carbon dioxide-emitting facilities in Finland, whose total emissions exceed 0.1 MtCO2 per year per facility. The facility-specific costs for carbon dioxide capture, transportation and storage in the North Sea region have been calculated. In addition, the prospects of geological storage capacity in Northern Europe have been examined based on public projects, anticipating the potential amount of available capacity for Finland's technological sinks. This study also explores reverse auctions, or competitive bidding, as a possible support mechanism for technological carbon sinks, which currently lack direct economic incentives in Finland, except for units produced for voluntary carbon markets.

The combined biogenic emissions from these facilities are approximately 28 $MtCO_2$ per year. Biogenic carbon dioxide emissions exceed 1.0 $MtCO_2$ per year in nine facilities, resulting in cost reductions for producing technological sinks due to economies of scale. From these larger facilities, a total of 7.3 $MtCO_2$ per year of biogenic carbon dioxide could be captured from facilities on the coast, and 8.4 MtCO2 per year from facilities inland. The unit cost of producing carbon sinks from Finland’s industrial emission sources varies at approximately €120–€240/tCO_2 on a case-by-case basis. Costs are the lowest for large facilities located on the coast. The most cost-effective facilities are often those in manufacturing industries, where larger facility sizes are common due to economies of scale in production. The forest industry stands out among the most cost-effective sources of biogenic CO_2. For small facilities, costs could be significantly reduced by sharing transportation infrastructure with other facilities.

Based on current knowledge, a significant amount of carbon dioxide storage capacity is expected to be available on the market from 2030 onwards. Based on public sources of storage project assessments, free storage capacity in Northern Europe is expected to be around 10 $MtCO_2$ per year at that time, although the latest project plans from Denmark may increase the estimate of available storage capacity. Storage capacity could pose a significant constraint on Finland’s technological sinks during the study period which extends until 2035, unless there is a significant increase in negotiation and project preparation activity.

An investigation into reverse auctions or other support mechanisms should be initiated soon if projects are to be implemented in the early 2030s. There are several facilities in Finland that could potentially participate in the bidding process, with preliminary cost estimates for implementing technological sinks ranging from €120 to €150/tCO_2. The actual bids and, thus, the required budget are difficult to estimate, as there is as of yet insufficient experience in the operation and costs of the technology as well as the whole carbon dioxide transport and storage value chain.

TIIVISTELMÄ

Tässä selvityksessä on tarkasteltu teknologisten hiilinielujen potentiaalia, kustannuksia ja realistista kokoluokkaa Suomessa keskipitkällä aikavälillä aiempaa julkista kirjallisuutta tarkemmin. Teknologisilla hiilinieluilla voidaan viitata useaan eri teknologiaan pohjautuvaan keinoon poistaa hiilidioksidia pysyvästi ilmakehästä. Työ on rajattu koskemaan ainoastaan bioperäisen hiilidioksidin talteenottoa ja geologista varastointia energiantuotannosta ja teollisista laitoksista Suomessa. Rajauksen taustalla on oletus, että kyseisillä keinoilla voidaan Suomessa saavuttaa suurin teknologinen nielu keskipitkällä aikavälillä.

Selvityksessä on koostettu ajantasainen tieto kokonaispäästöiltään yli 0,1 $MtCO_2$/vuosi suuruisista bioperäistä hiilidioksidia päästävistä laitoksista Suomessa sekä laskettu laitoskohtaiset kustannukset hiilidioksidin talteenotolle, kuljetukselle ja varastoinnille Pohjanmeren alueelle. Lisäksi hiilidioksidin geologisen varastokapasiteetin näkymiä on tarkastelu julkisten hankkeiden osalta ja näin ennakoitu mahdollisesti vapaan kapasiteetin määrää Suomen teknologisille nieluille. Työssä tarkasteltiin myös käänteistä huutokauppaa, eli tarjouskilpailua, mahdollisena tukimekanismina teknologisille hiilinieluille, joiden tuottamiseksi ei Suomessa ole tällä hetkellä suoria taloudellisia kannustimia, lukuun ottamatta vapaaehtoisia päästömarkkinoita.

Laitosten yhteenlaskettu bioperäinen päästö on n. 28 $MtCO_2$/vuosi. Yhdeksässä laitoksessa bioperäiset hiilidioksidipäästöt ovat suuruudeltaan yli 1,0 $MtCO_2$/vuosi, jolloin mittakaavaedut laskevat teknologisen nielun kustannuksia. Kyseisistä suuremmista laitoksista voitaisiin talteenottaa yhteensä 7,3 $MtCO_2$/vuosi bioperäistä hiilidioksidia rannikolta ja 8,4 $MtCO_2$/vuosi sisämaasta. Hiilinielun tuottamisen yksikkökustannus Suomen teollisista päästölähteistä vaihtelee välillä n. 120—240 €/tCO_2 tapauskohtaisesti. Kustannukset ovat edullisimpia suurista rannikolla sijaitsevista laitoksista. Kustannuksiltaan edullisimmat laitokset ovatkin pitkälti valmistavan teollisuuden laitoksia, joissa suuri laitoskoko on tuotannon mittakaavaetujen takia yleistä. Bioperäisten laitosten osalta erityisesti metsäteollisuus korostuu edullisimpien laitosten joukossa. Pienten laitosten osalta kustannuksia alentaisi merkittävästi kuljetusinfrastruktuurin jakaminen muiden laitosten kanssa.

Hiilidioksidin varastokapasiteettia alkaa nykytiedon valossa olla merkittävästi tarjolla kilpailtavaksi vuodesta 2030 alkaen. Julkisten lähteiden varastohankekartoitusten perusteella vapaata varastokapasiteettia Pohjois-Euroopassa on tuolloin odotettavissa noin 10 $MtCO_2$/vuosi, joskin viimeisimmät Tanskasta julkaistut hankesuunnitelmat voivat kasvattaa arviota vapaasta varastokapasiteetista. Varastokapasiteetti voi asettaa merkittävän rajoitteen Suomen teknologisille nieluille tarkasteluaikajaksolla vuoteen 2035 asti, ellei tapahdu merkittävää lisäystä neuvottelu- ja hankevalmisteluaktiivisuudessa.

Käänteisen huutokaupan tai muun tukimekanismin selvitystyö tulisi käynnistää pian, jos hankkeita halutaan toteuttaa 2030-luvun alkupuolella. Suomessa on useita laitoksia, jotka potentiaalisesti voisivat osallistua tarjouskilpailuun ja joissa teknologisen nielun toteuttamisen alustavat kustannusarviot vaihtelevat välillä 120–150 €/tCO_2. Toteutuvien hintapyyntöjen suuruutta ja siten tarvittavaa budjettia on vaikea arvioida, sillä teknologian sekä hiilidioksidin kuljetus- ja varastointiketjun toimivuudesta ja kustannuksista ei ole vielä kokemuksia.

SAMMANDRAG

I den här utredningen undersöks potentialen, kostnaderna och den realistiska storleksordningen för tekniska kolsänkor i Finland på medellång sikt mer ingående än i tidigare publicerad offentlig litteratur. Tekniska kolsänkor kan avse ett antal olika teknikbaserade metoder för att permanent avlägsna koldioxid från atmosfären. Utredningen har avgränsats till upptagningen av biobaserad koldioxid och geologisk lagring av biobaserad koldioxid från energiproduktion och industrianläggningar i Finland. Avgränsningen bygger på antagandet att de här metoderna lämpar sig bäst för att Finland ska kunna öka omfattningen av de tekniska kolsänkorna på medellång sikt.

Utredningen innehåller aktuell information om anläggningar i Finland vars totala utsläpp överstiger 0,1 MtCO$_2$ per år, och beräknade kostnader per anläggning för avskiljning, transport och lagring av koldioxid vid Nordsjön. Utsikterna för den geologiska koldioxidlagringskapaciteten för offentliga projekt analyseras, i syfte att förutse mängden potentiellt tillgänglig kapacitet för tekniska kolsänkor i Finland. Även omvänd auktionering, dvs. budgivning, granskas som en möjlig stödmekanism för tekniska kolsänkor. För närvarande finns det inga direkta ekonomiska incitament i Finland för tekniska kolsänkor, bortsett från den frivilliga utsläppsmarknaden.

Anläggningarnas sammanlagda biobaserade utsläpp uppgår till cirka 28 MtCO$_2$ per år. Nio av anläggningarna släpper ut över 1,0 MtCO$_2$ biobaserad koldioxid per år, varvid stordriftsfördelarna sänker kostnaden för en teknisk kolsänka. Totalt kan dessa större anläggningar avskilja 7,3 MtCO$_2$biobaserad koldioxid per år vid kusten och 8,4 MtCO$_2$/år i inlandet. Enhetskostnaden för en kolsänka från industriella utsläppskällor i Finland varierar mellan cirka 120–240 €/tCO$_2$. Kostnaderna är lägst för stora anläggningar som ligger vid kusten. De kostnadsmässiga fördelarna är framför allt störst inom tillverkningsindustrin, där stora anläggningar är vanliga på grund av stordriftsfördelar inom produktionen. När det gäller biobaserade anläggningar är det främst skogsindustrin som utmärker sig bland de fördelaktigaste anläggningarna. Bland små anläggningar skulle en gemensam transportinfrastruktur med andra anläggningar minska kostnaderna betydligt.

Mot bakgrund av nuvarande kunskap kommer det att finnas en betydande mängd koldioxidlagringskapacitet som är tillgänglig för konkurrens från och med 2030. Offentligt tillgängliga utredningar för lagringsprojekt visar att den lediga lagringskapaciteten i Nordeuropa torde uppgå till cirka 10 MtCO$_2$ per år vid den tidpunkten, även om de senaste projektplanerna som publicerats i Danmark kan öka den beräknade tillgängliga lagringskapaciteten. Lagringskapaciteten kan bli en betydande begränsande faktor för Finlands tekniska sänkor fram till 2035, om inte aktiviteten ökar i fråga om förhandlingar och projektberedningar.

Utredningsarbetet för omvända auktioner eller andra stödmekanismer bör inledas inom kort om projekten ska kunna genomföras i början av 2030-talet. Det finns flera anläggningar i Finland som potentiellt skulle kunna delta i ett anbudsförfarande och där kostnadsberäkningen för att genomföra en teknisk kolsänka varierar mellan 120–150 €/tCO$_2$. Offerter och därmed budgetar är svåra att räkna ut eftersom det ännu inte finns någon erfarenhet av tekniken eller av driften och kostnaderna för transport- och lagringskedjan för koldioxid.

FOREWORD

In order to lay a foundation for its recommendations concerning Finland’s climate targets, the Finnish Climate Change Panel has gathered research data on the realistic commissioning potential, schedules and costs of technological carbon sinks in Finland. The aim of this report is to provide more detailed information on technological sinks based on the capture of industrial biogenic carbon dioxide emissions than has been previously available.

The study was performed by group of researchers from VTT Technical Research Centre of Finland, with assistance from the Finnish Climate Change Panel. The Finnish Climate Change Panel’s member responsible for the work has been Antti Arasto.

The Authors

15 December 2023

1. INTRODUCTION

1.1. Background

In its latest report (IPCC AR6, WG3, 2022), the Intergovernmental Panel for Climate Change IPCC has brought up the need for dramatic and immediate emission reductions in order to make it possible to limit global average temperature increase to 1.5 degrees. According to the IPCC's 1.5 degree emissions reduction scenarios, anthropogenic carbon dioxide emissions and carbon removal should be equal by the middle of the current century and, during the latter half of the century, removed amounts should be higher than the emissions (IPCC 2022). Removing carbon dioxide from the atmosphere may compensate for emissions that are otherwise very difficult or expensive to reduce, and help to restore the climate on the 1.5 degree track if the carbon dioxide concentration has temporarily overshot the target path (IPCC 2022). Carbon dioxide may be removed from the atmosphere by increasing and strengthening natural carbon sinks, such as forests and soil, and by removing carbon dioxide from the atmosphere and placing it in permanent storage. The latter means are referred to as technological carbon sinks.

Technological carbon sinks can refer to various technological solutions for permanently removing carbon dioxide from the atmosphere. Of these, the key option is the capture of biogenic carbon dioxide originating from the combustion of forest or other biomass, combined with the geological or mineral-based storage of carbon dioxide (bioenergy with carbon capture and storage, BECCS). During its growth, biomass has captured carbon dioxide from the atmosphere; when this carbon dioxide is captured during the combustion of the biomass and stored permanently, this results in negative emissions. Carbon dioxide may also be captured directly from the air and stored by permanently (direct air capture and storage, DACCS). The geological storage of carbon dioxide into sandstone and saltwater formations located deep in the earth's crust or depleted oil and gas deposits as well as its mineralisation into stone aggregates are considered permanent carbon storage, and these methods are allowed as part of the capture and storage of fossil carbon dioxide (carbon capture and storage, CCS) within the EU's emission trading system. At the EU level, the geological storage of carbon dioxide is regulated via the CCS directive (EU 2009), the aim of which is to advance the safety of CO_2 transport and storage. In addition, the regulation clarifies responsibilities regarding the supervision of the storage sites and actions to be taken in case of emergency.

A third significant, technology-based carbon dioxide removal method is the conversion of biomass into biochar via pyrolysis. Waste and side streams may be used as raw materials for biochar, and the product may be utilised as a soil conditioner in agriculture, as it has many beneficial characteristics for farming. The permanence of biochar as a carbon storage depends on the chemical properties of the material, such as the amount of hydrogen and oxygen in proportion to organic carbon. The production process may affect these chemical properties of the biochar (Rodriques et al. 2023).

The carbon dioxide removed from the atmosphere using the methods described above may also be utilised in the manufacture of synthetic fuels, for example, or stored in products with short or long service lives such as plastics (carbon capture and utilisation, CCU). However, synthetic fuels or other short-lived products cannot act as technological carbon sinks, as the carbon dioxide contained in them will be quickly released back into the atmosphere. Instead, they may provide emission reductions by replacing counterfactual products with higher life cycle emissions (e.g. fossil fuels).

The capture and storage of fossil carbon dioxide does not create technological carbon sinks, since it does not remove carbon dioxide from the atmosphere; it only prevents the carbon dioxide from entering the atmosphere. However, the capture of fossil carbon dioxide is an important means of climate change mitigation for industrial processes where reducing fossil emissions by other means is technically very difficult or expensive. That being said, the capture and storage of fossil carbon dioxide must not act as a means to extend reliance on fossil fuels.

1.2. Outlook for technological carbon sinks in Finland

The carbon sink provided by Finland's land use sector has diminished in recent years due to the reduction of the carbon sink available from forests (Ilmastovuosikertomus 2023). Therefore, emissions must be reduced even more efficiently and natural carbon sinks must be reinforced by means of various actions. The Finnish Climate Change Panel's memorandum (Suomen ilmastopaneeli 2023) states that the net carbon sink must be grown by approximately 19 Mt by 2035 compared to the 2021 level. Actions for increasing the carbon sink have been identified in the land use sector's climate plan. Even after taking these actions, the gap to the carbon sink target remains substantial; according to the Finnish Climate Change Panel's estimate, the difference is approximately 8 Mt. Covering this gap requires actions such as reducing soil emissions, minimising deforestation or changing harvest regimes and/or taking other actions in order to reinforce the net sink. Furthermore, Finland's carbon sink could also be reinforced by commissioning technological carbon sinks.

The CURPP project funded by the Prime Minister's office (Kujanpää et al. 2023) examined the potential of technological carbon sinks in Finland as part of a broader study of opportunities for the utilisation and removal of carbon dioxide. The study found that Finland has substantial potential for technological carbon sinks, especially as regards biogenic emissions from industrial facilities. Based on actual emissions, the study preliminarily mapped approximately 7–9 Mt of biogenic emissions from the forest industry and a further 2–3 Mt of other biogenic emissions from coastal areas, from where emissions could, in the medium term, be transported from deep-water ports via sea routes to geological storage. The project also recommended a national strategy for the utilisation and removal of carbon dioxide, and further analysis regarding actions related to an incentive policy which technological sinks are now lacking.

At the moment, there are no direct financial incentives for implementing technological carbon sinks in Finland, with the exception of the voluntary carbon markets (Laine et al. 2023, Laininen et al. 2022). Furthermore, technological carbon sinks do not currently offer any direct monetary benefits within the EU Emissions Trading System (ETS), and no other EU-wide subsidy systems have been created for them so far (with the exception of specific investment subsidies that have been granted). The EU's ETS directive (2023/959) states that, by the end of July 2026, the European Commission should report to the European Parliament and to the Council on "how emissions removed from the atmosphere and safely and permanently stored" could potentially be covered by emissions trading. The European Commission is also presently surveying voluntary certification systems for carbon dioxide removal mechanisms (EC 2022). In the Commission's public consultation on the EU's climate policy for 2040, the majority (54%) of respondents considered that a separate target should be set for technological carbon sinks for the year 2040, in addition to the emission reduction target and the target for the LULUCF sector (EC 2023a). The implementation of technological carbon sinks within the EU may also be expedited by the Commission's proposed Net-Zero Industry Act which targets the increasing of geological carbon dioxide storage capacity by 50 Mt each year starting from 2030 (EC 2023b). However, regulation and goals concerning climate policy within the EU beyond 2030 are completely undecided on for the time being. The Commission published a communication and impact assessment on the climate goals for 2040 in early 2024, and negotiations concerning legislation beyond 2030 will be started later (EC 2024a, EC2024b).

In Finland, the programme of Petteri Orpo's government (Valtioneuvosto 2023) contains a statement regarding supporting the commissioning of and investments in technological carbon sinks and surveying subsidy systems. Based on the survey, "a reverse auction of negative emissions or a similar mechanism" will be introduced.

1.3. Target and limitations

This study provides specific information on the realistic commissioning potential, schedules and costs of technological carbon sinks in Finland. The study focuses on industrial sources of biogenic carbon dioxide and the BECCS technology; for example, biochar, which in itself is a usable but rather different technology, is left out of the scope for the study. The outlook for developing and commissioning carbon dioxide storage opportunities and technologies in Finland and in nearby regions is also being surveyed. The aim of the study is to support the work of the Finnish Climate Change Panel in drawing up recommendations concerning Finland’s climate targets.

This study reviews the industrial sources of carbon dioxide emissions in Finland in light of the latest statistics and per facility, with special emphasis on biogenic emissions. It provides a growth outlook for carbon dioxide storage projects in the short and medium term as regards the amount of storage capacity and the number of projects. In other words, the risk to the timely availability of storage capacity is discussed qualitatively. The survey of storage capacity focuses on geological storage due to its significant potential. In addition, the sensibility of carbon dioxide storage is assessed from the point of view of CCU, i.e. whether a sufficient amount of carbon dioxide will be available for the production of synthetic fuels in the medium term. In future, the analysis on the potential for technological sinks while considering the various alternatives for CO_2 utilisation should be expanded.

