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CO2 Logistics by Ship Phase IV

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CO_2LOS IV- Final public report

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Contents

1 SUMMARY

This report presents the public findings from the CO_2LOS IV project, a Joint Industry Project conducted in 2024–2025 by Brevik Engineering and SINTEF in collaboration with the following partners: ABS, BP, Equinor, ExxonMobil, Gassco, Mitsubishi Heavy Industries, Mitsubishi Corporation, Mitsui O.S.K Lines, Imodco, and TotalEnergies. The project was funded by CLIMIT and the partners and aimed to expand the knowledge for ship-based CO_2 transport as part of future Carbon Capture and Storage (CCS) solutions. CCS is recognized as a key technology for achieving net-zero emissions by 2050, and while pipelines have traditionally been the preferred transport method, shipping offers a flexible alternative for long distances and smaller volumes. Estimation of cost and emissions for both pipeline and ship scenarios, and also combinations of those, gives valuable insight into the possibilities for CO_2 logistics.

This report describes four realistic case studies: transport from multiple sources to storage in the North Sea, a return cargo concept combining CO_2 and stone aggregates, long-distance transport from Japan to Indonesia, and a comparison of co-loading versus single-loading strategies. It also introduces a cost tool developed to estimate both costs and emissions for different transport configurations. The analysis confirms that pipelines are generally more cost-effective for short distances, while ships become competitive over longer distances. Life-cycle assessments show that emissions from transport are relatively low compared to the amount of CO_2 captured and become net-negative within a few months.

In addition to economic evaluations, the report addresses technical challenges such as boil-off calculations, material selection for low-temperature operations, and corrosion protection for CO_2 tanks. The findings underline that ship transport is a viable and flexible solution for CCS, though operational complexity and technology readiness must be considered. Overall, the report provides a comprehensive overview of technical, economic, and environmental aspects of ship-based CO_2 transport and identifies key areas for further development.

This public report gives selected results from all the work packages. Some of the results, and access to the developed cost tool, are restricted and for the partners only.

2 INTRODUCTION

The International Energy Agency (IEA) identifies Carbon Capture and Storage (CCS) as a key technology in pathways towards net-zero CO_2 emissions by 2050 (NZE), aimed at limiting global temperature rise. Achieving this target will require large-scale logistics systems. To date, CO_2 transport for CCS and CCU has mainly relied on pipelines, while ship-based transport represents an alternative where pipelines are not cost-effective due to distance, volume, or depreciation period. Although ship transport of food-grade CO_2 has been practiced for decades, the transported volumes are small compared to those envisaged for future CCS projects.

The scope of the CO_2LOS IV (CO2 Logistics by Ship Phase IV) project is to further increase the knowledge base for future ship-based CCS projects logistics operations. The project is a continuation of the CO_2LOS II +III project and utilises relevant results from these projects. The CO_2LOS IV project started in May 2024 with a duration of approximately 1.5 years. This document is the public version of the final report documenting the CO_2LOS IV project. The report summarizes the non-confidential parts of the work performed. Below is an overview of the work pages in the project:

WP1 - Detail description of the cases in WP 3-6
WP2 - Cost tool expansion with emission data (ref. the cost tool from CO_2LOS III)
WP3 - Case 1 Europe case with multiple sources and storage in the North Sea
WP4 - Case 2 Return cargo case
WP5 - Case 3 Long distance case Japan to storage in Indonesia
WP6 - Case 4 Co-loading
WP 7- BOG calculations (ABS)
WP 8 Painting and Cladding (ABS)
WP 9- Material selection (ABS)

This report starts with a brief overview of the selected cases, and a description of the CO_2LOS cost tool that is used to estimate the cost and emissions for the cases. This report also gives a summary of the work performed by ABS regarding Boil off gas calculation, Liquid CO_2 Tank Internal Coating or Cladding and material selection for low temperature CO_2 transport.

