PUBLIC SUMMARY REPORT

Publishing date 4.10.2024

Outlook of CO_2 logistics in Finland for CCUS

Summary

This report summarizes the results from our study on potential development of CO_2 logistics in Finland, for the purposes of carbon capture, utilization, and storage (CCUS). The study provides an outlook on Finland's industrial carbon dioxide emission sources, evaluates potential CO_2 hub locations, export terminals and inland intermediate storage facilities, and assesses transport costs and required investments for CO_2 logistics infrastructure.

The examined industrial facilities emitted a total of 45 $MtCO_2$/year in 2022, of which 30.1 $MtCO_2$/year is biogenic. Nine potential regional CO_2 hubs were identified and used to create three scenarios for future CO_2 logistics system in Finland. The scenarios show how 25.2 $MtCO_2$/year (of which 21.0 Mt is biogenic) could be collected for utilization or geological storage from the hubs. Additionally, we investigated two alternative trunkline scenarios with higher capacities, allowing to transport CO_2 between the hubs while also providing greater coverage of the transport networks to regions outside the larger CO_2 hubs.

Assuming rail transport of CO_2 for facilities connected by the railway network, the weighted average transport cost in the hubs was between 20–59 €/tCO_2. The cost includes initial compression or liquefaction and buffer storage at the destination for both utilization and permanent storage options. Capital costs in the scenarios were between €3.7–4.7 billion. Required investment was the lowest in the utilization-heavy scenario as it also has the lowest transport demands of all the scenarios. Highest investments were required in the scenario with an emphasis on geological storage where a significant amount of CO_2 is transported to coastal locations for further shipping to storage sites. The trunkline scenarios examine transport of 23.2–38.1 $MtCO_2$/year (of which 20.1–25.8 Mt is biogenic) to utilization sites and hubs in four coastal locations. The total weighted average cost of transport was between 40–60 €/tCO_2 in the assessed trunklines.

Utilizing the existing railway infrastructure for CO_2 transport is economically sensible based on the results. Comparison of the assessed transport modes shows that pipelines are less expensive option to transport CO_2 over shorter distances when capacity is high enough. If capacity becomes under 1 $MtCO_2$/year, pipelines start to lose their advantage over rail and road transportation.

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1. Introduction – the need for CCUS and the role of logistics

To reach the global warming limit of 1.5–2°C net zero emissions should be reached by mid-century after which net-negative emissions, i.e., carbon removal from the atmosphere, are required. Carbon capture, utilization, and storage (CCUS) has emerged as critical complementary technology in reaching the climate targets by enabling to capture CO_2 emissions to be used as feedstock for products or processes, or permanently storing it to avoid its release into the atmosphere.

CO_2 utilization could replace production based on virgin fossil sources, whereas permanent storage of CO_2 could reduce hard-to-abate fossil CO_2 emissions and enable creation of technological carbon sinks by permanently removing biogenic or atmospheric CO_2 from the natural carbon cycle.

European Commission's communication on EU's 2040 climate target states that net emission reduction of 90 % relative to 1990 is required by 2040. According to the Commission's impact assessment, EU's annual carbon capture capacity should rise to 50 million tonnes by 2030 and 450 million tonnes by 2050 to achieve the climate targets. Additionally, industrial carbon removals of 50–70 $MtCO_2$/year should be reached by 2040.

Finland has especially high potential for bio-CCUS. Due to significant roles of forest industry and bioenergy production major part of industrial CO_2 emissions in Finland are biogenic. According to Statistics Finland[1] a total of 42.2 Mt of biogenic CO_2 was emitted from Finnish economy and households in 2022. The most significant emitters of biogenic CO_2 were the forest industry (18.1 Mt) and electricity, gas, steam and air conditioning supply (14.8 Mt).

Logistics is at a critical role to enable the realization of CCUS value chains. If CO_2 cannot be stored or utilized at site of capture, it must be transported to a suitable location via pipelines, ships, trains, or trucks. As Finland lacks suitable sites for geological storage of CO_2, ships are needed to reach the nearest storage sites in the Baltic Sea or the North Sea.

Developing shared infrastructure for CO_2 logistics could reduce logistics costs of the participants due to economies of scale benefits, while also encouraging to participate into CCUS due to ease of access and reduced investment risks. Development of CO_2 transport infrastructure is also at a key role in EU's industrial carbon management strategy, which aims to develop regulatory frameworks, market design and infrastructure planning, as well as set accounting rules, establish standards, and assess the use of existing infrastructure for CO_2 transport.

1.1. Goal and scope of the study

The goal of this study, which concerns the transport network required for carbon capture, utilization, and storage (CCUS) in Finland, was to investigate how a CO_2 logistics system could be implemented in such a way that industrial facilities taking part into CCUS activities could benefit from cost reductions due to economies of scale benefits reached through shared logistics infrastructure.

The work was divided into three sub-tasks:

[1] Statistics Finland. 2024. Emissions into air by industry 2022. Available at: https://pxdata.stat.fi:443/PxWeb/sq/bc87d98d-7ccd-46ed-8e99-4c3b4814829a

1. Outlook on Finland's industrial carbon dioxide sources, potential CO_2 hubs for CCUS, and transport scenario design

2. Carbon dioxide transport options and transport costs

3. Investment costs of CO_2 logistics infrastructure

The work was carried out as a literature-based study, incorporating techno-economic assessments using spreadsheet calculations.