The unit costs for the capture, transport and storage of carbon dioxide are examined on a per-facility basis. The investigation focuses on industrial facilities whose carbon dioxide emissions are entirely or partially biogenic. The investigation also uses examples to assess the suitability of carbon sinks as a means of emissions reductions compared to the utilisation of carbon dioxide in the refining of synthetic fuels. A national economic assessment is not made within the scope of the study. The cost estimates that are presented are adapted to the cost data presented in the literature, and the work does not involve in-house cost calculation based on process models.

As regards subsidy mechanisms, the study briefly examines the reverse auction being arranged in Sweden; it is a competitive bidding system where the government invites actors to implement technological carbon sink projects and to suggest a compensation for which they are willing to carry out such activities. From society’s point of view, the competitive bidding provides the least expensive means of implementing biogenic carbon dioxide capture and storage projects, as the bids are arranged on the basis of € per tonne of generated negative emissions, from lowest to highest, and the winning bids are selected in this order. The report examines the suitability of a similar system for Finland. The report does not examine the policy measures in a broader sense or estimate their impacts on the national economy.

2. INDUSTRIAL SOURCES OF BIOGENIC CARBON DIOXIDE IN FINLAND

The report estimates the potential of technological carbon sinks on the basis of Finland's industrial biogenic carbon dioxide sources. Emissions data is reviewed on the basis of the latest data in the European Pollutant Release and Transfer Register, the data for 2021 (EEA 2023). For carbon dioxide emissions, the register contains emissions data for industrial facilities with a minimum annual carbon dioxide emissions amount of 100 kt, including carbon dioxide emissions of fossil and biogenic origin. Only the capture and storage of biogenic and atmospheric carbon dioxide can create technological carbon sinks. However, emissions sources for fossil carbon dioxide are included in the report data in order to examine their share and to form a better view of the opportunities of carbon capture.

In order to ensure that the data is up to date, the data from the register is mechanically updated as regards decommissioned and new facilities as well as any possible missing data. For this work, the following facilities have been removed from the original emissions register data due to decisions of decommissioning: Helen Hanasaari B, Helen Salmisaari power plants, Stora Enso Veitsiluoto mills and Stora Enso Sunila mill. The following new facilities have been added to the data: Metsä Fibre Kemi, Helen's Vuosaari bioenergy heating plant and Vantaan Energia's hazardous waste incineration plant (included as part of the emissions from the Långmossebergen waste to energy plant in the review). Missing data for the following facilities has been updated: Vantaan Energia's waste to energy power plant (missing bio-CO$_2$), Fortum Waste Solutions' Riihimäki waste incineration plant (missing bio-CO$_2$), Alva Keljonlahti power plant (missing bio-CO$_2$). The facilities examined during the work and their emissions are set forth in Appendix 1. Table 1 presents the amount of carbon dioxide emissions from the industrial emissions sources examined during the work, and their distribution by area of industry.

According to the updated data based on the emissions register, Finland's annual industrial carbon dioxide emissions amount to 44.4 Mt, of which 63% (28.1 Mt) are of biogenic origin. The most significant sources of biogenic carbon dioxide are the forest industry (19.6 Mt$_{bio}$), thermal power stations (8.0 Mt$_{bio}$) and waste incineration (0.6 Mt$_{bio}$).

The magnitude of the emissions sources and the characteristics of the emissions streams vary depending on the field of industry and the processes used at the facilities. The average amount of carbon dioxide emissions from the examined facilities is 693 kt, and the median is 370 kt. Figure 1 presents the facilities examined in the work by order of CO$_2$ emissions and grouped by field of industry.

Table 1. Amount of Finland's industrial carbon dioxide emissions and their distribution by field of industry.

Field of industry	CO$_2$ emissions [MtCO$_2$]	Biogenic CO$_2$ emissions [MtCO$_2$]	Fossil CO$_2$ emissions [MtCO$_2$]	Share of biogenic emissions [%]	Share of fossil emissions [%]	Share of all emissions [%]
Forest industry	20.9	19.6	1.4	93%	7%	47%
Thermal power stations and other incineration facilities	15.1	8.0	7.1	53%	47%	33%
Iron and steel	3.0	0	3.0	0%	100%	7%
Oil refining	2.4	0	2.4	0%	100%	5%
Waste incineration	1.2	0.6	0.7	46%	54%	3%
Cement and lime mud	1.1	0	1.1	0%	100%	2%
Chemicals	0.7	0	0.7	0%	100%	2%
Total	44.4	28.1	16.3	63%	37%	

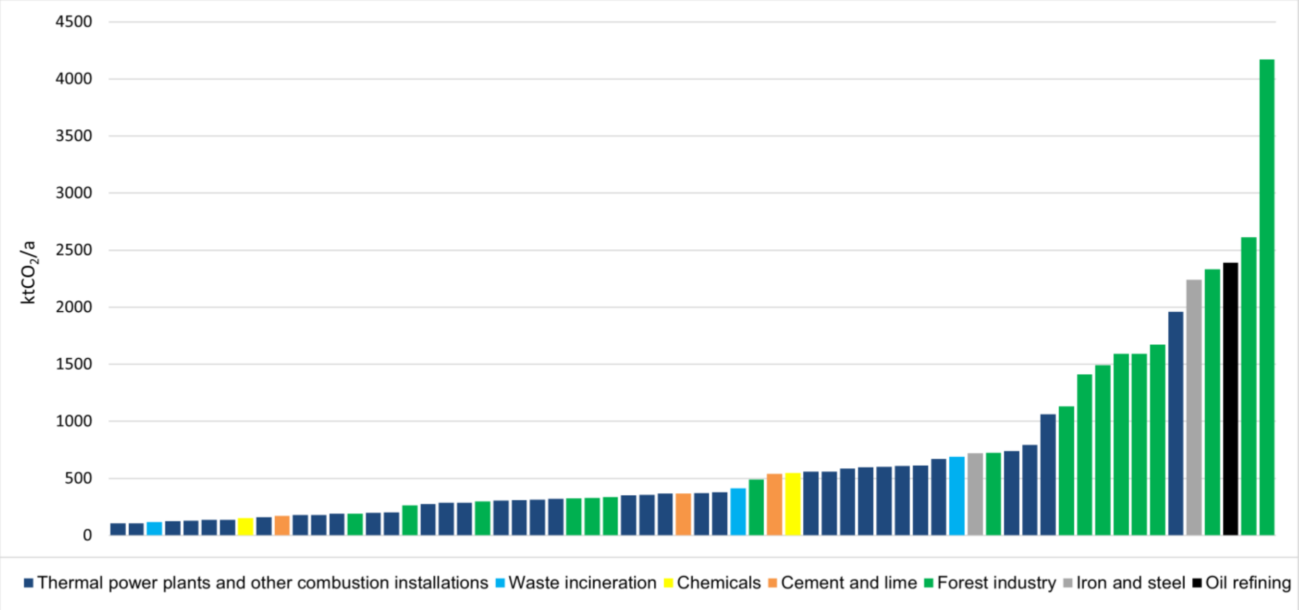

Figure 1. Amounts of carbon dioxide emissions from the facilities examined in this report (ktCO$_2$/a) by field of industry. The amounts include both fossil and biogenic carbon dioxide emissions from the facilities.

Figure 1 shows us that, in terms of numbers, the CO$_2$-emitting industrial facilities in Finland mostly consist of thermal power stations and other incineration facilities as well as forest industry facilities, whereas other manufacturing industry facilities (such as iron and steel, oil refining) are substantially fewer in number. As regards the amount of emissions, incineration facilities are on average substantially smaller compared to manufacturing industries. The forest industry, in particular, has several plant units with high emissions amounts.

Most of the industrial emissions sources covered by the emissions register are based on incineration processes, where carbon dioxide occurs in low concentrations in the flue gases; depending on the process, this typically varies between 3 vol-% and 30 vol-%. In such emissions sources, carbon dioxide capture requires a specific separation technology which, due to the high energy requirements of the processes, may make carbon dioxide capture relatively expensive. In some emissions sources, such as biogas upgrading or bioethanol production, carbon dioxide may occur in the exhaust gases as an almost pure stream, in which case a specific separation technology is not required and therefore the costs of capture are also low. However, the quantitative capture potential from these sources of high carbon dioxide concentration is low, as there are few facilities based on such applications. Furthermore, scales of such facilities are commonly substantially smaller compared to facilities of energy production and manufacturing industries. Due to the small scale of such facilities, they are also not included in the emissions register in Finland and, therefore, they are not included in this review. For small-scale sources with high carbon dioxide concentrations, the cost-effective implementation of technological carbon sinks may require using a local solution for CO$_2$ binding or storage (such as mineralisation) or participating in a larger, regional carbon dioxide cluster. Such sources may also offer an inexpensive route for the utilisation of carbon dioxide at a local level.

3. USES FOR CARBON DIOXIDE AND OUTLOOK FOR STORAGE

3.1. Use of carbon dioxide in the manufacture of synthetic fuels

The EU's climate targets and efforts to reduce the consumption of fossil energy and non-renewable raw materials will create demand for biogenic carbon dioxide. In this study, we are anticipating demand for the utilisation of carbon dioxide based on binding targets that are recorded in the legislation. They apply to the minimum required amounts of synthetic fuels between 2030 and 2050 in road traffic, marine traffic and aviation. The goals for e-fuels in the renewable energy directive (REDIII) as well as the ReFuelEU Aviation and FuelEU Maritime initiatives were published as part of the EU's FitFor55 package. The final targets were approved for enforcement in 2023.

The EU's targets for renewable energy within the traffic sector consist of an overall target that is technology neutral under certain conditions and of minimum amounts that need to be covered by means of renewable liquid and gaseous fuels of non-biological origin (RFNBO). For example, green hydrogen and synthetic fuels produced from it together with CO_2 are classified as RFNBO. The target set in the renewable energy directive for RFNBOs in 2030 is one per cent of the total consumption of traffic.

The ReFuelEU Aviation initiative sets targets for the use of sustainable aviation fuels (SAF) in 2030 and 2050. In the target for 2030, six per cent of energy consumed by aviation will be covered by means of sustainable aviation fuels, of which 1.2 per cent must be synthetic fuels. The share of synthetic fuels in aviation must increase to six per cent by 2035. By 2050, the share of SAFs must increase to 70 per cent of fuels consumed in aviation. From this, 35 per cent must be synthetic fuels. In addition to RFNBOs, sustainable biofuels and recycled carbonaceous fuels pursuant to the renewable energy directive that have been manufactured under specific conditions using non-renewable waste streams or unavoidable industrial emissions are counted as SAFs.

According to the FuelEU Maritime regulation, the emissions intensity of the energy used in marine traffic must fall from the provided reference level by six per cent by 2030 and 80 per cent by 2050. The minimum amount of RFNBOs by 2031 is one per cent. If this is not met, the target will be increased to two per cent from 2034.

The assumed energy consumption of the traffic sector in Finland and the EU is presented in Table 2. As regards the EU, energy consumption is based on the estimate for 2030 presented by Yugo et al. (2021). Energy consumption on Finland's traffic sector is based on Statistics Finland's (2023) data on actual energy consumption in 2022; in this study, the value is assumed to remain constant.

Table 2. Fuel consumption for the traffic sector in 2030 as assumed in this report.

	Finland* (Mtoe)	EU (Mtoe)
Road traffic, rail traffic and internal marine traffic	3.8	259.5
Aviation	0.1	58.3
Marine traffic		54.8
Source	Statistics Finland 2023	Yugo et al. 2021

*the assumption used is the level for domestic traffic in 2022

Table 3. Demand scenario assumed in the report for synthetic fuels produced in Finland for 2030, 2035 and 2050. Carbon dioxide and electricity demand are based on Yugo & Soler (2019).

	2030	2035	2050	Unit
Demand scenario for synthetic fuels	490	815	2776	ML/a
Need for biogenic carbon dioxide	1.6	2.6	9.0	Mt/a
Need for renewable electricity	11.2	18.5	63.2	TWh/a

In order to conceptualise the magnitude of demand for synthetic fuels, this study assumes a demand scenario (see Table 3) where the carbon dioxide captured in Finland is refined to an extent that creates the statutory minimum for use in Finland and ten per cent of the minimum required on the European traffic sector. This coarse estimate assumes that energy consumption in traffic remains at the same level in 2030–2050 and that the increase in demand for synthetic fuels is driven by stricter obligations for their minimum amounts within aviation. Under these assumptions, Finland would produce 490 ML of synthetic fuels in 2030, 815 ML in 2035 and 2,776 ML in 2050. Correspondingly, the amount of biogenic carbon dioxide required to refine this amount would be 1.6 $MtCO_2$/a in 2030, 2.6 $MtCO_2$/a in 2035 and 9.0 $MtCO_2$/a in 2050. Most of the amount is due to assumed export for synthetic aviation fuel needs within the EU.

In addition to carbon dioxide, the refining of synthetic fuels requires green hydrogen production capacity, the electricity consumption of which in the assumed scenario would be 11 TWh in 2030 and 63 TWh in 2050.

3.2. Outlook for geological storage in Northern Europe

This study updates the status of geological carbon dioxide storage from Finland’s point of view based on carbon dioxide storage projects that are being publicly prepared and under way in Northern Europe. The data regarding carbon dioxide storage projects is based on the Global CCS Institute’s report for 2022 (GCCSI 2022), and the information has been supplemented from the websites of several projects. The Global CCS Institute recently released its report for 2023 (GCCSI 2023), but there was no time to update the information in the results diagrams in this report. The key findings from the report for 2023 were as follows:

- The growth of capture capacity in the globally prepared CCS projects has continued along an exponential trajectory (+57…+68%) for four consecutive years (2020–2023).
- Denmark’s new plans contain up to 52 $MtCO_2$/a of storage capacity for 2030–2032, which constitutes a significant increase to the projects described in the status report for 2022 (in particular compared to 8 $MtCO_2$/a in Denmark).
- In Norway, storage capacity in the Northern Lights is, according to the data recorded in the report for 2023, “full according to oral reports”, but Norway is planning 30–40 $MtCO_2$/a of carbon dioxide pipe transport for storage in the North Sea as part of the EU2NSEA project. No detailed schedule information was provided.

The websites of carbon dioxide storage projects were examined in order to determine the following:

a) How large of an annual storage capacity will the project create?

b) Which share of the storage capacity is already allocated for specific companies and, in turn, which share of it could Finnish actors openly compete for?
c) When is the storage capacity estimated to be available?

In terms of the information available on the website, special attention has been paid to whether carbon dioxide delivery volumes from specific partners have been published, whether new carbon dioxide suppliers are being actively sought, whether plans have been announced for expanding capacity and when the potential expansion would take place and whether, based on the other information, the storage can be assumed to be intended for national or international use. This information has been used to form Figure 2 "Carbon dioxide storage capacity in Northern European storage projects", where the storage capacity has been divided into three parts: The share that is likely to be available (i.e. open to competition), share of capacity, uncertain status and share that is already allocated. "*Storage capacity with no published allocation"* has been calculated according to formula (1), where *storage capacity with no published allocation* is the remaining share in storage projects for which additional carbon dioxide suppliers are being sought once the already disclosed delivery volumes have been subtracted from the storage capacity.

$$\begin{aligned}&\text{Storage capacity with no published allocation}\\&= (\text{Total storage capacities in Northern Europe, "more suppliers being sought"})\\&- (\text{disclosed } CO_2 \text{ deliveries}) \qquad (1)\end{aligned}$$

For some projects, the delivery volumes and suppliers for carbon dioxide have already been clearly announced. They are reported in the diagram under *"reserved capacity".* Some projects do not clearly communicate whether the project could accommodate more carbon dioxide suppliers and when this would be possible or whether international actors could also make deliveries. Furthermore, projects for carbon dioxide capture, transport and storage are sometimes very multi-faceted, and it is not always possible to directly determine whether or not an announced carbon dioxide delivery will reduce the announced storage capacity. For these reasons, there is an intermediate category for projects of *"capacity, uncertain status".*

Most projects reported a specific target schedule for the project's storage capacity linked to a specific year. In some early preparation stage projects, however, the total storage capacity for the location was known but yearly capacity had not been reported. In cases where the starting time for the project was not announced, the time was estimated in adherence with a typical CCS project in the GCCSI 2022 report: start-up would take six years from the identification of the storage, four years from the announcement of the storage capacity and two years from the start of construction. If the annual storage capacity was not announced, the total capacity has been divided across 20 years in adherence with the typical service life of an industrial investment. For example, in the Polaris project: 100 Mt CO_2/20 years = 5 MtCO_2/a.

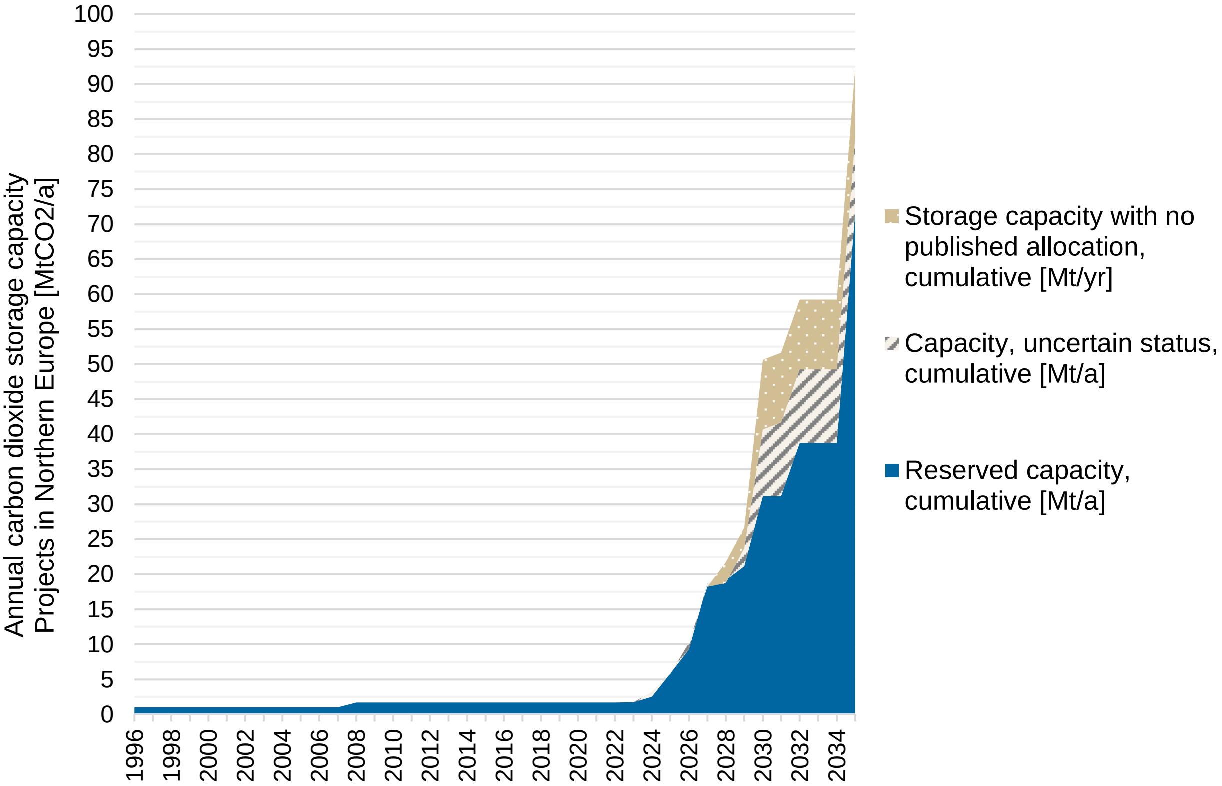

Figure 2. Carbon dioxide storage capacity in Northern European storage projects.