3 CASE SELECTION

The purpose of the CO_2LOS IV project is to do techno-economic studies of "real" CO_2 transport cases. "Real" means cases that are realistic and probable based on announced plans for CCS-projects. Four generic cases were selected and studied in detail. The cases were chosen based on workshops and discussions among the partners, and also learnings from CO_2LOS II and III. The cases are presented briefly below.

Case 1: Europe case with multiple sources and storage in the North Sea

This case involves the transport of CO_2 captured at two cement plants to a CO_2 hub at the port of Gdansk, Poland. The first capture plant is located at Holcim's cement factory in Kujawy, approximately 170 km south of Gdansk. The second capture plant is at Heidelberg's cement factory in Slite, on the island of Gotland, Sweden. From Gdansk, the CO_2 is transported by ship or pipeline to storage at the Trudvang field in the Norwegian sector of the North Sea. This transport scenario was chosen due to the Baltics' potential as a promising market for ship-based CO_2 transport. Additionally, the capture projects at these cement factories are funded by the EU and have outlined plans for shipping CO_2 to the North Sea.

Case 2: Return Cargo Case

Finding a "real" case where the cargo in the tanks could be switched proved challenging. The difficulty arises because time needed for cleaning of the tanks and as such costs when switching cargoes likely makes it difficult to compete with specialized vessels. As a result, the project decided to focus on a ship design with two separate cargo systems to avoid these switching costs. The selected case involves transport of aggregates and CO_2 between ports in the North Sea region.

Case 3: Long distance case Japan to storage in Indonesia

In 2023, the Japanese government funded seven CCS projects, two of which include plans to ship CO_2 to storage sites in Southeast Asia. Meanwhile, Indonesia is also developing CCS projects, some of which are considering the import of CO_2 for storage. These "real" projects serve as references for a case study focused on the technical challenges of long-distance CO_2 transport in warm ambient temperatures.

Case 4: Co- loading

Case 4 was defined to be a comparison between co-loading ship (CL) transport and single loading (SL) ship transport. Co-loading ship transport means that one ship supports more than one export terminal during a round trip, while single loading ships support only one export terminal each. The illustration below shows the principal differences between Co-loading (left) and Single loading (right). Here with one ship supporting 3 export terminals (CL) and 3 smaller ships supporting the same sites (SL).

Figure 1: Co-loading (left) and Single loading (right)

4 COST TOOL DESCRIPTION/DEVELOPMENT

This chapter presents the development and application of the CO_2LOS transport cost and emission tool , which was originally developed in an earlier phase of the CO_2LOS project completed in May 2023. The tool is presented by the analysis of three generic test cases:

(A) comparison of pipeline and ship transport as a function of distance,
(B) comparison of low-pressure (LP) and medium-pressure (MP) ship transport as a function of distance,
(C) comparison of single-ship and two-ship transport configurations as a function of distance.

In all cases, the annual CO_2 mass flow is fixed at 1.0 Mtpa, while transport distance varies between 100 and 1000 km. For ship transport, LP cargo pressure is set to 6.5 barg and MP cargo pressure to 15 barg. These assumptions are representative of expected mass flows and transport distances for first-generation CCS projects in Europe.

Results from Case A show that ship transport has lower capital expenditure (CAPEX) than pipeline transport, while pipeline transport has lower operating expenditure (OPEX).