2. Methodology

2.1. Review on CO_2 emissions in Finland and existing transport infrastructure

Location and amount of large CO_2 emission point sources in Finland were examined based on public data on industrial facilities with annual CO_2 emissions of ≥100 kt. As Table 1 shows, the 72 industrial facilities examined in this work accounted for 45.3 Mt of CO_2 emissions in 2022, of which 30.1 Mt was biogenic. Seasonal variation of district heating plants was also studied as annual fluctuation of CO_2 emissions affects dimensioning of the logistics infrastructure.

Table 1. Industrial CO_2 emissions in Finland by the industry sector, 2022.

Industry	No. of facilities	Total $MtCO_2$	Bio $MtCO_2$	Share of bio-CO_2
Forest industry	20	21.7	20.5	94 %
Thermal power stations and other combustion installations	40	15.2	8.7	58 %
Iron and steel	2	2.8	0	0 %
Oil refining	1	2.6	0	0 %
Waste-to-energy	5	1.4	0.8	58 %
Cement	2	0.9	0	0 %
Chemicals	2	0.7	0	0 %
All industries	72	45.3	30.1	66 %

In addition to the emission data, existing transport infrastructure, announced CO_2 utilization projects, and potential CO_2 mineralisation storage sites were examined to facilitate the design of the CO_2 logistics system. Figure 1 presents a map of the existing transport infrastructure in Finland with locations and annual volumes of industrial CO_2 emission point sources, CO_2 demand for utilization projects, and mineralisation storage potential.

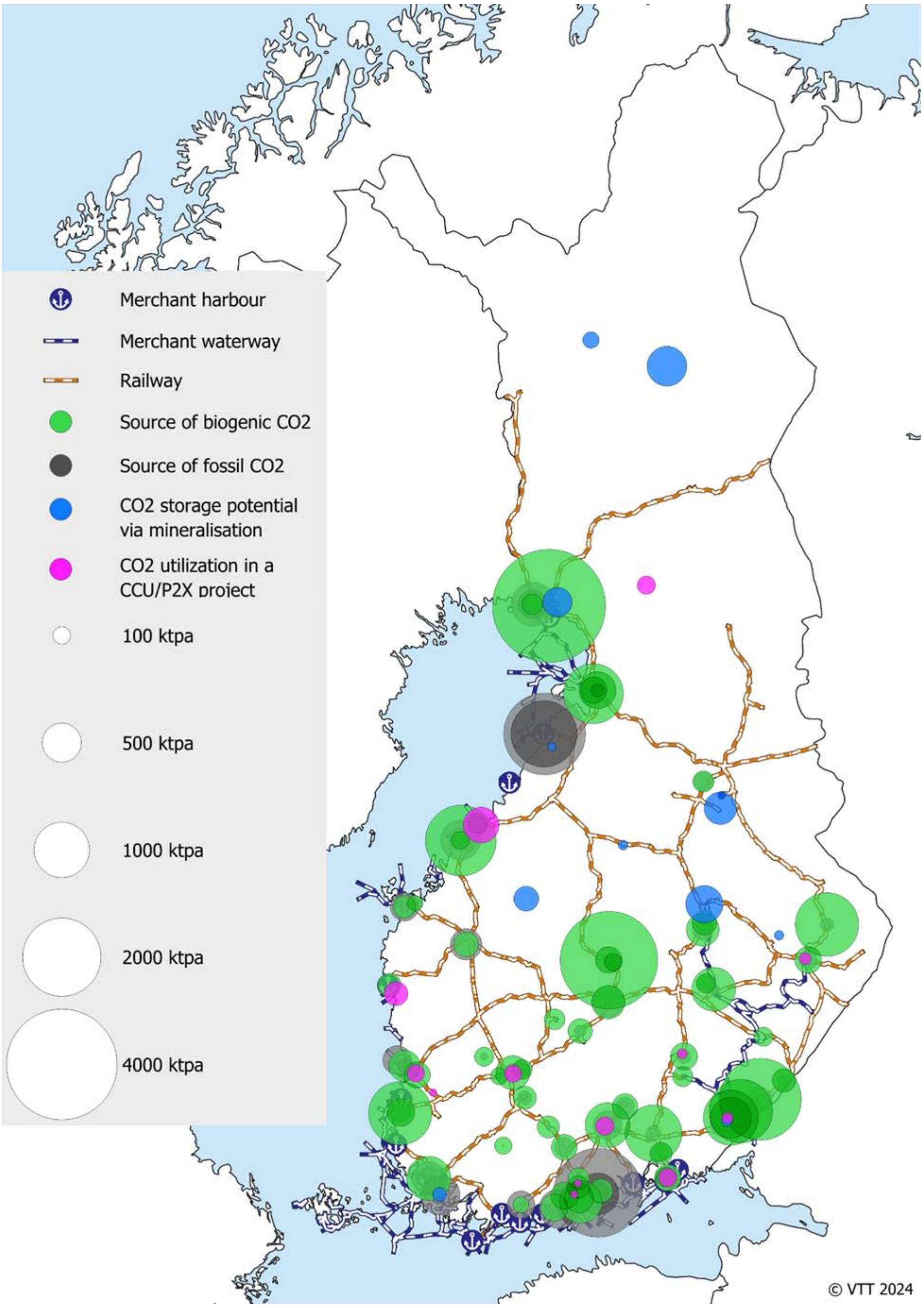

Figure 1. Industrial CO_2 emission point sources, CO_2 demand in utilization projects, mineralisation storage potential, and existing infrastructure relevant for CO_2 transport.