3.2.1. Development of carbon dioxide storage projects by 2035

The anticipated carbon dioxide storage capacity for Northern Europe consists of 16 projects and their subprojects, numbering 25 in total. The carbon dioxide storage projects considered herein are Sleipner (Global CCS Institute 2022), Snøhvit (Global CCS Institute 2022), Orca (Climeworks n.d.), Northern Lights (Northern Lights n.d.a, Northern Lights n.d.b, Yara 2022), Mammoth (Climeworks 2022), Antwerp@C (Antwerp@C n.d.), Project Greensand (Project Greensand 2023), Porthos (Porthos 2023), Coda (Carbfix n.d.), East Coast Cluster (East Coast Cluster n.d.), HyNet (HyNet 2023), Polaris (Horisont Energi n.d.), Acorn (Acorn 2023), MEDWAY (Brook-Jones 2023; Wessel 2022) and H21 (H21 2023). Most of the storage projects are located in the sea areas of the United Kingdom, Ireland, Norway and Denmark, and most of the planned capture and storage capacity concerns the storage of fossil carbon dioxide.

At the time of writing this report, storage capacity for carbon dioxide is no more than 2 $MtCO_2/a$, but it is expected to increase more than tenfold within only five years as a result of the Northern Lights, Mammoth, Antwerp@C, Project Greensand, Porthos, Coda, East Coast Cluster and HyNet projects. Thereafter, storage capacity is assumed to increase further – by more than 90 $MtCO_2/a$ – by 2035, even though the intermediate goals for projects between 2032 and 2034 have not always been published; in the diagram, this can be seen as a stable period.

Storage capacity with no published allocation will be available in substantial amounts from 2030 onwards. Based on the 2022 Global CCS Institute report, there would be approximately 10 $MtCO_2/a$ of *storage capacity with no published allocation* in 2030–2035. This amount could likely still be available to open competition on the Northern European market, but only a part of it could be available for actors in Finland. However, according to the 2023 report by the Global CCS Institute, Denmark is planning many times more carbon dioxide storage capacity, up to 52 Mt CO_2/a, already for 2030–2032; however, the degree of reservations for this capacity is unknown as yet. In addition to Denmark's new storage projects, a substantial part of the storage capacity with an unknown degree of reservation is connected to the United Kingdom's East Coast Cluster project that seems to be mainly intended for actors within the United Kingdom.

3.2.2. Key projects in terms of available storage capacity

The *storage capacity with no published allocation* in Figure 2 mainly consists of four projects: Northern Lights (stage 2), Polaris, Project Greensand (stage 2) and Acorn. It should also be noted that the situational picture available on the basis of public information may change significantly even during the course of one year, as the example from Denmark shows.

The plan is to launch the **Northern Lights** project in two stages, the first of which comprises marine transport of 1.5 $MtCO_2$/a of carbon dioxide to a terminal on the west coast of Norway and its transport via pipe to a geological storage facility below the North Sea (Northern Lights, n.d.b). In the second stage that will be started later, approximately in 2028, capacity will be increased by 3.5 $MtCO_2$/a. The implementation of the second stage is based on demand, that is, storage capacity has so far not been publicly allocated for use by companies named in advance. The project website (Northern Lights, n.d.a) continues to advertise the storage opportunity to European actors, but the Global CCS Institute's recent report (GCCSI 2023) states that the entire storage capacity is already full "according to oral information".

Horisont Energi's **Polaris** storage project has a reported total storage capacity of 100 $MtCO_2$ and it is located in the Norwegian sea area, on the Barents Sea (Horisont Energi, n.d.). Limited public information on the storage project is provided, and the project has no reported target for annual storage capacity or a starting date for storage. Based on the reported total capacity and the assumed operating time of 20 years, the starting year for the storage facility is *estimated* to be approximately 2029 and the annual capacity is estimated at 5 $MtCO_2$/a.

The **Acorn** storage project, located in the United Kingdom in Scotland's sea area has a reported total storage capacity of 240 $MtCO_2$ (Acorn 2023). The aim of the project is to store at least 5 $MtCO_2$/a by 2030. The project intends to offer its capacity for use by several capture facilities from Scotland, England and the EU. In this study, the starting year for the project has been assumed to be 2030 and the annual storage capacity to be 12 $MtCO_2$/a; this is based on the reported total capacity and the assumed operating time of 20 years. Furthermore, it is assumed that, after the United Kingdom's domestic reservations (target of 5 $MtCO_2$/a), approximately 7 $MtCO_2$/a would be open to other actors from Europe. However, it is possible that the storage capacity available to other actors in Europe could be much lower or available much later than in 2030.

The target for the first stage of the Danish **Project Greensand** storage project, which entered the pilot stage in 2023, is to reach a storage capacity of 1.5 $MtCO_2$/a in 2025–2026. (Project Greensand 2023). The aim is to increase storage capacity to 8 $MtCO_2$/a by 2030, and this second stage involves a substantial opportunity for Finnish actors as well. Furthermore, the latest announced plans (GCCSI 2023) propose a total of up to 52 $MtCO_2$/a of storage for Denmark already in 2030–2032, which would be a very significant addition to the projects assessed in more detail herein.

4. COSTS AND PROFITABILITY OF TECHNOLOGICAL CARBON SINKS

4.1. Costs for the capture, transport and storage of carbon dioxide

4.1.1. Cost of carbon capture

The cost of carbon capture consists of the investment and operating costs for the technology required for separating carbon dioxide. Carbon capture technology is capital intensive and requires major investments, especially for emissions sources with low carbon dioxide concentrations. In terms of operating costs, the main component is typically energy consumption that derives costs via lost energy generation capacity as the facility's own energy consumption increases due to capture, or as the result of constructing and operating additional energy generation capacity.

In this study, capture costs are calculated per facility based on reference data collected from literature. The capture cost per facility is estimated based on the facility's size (i.e., the amount of CO_2 emissions) and the partial pressure of carbon dioxide and a process-specific scale factor. The facility's amount of emissions is based on information from the emissions register (see Chapter 2). The partial pressure of carbon dioxide in each facility is estimated on the basis of the facility's type and facility-specific information (such as the environmental permit). The following assumptions have been used in the estimation of capture costs:

- 90 % capture rate (the share of the emission source's carbon dioxide that can be captured)
- If the facility contains several point sources of emissions, it is assumed that these can be combined into one stream for carbon capture (such as the recovery boiler, bark boiler and lime kiln in a pulp mill).

Cost of carbon capture is estimated based on reference data collected from literature. As the reference data, we use the capture costs estimated by the Global CCS Institute (Kearns et al. 2021) for industrial emissions sources at different scales that are calculated on the basis of well known, technologically mature MEA capture technology. The cost data has been updated to EUR_{2023}. Additionally, the data is used as the basis for calculating a process-specific scale factor for capture cost, which is used for scaling the cost data in each facility. Table 4 presents the reference data used as the basis for calculating capture costs regarding the costs of carbon capture in industrial emissions sources at different scales, and the process-specific scale factors calculated based on the capture costs.

Table 4. Costs for the capture of carbon dioxide in industrial emissions sources of various size categories (based on Kearns et al. 2021).

Emission source	Partial pressure of carbon dioxide [kPa]	Amount of emissions from the facility [ktCO₂/a]	Capture cost [€/tCO₂]	Scale factor (calculated) [-]	Reference
Aluminium smelter	1 kPa	20	326	-0.213	[1]
		200	199		
Steel plant dedusting chimney	2 kPa	40	200	-0.222	[1]
		400	120		
NGCC, sintering of steel	4 kPa	70	133	-0.223	[1]
		660	81		
Natural gas and petroleum coke power plants	8 kPa	120	93	-0.156	[1]
		1200	65		
Waste incineration	10 kPa	500	71	-0.147	[2] Interpolated
Biopower plant	12 kPa	130	81	-0.138	[1]
		1300	59		
Recovery boiler	13 kPa	500	66	-0.128	[3] Interpolated
Coalpower plant, pulp mill (all emissions sources)	14 kPa	150	75	-0.119	[1]
		1500	57		
Cement kiln	18 kPa	180	68	-0.092	[1]
		1800	55		
Lime kiln	20 kPa	500	61	-0.085	Interpolated
Steel production (blast furnace)	26 kPa	200	60	-0.066	[1]
		2000	51		
Steel production (COREX), methane steam reforming	35 kPa	200	57	-0.080	[1,4]
		2000	47		

[1] Based on Kearns et al. 2021, [2] IPCC 2005, [3] Onarheim et al. 2017a, [4] Bains et al. 2017

Table 4 shows that the partial pressure of carbon dioxide and the scale of the facility have a substantial impact on capture cost. The impact of scale on capture cost is substantially higher for emissions sources with a low partial pressure of carbon dioxide. Based on the information presented in Table 4, Equation 1 can be used to calculate a carbon capture cost estimate for industrial emissions sources.

$$c_{capture,1} = c_{capture,2} \left(\frac{m_1}{m_2}\right)^s \qquad \text{(Equation 1)}$$

$c_{capture}$ = capture cost (€/tCO_2)
m = amount of captured CO_2 (t/a)
s = scaling factor (-)

The equation below presents an example calculation for carbon capture cost in a biopower plant with an annual carbon dioxide emissions volume of 300 kt, assuming a capture rate of 90 %.

Example: $c_{capture,1} = 58,6\frac{€}{tCO2}\left(\frac{0.9*300\ kt/a}{1300\ kt/a}\right)^{-0.138} = 72.8\frac{€}{tCO2}$

It should be noted that the facility-specific capture costs estimated in this study are indicative, since accurately calculating the capture cost requires considering facility-specific data such as the fuel being used, the process conditions and the operating environment, such as the opportunities for energy integration.

4.1.2. Cost of carbon dioxide compression

Following capture, once the carbon dioxide has been separated into a pure product stream, it will be compressed in order to achieve a form that is logistically more cost-effective. In this study, the cost of compression is calculated as a function of the amount of carbon dioxide captured.

The following assumptions are used for the compression of carbon dioxide:

- Price of electricity: 0.1 €/kWh
- Electricity consumption: 105 kWh/tCO_2 (Aspelund & Jordal 2007)
- Electricity cost: 10.5 €/tCO_2 (0.1 €/kWh, 105 kWh/tCO_2)
- Investment cost (equipment costs including installation): 28 M€ at 400 ktCO_2/a, annuity 2 693 679 € (Eldrup et al. 2019, converted to EUR2023)
- Scaling factor for investment cost: 0.65 (Eldrup et al. 2019)
- Maintenance cost: 4% of annual investment cost (Eldrup et al. 2019)
- Labour costs: 1.6 €/tCO2 (635 k€/a at 400 ktCO2/a, Eldrup et al. 2019, converted to EUR2023)

The cost of compression is calculated using Equation 2.

$$c_{compression} = \frac{1.04 * 2\ 693\ 679\ € \left(\frac{m}{400\ 000}\right)^{0.65}}{m} + 10.5\frac{€}{tCO2} + 1.6\frac{€}{tCO2}$$

$$= \frac{639.8\ €}{m^{0.35}} + 12.1\frac{€}{tCO2} \qquad \text{(Equation 2)}$$

$c_{compression}$ = compression cost (€/tCO_2)

m = amount of CO_2 captured (t/a)

The equation below presents an example calculation for carbon dioxide compression cost in a biopower plant with an annual carbon dioxide emissions volume of 300 kt, assuming a capture rate of 90 %.

For example, $c_{compression} = \frac{639.8\ €}{(0.9*300\ 000\ t/a)^{0.35}} + 12.1\frac{€}{tCO2} = 20.1\ €/tCO2$

4.1.3. Transport and storage costs

Finland does not have suitable geology for the permanent storage of carbon dioxide (Teir et al. 2016), and the most potential storage areas in Northern Europe are located in the North Sea region (IEA 2021). The captured carbon dioxide may pass through several means of transport and interim storage before its arrival at and placement in permanent storage (see Figure 3). Carbon dioxide may be transported along pipelines or, in liquid form, on board ships, trains or tankers. In Finland's case the carbon dioxide to be stored needs to first be transported to a port, from where it is transported by ship either directly to the storage area or a receiving port that has a pipe connection to the storage area.

In this study, the estimation of transport costs is based on the unit costs (€/tCO_2) presented in the literature for the various means of transport at different distances and with different amounts of carbon dioxide. The estimate aims to use the latest literature or literature that has been determined to be reliable, including both public reports and peer reviewed scientific publications. Therefore, the estimates that are presented herein are adapted to the cost data presented in the literature, and the work does not involve in-house cost calculation based on process models. The costs have been index adjusted to 2022 values, and they are estimates of the commercial price levels for carbon dioxide transport and storage following the first commercial demonstrations. In other words, the first investments into carbon dioxide transport and storage in Northern Europe may be more expensive than the costs estimated in this study.

The estimation of transport costs has been simplified by limiting the means of transport to pipeline and marine transport. Marine transport costs are based on Kjärstad et al. 2016, IEAGHG 2020 and GCCSI 2021. Pipeline transport costs are based on GCCSI 2021, IEAGHG 2020 and Stolaroff et al. 2021.

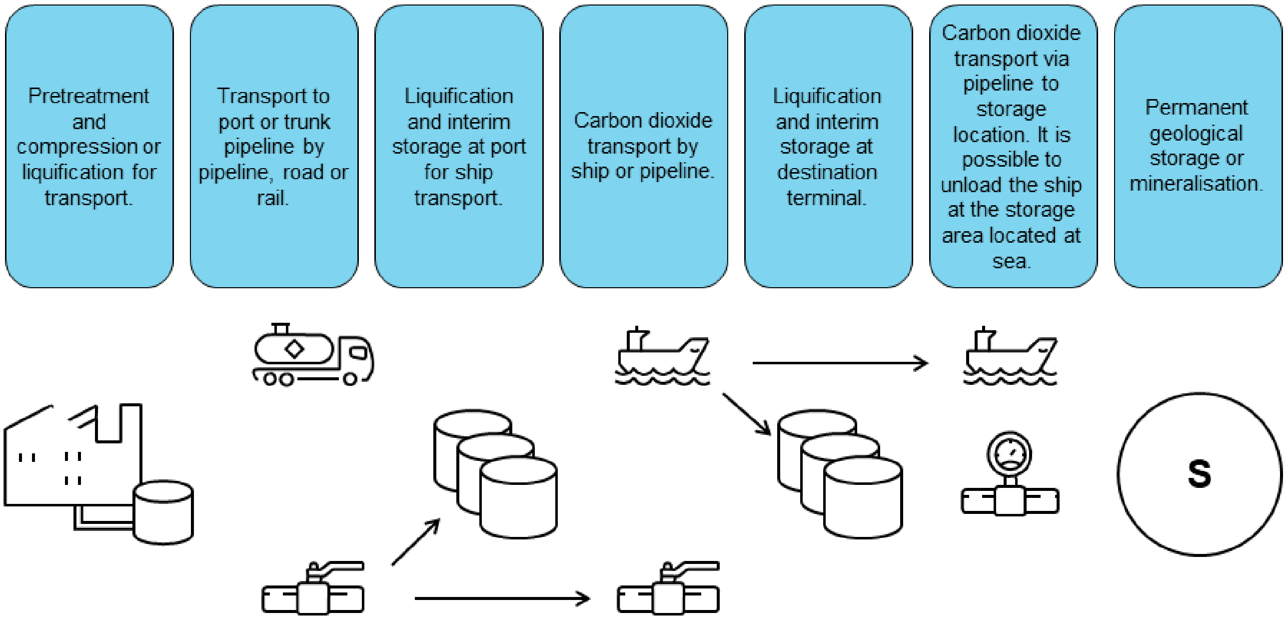

Figure 3. Carbon dioxide logistics stages and alternatives from the capture facility to permanent storage.

The marine transport cost fit for distances above 1,000 km is shown below in Equation 3.

$$A_{ship} = 2{,}304703 + 19{,}527697 * B^{-0{,}132486} + \frac{C-1000}{50} * 0{,}3 \qquad \text{(Equation 3)}$$

where A_{ship} is the marine transport cost in €/tCO₂, B is the recovered amount in MtCO₂/a and C is the transport distance in km.

The costs for pipeline transport have been estimated according to Equation 4.

$$A_{pipeline} = 0{,}076149 * B^{-0{,}504135} * C \qquad \text{(Equation 4)}$$

where $A_{pipeline}$ is the pipeline transport cost in €/tCO₂, B is the recovered amount in MtCO₂/a and C is the transport distance in km.

The estimate of storage costs, €18/tCO₂, is based on GCCSI 2021 and ZEP 2010. The cost applies to an undersea geological storage formation that does not contain any decommissioned oil production wells for injecting purposes. The storage cost is constant for all capture facilities. €8/tCO₂ will be added to the storage costs, which includes the unloading of the ship at the destination port and pipeline transport to storage.

The known storage areas have not been assumed as the destinations when estimating transport costs; the shipping routes terminate at a chosen point on the North Sea. The length of an individual shipping route is determined on the basis of the coastal area in Finland where the port is located (see Table 5). For inland facilities, pipeline transport to the nearest port with other nearby emissions sources is added. At the same time, a picture has formed of emissions hubs along the coast where targeting economies of scale in terms of transport costs would make sense.

The transport costs from one capture facility depend on whether the costs of shipping or the pipeline connection can be shared with other facilities. In this study, the transport network has not been defined by means of optimisation; instead, costs have been given a higher estimate that is based on an individual transport solution and a lower estimate that is based on transport infrastructure that is as shared as possible and targets economies of scale. Therefore, the facility-specific transport cost is calculated using two assumptions: By dimensioning the transport infrastructure for the facility in question or by using the maximum total amount, inclusive of the sources of carbon dioxide near the port and carbon dioxide sources gathered along the pipeline that runs from an inland location to the port. The lower transportation cost estimates for inland capture facilities assume that carbon dioxide runs along a shared trunk line for the entire distance to the port, regardless of whether the sources are along the same trunk line. While unrealistic in itself, this manner of calculation has been chosen for its simplicity, and it describes the transportation costs that could be reached from inland locations in an ideal case. The marginal cost for the capture, transport and removal of carbon dioxide defined in the study (see Figure 4) follows the facility-specific unit costs based on the higher estimate of transport costs using an individual transport infrastructure.