Table 1 Pipeline vs. ship transport data at 500 km

Pipeline vs ship transport 500 km	CAPEX [M€]		OPEX [M€/y]		Levelized cost [€/t]	
Transport chain modules	Pipeline	Ship	Pipeline	Ship	Pipeline	Ship
capture to pipeline	51	-	12	-	18	-
pipeline transport 1	540	-	3	-	66	-
capture to ship	-	69	-	14	-	22
ship terminal 1	-	37	-	2	-	6
ship transport 1	-	47	-	8	-	13
ship terminal 2	-	37	-	2	-	6
ship to pipeline	-	3	-	1	-	1
sum	591	193	15	26	85	48
Ship net cargo capacity in 500km case	[m3]	9 350				

This project is co funded by CLIMIT. CLIMIT Project No. 623405

The levelized cost (LC) is calculated as (CAPEX annuity + OPEX/year)/(CO2 mass flow per year). LC is a measure to compare the cost of transport by pipeline and ship over the lifetime of the project. In the test cases presented here, LC is calculated with a real discount rate of 10% and an economic lifetime of 20 years. These values were chosen based on input from a CCS project owner who specified them for their project. What the appropriate values are for other CO2 transport projects is up to the project owners or investors to decide. There is no inflation rate factored into these calculations.

The graph below shows that the pipeline case has lower levelized costs for transport distances up to about 200 km. This finding aligns with the prevailing understanding within the industry that pipelines are generally more cost-effective than ship transport for shorter distances. At this point, it would be appropriate to explore how the levelized cost changes as a function of discount rate and economic lifetime. A reduction in the discount rate reduces the levelized cost. An increase in the economic lifetime also reduces the levelized cost. It's a reasonable assumption that pipelines have lower operational risks and a longer economic lifetime than ships. If the discount rate is reduced to 5% for the pipeline, and the economic lifetime is increased to 50 years, then the levelized cost for pipeline is reduced by 30-50%, moving the crossing point up to about 400km.

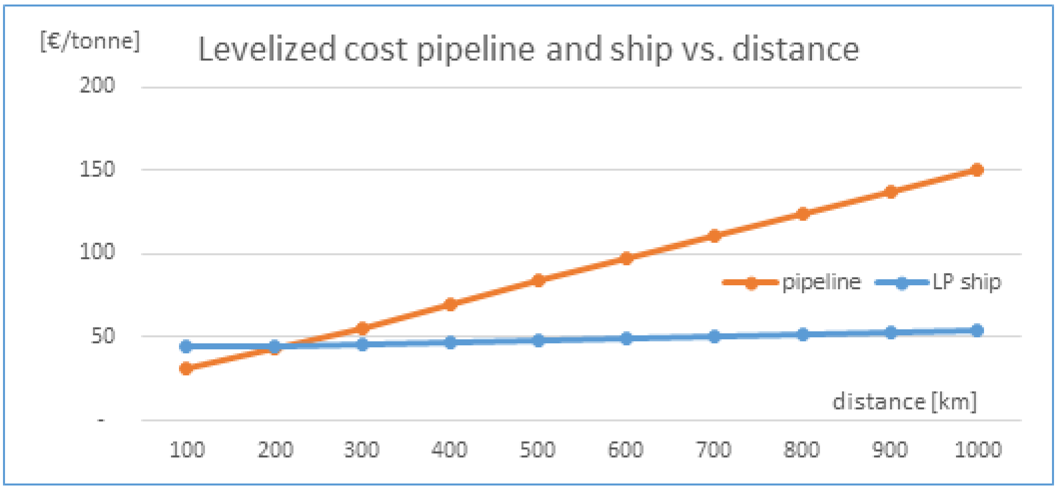


Figure 2 Levelized costs for pipeline vs. ship transport

This finding is consistent with established industry understanding and previous research.

Case B concludes that LP ship transport has lower CAPEX than MP transport, while OPEX differences vary with distance. For distances below approximately 500 km, MP transport has lower OPEX due to reduced liquefaction energy requirements. At longer distances, lower fuel consumption for LP transport outweighs this advantage. Overall, LP transport results in lower levelized costs, with the cost difference increasing with distance. LCA results indicate similar total life cycle CO_2e emissions for LP and MP scenarios, as lower operational emissions for MP transport are offset by higher construction-related emissions.

