Investigating costs and emissions for several different logistic chains in the CO2LOS IV project

Introduction

Achieving large-scale deployment of Carbon Capture and Storage (CCS) is widely recognised as essential for reaching net-zero greenhouse gas emissions. While pipeline transport has traditionally dominated CO_2 transport for industrial applications, emerging CCS value chains increasingly involve distributed emission sources, phased capacity build-up, and cross-border transport requirements. Under such conditions, ship-based CO_2 transport offers flexibility advantages and may reduce investment risk. The CO_2LOS IV Joint Industry Project (2024–2026), led by Brevik Engineering AS and SINTEF was initiated to expand the technical, economic, and environmental knowledge base for ship-based CO_2 transport. The project builds on earlier phases of the CO_2LOS project and focuses on realistic CCS transport cases reflecting announced industrial developments in Europe and Asia. Four case studies were analysed:

(1) Transport from multiple Baltic capture sites to offshore storage in the Norwegian North Sea;
(2) A dual-cargo concept combining CO_2 and bulk aggregates;
(3) Long-distance intercontinental transport from Japan to Indonesia;
(4) Comparison of co-loading and single-loading vessel concepts.

The objective was to quantify cost competitiveness, emission performance, and technical feasibility of ship-based CO_2 transport under realistic boundary conditions.

Methodology

A transport cost and emission assessment tool developed in previous CO_2LOS phases was expanded to include life-cycle emission data and applied consistently across all cases.
The model calculates:

- Capital expenditure (CAPEX)
- Operating expenditure (OPEX)
- Levelized transport cost (LC)
- Life-cycle CO_2-equivalent emissions

Levelized cost is defined as:
LC = (CAPEX annuity + annual OPEX) / annual transported CO_2
The tool allows modelling of up to three transport stages (pipeline and/or ship) and includes terminal and conditioning modules. For shipping cases, both low-pressure (LP, ~6.5 barg) and medium-pressure (MP, ~15 barg) transport were assessed. Life-cycle emissions include construction, ship operation, terminal operation, and conditioning energy consumption. Electricity carbon intensity is treated as a key sensitivity parameter. The tool gives both cost and emission data for each transport module and can handle transport routes with up to 3 transport stages. The dashboard looks like this (dummy numbers):

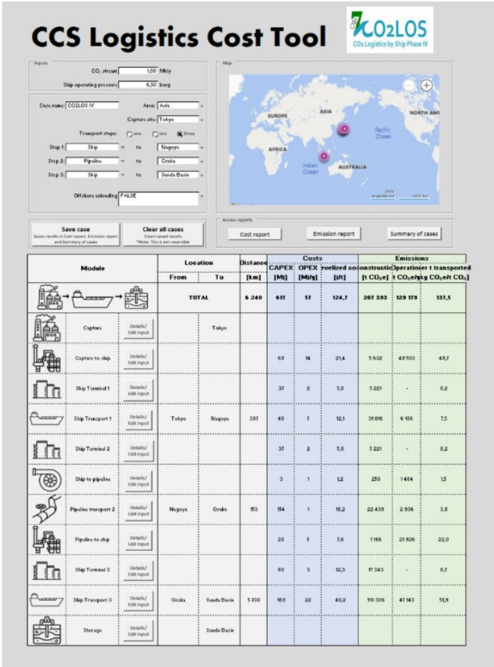

Figure 1*: CO2los IV cost tool dashboard*

Results and Discussion
Below are short descriptions and findings from the four cases that have been analysed.

<u>Baltic Multi-Source Case</u>
The European case considered 3.0 Mt/y aggregated CO_2 from Poland and Sweden via a hub in Gdansk to offshore storage in the Norwegian North Sea. Sixteen transport configurations were screened. Results confirm that pipelines are generally more cost-effective at short transport distances. For base assumptions, the cost crossover between pipeline and ship transport occurs at approximately 200 km. When assuming lower discount rates and longer lifetimes for pipelines, this crossover point may shift toward 400 km. A general overview of emitters, ship and pipeline transport route alternatives, hubs and storage site is shown in Figure 1.

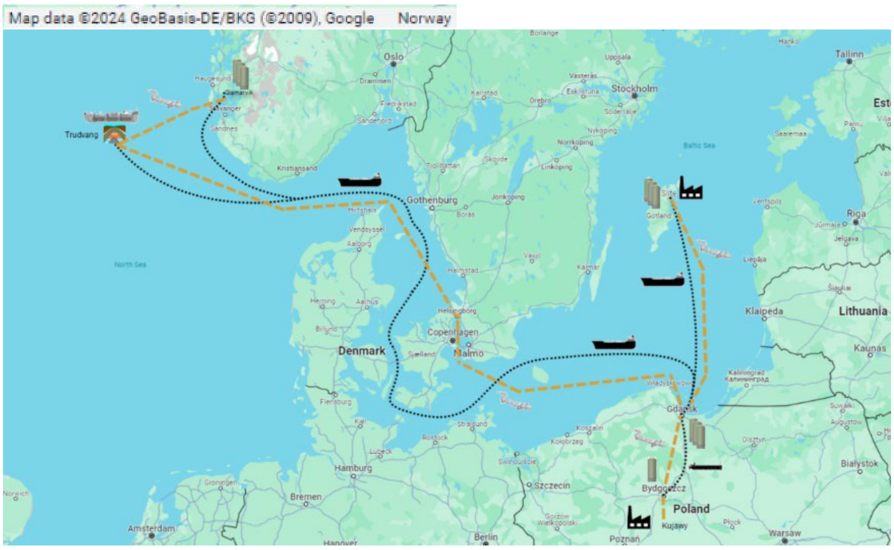

Figure 1 *Case overview, screening alternatives for the Baltic Multi-Source Case*

Low-pressure shipping was approximately 20% less costly than medium-pressure shipping for the investigated configurations. The levelized cost varies between 78 €/t to 148 €/t, and the most economic favourable scenario is pipeline transport from the Polish plant to Gdansk and ship transport from the plant in Sweden to Gdansk, followed by ship transport with direct injection in the North Sea.