Table 5. Assumed transport distances and amounts of carbon dioxide for the examined routes. A hub refers to a carbon dioxide hub formed by capture facilities located near the port which allows for targeting economies of scale in terms of transport costs.

Region	Transport distance	Amount of CO_2 in case of non-shared logistics	Amount of CO_2 in case of shared logistics
Bay of Bothnia	Ship, 2,200 km	Captured amount from facility of origin	Total amount for hub
Sea of Bothnia	Ship, 1,800 km	Captured amount from facility of origin	Total amount for hub
Finnish Archipelago Sea	Ship, 1,650 km	Captured amount from facility of origin	Total amount for hub
Gulf of Finland	Ship, 1,800 km	Captured amount from facility of origin	Total amount for hub
Inland	Pipeline: to nearest hub on the coast, ship: based on region	Pipeline and ship: Captured amount from facility of origin	Ship: Total amount for hub, Pipeline: Emissions from all facilities transporting into the area in one trunk pipeline

4.1.4. Marginal costs for the capture and storage of carbon dioxide in Finland’s industrial emissions sources

Adding together the estimates regarding the costs of carbon dioxide capture, compression, transport, and storage allows for calculating an estimate of the costs for technological carbon sinks based on the geological storage of carbon dioxide in Finland’s industrial emissions sources. The cost examination was performed for three different scenarios depending on the natural origin of the carbon dioxide emissions.

- CASE 1 includes all industrial facilities regardless of the natural origin of the carbon dioxide emissions, including both fossil and biogenic emissions.
- CASE 2 includes facilities emitting biogenic carbon dioxide, but it also covers fossil emissions from facilities that generate fossil emissions in addition to biogenic emissions.
- CASE 3 includes facilities emitting biogenic carbon dioxide and the capture capacity has been dimensioned to only cover the biogenic emissions from the facility, that is, all fossil emissions have been ignored.

From these scenarios, CASE 3 is the most central in terms of technological carbon sinks, as it only covers biogenic carbon dioxide. Figures 4, 5 and 6 present the cost estimates for the capture, compression, transport and storage of carbon dioxide for Finland’s industrial emissions sources, in the order of least to most expensive, in the different scenarios (CASE 1–3).

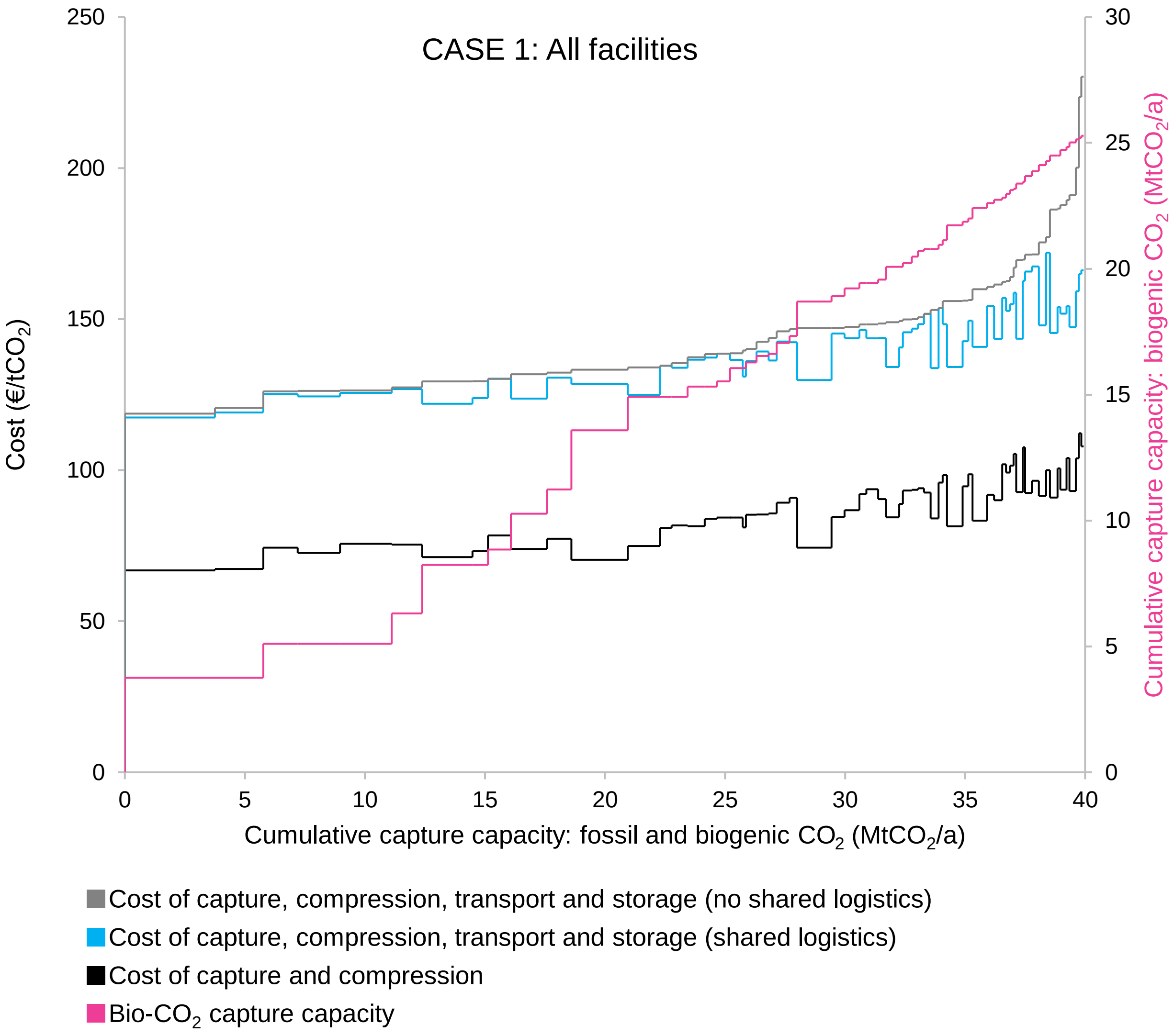

Figure 4. Marginal costs for the capture, transport and storage of carbon dioxide in Finland, including all industrial facilities regardless of the natural origin of the carbon dioxide emissions, including both fossil and biogenic emissions.

When looking at all industrial emissions sources in Finland, the cumulative capture capacity is 39.9 Mt/a, of which 25.3 Mt is biogenic carbon dioxide. Estimates of the unit costs including capture, compression, transport and storage found in these sources vary at €119—€230/tCO$_2$ (no shared logistics) and €117—€172/tCO$_2$ (shared logistics). The facility-specific average for the costs is €154/tCO$_2$ (no shared logistics) and €142/tCO$_2$ (shared logistics), whereas the weighted (arithmetic) average is €139/tCO$_2$ (no shared logistics) and 132 €/tCO$_2$ (shared logistics). As the annual capture capacity increases, the costs increase mildly, which is explained by the similarity of the facilities with the lowest costs: They are large in scale and the emissions sources have similar characteristics. Costs increase significantly only in the latter section of capture capacity (>35 MtCO$_2$/a); this is explained by the small size and inland locations of the facilities with the highest costs. At these locations in particular, the costs may be substantially lower if the facilities can utilise shared logistics with other facilities in the area.

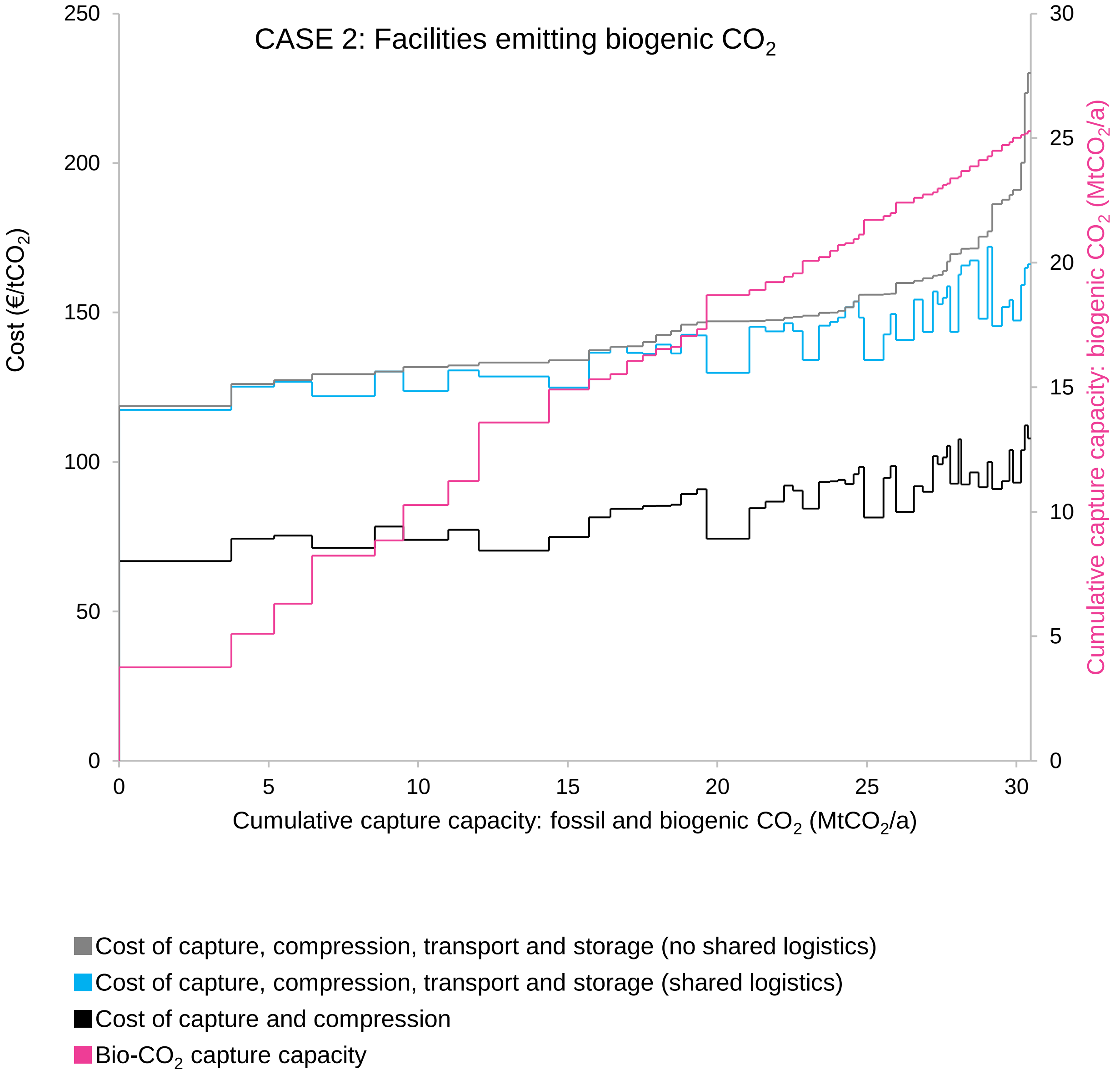

Figure 5. Marginal costs for the capture, transport and storage of carbon dioxide in Finland, including facilities emitting biogenic carbon dioxide but also covering fossil emissions from facilities that generate fossil emissions in addition to biogenic emissions.

When facilities emitting only fossil-based emissions are excluded, the cumulative capture capacity drops from 39.9 Mt/a to 30.5 Mt/a, of which 25.3 Mt remains biogenic. The range of variation for the costs of capture, compression, transport and storage remains the same: €119—€230/tCO_2 (no shared logistics) and €117—€172/tCO_2 (shared logistics). The average facility-specific cost increases slightly: €157/tCO_2 (no shared logistics) and €144/tCO_2 (shared logistics). The weighted (arithmetic) average also increases slightly: €141/tCO_2 (no shared logistics) and €133/tCO_2 (shared logistics). The profile of the cost abatement curve remains similar: The costs increase mildly and steadily due to the similarity of the facilities until, in the final stages of the cumulative capture capacity, the increase becomes significantly steeper due to the small scale and inland locations of the facilities.

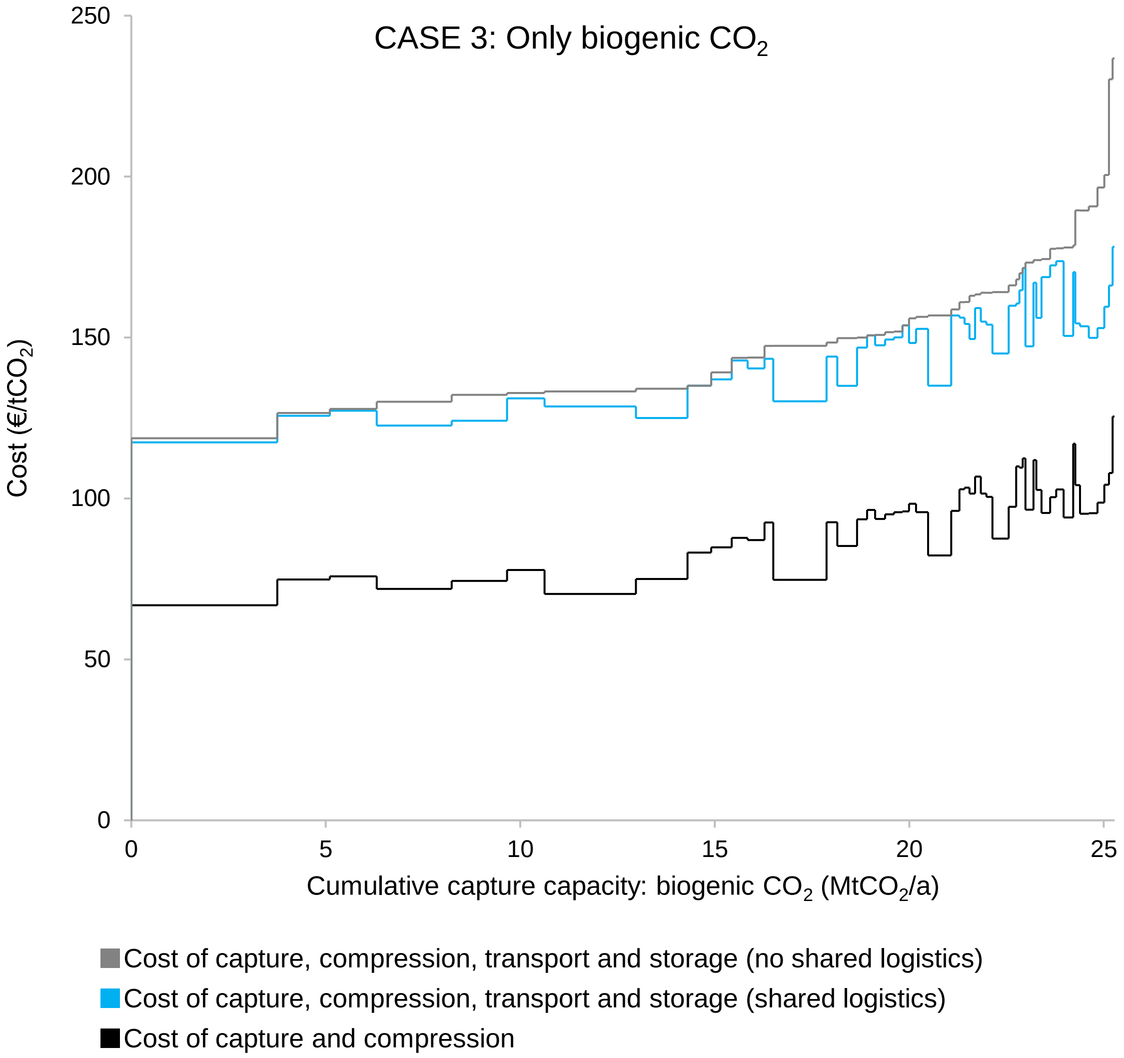

Figure 6. Marginal costs for the capture, transport and storage of carbon dioxide in Finland, including only biogenic carbon dioxide emissions from industrial facilities.

When looking at only the biogenic carbon dioxide emissions, the cumulative capture capacity is 25.3 Mt/a, all of which is biogenic. The variation range for costs of technological carbon sinks is €119—€237/tCO_2 (no shared logistics) and €117—€178/tCO_2 (shared logistics). For CASE 3, costs increase at the facilities that generate both fossil and biogenic emissions due to the reduction in capture capacity when fossil emissions are excluded from the analysis. The average facility-specific cost increases slightly: €161/tCO_2 (no shared logistics) and €149/tCO_2 (shared logistics). The weighted (arithmetic) average remains nearly unchanged: €141/tCO_2 (no shared logistics) and €134/tCO_2 (shared logistics). The profile of the cost abatement curve still remains similar: They increase mildly and steadily due to the similarity of the facilities until, in the final stages of the cumulative capture capacity, the increase becomes significantly steeper due to the small scale and inland locations of the facilities.

Table 6 presents the results for the unit costs of technological carbon sinks in Finland's industrial emissions sources.

Table 6. Unit cost of technological carbon sinks in Finland’s industrial emissions sources.

	CASE 1: All facilities		CASE 2: Facilities emitting biogenic CO_2		CASE 3: Bio-CO_2 only	
	No shared logistics	Shared logistics	No shared logistics	Shared logistics	No shared logistics	Shared logistics
Range of variation	€119–230/tCO_2	€117–172/tCO_2	€119–230/tCO_2	€117–172/tCO_2	€119–237/tCO_2	€117–178/tCO_2
Plant-specific average	€154/tCO_2	€142/tCO_2	€157/tCO_2	€144/tCO_2	€161/tCO_2	€149/tCO_2
Weighted average	€139/tCO_2	€132/tCO_2	€141/tCO_2	€133/tCO_2	€141/tCO_2	€134/tCO_2

4.2. Feasibility of technological carbon sinks and utilisation of carbon dioxide in the selected case studies

In this study, income and costs have been calculated for technological carbon sinks in two example cases and for the utilisation of carbon dioxide in the manufacture of synthetic fuels in one example case. The facility types, captured amounts, and required transport distances for the example cases are shown in Table 7. The carbon dioxide sources selected for the example cases are, for technological carbon sinks (cases 1 and 2), the two largest forest industry facilities on the coast and inland; for the reutilisation case (3), the source is a bioenergy plant that corresponds to the carbon dioxide needs of a largeish fuel production unit. The cases are used to illustrate the relationship between capital expenditure and operating income and costs as well as the impact of the facility’s location on the costs in the case of technological carbon sinks. Based on the magnitude of fixed capital expenditure, the capital required for the investment and the maximum impact of subsidies, such as investment subsidies, on the project finances are assessed. The cost of emissions reductions is also compared between carbon dioxide removal and utilisation.