There are large CO_2 emission point sources (≥100 ktCO_2) scattered evenly within Finland, excluding the northernmost Lapland region. There are several large emission sources located on the coastline, from where CO_2 could be transported forward via ships unless utilized. Majority of the sources are also within the range of the existing railway infrastructure. Announced utilization projects are largely located near existing CO_2 point sources, from where CO_2 could be supplied to these projects if carbon capture is implemented. Potential sites for CO_2 storage via mineralisation are mainly located at central and northern parts of Finland. Some potential mineralisation sites are neither near CO_2 point sources nor railways, meaning that pipelines or road transport would be needed to supply CO_2 into these locations if they were to be used for CO_2 storage.

2.2. Design of CO_2 transport scenarios

Transport scenarios were constructed to study efficient strategies for CO_2 logistics implementation in Finland. In the scenarios, CO_2 hubs were created for adjacent facilities within a single region based on areas that have significant CO_2 emission point sources within a reasonable distance from each other. Nine regional emission clusters were identified to create CO_2 hubs for the transport scenarios (Table 2).

Table 2. Regional CO_2 hubs examined in the transport scenarios and annual CO_2 emission volumes of the hubs.

Hub	Total $MtCO_2$	Bio $MtCO_2$
Tornio-Kemi	5.2	4.3
Oulu	2.3	1.9
Keski-Suomi	4.1	3.8
Savo-Karjala	2.6	2.3
Pori-Rauma	2.3	2.1
Pirkanmaa	1.0	0.8
Etelä-Karjala	5.8	5.0
Kymenlaakso	2.0	1.6
Uusimaa	2.8	1.7

Carbon capture with a 90 % capture rate is assumed to take place in all facilities included to the hubs. For simplicity, each hub is assigned either to storage or utilization in total, meaning that all the captured CO_2 within that region is directed either to storage or utilization. In storage hubs, the CO_2 is transported to the nearest harbour and transported to the North Sea for geological storage. In utilization hubs, the CO_2 is transported to a key location within that hub, which is typically chosen to be the largest CO_2 point source of the hub to minimize transport demands. If there is an announced utilization project within the hub, CO_2 is supplied to the project from nearby facilities regardless of designated purpose of the hub. Mineralisation storage sites are only included to the extended Trunkline 2 scenario due to low maturity and uncertainty of storage potential in these sites.

Transport routes within the hubs are designed manually. Regarding the route design, the following guidelines are roughly implemented: 1) railways are utilized for transport if on route; 2) the routing aims to minimize transport distance and transported amount of CO_2; 3) coastal hubs are prioritized for CO_2 storage/ship export to reduce transport demands from inland hubs to shores.

We examined five transport scenarios for CO_2 logistics implementation: three primary scenarios A, B and C consisting of regional hubs that have individual logistics (Figure 2) and two additional trunkline scenarios Trunkline 1 and Trunkline 2 where adjacent regional hubs are connected, and coverage of the transport network is expanded (Figure 3).

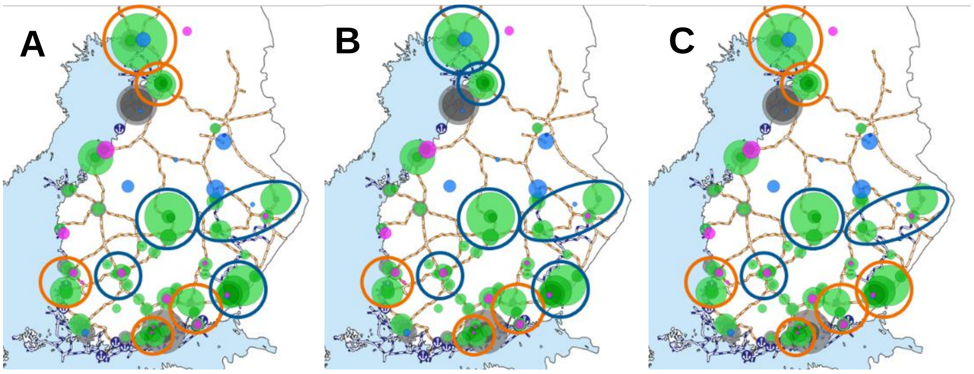

Figure 2. CO_2 hubs of scenarios A, B and C. Orange circles illustrate storage hubs and blue circles illustrate utilization hubs.

Scenario A is designed to supply similar amounts of CO_2 to both utilization and storage, whereas Scenario B emphasizes utilization and Scenario C emphasizes storage. CO_2 storage capacity of Scenario A is 13.1 Mt (10.4 Mt biogenic), and utilization capacity is 12.2 Mt (10.7 Mt biogenic). CO_2 storage capacity in Scenario B reduces to 6.4 Mt (4.8 Mt biogenic), whereas utilization capacity increases to 18.9 Mt (16.3 Mt biogenic). CO_2 storage capacity in Scenario C increases to 18.3 (14.9 Mt biogenic) and utilization capacity reduces to 7.0 Mt (6.2 Mt biogenic).