Case C compares single-ship and two-ship transport configurations. The two-ship scenario shows lower CAPEX due to reduced terminal storage requirements, while OPEX is higher than for the single-ship case, though less than double. As a result, levelized costs for the two configurations are very similar across all distances. LCA results likewise show comparable total emissions, as lower terminal construction emissions in the two-ship scenario offset the additional emissions from constructing an extra vessel.

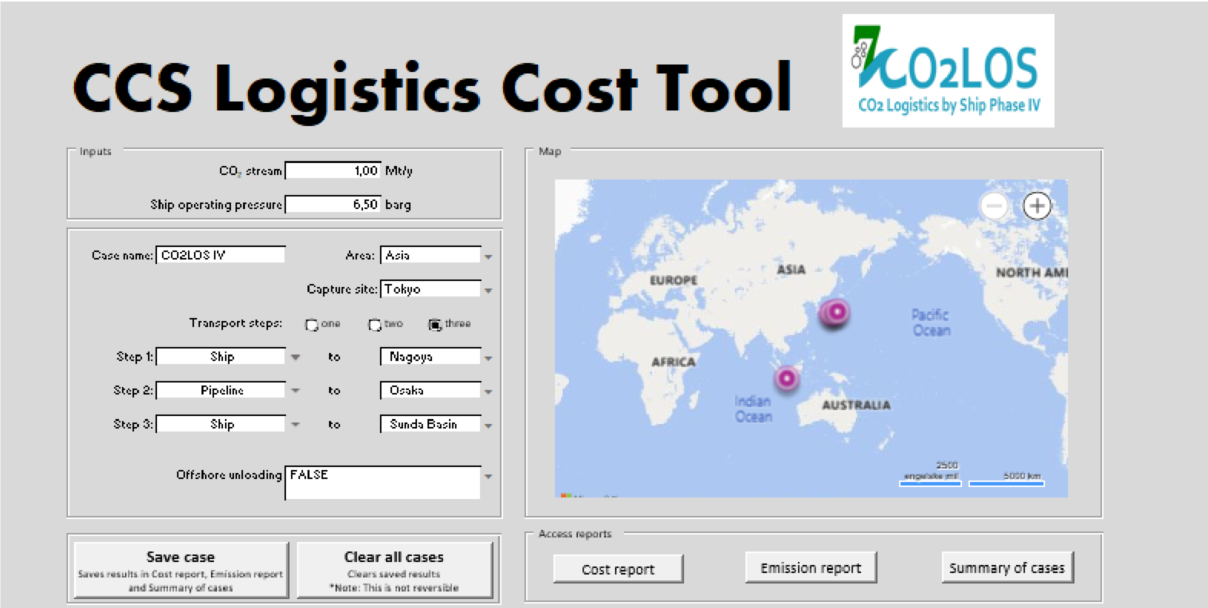
This project is co funded by CLIMIT. CLIMIT Project No. 623405

Overall, the cost application produces high-level, unclassified cost estimates whose accuracy depends on the quality of input data. The application nevertheless provides a consistent framework for comparing transport concepts and examining sensitivities related to distance, pressure level, ship configuration, discount rate, and economic lifetime.

The results confirm that pipelines are generally more cost-effective for short transport distances, while ship transport becomes competitive at longer distances. Sensitivity analyses indicate that assumptions regarding discount rate and project lifetime can significantly influence the relative cost performance of pipeline and ship transport, highlight the importance of project-specific financial parameters when applying the cost application in practice.

The assessment of life cycle CO_2e emissions in Case A shows that emissions from the construction of the transport chains are in the range of 50–80 and 15–200 ktonnes for the ship and pipeline transport chains, respectively. Overall emissions from the transport chain 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 CO_2e/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, as shown by the huge difference in emissions based on the carbon intensity of Poland vs Sweden.