Table 7. Descriptions for the example cases.

Example case	Transport distance (km)	Captured amount ($MtCO_2/a$)
1: Capture from a forest industry facility located on the coast, transport and storage	Ship: 2,200	3.7
2: Capture from a forest industry facility located inland, transport and storage	Pipeline: 250 and ship: 1,800	2.4
3: Capture from a bioenergy plant and refining into synthetic fuel	0	0.5

4.2.1. Capture, transport and storage from large facilities on the coast and inland

In the example case, 2.4 $MtCO_2$/a is captured from a factory located inland and 3.7 $MtCO_2$/a from a factory located on the coast, for the purpose of geological storage. The captured amounts from both facilities are fairly large, which in itself introduces economies of scale in the capture and transport costs.

In the example cases, the cost of carbon dioxide capture and storage is €119/tCO_2 from the coast (see Figure 7) and €133/tCO_2 from inland (see Figure 8). The cost estimate is based on the sources and assumptions presented above, and the facilities were picked from the marginal cost curve for capture that was presented in Figure 4. In the case of an inland recovery facility, costs are increased by the required pipeline transfer to port and the lower capture volume compared to the example case from the coast. Costs are lowered by the slightly shorter distance for ship transport.

The value of capital expenditure is based on the capital expenditure as regards capture and transport that is presented in the literature. The share of capital expenditure in the capture investment is assumed to be 25 per cent of unit costs (€/tCO_2), based on Roussanaly 2018 and Ho 2011. The assumed corresponding share of capital expenditure in pipeline transport is 85%, based on ZEP 2010 and IEAGHG 2020. As regards ship transport, the assumed capital expenditure is also 25 per cent of the equalised total costs according to IEAGHG 2020. According to estimates set forth by Kjärstad et al. (2016), a higher share of costs for ship transport, approximately 46 per cent, could be capital expenditure. In this study the later analysis was used.

Due to the substantial additional investment required by the pipeline and the lower captured amount, the equalised capital expenditure in the inland facility's case are the higher of the two, €34/tCO_2. Therefore, the maximum theoretical share of BECCS costs covered by domestic investment subsidies in the example cases would be 20–26 per cent. Depending on the level of investment subsidy, the stored carbon dioxide needs to generate a minimum income of €96–99/tCO_2.

Few public sources discuss the investment costs for capture, transport and storage of carbon dioxide; as a result, this study estimates the capital required by the technology using capital expenditure that is equalised per tonne of captured carbon dioxide, using 20–30 years as the economic lifetime of the investment and an interest rate of 5–8 per cent. In this case, an indicative estimate of the investment comprising a capture facility and transport network is EUR 930–1,030 million for an inland capture facility and EUR 970–1,070 million for a coastal capture facility.

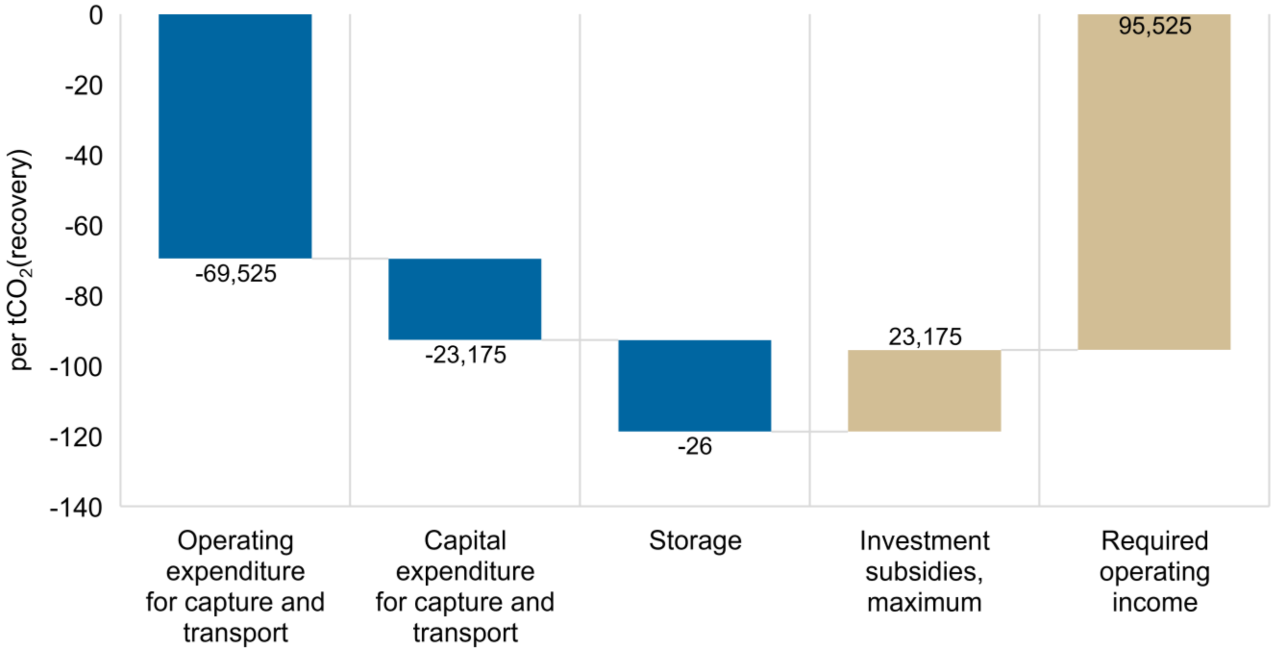

Figure 7. Costs and income from a technological carbon sink in an example case where the capture facility is located on the coast, capture capacity is 3.7 $MtCO_2/a$ and the carbon dioxide is placed in geological storage (BECCS). Investment subsidies indicate the maximum possible theoretical income from investment subsidies (100% of capital expenditure) and operating income indicates the income required for covering the remaining costs.

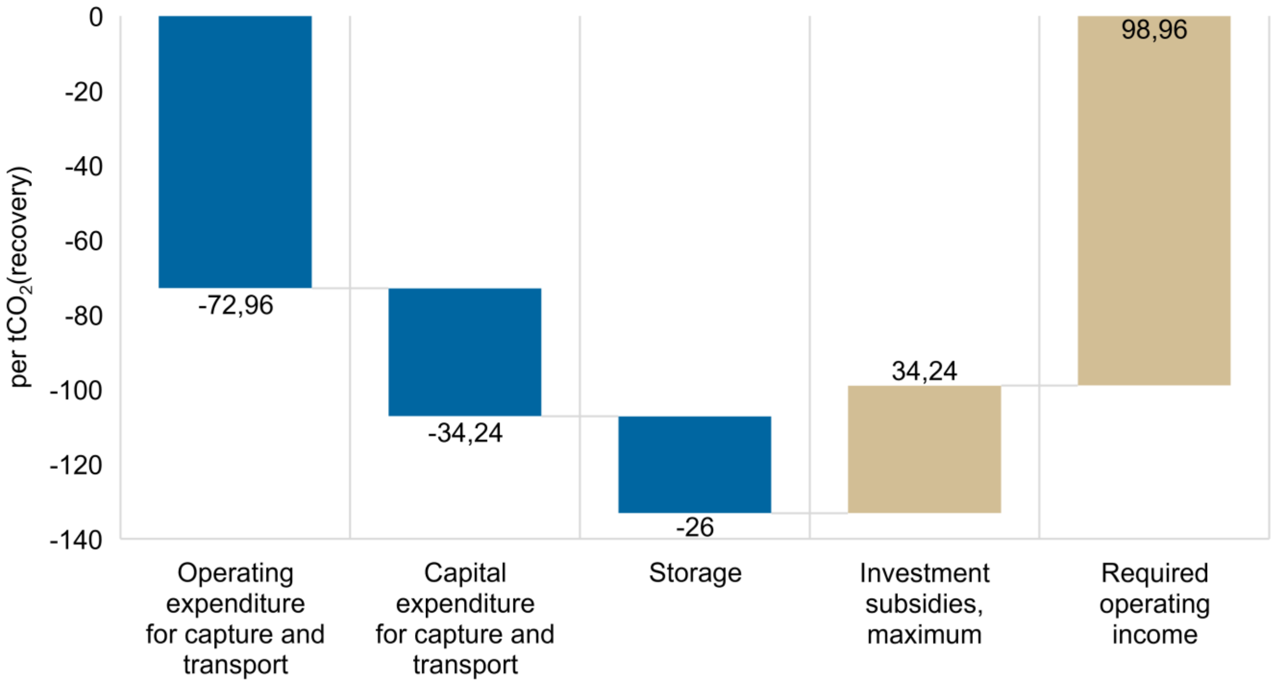

Figure 8. Costs and income from a technological carbon sink in an example case where the capture facility is located inland, capture capacity is 2.4 $MtCO_2/a$ and the carbon dioxide is placed in geological storage (BECCS). Investment subsidies indicate the maximum possible theoretical income from investment subsidies (100% of capital expenditure) and operating income indicates the income required for covering the remaining costs.

4.2.2. Capture of carbon dioxide and refining it into synthetic fuel

In the third example case, instead of placing the captured carbon dioxide in storage, it is used to manufacture synthetic fuel with the assistance of green hydrogen. The investigation assumes that the captured carbon dioxide is not transported and instead refined at the same location. A facility that produces 0.5 $MtCO_2/a$ of biogenic carbon dioxide has been chosen for the example. Producing one litre of synthetic fuel requires approximately 3.25 $kgCO_2$ (Yugo & Soler 2019). As a result, 154 ML/a of synthetic fuel will be produced in the example case.

Compared to a fossil alternative, the reduction in emissions from synthetic fuel is assumed to be 97 per cent, based on the emissions coefficient of 4 gCO_2/km for fuel produced using green hydrogen and a fossil fuel's emissions coefficient of 122 gCO_2/km (Yugo & Soler 2019). Based on the assumptions mentioned above, the estimated reduction in emissions from traffic would be 0.347 $MtCO_2/a$ in the example case.

The cost estimate for the capture of carbon dioxide and its refining into synthetic fuels in the example case is €582/tCO_2 (see Figure 9) or €1.89/L of fuel. For carbon dioxide capture, the cost estimate is based on the assumptions set forth in the previous paragraph. In the estimate, the cost of refining synthetic fuel has been assumed to be €1.62/L exclusive of the capture of carbon dioxide, based on preliminary estimates in Yugo & Soler (2019) and Martin et al. (2023). With reference to estimates set forth by Martin et al. (2023), 90% of the cost of refining synthetic fuels is made up of variable costs, such as electricity consumption. Therefore, this study also assumes that the share of capital expenditure in refining is ten per cent of the total cost. Using the assumptions mentioned below, the theoretical maximum covered by investment subsidies in this utilisation case would be 12 per cent of costs. An indicative total investment value for the capture and utilisation of carbon dioxide, again using the assumptions stated in the previous paragraph, would be EUR 400–440 million.

By comparing the amount of emissions reductions in the example case (0.347 $MtCO_2/a$) and the additional cost when compared to the price of fossil fuel, we arrive at an emissions reduction cost of €328/tCO_2 in this example case. The estimate assumes that the cost of fossil fuel, exclusive of tax, is €1.15/L, based on the price level for 2023 (Autoalan tiedotuskeskus 2023).

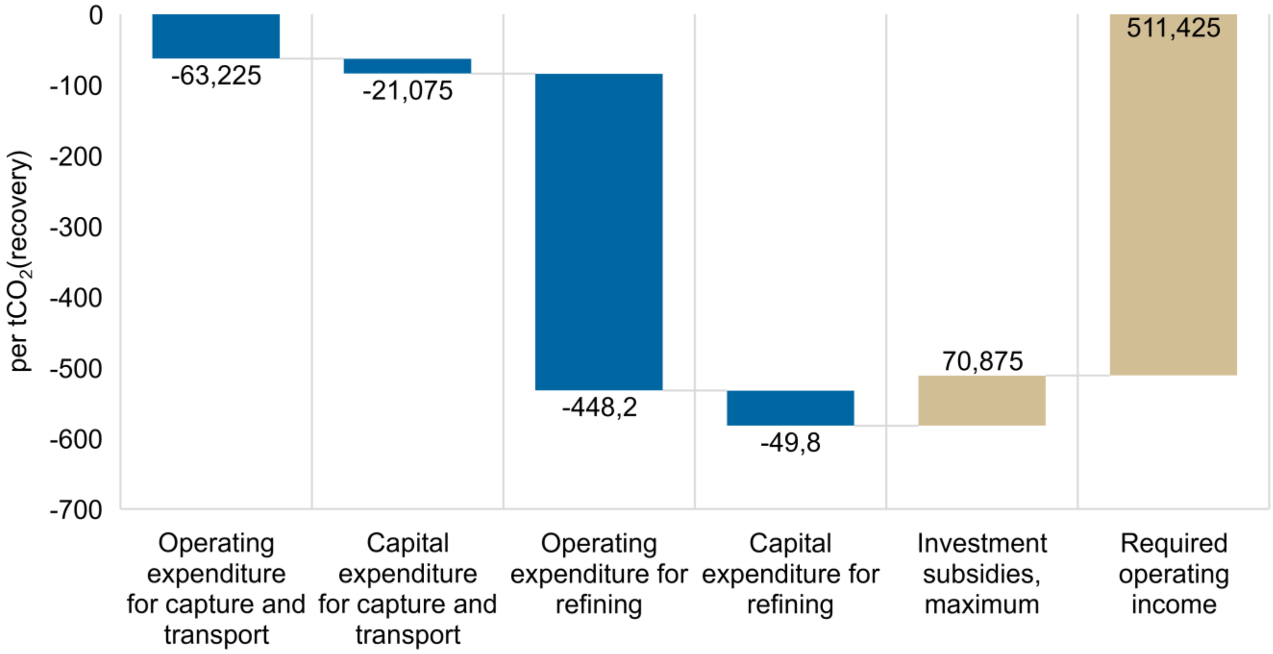

Figure 9. 0.5 $MtCO_2/a$, manufacture of synthetic fuels. Costs of and income from the utilisation of carbon dioxide in an example case where capture capacity is 0.5 $MtCO_2/a$ and carbon dioxide is refined in to synthetic fuel for use in traffic (Bio-CCU). Investment subsidies indicate the maximum possible theoretical income from investment subsidies (100% of capital expenditure) and operating income indicates the income required for covering the remaining costs.

4.3. Most suitable sources of carbon dioxide for technological sinks

If the potential storage areas are located in the North Sea region, the best capture facilities in terms of the costs of technological sinks would be located on the coast of Finland. According to the presented marginal cost curve for the capture and storage of carbon dioxide (see Figure 4), the unit cost is lower for facilities along the coast that avoid the cost of carbon dioxide pipeline transport. In addition to the increase in investment costs, pipeline transport from inland to the coast increases the complexity of carbon dioxide and, potentially, the challenges involved in the planning and licensing of the investment.

The costs of carbon dioxide capture and transport are affected by the amount of carbon dioxide and the transport time. Furthermore, the partial pressure of carbon dioxide prior to capture will affect the capture costs. As the amount of carbon dioxide increases, equalised costs will decrease due to economies of scale. The decrease is especially remarkable for pipeline transport at levels below 0.5–1.0 $MtCO_2/a$ (GCCSI 2021). Finland has nine facilities where biogenic carbon dioxide emissions exceed 1.0 $MtCO_2/a$. Of these facilities, five would need to invest in a pipeline for transporting carbon dioxide to port. Combined, these facilities allow for the capture of 7.3 $MtCO_2/a$ of carbon dioxide from the coast and 8.4 $MtCO_2/a$ from inland. The average amount of emissions from the ten facilities with the lowest costs is 1.8 Mt/a for CASE 1 (all facilities) and 1.6 Mt/a for CASE 2 (facilities emitting biogenic carbon dioxide). The most cost-effective facilities are often those in manufacturing industries, where larger facility sizes are common due to economies of scale in production. The forest industry stands out among the most cost-effective sources of biogenic CO_2.

There are several regions on the coast of Finland that have emissions hubs for biogenic and fossil carbon dioxide in the magnitude of more than 1.0 MtCO$_2$/a (see Figure 10). These emissions hubs would allow even small capture facilities to benefit from economies of scale in terms of transport costs, as the transport system would be divided between several capture facilities. Substantial hubs for biogenic carbon dioxide on the coast include Kemi (5.8 MtCO$_2$/a), Oulu (1.6 MtCO$_2$/a) and Kotka (1.7 MtCO$_2$/a). In addition to Kotka, the Pori region could be a potential hub where carbon dioxide from inland facilities would be transported for further shipping to the storage area. In theory, 9.8 MtCO$_2$/a of biogenic carbon dioxide could pass through Kotka and 4.0 MtCO$_2$/a could pass through Pori; however, the high cost of pipeline transport for some of the facilities would likely prevent reaching this level.

The carbon dioxide capture investments can be retrofitted into existing facilities or included in the construction of new facilities. In addition to costs, the realism of the capture investments is affected by the anticipated remaining service life for the current facilities and the current and future decisions of the facilities' owners regarding them. Creating an outlook of this while solely relying on public information. At a minimum, new facilities with long remaining service lives may be considered suitable sources for biogenic carbon dioxide. In energy generation and the manufacturing industry, the technical service life of facilities is typically several decades, approximately 30–40 on average; following this a full overhaul or significant renewal investments are required if production is to continue. Due to the challenges related to estimating the service life of complex facility systems, it was not possible to estimate the remaining technical service life for all of the facilities examined in this study. However, when looking at the ten facilities emitting biogenic carbon dioxide with the lowest unit costs, we can see that a short remaining technical service life does not appear to be a major risk in terms of commissioning technological carbon sinks, as most of these facilities have received investments to extend their technical service life as well as renovations in terms of at least some production lines in recent years, or the facilities are relatively new (started during the past 10 years).