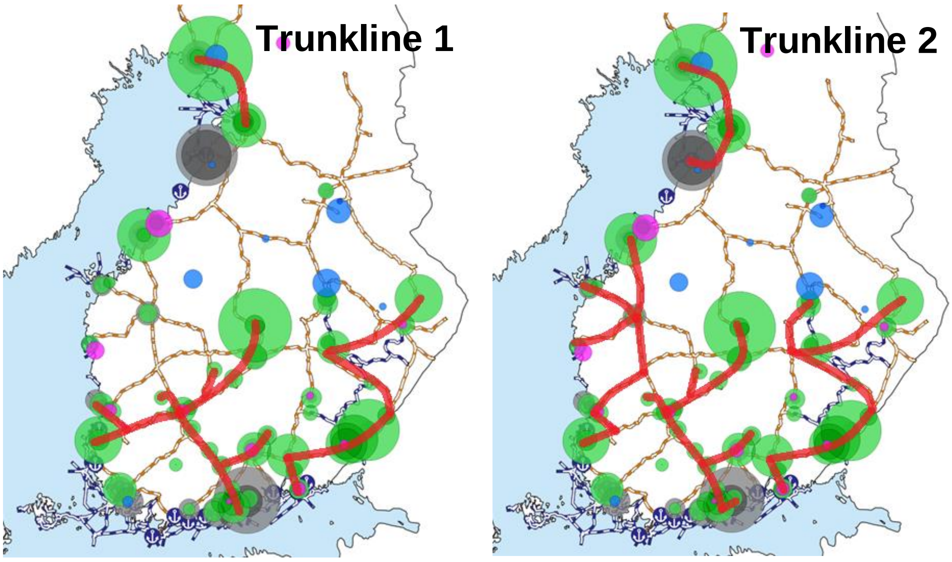

Figure 3. Transport routes of Trunkline 1 and Trunkline 2 scenarios.

In the Trunkline scenarios adjacent hubs are connected to examine feasibility of CO_2 transport between regional hubs. As the trunklines provide larger coverage more facilities that were excluded from Cases A, B and C are also included to the transport network. In the Trunkline 1 scenario, the examined trunklines have CO_2 transport capacities of 6.7–9.6 Mt (5.6–8.2 Mt biogenic). In the Trunkline 2 scenario, the trunklines are further extended to reach larger coverage. Additionally, potential mineralisation storage sites near the trunklines are included to the routing. In the Trunkline 2 scenario, the examined trunklines have CO_2 transport capacities of 5.5–12.4 Mt (4.2–8.7 biogenic).

2.3. Cost estimation model for CO_2 logistics

The transport cost estimation model accounts for compression and liquefaction at the CO_2 capture facility, transport to CO_2 logistic hub with possible intermediate storage, further transport to final onshore destination, and finally in case of geological storage, ship transport to a terminal close to the storage site (Figure 4). CO_2 capture costs are excluded.

For road, rail and ship transport, liquefaction from 1 bar is included. We assume low-pressure state for the CO_2 in all transport stages where CO_2 is liquid. Intermediate storage is included when transport continues with truck, train or ship after liquefaction. Compression to 100 bar is assumed for pipeline transport.

Each capture facility is connected either directly to a utilization site, a harbor or an inland hub where several transport routes merge or divide. The mode of transportation can change for part or all the CO_2 entering the same inland hub. In this case, the appropriate capacity to condition CO_2 from 100 bar to low-pressure liquefied or vice versa is included in the hub costs. The inland hubs also include the required intermediate storage capacity and on- or off-loading capacity corresponding to the truck or rail connections.

At the end of transport chains, CO_2 is either utilized or geologically stored. In utilization, an intermediate storage corresponding to a week's worth of CO_2 demand is assumed. In geological storage, a buffer storage equal to the capacity of the ship is included at the receiving terminal. Costs from forwarding the CO_2 to the injection well, injection of CO_2 into the reservoir, or other activities such as monitoring and verification are not included. Similarly, costs of utilization of CO_2 are not included.

Due to seasonal variation, the average flow of transported CO_2 on a route can be lower than the design capacity, which corresponds to the flow of CO_2 during peak months in the winter. The cost model estimates all investment and fixed costs based on the design capacity, which can mean that on average, the transport system runs on partial load.

All the costs in the study have been corrected to 2023 level using Chemical Engineering Plant cost index (CEPCI). Economic life is 20 years and interest rate 5%.

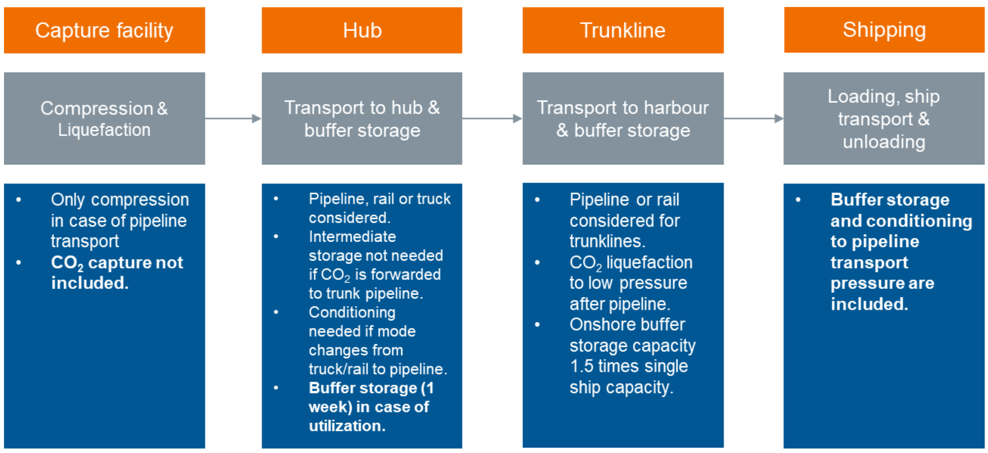

Figure 4. The scope of the transport cost estimation model.