The tool gives both cost and emission data for each transport module and can handle transport routes with up to 3 transport stages. The front page looks like this (dummy numbers):



Module		Location From	Location To	Distance [km]	Costs CAPEX [MI]	Costs OPEX [MI/y]	Costs evelized co [I/t]	Emissions onstructio [t CO_2e]	Emissions Operatio [t CO_2e/y]	Emissions er t transported [kg CO_2e/t CO_2]
TOTAL				6 240	617	57	124,7	207 393	129 179	137,5
Capture	Details/ Edit Input		Tokyo							
Capture to ship	Details/ Edit Input				63	14	21,4	5 632	49 503	49,7
Ship Terminal 1	Details/ Edit Input				37	2	5,8	5 221	-	0,2
Ship Transport 1	Details/ Edit Input	Tokyo	Nagoya	387	48	7	12,1	31 816	6 186	7,5
Ship Terminal 2	Details/ Edit Input				37	2	5,8	5 221	-	0,2
Ship to pipeline	Details/ Edit Input				3	1	1,2	250	1 484	1,5
Pipeline transport 2	Details/ Edit Input	Nagoya	Osaka	153	154	1	18,2	22 439	2 936	3,8
Pipeline to ship	Details/ Edit Input				20	5	7,6	1 166	21 926	22,0
Ship Terminal 3	Details/ Edit Input				80	3	12,3	17 343	-	0,7
Ship Transport 3	Details/ Edit Input	Osaka	Sunda Basin	5 700	169	22	40,2	118 306	47 143	51,9
Storage	Details/ Edit Input		Sunda Basin							

Figure 3 Cost tool front page

5 CASE 1: TRANSPORT FROM MULTIPLE SOURCES AND STORAGE IN THE NORTH SEA

This case describes a structured, phased approach on developing a solution for the transportation of CO_2 captured at two cement plants in the Baltic Sea region. The case involves CO_2 capture at Holcim's cement plant in Kujawy, Poland, and Heidelberg's cement plant in Slite, Sweden. CO_2 is transported from these sites to the Trudvang storage field in the Norwegian sector of the North Sea via a common hub in Gdansk, Poland. The transport scenario was chosen due to the Baltics' potential as a promising market for ship-based CO_2 transport. Additionally, the capture projects at these cement plants are funded by the EU and have outlined plans for shipping CO_2 to the North Sea. Also, the Gdansk hub and the Trudvang storage have ongoing plans for CCS. The work in this case consists of 4 phases:

1. Developing a design basis for the screening of different transport scenarios
2. Screening of transport options with the CO_2LOS cost tool and concluding with one scenario
3. Further refinement of the selected scenario and engineering of one selected item
4. Document findings and areas of improvement experienced from use of the CO_2LOS cost tool

A general overview of emitters, ship and pipeline transport route alternatives, hubs and storage site is shown in Figure 4.