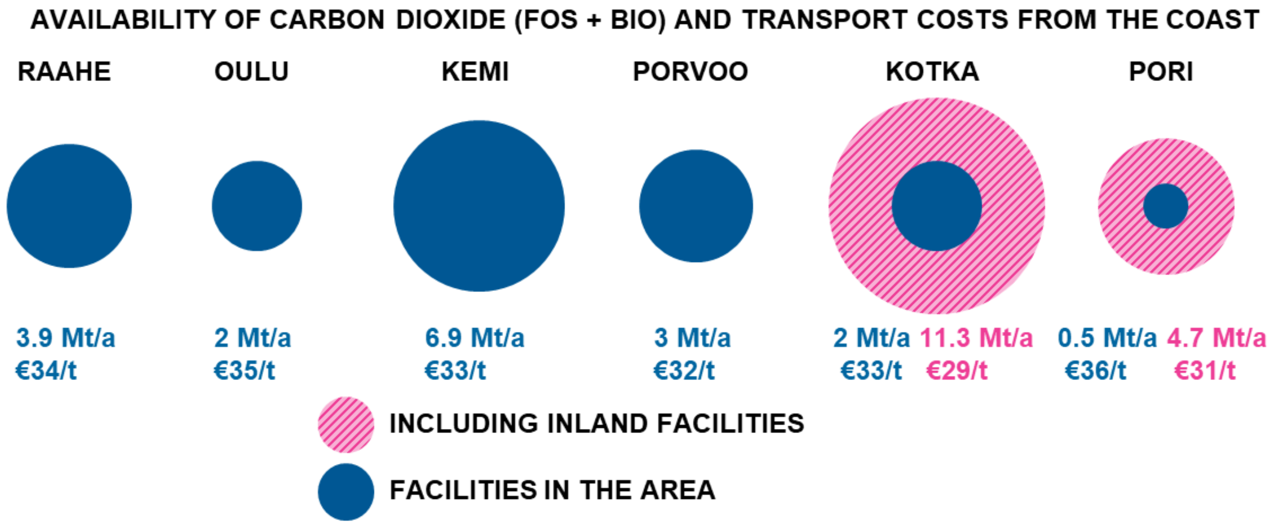

Figure 10. Carbon dioxide emissions hubs on the Finnish coast and possible ports for carbon dioxide transported from inland. The transport volumes include fossil and biogenic carbon dioxide.

5. SUBSIDY MECHANISMS FOR TECHNOLOGICAL CARBON SINKS

At the moment, there are no direct financial incentives for implementing technological carbon sinks in Finland, with the exception of the voluntary carbon markets (Laine et al. 2023, Laininen et al. 2022). For example, technological carbon sinks do not offer any direct monetary benefits within the EU ETS, and no other EU-wide subsidy systems have been created for them so far (with the exception of specific investment subsidies that have been granted). At the moment, the technological sinks created by BECCS would be considered in accordance with the IPCC's emissions inventory guidelines (EU 525/2013) as reducing Finland's overall emissions in the UN's emissions inventory. Since the emissions from the Effort Sharing Regulation (ESR) sector are calculated by removing the ETS sector's emissions from the inventory's total emissions, the benefit of BECCS projects could then be seen on the ESR sector (Kujanpää et al. 2023). The European Commission is presently surveying voluntary certification systems for carbon dioxide removal mechanisms[1]. An expert group on carbon removals has been put together to support the analysis.[2] Furthermore, the EU ETS directive (2023/959) states that, by the end of July 2026, the European Commission should report to the European Parliament and to the Council on "how emissions removed from the atmosphere and safely and permanently stored" could potentially be included in the ETS.

In Finland, the programme of Petteri Orpo's government contains an entry regarding supporting the commissioning of and investments to technological carbon sinks and surveying subsidy systems. Based on the survey, "a reverse auction of negative emissions or a similar mechanism" will be introduced (Valtioneuvosto 2023).

This study presents a brief overview of the reverse auction system or competitive bidding that Sweden is introducing for BECCS technologies. In Finland, the Ministry of Economic Affairs and Employment (MEAE) has, in 2016, published an extensive report that discusses various models of competitive bidding for supporting the production of renewable energy (TEM 2016). These models are comparable to Sweden's reverse auction system, and their suitability for technological carbon sinks will also be briefly assessed.

5.1. The Swedish model of reverse auctions for BECCS projects

5.1.1. Background

Sweden has in place a carbon neutrality target for 2045, including an emissions reduction target of 85 per cent (compared to the year 1990). The rest of the target is covered by what are referred to as "additional measures", which may also result in net negative emissions. The carbon neutrality target does not include the current sink from the LULUCF sector; only increase in forest carbon sinks achieved by additional measures (such as improved forestry practices) is counted towards it. Verified emissions reductions abroad and "negative emissions" generated by means of BECCS are also counted as additional measures. In 2030, 3.7 $MtCO_2$ of additional measures may be counted towards the carbon neutrality target (of which 1.8 Mt can originate from BECCS); in 2045, the amount may be 10.7 $MtCO_2$ (of which 3–10 Mt can originate from BECCS). Sweden has not defined a separate target for carbon dioxide removal or negative emissions (Energimyndigheten 2021).

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[1] https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/carbon-removal-certification_en

[2] https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/expert-group-carbon-removals_en The expert group's meeting on 10/2023 discussed various voluntary certification systems for technological carbon sinks.

Sweden has decided to launch a reverse auction for negative emissions generated via BECCS. The local energy authority (Energimyndigheten) is responsible for preparing the auction. The aim was to start the auction in 2022, but the start has been delayed due to time required for the preparation and analysis work for the subsidy system and the approval required from the European Commission for the state subsidies. At the moment (11/2023), the estimate is that the auction can be started at the latest within six months from when the European Commission has issued its decision on the approval of the state subsidy system (Energimyndigheten 2023a).

In the reverse auction or competitive bidding, the state calls on actors to submit their bids for generating negative emissions and to present their requests for compensation related to it. The actors who generate the promised amounts of negative emissions at the lowest price will be selected as the winners of the competitive bidding. A total of SEK 36 billion (approximately EUR 3.3 billion) has been granted to the Swedish energy authority for the purposes of the auction between 2026 and 2046. The maximum available amount per year is SEK 1.7 billion (approximately EUR 144 million). The subsidy will be distributed during one or more auctions (Energimyndigheten 2021).

Inside a single auction, the subsidy may be divided into three periods (planning, construction and operation of a BECCS project). The planned duration of the subsidy period for the operating stage is 15 years. In addition, the actors have been estimated to require three years for constructing the facility, developing the transport and storage logistics for carbon dioxide and signing agreements on the permanent storage of carbon dioxide. The entire subsidy period has an estimated length of approximately 18 years and 7 months.

The reductions in emissions from technological carbon sinks generated through the reverse auction belong to the Swedish state. However, the Swedish energy authority has proposed that it shall be possible for the companies receiving subsidies to sell “negative emissions” into the voluntary market as “contribution claims”. In this case, the subsidy received from the auction is reduced in accordance with the sale price. For the avoidance of double accounting, the seller shall inform the purchaser of the “negative emissions” that the reduction in emissions has already been observed as an emissions reduction by the Swedish state. In other words, the buyer can report that it is contributing to meet the Sweden’s climate targets, but cannot compensate for their own emissions. (Energimyndigheten 2023b)

5.1.2. Projects participating in the auction

Initially, only BECCS projects where carbon dioxide is stored in geological permanent storage facilities will be accepted for Sweden’s reverse auction. Companies with biogenic carbon dioxide emissions from CHP plants, paper or pulp production or other industrial facilities can participate in the auction.

The inclusion of biochar in the auction system was also investigated during the preparation stage, but it has so far been left out of the auction. This decision was affected by the small size of the projects and the challenges with verifying the carbon dioxide removal by biochar application. The major differences between the projects, such as industrial scale BECCS and smaller biochar projects, were also seen as a potential problem in terms of the functionality of the auction mechanism.

In its preliminary analysis, the Swedish energy authority has defined the requirements for participants in the reverse auction as follows. Participants in the application process shall:

- be the owners of the facility;
- determine the size of the bid as tonnes of carbon dioxide (in multiples of 10,000 t CO_2);
- determine the amount of subsidy required per tonne of carbon dioxide in SEK;
- provide an account of the other investment subsidies they have received and the submitted subsidy applications (such as from the EU or Industriklivet).

The preliminary recommendation from the energy authority is that, in the first auction, the size of the bids should be at least 50,000 tonnes of carbon dioxide. It is recommended that a longer time for submitting bids is provided for the first auction, in order to provide as many companies as possible with the opportunity to participate.

In order for companies to participate in the auction, they need to carry out project planning for their BECCS facility in order to estimate the carbon dioxide separation costs. This can be a burden especially for small actors. Therefore, it is important that companies receive support and training before the auction begins. Auctions that occur regularly may alleviate this problem (Energimyndigheten 2021).

5.2. The suitability of a reverse auction or a similar subsidy mechanism for Finland

5.2.1. Suitability for Finland

The conditions in Finland as a producer of technological carbon sinks are fairly similar to Sweden, since both countries have substantial potential for BECCS projects due to biogenic carbon dioxide emissions (CHP plants and the pulp and paper industry). In both countries, the large-scale storage of carbon dioxide would likely occur outside of the country's borders.

This study surveyed the realistic BECCS potential in Finland. The results allow for the coarse estimate that Finland has several facilities where the preliminary cost estimates for implementing BECCS vary in the range of €120–€150/t CO_2 (cf. the cost of emission rights on the EU's emissions market in 2023, which varied in the range of €80–€100/t CO_2). Table 8 lists example costs for the auction at various levels of compensation and various targets for technological carbon sinks. The required compensation could be affected by any possible other investment subsidies and the opportunity of the actors to "productise negative emissions" on the voluntary market in the form of contribution claims (cf. the Swedish model).

Various benefits and challenges have been listed for the reverse auction system in different contexts. Table 9 lists various aspects and estimates their relevance in terms of Finland.

Table 8. Total costs for a reverse auction at different levels of compensation.

	Technological sink being targeted: 1.5 Mt CO_2	Technological sink being targeted: 3 Mt CO_2	Technological sink being targeted: 6 Mt CO_2
Compensation €/tCO_2	Total cost EUR million/a	Total cost EUR million/a	Total cost EUR million/a
100	150	300	600
120	180	360	720
150	225	450	900

Table 9. Benefits and challenges of a reverse auction and notes on the situation in Finland.

Benefits of a reverse auction	Special notes regarding the situation in Finland
Potentially a cost-effective way to launch BECCS projects. Competitive bidding helps to determine the current price for the capture and storage of carbon dioxide at any given time.	Cost-efficiency is not achieved very well if the auction has too few participants. Finland has plenty of potential participants, but are BECCS projects a top priority for them as regards investment decisions?
The state can control the costs of the system, that is, decide in advance on the total sum to be distributed.	
The possibility of arranging several rounds of auctions allows for adjusting the price ceiling, for example. This minimises the risk of the authority incorrectly estimating the price and overpaying for the capture due to rapid advances in technology.	Allows for adjusting to varying technology costs and developments in other policy-making (such as the EU’s subsidies for technological sinks).
Challenges of a reverse auction	**Special notes regarding the situation in Finland**
Participating in the auction requires substantial preparations from the actors which consume resources.	This may reduce the number of auction participants in Finland, especially as regards small actors.
If only a few actors participate in the auction, cost-efficiency will be difficult to achieve.	This is a possible situation in Finland if, for example, only larger companies were to participate. Companies may be more interested in the utilisation of carbon dioxide, which is seen as a better source of income.
If the auction is limited solely to BECCS projects, technology neutrality is not achieved.	Technology neutral treatment of different projects would be preferable, but it may be challenging due to practical reasons. It might be possible to implement the auction system separately for projects of different types.

When assessing the implementation of a reverse auction or another type of subsidy mechanism, the following aspects should be considered at a minimum:

- The number of possible participants and their willingness to invest
- Technology neutrality
    - Only BECCS with geological storage was included in the Swedish system. Biochar was considered, but it was excluded due to the small size of the projects and difficulties in verification.
    - In Finland, the most significant potential for technological carbon sinks lies with the application of BECCS. Permanent storage on a large scale would likely be based on geological storage

    but, on a smaller scale, storage facilities implemented by means of mineralisation would also be possible.
  - Potential technologies that are in development or already in operation include the following, for example:
    - Biochar production
    - Binding of carbon into concrete through carbonation
    - Other CCU applications with long-term storage (such as construction materials)
- Including criteria or weighting factors other than cost in the auction system or other type of subsidy mechanism would be possible.
  - As regards BECCS projects, in particular, ensuring the future sustainability of the biomass being used is essential. Here, the sustainability criteria in the EU's RED directive (EU 2023/2413), for example, could be taken into account where applicable.
- The carbon dioxide removal taking place in the projects should be ensured through life cycle calculation, for example, ensuring that the emissions from the capture, transport and storage of carbon dioxide are considered.
  - The permanence of carbon dioxide storage must be ensured, responsibility for supervising the storage must be determined and any possible leaks must be observed and reported.

5.2.2. Hypothetical example of implementation schedule

Developing the subsidy mechanism for technological carbon sinks and the planning and implementation of the projects themselves take time. The imaginary example below (Figure 11) illustrates how technological carbon sink projects could be launched in Finland and how the schedules should advance in order for projects to be implemented in the early 2030s.

The example describes a case where, as a result of the first auction, three small (less than 0.3 Mt) BECCS projects would receive compensation and be implemented, and the second auction would provide compensation to two smaller and one larger BECCS projects (total of 4 Mt). The capacity of these projects has been compared to the available storage capacity.

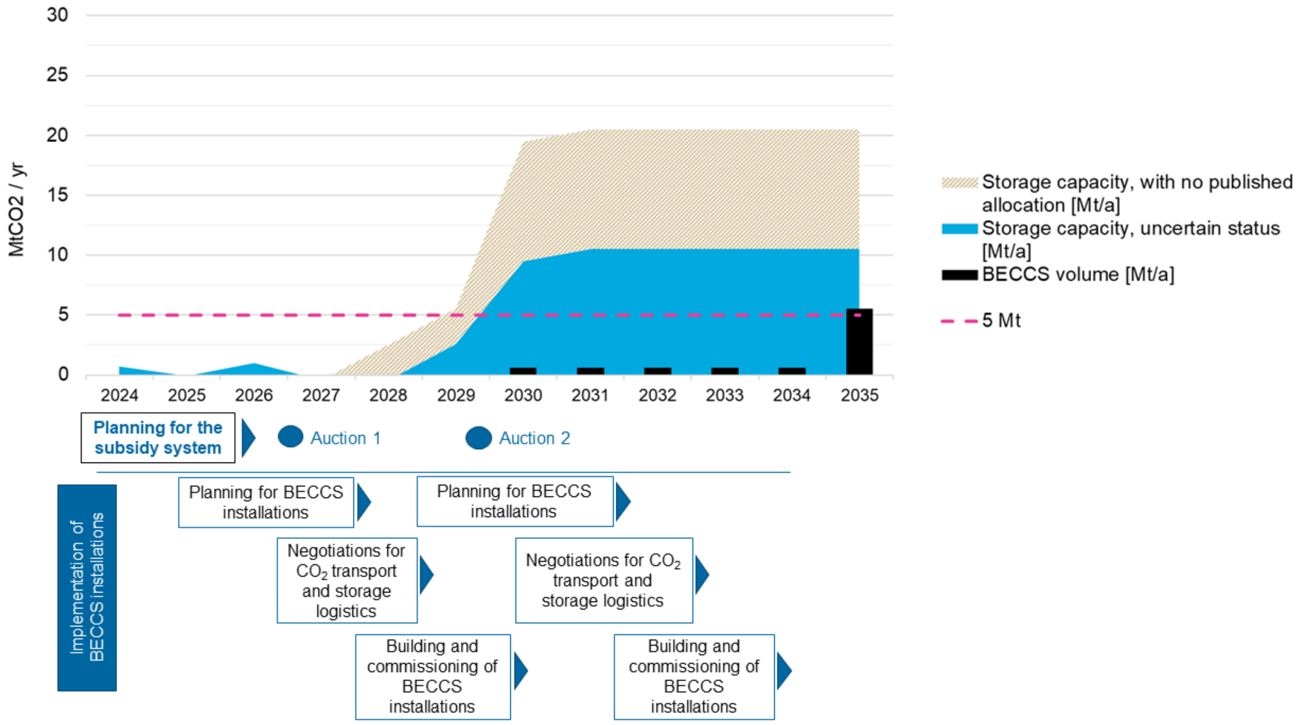

Figure 11. Hypothetical schedule example for promoting technological carbon sink projects. (Schedule estimated according to GCCSI 2023, Figure 14).

5.2.3. Earlier models of competitive bidding in Finland

The Ministry of Economic Affairs and Employment (MEAE) has, in 2016, published an extensive report that discusses various models of competitive bidding for renewable energy (TEM 2016). The MEAE's report compares the various models of competitive bidding and their benefits and detrimental impacts. The report examines a closed competitive bidding, descending and ascending clock auctions and combinations thereof. Closed competitive bidding is seen as the simplest to implement and attractive to a larger group of project developers. It is also stated to work, even if there is less competition. For these reasons, it might possibly be the best alternative in the case of technological carbon sinks.

The report also considers the planning of the competitive bidding, such as the prerequisites concerning the project developers and the projects, the boundary conditions concerning bids, the risks of strategic bids and the implementation of the project that wins the competitive bidding. Where applicable, these considerations can be utilised for projects involving technological carbon sinks.

The Energy Authority's premium system for renewable energy in 2018 was based on the analysis in the MEAE's report (Energiavirasto 2018). It might also be possible to apply parts of the implementation principles of the premium system to technological carbon sinks. However, the implementation of technological carbon sinks differs from the situation in 2018 for implementing renewable electricity generation projects – in the following ways, for example:

- The technologies for technological carbon sinks have seen fairly little use for the time being, whereas the technologies for generating renewable energy were mature in 2018 and there was plenty of experience available from various types of projects.
- The real cost of technological carbon sink projects is more difficult to estimate for the actors (regarding the first applications, such as BECCS in the forest industry).

- Overall, the production processes for renewable electricity are simpler to approach than the capture and storage of carbon dioxide. Uncertainties related to the transport and storage logistics for carbon dioxide may increase uncertainty in the cost estimate.

6. REVIEW OF RESULTS

6.1. Costs of technological carbon sinks

Based on this work, the unit costs for technological carbon sinks based on geological storage in the case of Finland's industrial emissions sources (Table 6), inclusive of carbon dioxide capture, compression, transport and storage, vary between €119—€237/tCO_2 (no shared logistics) and €117—€178/tCO_2 (shared logistics). Depending on the scenario, the facility-specific average for the costs varies between €157–€161/tCO_2 (no shared logistics) and €142–€149/tCO_2 (shared logistics), whereas the weighted (arithmetic) average varies between €139–€141/tCO_2 (no shared logistics) and 132–134 €/tCO_2 (shared logistics).