Dual-Cargo Concept
Return cargo or dual cargo concept can be accommodated by two types of ship design:
1. A multigas carrier using the same cargo system for different products.
2. Separate cargo systems for CO_2 and alternative cargoes.
The dual-cargo concept the project has evaluated is a combined CO_2 transport (Germany–Norway) with bulk aggregate transport on the return leg to reduce ballast sailing. Although the dual-cargo vessel showed approximately 40% lower emissions per transported tonne due to elimination of empty return voyages, the levelized costs were nearly identical to the reference scenario using two specialised vessels. Higher CAPEX, lower technology readiness level (TRL), and increased operational complexity reduce its attractiveness despite emission benefits. It has proven difficult to find realistic, economical viable cases where return transport is used, as the CO_2 cargo tanks is kept pressurized and cold with small amounts of CO_2 at the return voyage. If these tanks are used for other gases/ liquids, the cleaning regime is severe and may take several days.

Long-Distance Japan–Indonesia Case
The intercontinental case evaluated a 5,700 km shipping route with volumes of 1, 3, and 6 Mt/y from a port in Japan to Storage in Indonesia. The analysis shows that low-pressure (LP) transport at approximately 6.5 barg provides the most cost-effective operating condition for the long-distance shipping case. An average sailing speed of around 12 knots was identified as the optimal balance between transport cost and fuel-related emissions, offering a favorable trade-off between voyage duration and energy consumption. At this speed, the roundtrip time is approximately 22 days. Due to the long voyage distance and associated scheduling constraints, operation with multiple vessels is necessary to ensure reliability, maintain continuous CO_2 delivery, and optimize terminal storage capacity. Full-chain levelized costs decrease significantly with scale:

- ~112 EUR/t at 1 Mt/y
- ~88 EUR/t at 3 Mt/y
- ~74–81 EUR/t at 6 Mt/y

Economies of scale play a significant role in capital-intensive transport systems, with unit costs decreasing markedly as capacity increases. However, uncertainties remain concerning impurity behavior in the CO_2 stream and the achievable holding time during low-pressure (LP) voyages, particularly for extended transport distances.

Co-Loading vs Single-Loading
Co-loading vessels serve multiple export terminals per roundtrip, whereas single-loading assigns one vessel per terminal, See figure 2.

***Figure 2**: Co-loading (left) and Single loading (right)*

Co-loading vessels are larger than single-loading vessels, as they must serve multiple export terminals on a single roundtrip. The number of vessels, vessel size, and terminal storage capacity influence both capital expenditures (CAPEX) and operating expenditures (OPEX). Across all cases, the difference in levelized cost (LC) between co-loading and single loading is relatively small, ranging from –14% to +2%, indicating that neither concept is clearly superior based on cost alone. In general, CAPEX is higher for co-loading scenarios, while OPEX is lower, and these opposing effects largely offset each other, resulting in modest differences in levelized cost. Operational complexity and scheduling risks may favour single-loading in practice.

Life-Cycle Emissions for the cases
Overall emissions from the transport chains are relatively low — around 30–40 kg CO_2e per ton of CO_2 transported, with 10–30% attributable to construction. This means the life cycle carbon footprint of the transport chains becomes negative in a matter of months, highlighting CCS's potential as an effective emissions-reduction tool. The majority of emissions stem from the liquefaction or compression processes upstream of the transport leg. These emissions depend on the carbon intensity of the electric power consumed. The analysis uses a carbon intensity of 0.250 kg CO2e/kWh, representing the average carbon intensity of electric power in Europe's six largest economies in 2023. The key finding of the analysis is the impact of the carbon intensity of power, and that is highlighted with the huge difference in emissions based on the carbon intensity of Poland vs Sweden in the Baltic Multi source case.

Conclusions

The CO_2LOS IV demonstrate that ship-based CO_2 transport is both technically feasible and economically competitive across a broad range of realistic CCS deployment scenarios. The results confirm that pipelines remain the most cost-effective solution for short-distance, stable, and high-volume transport routes where long operational lifetimes and favourable financing conditions can be assumed. However, as transport distances increase, typically beyond approximately 200–400 km, depending on economic assumptions and project lifetimes, ship-based solutions become increasingly competitive.

The study further shows that economies of scale play a decisive role in reducing full-chain CCS costs, particularly in capital-intensive systems. Increasing annual transport volumes leads to substantial reductions in unit costs, strengthening the business case for coordinated infrastructure development. In terms of environmental performance, transport-related emissions represent only a small fraction of the total amount of CO_2 permanently stored, confirming that shipping does not materially undermine the climate mitigation effect of CCS.

At the same time, cost metrics alone are insufficient for infrastructure planning. Operational complexity, scheduling flexibility, system integration, and technology readiness must also be carefully considered when selecting transport solutions. Overall, ship-based CO_2 transport should not be viewed merely as an alternative to pipelines, but as a necessary complement that enables international, flexible, and scalable CCS value chains, particularly in early-phase developments and cross-border applications.

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