We estimate a total transport cost for each capture site included to the scenarios and aggregate the costs into weighted average costs for each hub. Weighted average unit cost in a hub is the price that would cover all the costs in the transport system if all capture facilities were to pay that same amount per transported CO_2. The capture facility specific total transport cost includes compression or liquefaction, transport to the first inland hub, and subsequently a share of all following transport segments and hubs. This share corresponds to the average annual capture rate from the facility where the CO_2 originates per total average transport rate in a given hub or transport segment.

3. Results and conclusions

3.1. Transport costs

Average unit cost of transporting CO_2 in scenarios A, B and C is between 45–52 €/tCO_2 (see Table 3). Transport costs to geological storage are highest in the utilization-heavy scenario B, due to lower shipping capacity. Transport costs in hubs focusing on utilization are significantly lower in comparison, in the range of 24–28 €/tCO_2.

Scenario B, which has the lowest transport demands, requires the lowest investment costs for the transport infrastructure, totalling €3.7 billion. The highest investment costs at €4.7 billion are needed in scenario C with emphasis on geological storage where a significant amount of CO_2 is transported to coastal locations for further shipping to storage sites.

In scenario A, lowest average transport costs at 35 €/tCO_2 are estimated for the hub of Tornio-Kemi. Highest average transport costs at 56 €/tCO_2 are estimated for the hub of Uusimaa, largely due to the higher seasonal variation and lower capacity in the transported flow of CO_2. Seasonal variation leads to oversizing the transportation capacity compared to the average annual transportation rate, which leads to higher investment costs and higher unit costs of CO_2 transportation. In total, investments to transport infrastructure in scenario A for geological storage of CO_2 would amount to €2.9 billion, resulting in storage of 12.8 MtCO_2 annually.

In the four hubs focusing on utilization of CO_2 in scenario A, transport costs are lowest in Etelä-Karjala (22 €/tCO_2) and highest in Pirkanmaa (37 €/tCO_2). The required investment costs, €1.4 billion, are also lower compared to hubs where CO_2 was transported for storage.

In the utilization-heavy scenario B, 6.1 MtCO_2 from three hubs is transported for geological storage while 19.1 Mt from six hubs are designated to utilization. Transport costs to geological storage are between 43 to 59 €/tCO_2, whereas transport costs to utilization are between 20 to 33 €/tCO_2, correlating with the capture amount in the hubs.

In scenario C, 18.0 MtCO_2 is transported for geological from five hubs, while only 7.3 MtCO_2 is utilized in three hubs. Requirements for shipping and longer distance transportation routes result in higher investment and average transport unit costs compared to scenario A and B. With similarity to scenario A, the transport unit costs to geological storage are between 35 to 56 €/tCO_2. Although on the scenario level, the average transport cost to storage is roughly the same between Scenarios A and C (see Table 3), connecting the hubs of Etelä-Karjala and Kymenlaakso result in lower local transport cost levels in Scenario B, together with higher transport capacity to storage. Lowest average transport costs to utilization are 24 €/tCO_2.

Table 3. Summary of transport costs in scenarios A, B and C. The capture amount of CO_2 in all scenarios is 25.2 $MtCO_2$/year, of which 21.0 $MtCO_2$/year biogenic.

Scenario	Destination		Transport costs			
	Storage (Mt)	Utilization (Mt)	Investments (M€)	Average unit cost to storage(€/t)	Average unit cost to utilization (€/t)	Average unit cost (€/t)
A – balanced	12.8	12.4	4 220	45	26	36
B – utilization	6.1	19.1	3 690	52	24	31
C – storage	18.0	7.3	4 690	45	28	40

Several trunkline routes were investigated in two additional transport scenarios. In Trunkline 1 scenario, key hubs were connected in order to accumulate larger amounts of CO_2 into selected harbours. The Trunkline 1 scenario includes four trunklines of which one leading from Central-Finland to west coast or the capital region has two alternative routing option. Due to these alternative trunklines, the total investment costs in the scenario would be €5.0–6.0 billion in a transport infrastructure for geologically storing 22.8–25.1 $MtCO_2$/year. The average unit cost of transport is between 40 to 59 €/tCO_2, being the least expensive in Tornio-Oulu-Kemi trunkline. The transport costs on a trunkline transporting 9.0 $MtCO_2$/year from Keski-Suomi hub to Uusimaa, would be 59 €/tCO_2 on average, including ship transport to geological storage.

In Trunkline 2 scenario, coverage of the trunklines was expanded beyond the hubs assumed in previous scenarios. This resulted in considerably higher assumed capture amounts, totalling at 38.1 $MtCO_2$ (25.8 Mt biogenic) across all the investigated trunklines. In total the extended trunklines would require €8.5 billion in investments. The average transport unit costs are within 43–60 €/tCO_2, including shipping to geological storage, which is slightly above the costs in the Trunkline 1 scenario. The average cost of transportation in the largest trunkline from Central-Finland to capital region is 55 €/tCO_2, providing 12.1 $MtCO_2$ to geological storage. The Eastern trunkline would transport the highest amount of biogenic CO_2, 8.7 $MtCO_2$, to storage with an average unit cost of 51 €/tCO_2.