The Climate Action Task Force (CATF 2023) has developed a tool for estimating the costs of CCS in European emissions sources that are included in the emissions register (>100 ktCO_2/a). According to the CATF tool, CCS costs for Finland's emissions sources would be as follows under the different scenarios:

- €184–€235/tCO_2 (high cost estimate, no new pipeline infrastructure, short term)
- €137–€189/tCO_2 (high cost estimate, new pipeline infrastructure is possible, long term)
- €109–€200/tCO_2 (low cost estimate, new pipeline infrastructure is possible, short term)
- €87–€118/tCO_2 (low cost estimate, new pipeline infrastructure is possible, long term)

Depending on the applied scenario, the costs estimated using CATF's tool are either more optimistic or pessimistic than the costs estimated in this study. The cost estimates are close to each other when the scenario being used includes the possibility of new pipeline transport infrastructure and either a high cost estimate and a long time span or a low cost estimate and a short time span.

Johnsson et al. (2020) estimated the costs of carbon dioxide capture based on amine scrubbing (MEA) and the transport and storage of carbon dioxide in Sweden's industrial emissions sources with an annual emissions amount above 500 ktCO_2. Their study covers facilities emitting both fossil and biogenic carbon dioxide emissions (28 facilities in total). According to their estimate, the cost of capture in the Swedish emissions sources varies in the range of €40–€110/tCO_2, the cost of transport and storage varies in the range of €25–€40/tCO_2 and the total combined cost is €80–€135/tCO_2. The cost estimate is substantially more optimistic than the results of this study, since the estimates for transport and storage costs are significantly higher in this study. The method used for estimating transport costs in this study differs from the approach used by Johnsson et al. (2020). For example, transport distances are considered for ship transport, as are the facility-specific coarse estimates for the cost of pipelines leading from inland to the ports. Furthermore, the cost of storage has been assumed to be higher in this study (€18/tCO_2 for injecting into storage and €8/tCO_2 for unloading the carbon dioxide and transporting it via an underwater pipeline to the storage facility from the receiving terminal).

In this study, the cost of carbon dioxide capture was calculated on the basis of the technologically mature MEA capture process using data available in the literature. The cost per facility was calculated by using the facility's scale (emissions amount), the partial pressure of carbon dioxide and a process-specific scale factor. The range of carbon capture costs in all the examined facilities is €51–€89/tCO_2 and €67–€112/tCO_2 when the cost of carbon dioxide compression is also included. The magnitude of the costs calculated in this study matches other estimates found in the literature regarding the costs of carbon capture from industrial emissions sources. Onarheim et al. (2017b) calculated that the cost of carbon capture using amine scrubbing is €52–€66/tCO_2 for a modern sulphate pulp mill and €71–€89/tCO_2 for an integrated paperboard and pulp mill, with capture capacity being 1.5–1.9 MtCO_2/a. Johnsson et al. (2020) estimate that the cost of carbon capture based on the MEA process is €40–€110/tCO_2 for Sweden's industrial emissions sources, which is a larger range of variation than that in the results of this study. Johnsson et al. included the utilisation of potential waste heat streams in their analysis, which may significantly reduce the costs of capture. According to their estimate, the cost of capture would be less than €70/tCO_2 in 84% of the capture capacity formed by Sweden's industrial emissions sources, which is aligned with the results of this study, as it found that the cost of carbon dioxide capture (exclusive of compression) in Finland's industrial emissions sources would be less than €70/tCO_2 in approximately 85% of the available capture capacity. As regards the cost estimates for ship transport and storage, the results can be compared to the price level communicated by the Northern Lights project, since the project's logistics are similarly based on ship transport and using an undersea pipeline to transport carbon dioxide to the storage area from the receiving terminal. The Northern Lights project has communicated that it is targeting a transport and storage cost of €30–€55/tCO_2 by 2030 (Northern Lights 2020). For example, the estimated transport costs from the emissions hubs on the coast (see Figure 10), inclusive of storage, would be approximately €50–€54/tCO_2. Assuming that transport distances from Finland would be similar to the longest distances in the Northern Lights project, the cost estimate fits well with the target price set forth by the project.

The study also compares the costs of technological carbon sinks to the costs of emissions reductions achievable through the production of synthetic fuels by means of an example review. For this part, the results are based on a concise review that does not comment on the various process and value chain alternatives available for the production of synthetic fuels, and the assumed forecast on the costs of synthetic fuel refining and its fossil reference, among other things, is uncertain. Therefore, the results do not allow for drawing a final conclusion on the financial competitiveness of carbon dioxide storage versus its utilisation. The example calculation assumes that the production cost of synthetic fuels is €1.62/L exclusive of costs related to the CO_2 raw material and €1.89/L inclusive of carbon dioxide capture. The assumed cost is slightly lower than, for example, the ICCT's (2022) estimate of $2.32/L (approx. €2.20/L) for synthetic diesel in Europe in 2035. On the other hand, the literature also includes more optimistic estimates of the price development of synthetic fuel, such as a cost of €0.98–1.75/L for synthetic, refinable oil in 2030 (Prognos, Fraunhofer & DBFZ 2018).

6.2. Storage capacity

At the time of this report's writing, storage capacity for carbon dioxide remains below 2 MtCO_2/a in Northern Europe. Based on the data gathered during this project, however, storage capacity is expected to increase more than tenfold over the next five years, that is, by 2028, and to reach a level of approximately 50 MtCO_2/a by 2030. Furthermore, approximately 90 MtCO_2/a of storage capacity is being planned by 2035. The capacity planned for implementation by 2035 will probably increase in the coming years, as project planning progresses and new projects are started and announced. Therefore, the anticipated development path seems to be a path of very strong growth. Figure 12 presents the increase in total volume for Northern European storage projects from 2020 until 2035 as well as growth scenarios using various trendlines until 2040.

Using the best fitting trendline for the present data, the estimate for 2040 would be approximately 150MtCO_2/a of stored carbon dioxide, even though the estimate is very uncertain. The carbon dioxide capture capacity covered by globally prepared carbon dioxide capture and storage (CCS) projects (MtCO_2/a) has grown rapidly during the past four years, by 57–68 per cent per year, but the capacity increase included in the globally prepared projects may also be located further in the future, such as the time period past 2040. Furthermore, this growth does not consider capacity that has already been constructed and is operational.

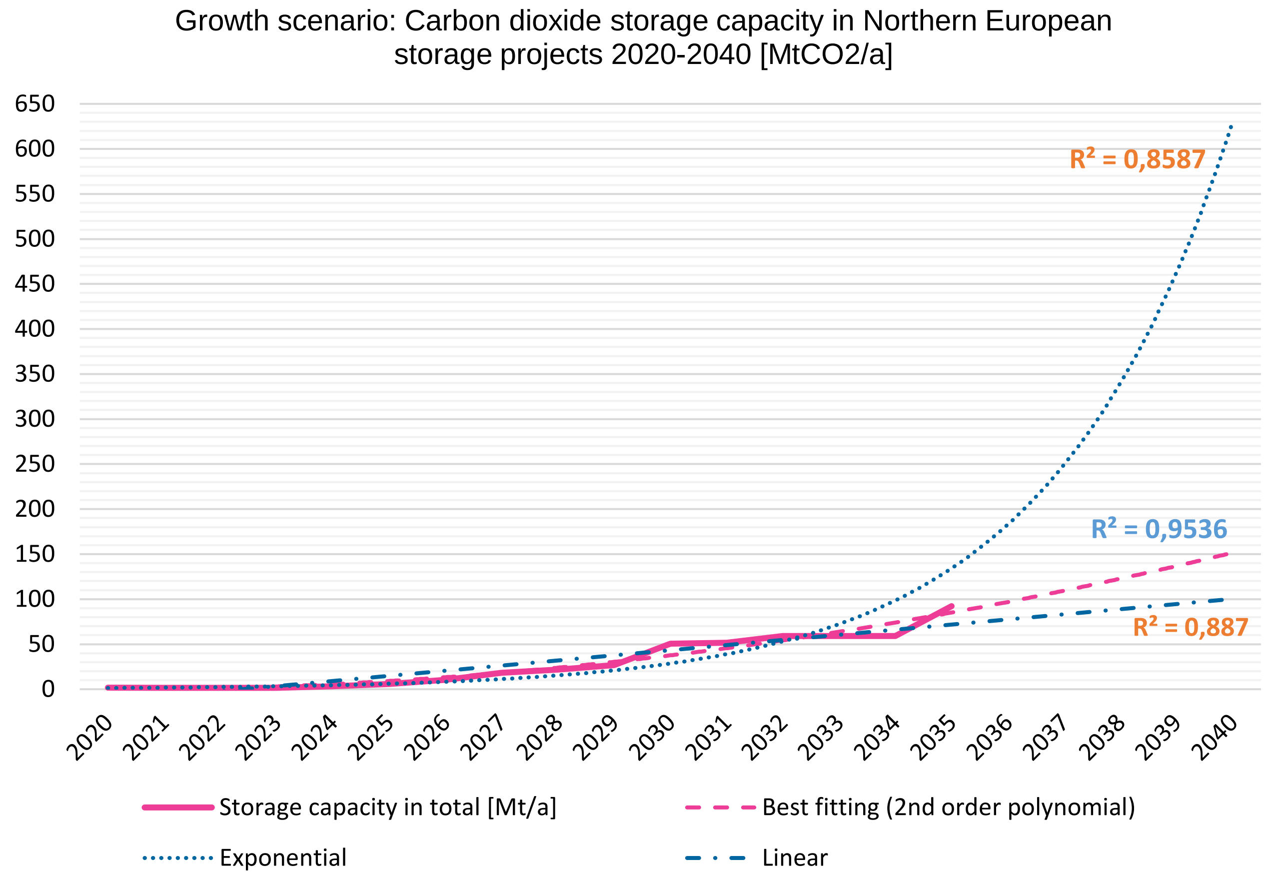

Figure 12. Growth scenarios for carbon dioxide storage capacity in Northern Europe for 2020–2040, using various trendlines to storage projects announced for 2020–2035. Using the best fitting trendline storage capacity in 2040 would be approx. 150 $MtCO_2$/a.

In other words, capacity being prepared is growing substantially, but the growth of completed storage capacity has not yet started in Northern Europe. During the next 3–4 years, the situation should be closely monitored in terms of the starting of the Northern Lights, Antwerp@C, Greensand and Porthos projects, for example. The history of CCS projects suggests that delays, unexpected changes and even project cancellations can be expected, as many countries are now preparing their first industrial scale CCS project. For example, Sweden's reverse BECCS auction has been delayed (Swedish Energy Agency 2023a), the Porthos project experienced a delay due to the assessment of impacts on a nature conservation area and the processing of an appeal by the Council of State (Porthos 2023) and the Sleipner and Snøhvit storage projects, which were already under way, also did not advance as planned (Hauber 2023). The IEEFA's report (Hauber 2023) also raises the possibility of a leak in the geological storage facility. Even if there are no leaks, storage may need to be interrupted while the project is already under way if the carbon dioxide storage begins to behave in a manner that deviates. In light of Finland's carbon neutrality target for 2035, the risk of CCS projects being delayed could be taken into account by planning the capture and storage of carbon dioxide from Finnish facilities in a manner where it would be implemented in several storage projects that are planned to start in 2030–2034. Implementing the capture and storage of carbon dioxide prior to 2030 seems very challenging due to the duration of a typical CCS project (approx. 7 years from the start of commercial negotiations) (GCCSI 2022).

However, it is possible that the growth of storage capacity being implemented in Northern Europe could, in the coming years, shift more towards the exponential. In Denmark, for example, the planned volume of carbon dioxide storage projects has been increased substantially over the past year, which increases storage capacity for 2035. According to the exponential growth fitment, the storage capacity in Northern Europe could reach an annual level of up to 630 $MtCO_2$/a by 2040; however, the trendline does not describe the current development of the projects' combined capacity very well for the time being. The picture received on the basis of public data will, however, unavoidably be behind the negotiations held between companies, as demonstrated by the example from the Northern Lights project: Based on the Global CCS Institute's report from 2022 and the information on the website, it had been estimated that most (approx. 3 $MtCO_2$/a) of the second stage's storage capacity (3.5 $MtCO_2$/a) would be open to competition; however, the report for 2023 states that this capacity is practically already reserved.

The need for technological carbon sinks in Europe has been recently studied by means of scenario modelling (Lehtilä et al. 2023). The results of the modelling are based on cost optimisation and, thus, they do not directly forecast the future need for carbon dioxide storage capacity. They also do not assume a dramatically tighter emissions reduction policy, such as abandoning fossil fuels. However, they do paint a picture of the possible scale at which technological carbon sinks could be required in order to achieve the EU's climate-neutrality target in 2050 (see Figure 13). For example, in 2040, the combined BECCS and DACCS[3] capacity could be approximately 160–200 $MtCO_2$/a, and the need for storage capacity would be even higher, as fossil carbon dioxide should also be stored as an emissions reduction action. Even at the moment, in the projects being prepared for Northern Europe, most of the carbon dioxide that is planned for storage is of fossil origin. The need for fossil CCS may be reduced by taking even more efficient emissions reduction actions, improving energy efficiency and reducing consumption.

Even though this comparison is between the growth trajectory based on storage projects in *Northern Europe* and the BECCS and DACCS carbon dioxide storage projects in the scenario modelling for *all of Europe* in 2040 (and later), it is fairly relevant, as most of the CCS projects in all of Europe are currently located in Northern Europe and, more specifically, in the North Sea (GCCSI 2023). In order to make possible the amount of technological carbon sinks described in the scenarios, Europe would need to substantially accelerate the number of carbon dioxide storage projects towards an exponential growth trajectory, at least until 2050. This has been addressed in the EU's Net-Zero Industry Act, one of the targets of which is the increase in carbon dioxide storage capacity by 50 Mt per year, starting from 2030.

Even if sufficient funding for Finnish CCS projects could be found, under the current trajectory the insufficiency of storage capacity would form a significant bottleneck for the implementation of technological carbon sinks in Finland and Europe in general. For Finland, the amount of available storage capacity is also significantly limited by international competition: According to current project activity, most of the identified capacity that is open to competition for 2030–2034, which amounts to approximately 10 $MtCO_2$/a, would be taken up by the industry in the United Kingdom, Ireland, Norway, Denmark, Sweden and the Netherlands.

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[3] DACCS= direct air capture and storage of CO_2.

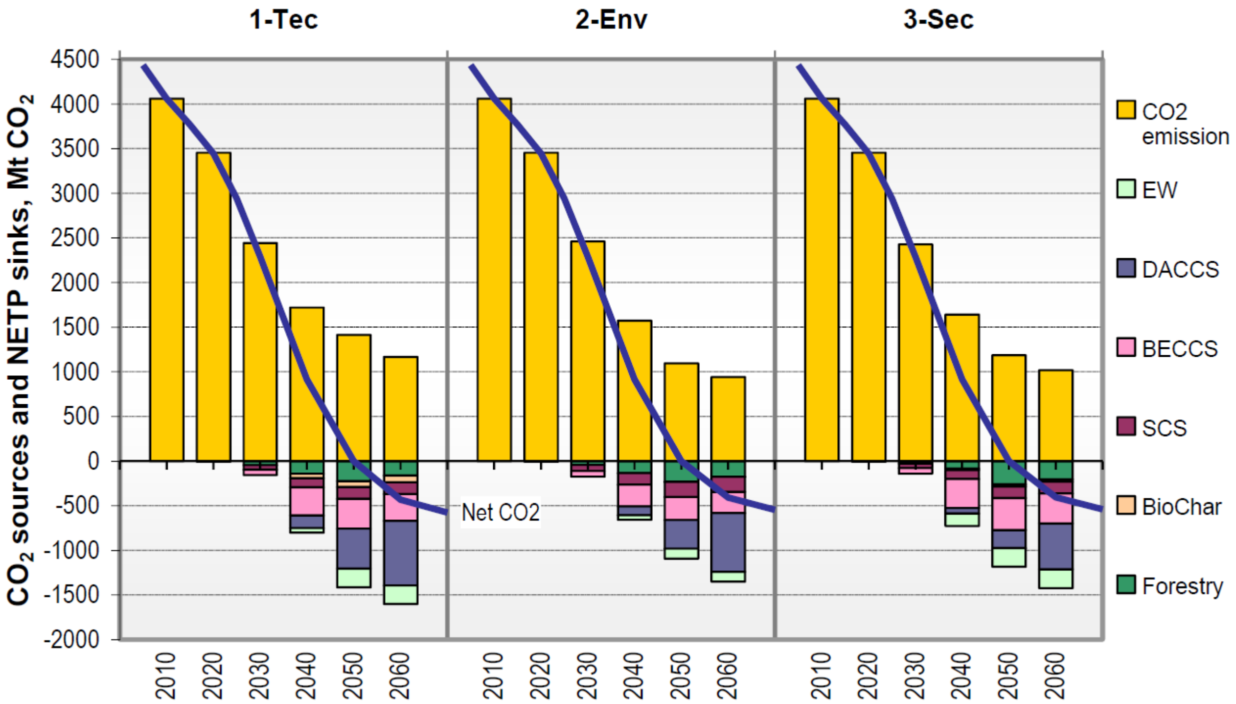

Figure 13. The need for technological carbon sinks in Europe for achieving the 2050 carbon neutrality target in three different scenarios that emphasise different future outlooks (Tec = rapid technological development and global cooperation, Env = protecting the environment and planetary boundaries, Sec = security perspective and slowing of global cooperation) (Lehtilä et al. 2023).

7. CONCLUSIONS

7.1. Costs and potential for the capture, transport and storage of Bio-CO_2 in Finland

The availability of biogenic carbon dioxide, which is essential in terms of technological carbon sinks, is currently very good in Finland due to the strong position of the forest industry and bioenergy production. The unit cost for technological carbon sinks based on geological storage in the case of Finland's industrial emissions sources, inclusive of carbon dioxide capture, compression, transport and storage, varies between €119—€237/tCO_2 (no shared logistics) and €117—€178/tCO_2 (shared logistics). The facility-specific average for the costs of technological carbon sinks is €161/tCO_2 (no shared logistics) and €149/tCO_2 (shared logistics), whereas the weighted (arithmetic) average is €141/tCO_2 (no shared logistics) and €134 /tCO_2 (shared logistics).

Due to economies of scale, carbon dioxide capture is substantially cheaper at large facilities with a lot of carbon dioxide emissions. The forest industry, in particular, has several large facilities where a lot of biogenic carbon dioxide is available at one location. *CO_2 hubs* that combine logistics for facilities close to each other can reduce the facility-specific transport and storage costs substantially, by eight per cent on average. Shared transport infrastructure is most beneficial to small capture facilities.

In other words, the suitability for carbon dioxide capture of current facilities is affected by (1) the captured amount, (2) the cost of capture at the facility, (3) location in terms of carbon dioxide transport and also (4) the facility's expected service life. In this study, it has been possible to examine carbon dioxide sources on the basis of public data while taking into account factors 1–3 that have a direct impact on the costs of capture and storage. Based on this review, the facilities with the lowest unit costs for technological carbon sinks are characterised – due to the reasons presented hereinabove – in particular by the large size of the facilities and their location near the coast.

In terms of carbon dioxide transport and storage, the best locations for capture facility investments are hubs of carbon dioxide emissions located on the coast. These areas allow for achieving economies of scale in terms of logistics, especially for smaller capture facilities. Pori and Kotka would be natural end points for pipelines that collect carbon dioxide from inland. The coastal emissions hubs (Oulu, Kemi, Porvoo, Kotka, Pori) offer a theoretical opportunity for capturing 9.8 MtCO_2 of biogenic carbon dioxide. When biogenic carbon dioxide that is transported from inland regions into the area is included, the amount rises to 13.8 MtCO_2. The theoretical capture potential from all bio-CO_2 sources (above 0.1 MtCO_2) on the coast is 13.6 MtCO_2.

Based on a review of the ten facilities emitting biogenic carbon dioxide with the lowest unit costs, the remaining technical service life being short does not appear to be a major risk in terms of technological carbon sinks. Most of these facilities have received investments to extend their technical service life as well as renovations in terms of at least some production lines in recent years, or the facilities have been started during the past ten years.

The presented estimates of the costs for the capture, transport and storage of carbon dioxide are based on trendline to costs presented in the literature. The study does not examine facility-specific capture and transport systems at the process or equipment level and, for example, the pipeline transport routes from the inland capture facilities have not been fitted to geographical features or routes that run via other sources of emissions. Therefore, the cost estimates contain uncertainties and they are only meant to be indicative.

7.2. Outlook for the utilisation and storage of Bio-CO_2

The European Union's REDIII, ReFuelEU Aviation and FuelEU Maritime legislations require that, in 2030, at least one per cent of the traffic sector's energy consumption must consist of synthetic fuels and hydrogen. This amount will not cause competition between the utilisation of carbon dioxide and technological sinks. In the assumed scenario where, in addition to the minimum requirement for Finland, ten per cent of the EU market's minimum need for synthetic fuels would be produced in 2030, 2–3 mid-sized capture facilities in Finland would be enough to cover the manufacture of the required amount. For the time being, the need for carbon dioxide synthetic fuels on the market in 2050 is challenging to define. The EU targets are, in part, common to sustainable biofuels and carbon-free and carbon dioxide based e-fuels. The requirements of the ReFuelEU Aviation regulation for synthetic fuels in aviation (6% in 2035 and 35% in 2050) provide the best opportunity to assess the need for synthetic fuels on the EU market. In the assumed demand scenario, the production of synthetic fuels in Finland would demand approximately 9 $MtCO_2/a$ in 2050; however, this estimate does not consider changes in the energy consumption of the private sector. The theoretical capture potential for bio-CO_2 from the facilities surveyed in this study is approximately 27 $MtCO_2/a$. Converted to synthetic fuel, this would represent approximately two per cent of the energy consumption of the EU's traffic sectors in 2030 or approximately 12 per cent of aviation's fuel consumption within the EU. In addition to the availability of carbon dioxide, production capacity for renewable electricity sets limits for the manufacture of synthetic fuels.

The carbon dioxide storage capacity being currently planned in Northern Europe consists of approximately 16 projects and their subprojects. At the moment, less than 2 $MtCO_2/a$ of storage capacity is operational; with the projects currently in preparation, it would increase more than tenfold during 2028, to approximately 50 $MtCO_2/a$ by 2030 and to more than 90 $MtCO_2/a$ by 2035 – even though several more projects starting in 2035 are likely to be announced. Most of the projects are located in the sea areas of the United Kingdom, Norway and Denmark, and most of the planned storage capacity concerns the storage of fossil carbon dioxide. For four consecutive years, the combined capture capacity of CCS projects being prepared globally has grown by 57–68 per cent per year.

Based on current knowledge, a significant amount of carbon dioxide storage capacity is expected to be available on the market from 2030 onwards. For capacity that starts before this, intercompany agreements on the deliveries of carbon dioxide have largely been signed. On the basis of the projects reviewed in this study, approximately 10 $MtCO_2/a$ of storage capacity would likely be available for open competition in 2030–2035, in the Project Greensand (Denmark), Polaris (Norway) and Acorn (United Kingdom) projects, for example. In addition to this, a substantial amount of new, planned carbon dioxide storage capacity has been only recently announced in Denmark for 2030–2032; its degree of reservation is not yet known. The preparation and implementation of new CCS projects typically takes several years, such as approximately seven years from the start of commercial negotiations; it is, therefore, unlikely that Finnish facilities for carbon dioxide storage could start before 2030. However, publicly available information will unavoidably be behind the negotiations held between companies. It could benefit Finnish actors in the field and the implementation of technological carbon sinks if the Government made strategic initiatives and combined separate actions into one united front for implementing carbon dioxide storage in several projects, such as in Denmark, Norway and the United Kingdom.

It is likely that the available storage capacity of approximately 10 $MtCO_2/a$ will place a significant constraint on Finland's carbon dioxide storage volume during the review period extending until 2035, even if sufficient funding is secured. According to current project activity, most of the identified available capacity would be taken up by the industry in the United Kingdom, Ireland, Norway, Denmark, Sweden and the Netherlands. It would require a significant change in negotiation and project preparation activity for 6 $MtCO_2/a$ of storage capacity, for example, to be available for Finland in 2035. Furthermore, risks of delays in carbon dioxide storage projects could be considered by agreeing to bind a significant portion of the storage capacity for carbon dioxide captured from Finnish facilities to projects that are starting already in 2030–2034.

7.3. Profitability of the capture, transport and storage of Bio-CO_2

This study estimated the costs for the capture, transport and storage of biogenic carbon dioxide at the facility level in three example cases. The unit costs for technological carbon sinks were €119/tCO_2 for a capture facility located on the coast and €133/tCO_2 for a capture facility located inland. Both emissions sources in the cases of technological carbon sinks were among the largest biogenic emissions sources, which also explains the reasonable additional cost of pipeline transport from and inland capture facility. In the example cases, the cost of a technological carbon sink created by the capture and storage of carbon dioxide (€119—€133/tCO_2) was lower than the cost of emissions reduction from the utilisation of carbon dioxide in the manufacture of synthetic fuels (€328/tCO_2). The example cases represent commercial facilities around the year 2030, following which changes may occur in the profitability of different technologies.

Investments into facilities require substantial capital; in the example cases, this ranges from hundreds of millions to more than one billion euros. Based on the review, however, the most part of the unit costs for technological carbon sinks, an estimated 75–80 per cent, consists of variable costs. Covering them requires operating income per each stored carbon dioxide unit, such as income from the sale of carbon removal units. Any possible investment subsidies would naturally reduce the need for private capital for implementing the projects, but the impact on the unit cost of carbon dioxide removal is not substantial.

If the operating subsidy were to cover the entire cost of the capture, compression, transport and storage of carbon dioxide, funding a technological carbon sink of 5 MtCO_2 would require EUR 605–705 million per year, depending on whether the estimate uses the weighted average from the two least expensive facilities or from all of the facilities where biogenic carbon dioxide can be captured.

7.4. Subsidy mechanisms for technological carbon sinks

There are currently no direct economic incentives for creating technological carbon sinks in Finland, except for units produced for voluntary carbon markets. Sweden is introducing a reverse auction or competitive bidding for capture and storage projects for biogenic carbon dioxide; in these, the actor who produces the sinks at the lowest price gets the subsidy. A total of SEK 36 billion (approximately EUR 3.3 billion) has been granted to the Swedish energy authority for the purposes of the auction between 2026 and 2046. The maximum available amount per year is SEK 1.7 billion (approximately EUR 144 million), and the subsidy will be distributed in one or more auctions. A similar system of subsidy could also be possible in Finland, and its benefits would be realised in particular if several actors took part in the auction.

An investigation into reverse auctions or other support mechanisms should be initiated soon if projects are to be implemented in the early 2030s. Aiming for early implementation would be a sensible act of risk management due to the potential delays of the projects. There are several facilities in Finland that could potentially participate in the reverse auction/competitive bidding, with preliminary cost estimates for implementing BECCS ranging from €120 to €150/tCO_2. However, the required level of compensation is affected by uncertainty in the cost estimates, since BECCS is still a lesser used technology, and the uncertainties related to the transport and storage chain of carbon dioxide are significant.

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APPENDIX 1. CO_2 EMISSIONS FROM FINNISH FACILITIES IN THE EMISSION REGISTER

Information is based on data from the European Pollutant Release and Transfer Register (EEA 2023). Mechanically updated data and its clarifications are marked in red in the table.

Reporting Year	parentCompanyName	nameOfFeature	mainActivityName	Bio ktCO2	Fossil ktCO2	Total ktCO2	Clarification
2021	UPM Communication Papers Oy, UPM Specialty Papers Oy	Jämsänkoski paper mill	Industrial plants for the production of paper and board and other primary wood products (such as chipboard, fibreboard and plywood)	274.1	60.9	335	
2021	Mondi Powerflute Oy	Wood processing industry, Mondi Powerflute Oy	Industrial plants for the production of paper and board and other primary wood products (such as chipboard, fibreboard and plywood)	195	101	296	
2021	STORA ENSO OULU OY	Oulu mill	Industrial plants for the production of paper and board and other primary wood products (such as chipboard, fibreboard and plywood)	1071.3	58.7	1130	
2021	UPM-Kymmene Oyj	Tervasaari, Valkeakoski	Industrial plants for the production of paper and board and other primary wood products (such as chipboard, fibreboard and plywood)	212	115	327	
2021	Stora Enso Publication Papers Oy Ltd	Anjalankoski mills (Anjala and Inkeroinen)	Industrial plants for the production of paper and board and other primary wood products (such as chipboard, fibreboard and plywood)	160	103	263	
2021	Stora Enso Oyj	Varkaus mills	Industrial plants for the production of paper and board and other primary wood products (such as chipboard, fibreboard and plywood)	660.2	63.8	724	
2021	Stora Enso Oyj, Uimaharju mill	Uimaharju mill, Enocell mill	Industrial plants for the production of pulp from timber or similar fibrous materials	1521.2	68.8	1590	
2021	Stora Enso Oyj	Heinola Fluting mill	Industrial plants for the production of pulp from timber or similar fibrous materials	214	112	326	
2021	Stora Enso Oyj	Imatra mills	Industrial plants for the production of pulp from timber or similar fibrous materials	2141	189	2330	
2021	Metsä Fibre Oy	Joutseno mill	Industrial plants for the production of pulp from timber or similar fibrous materials	1473.9	16.1	1490	
2021	MM Kotkamills Oy	Kotka mills	Industrial plants for the production of pulp from timber or similar fibrous materials	251	240	491	
2021	UPM-Kymmene Oyj	Kymi	Industrial plants for the production of pulp from timber or similar fibrous materials	1501.2	88.8	1590	
2021	UPM-Kymmene Oyj	Kaukaa mills	Industrial plants for the production of pulp from timber or similar fibrous materials	1581.6	88.4	1670	
2021	Metsä Fibre Oy	Rauma mill	Industrial plants for the production of pulp from timber or similar fibrous materials	1340.3	69.7	1410	
2021	Metsä Board Oyj	Metsä Board Kaskinen Pulp Mill	Industrial plants for the production of pulp from timber or similar fibrous materials	187.54	1.46	189	
2021	Metsä Fibre Oy	Äänekoski bioproduct mill	Industrial plants for the production of pulp from timber or similar fibrous materials	2610	0	2610	
-	Metsä Fibre	Kemi	Industrial plants for the production of pulp from timber or similar fibrous materials	4170		4170	Updated to match the data of the new bioproduct mill based on data from environmental permit PSAVI 164/2020
2021	Vantaan Energia Oy	Both incineration plants		164	249.9	413.9	
		Waste to energy power plant	Installations for the incineration of non-hazardous waste in the scope of Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste	164	164	328	Added missing bio-CO2 with the assumption of 50% bio
		Incineration plant for hazardous waste			85.9	85.9	Added data, new plant
2021	Riikinvoima Oy	Waste incineration plant	Installations for the incineration of non-hazardous waste in the scope of Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste	57.1	60.9	118	
2021	Fortum Waste Solutions Oy	Riihimäki branch	Installations for the recovery or disposal of hazardous waste	345	345	690	Added missing bio-CO2 with the assumption of 50% bio
2021	Neste Oyj	Porvoo refinery	Mineral oil and gas refineries	0	2390	2390	
2021	Sappi Finland Operations Oy	Kirkniemi power plant	Thermal power stations and other combustion installations	79	229	308	
2021	Porvoon Energia Oy	Tolkkinen power plants	Thermal power stations and other combustion installations	199.9	0.0779	200	
-	Helen Oy	Vuosaari bioenergy heating plant	Thermal power stations and other combustion installations	585.4		585	Added data, new plant
2021	Vantaan Energia Oy	Martinlaakso	Thermal power stations and other combustion installations	284	276	560	
2021	Loimua Oy	Vanaja power plant, Hämeenlinna	Thermal power stations and other combustion installations	172.9	5.14	178	
2021	Savon Voima Joensuu Oy	Joensuu power plant	Thermal power stations and other combustion installations	248	103	351	
2021	Kainuun Voima Oy	Kajaani steam plant	Thermal power stations and other combustion installations	246.5	64.5	311	
2021	Turun Seudun Energiantuotanto Oy	Naantali power plant	Thermal power stations and other combustion installations	677	383	1060	
2021	OULUN ENERGIA, Toppila power plants, Oulu	Toppila power plants	Thermal power stations and other combustion installations	146	220	366	
2021	Pori Energia Oy	Aittaluoto power plant	Thermal power stations and other combustion installations	254.6	21.4	276	
2021	Seinäjoen Voima Oy	Seinäjoki power plant	Thermal power stations and other combustion installations	235	366	601	
2021	Tampereen Sähkölaitos Oy	Naistenlahti power plant	Thermal power stations and other combustion installations	148	229	377	
2021	Vaskiluodon Voima Oy	Vaasa power plant, VL2	Thermal power stations and other combustion installations	230	382	612	
2021	Mäntän Energia Oy	Mäntän Energia Oy, power plant	Thermal power stations and other combustion installations	132.7	3.3	136	
2021	Kokkolan Energia Oy	Kokkolan Energia Oy, “Power” plant	Thermal power stations and other combustion installations	94.3	82.7	177	
2021	KUMPUNIEMEN VOIMA OY	KUMPUNIEMEN VOIMA OY, Power plant	Thermal power stations and other combustion installations	104.7	0.251	105	
2021	Metsä Fibre biopower plant (from 30 Nov 2019, previously Äänevoima Oy)	Metsä Fibre biopower plant (from 30 Nov 2019, previously Äänevoima Oy), Energy production	Thermal power stations and other combustion installations	251.2	34.8	286	
2021	Fortum Power and Heat Oy	Kivenlahti heating station	Thermal power stations and other combustion installations	286.3	0.681	287	
2021	ETELÄ-SAVON ENERGIA OY	PURSIALA POWER PLANT	Thermal power stations and other combustion installations	228.7	75.3	304	

2021	Kotkan Energia Oy	Hovinsaari power plant	Thermal power stations and other combustion installations	141.1	54.9	196	
2021	Oy Alholmens Kraft Ab	Pietarsaari power plant	Thermal power stations and other combustion installations	455	338	793	
2021	Kokkolan Energia Oy	Power plant Voima (Ykspihlaja power plant)	Thermal power stations and other combustion installations	81.6	25.4	107	
2021	Järvi-Suomen Voima Oy	Ristiina power plant	Thermal power stations and other combustion installations	133.9	1.1	135	
2021	Kaukaan Voima Oy	Kaukaan Voima Oy, Energy production	Thermal power stations and other combustion installations	564.3	43.7	608	
2021	OULUN ENERGIA OY	Laanila ecopower plant	Thermal power stations and other combustion installations	60.5	62.5	123	
2021	Porin Prosessivoima Oy	Porin Prosessivoima Oy, Energy production	Thermal power stations and other combustion installations	242.3	77.7	320	
2021	Rauman Biovoima Oy	Rauma power plant	Thermal power stations and other combustion installations	307.4	45.6	353	
2021	Tornion Voima Oy	Power plant and boiler unit in Röyttä industrial area	Thermal power stations and other combustion installations	92	279	371	
2021	Alva-yhtiöt Oy, Jyväskylän Voima Oy	Keljonlahti power plant	Thermal power stations and other combustion installations	464	206	670	Added estimate of missing bio-CO2 amount based on source KSML 2012
2021	Keravan Lämpövoima Oy	Kerava power plant	Thermal power stations and other combustion installations	159.9	0.058	160	
2021	Vantaan Energia Keski-Uusimaa Oy	Järvenpää power plant	Thermal power stations and other combustion installations	171.8	16.2	188	
2021	Oulun Energia Oy	Laanila biopower plant	Thermal power stations and other combustion installations	482	116	598	
2021	Linde Gas Oy Ab	Linde Gas Oy Ab, Kilpilahti hydrogen production plant	Chemical installations for the production on an industrial scale of basic inorganic chemicals: Gases, such as ammonia, chlorine or hydrogen chloride, fluorine or hydrogen fluoride, carbon oxides, sulphur compounds, nitrogen oxides, hydrogen, sulphur dioxide, carbonyl chloride	0	150	150	
2021	Borealis Polymers Oy	Borealis Polymers Oy, petrochemistry plants	Chemical installations for the production on an industrial scale of basic organic chemicals: Simple hydrocarbons (linear or cyclic, saturated or unsaturated, aliphatic or aromatic)	0	546	546	
2021	Finnsementti Oy	Finnsementti Oy, Lappeenranta cement plant	Installations for the production of cement clinker in rotary kilns	0	368	368	
2021	Finnsementti Oy	Finnsementti Oy, Parainen/Cement plant	Installations for the production of cement clinker in rotary kilns	0	539	539	
2021	NORDKALK Oyj Abp	NORDKALK Oyj Abp, Raahe limekiln	Installations for the production of lime in rotary kilns	0	170	170	
2021	SSAB Europe Oy (formerly RUUKKI METALS OY)	SSAB Europe Oy (formerly RUUKKI METALS OY), Raahe steel mill	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	0	2240	2240	
2021	Outokumpu Chrome Oy, Outokumpu Stainless Oy	Outokumpu Chrome Oy, Outokumpu Stainless Oy, Tornio mills	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	0	718	718	
2021	Helen Oy	Helen Oy, Vuosaari power plants	Thermal power stations and other combustion installations	0	739	739	
2021	Fortum Power and Heat Oy	Suomenoja power plant	Thermal power stations and other combustion installations	0	560	560	
2021	Tampereen Sähkölaitos Oy	Tampereen Sähkölaitos Oy, Lielahti power plant	Thermal power stations and other combustion installations	0	130	130	
2021	Raahen Voima Oy	Raahen Voima Oy, Energy production	Thermal power stations and other combustion installations	0	1960	1960	