Comparing the cost of transport to geological storage between the scenarios, the results show that the transport costs are lowest in scenario C, where transportation capacity to geological storage is the highest, and capture facilities in the hubs invest in shared infrastructure (see Figure 5). On a system level the average transport costs are higher in the trunkline scenarios, where the transport and storage capacity can, however, be increased considerably.

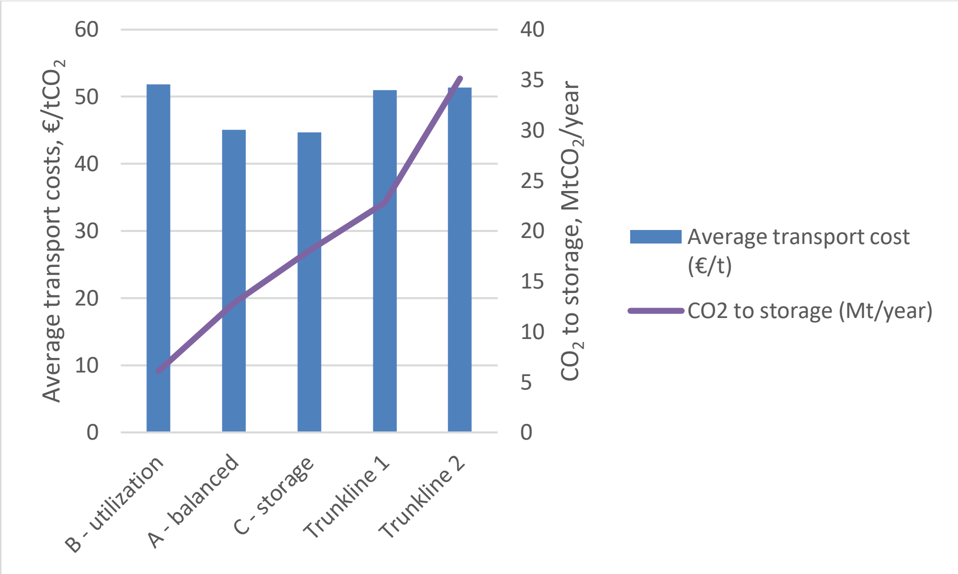

Figure 5. Average cost of CO_2 transportation to storage and the transport capacity in the studied scenarios.

3.2. Regional CO_2 hubs offer large potential for both utilization and storage

Scenarios A, B and C show how 25.2 $MtCO_2$/year (21.0 Mt biogenic) could be collected for utilization or geological storage from the nine examined CO_2 hubs in Finland. Based on the scenarios, CO_2 hubs could be created quite locally without the need for long distance and cross-country transports. Assuming rail transport of CO_2 for facilities connected by the rail network, the weighted average transport cost was between 20–59 €/tCO_2 in the hubs. Transport costs were lower in hubs focusing on CO_2 utilization, as costs of shipping the CO_2 to the North Sea for geological storage are avoided. The cost includes initial compression or liquefaction and buffer storage at the destination for both utilization and permanent storage options. Costs of capture and permanent storage, or utilization are excluded. The scope of the transportation system and other study-specific assumptions affect the results, such as the assumption to transport CO_2 to a central utilization site at the hubs, or inclusion of buffer storages of liquefied CO_2 at the end of all transport chains. The cost of CO_2 transportation to utilization will depend on the future locations, distribution and capacities of the utilization facilities.

Nine hubs with a capture potential of 25.2 $MtCO_2$/year (21.0 Mt bio) were identified. Focusing storage hubs at coast and utilization hubs inland could lead to a balanced system.

Capital costs in the scenarios A, B and C were between €3.7–4.7 billion. As expected, lowest investment costs are in the utilization-heavy scenario B that has lowest transport demands, and highest in scenario C with an emphasis on geological storage where a significant amount of CO_2 is transported to coastal locations for further shipping to storage sites.

Additional and alternative transport network layouts were further examined in two trunkline scenarios, where the hubs were connected and or expanded with large capacity connections to enable better economies of scale or coverage. The trunkline scenarios transport 23.2–38.1 $MtCO_2$/a (of which 20.1–25.8 Mt bio) to utilization sites and hubs in four coastal locations. The total weighted average cost of transport was between 40–60 €/tCO_2 in the examined trunklines.

There are different options how to allocate costs within a transport network. If each CO_2 capture facility would pay for the transport based on the share they are using each transport segment, the unit costs can be high for small upstream facilities while downstream capture facilities close or at the harbour hub have the lowest unit costs. If the costs are too high for the upstream capture facilities, they will not participate in the logistic system, reducing the extent of the trunkline. Therefore, if capture sites would pay transport rate based on weighted system average, the trunklines could theoretically enable maximum transport amounts for geological storage.

Biogenic CO_2 potential greatly surpasses the currently planned CO_2 utilization capacity and mineralization potential in Finland.

Considering only CO_2 transport infrastructure, focusing storage hubs with ship export to coasts and utilization hubs inland could lead to a balanced overall system, providing a compromise between economy of scale, utilization and storage capacity, coverage, network complexity and required capital. Product distribution and possible export logistics will naturally affect the location selection of utilization facilities as well, however.

Seasonal variation in CO_2 capture rates affect the costs and requirements for CO_2 transportation. Some of the hubs, such as Uusimaa, seem to be more challenged due to seasonal variation of the CO_2 capture rates. Forwarding more CO_2 to Uusimaa from, for example, Pirkanmaa would mitigate the cost penalty from seasonal variation in the region. This would change the logistics systems toward alternative options studied in the presented trunkline scenarios.

3.3. Ship and pipeline transport costs depend strongly on capacity

Looking at transport distance of 200 km, rail transportation, followed by road transportation is the least expensive option at transport capacities of 1 $MtCO_2$/year or less (see Figure 6). The cost of rail transport in the above range is between 31–38 €/tCO_2 encompassing compression (for pipelines), liquefaction (for road, and rail), and transport. At higher transport capacities, pipeline transportation becomes more economical, with a clear margin above 2 $MtCO_2$/year. The economy of pipeline transportation of CO_2 is more sensitive to scale compared road and rail transportation at the assumed distance.

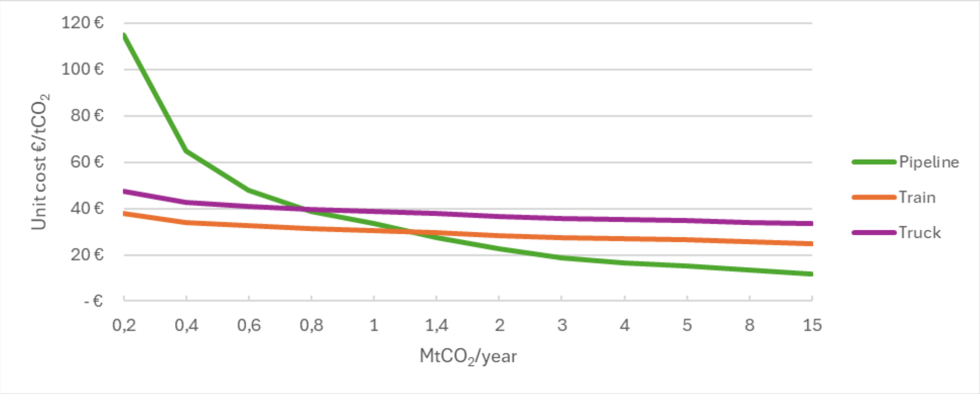

Figure 6. Cost of transporting CO_2 over 200 km by pipeline, rail or road. The costs include compression (for pipelines), liquefaction (for road and rail) and transport.

Figure 7 illustrates the costs of transporting CO_2 over a longer distance of 2000 km using ship, pipeline, rail, and road transport modes. At this distance, which can represent the one-way length of a transport route from Finland to geological storage site, ship are clearly the least expensive options. At capacities of 0.2–3 $MtCO_2$/year, the ship transport costs would be from 96 to 34 €/tCO_2, including, liquefaction, transport and a buffer storage and reconditioning to high pressure at the destination for shipping. At the assumed transport distance of 2000 km, a capacity of 15 $MtCO_2$/year would be needed for pipeline costs to go match ship transport costs.

Collecting at least 2–4 $MtCO_2$ to the same harbour would reduce the costs of shipping to a geological storage considerably.

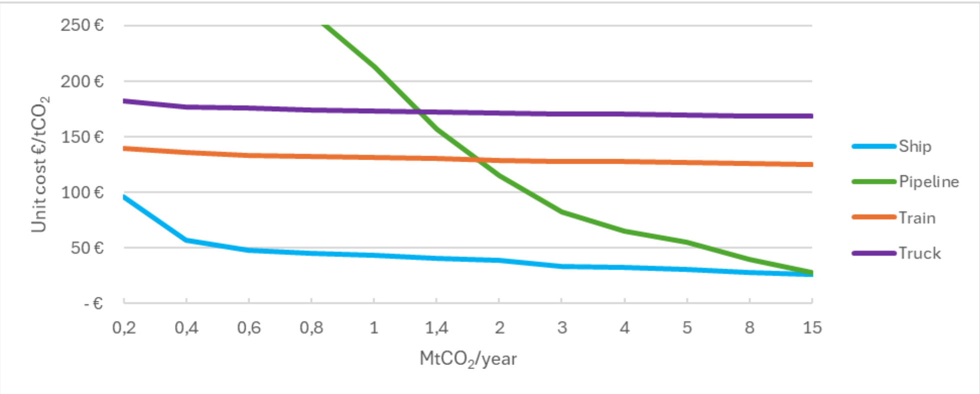

Figure 7. Cost of transporting CO_2 over 2000 km by ship, pipeline, rail or road. The costs include compression (for pipelines), liquefaction (for ship, road and rail) and transport. Buffer storage and reconditioning to high pressure at destination is included in the shipping costs.

Unit cost breakdown of transporting 1 $MtCO_2$/year by ships over distances of 1000 to 2500 km are presented in Figure 8. The total ship transport cost in this case is 36–48 €/tCO_2. Liquefaction and intermediate storages correspond to majority of the transport unit costs, especially at shorter distances, which is further augmented by the scope of the cost model covering intermediate storage at the receiving terminal. Halving the transport capacity to 0.5 $MtCO_2$ would increase the unit cost (49–55 €/tCO_2) significantly, especially on shorter distances. Increasing the capacity to 4 $MtCO_2$/year results in transport cost range of 27–35 €/tCO_2.

Investment cost of liquefaction and intermediate storages, and also indirect fixed costs, are the main cost factors and contribute to the uncertainty accordingly.

The investment costs are between €170–240 million. Considerable share of the investment comes from intermediate storages in harbours at both ends of the shipping route.

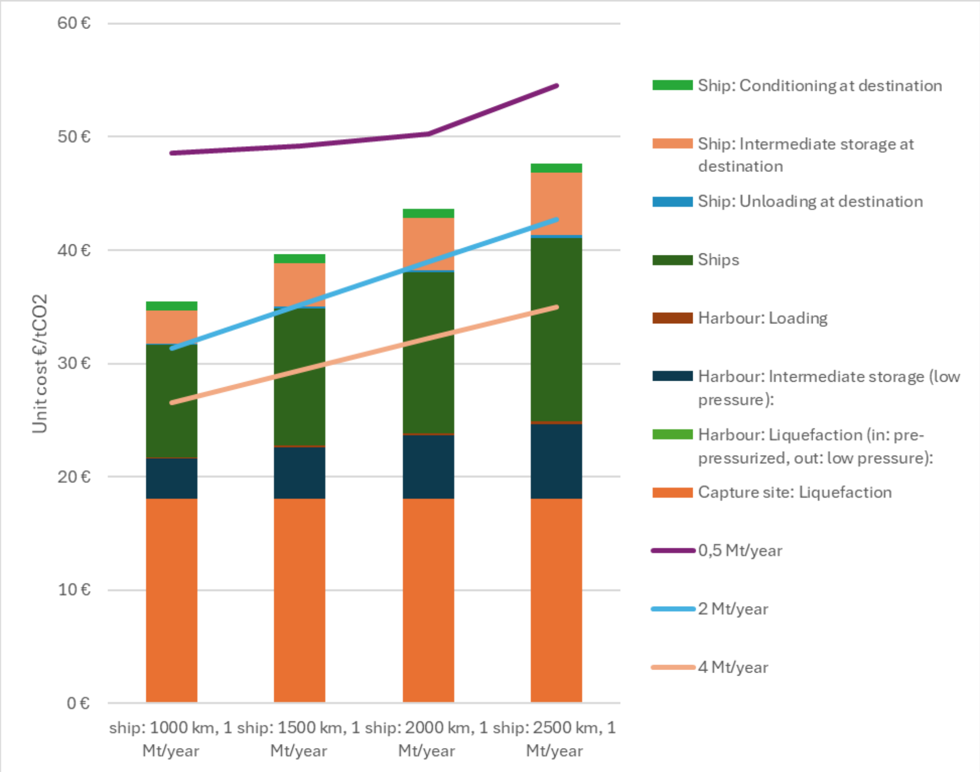

Figure 8. Ship transport costs of 0.5 to 4 $MtCO_2$/year over distance of 1000 to 2500 km. The stacked columns show transport cost breakdown for capacity of 1 $MtCO_2$/year.

3.4. Shared infrastructure brings cost benefits, and existing railways provide good coverage

The balanced Scenario A was used to compare the costs between road, rail and pipeline modes as default options. Assuming only road and ship transportation resulted in highest average costs across the hubs, 25–64 €/tCO_2. The baseline selection between the modes based on the availability of rails resulted in lowest costs, although results were close compared to pipeline network. Investment costs, when including compression, liquefaction, intermediate storages were lowest when road transport was assumed as default mode, although the order of magnitude was quite similar regardless of the assumed mode preference (€2.80–2.88 billion in storage hubs including ship transport and €1.33–1.54 billion in utilization hubs).

Utilizing the existing rail network appears cost-

efficient for CO_2 logistics. This is partly due to the need to liquefy CO_2 in all the examined scenarios.

Furthermore, the economic benefits of sharing CO_2 transport infrastructure was studied in the balanced scenario A. To do so, CO_2 transport costs were calculated for each facility from where the CO_2 is transported to geological storage assuming an independent transport system, and the costs were compared to baseline results in Scenario A, where shared infrastructure is assumed. When assessing the costs in the case of no shared infrastructure, the captured CO_2 was transported using the least expensive available method to the closest harbour for shipping to storage. The economic benefits from larger scale in shared transport infrastructure are considerable but facility specific, ranging from cost reduction of -2 % to -73 %. An average reduction of transport costs to geological storage for capture facilities in scenario A, due to shared infrastructure, was -30 %.

Expanding the transport network beyond the nine examined hubs could cover 80 % of industrial CO_2 sources, but it would increase the average transport costs up to 60 €/t.

There are different options how to allocate costs within a transport network. However, the extended Trunkline 2 scenario would theoretically enable maximum transport amounts if capture sites would pay transport rate based on weighted system average.

Authors

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Lauri Kujanpää is an energy concepts researcher interested in sustainable decision-making and policies. He has worked at VTT since 2008, specialising on novel energy and circular economy concepts, with CCUS as the main focus area. He is currently leading a research team on future energy and process concepts, with a focus on novel technologies for industrial decarbonisation, power-to-X and bioprocesses.

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Onni Linjala is a Research Scientist in VTT's Future energy and process concepts team. He has focused on analysing carbon capture technologies, identifying suitable carbon capture pathways for various industrial applications, evaluating techno-economic performance of CO_2 capture processes, and assessing CCUS policies. He holds background in energy conversion processes and power plant engineering.

Sampo Mäkikouri

Sampo Mäkikouri has nine years of expertise in the CCUS field. He has specialized in mineralization concepts including CO_2-cured concrete, artificial aggregates, industrial by-product and waste utilization and CO_2 storage. He is a proud co-inventor of VTT's award-winning carbon-negative concrete technology (EARTO, 2022), a project manager and a communicator, who has also organized workshops and media events together with companies, municipalities and politicians.

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