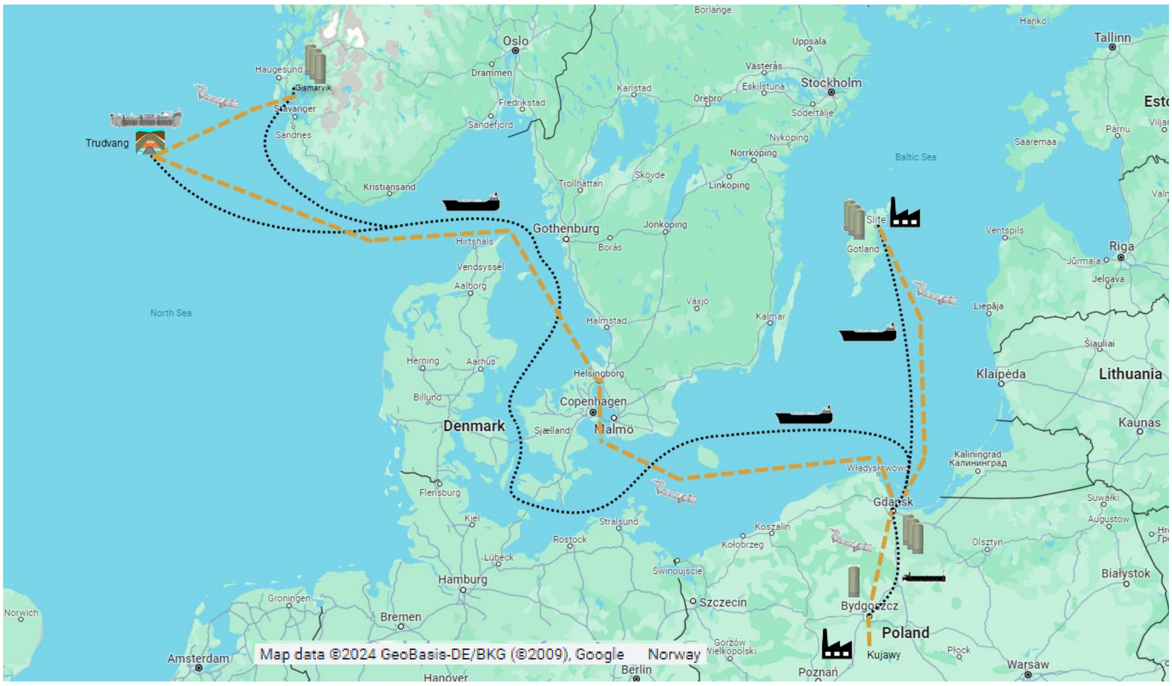


Figure 4 Case overview, screening alternatives

The following volumes is considered:

- 1.2 Mt/y of CO_2 captured at Kujawy and transported to Gdansk.
- 1.8 Mt/y of CO_2 captured at Slite and transported to Gdansk.
- Aggregated 3.0 Mt/y of CO_2 from Gdansk to Trudvang for injection and storage.

This phase presents cost tool estimates of ship and pipeline transport scenarios. In total 16 screening cases are analysed to cover the transport route alternatives and offloading options. Currently the tool does not support multiple capture locations, nor changing transport volumes along the transport chain. This is accommodated by splitting the 16 cases into sub cases solvable within the limitations of the program. Ships and pipelines are considered for the transport scenarios.

Table 2 Transport scenarios

Scenario	Pipeline from Kujawy to Bydgoszcz	Inland vessel from Bydgoszcz to Gdansk	Pipeline from Kujawy to Gdansk	Ship from Slite to Gdansk	Pipeline from Slite to Gdansk	Ship from Gdansk to Gismarvik terminal	Pipeline from Gismarvik to Trudvang	Pipeline from Gdansk to Trudvang	Ship from Gdansk to FSI at Trudvang	Ship from Gdansk with direct injection at Trudvang
1	x	x		x		x	x			
2			x	x		x	x			
3	x	x			x	x	x			
4			x		x	x	x			
5	x	x		x				x		
6			x	x				x		
7	x	x			x			x		
8			x		x			x		
9	x	x		x					x	
10			x	x					x	
11	x	x			x				x	
12			x		x				x	
13	x	x		x						x
14			x	x						x
15	x	x			x					x
16			x		x					x

Levelized cost of each scenario with a real discount rate of 10% and 25-years discounting period has been calculated. Tabular results are shown in Table 3 and Figure 5.

Tale 3 Levelized cost LP and MP

Scenario	Pipeline from Kujawy to Bydgoszcz	Inland vessel from Bydgoszcz to Gdansk	Pipeline from Kujawy to Gdansk	Ship from Slite to Gdansk	Pipeline from Slite to Gdansk	Ship from Gdansk to Gismarvik terminal	Pipeline from Gismarvik to Trudvang	Pipeline from Gdansk to Trudvang	Ship from Gdansk to FSI at Trudvang	Ship from Gdansk with direct injection at Trudvang	LP CAPEX [M€]	LP OPEX [M€]	LP Levelized cost [€/tonne]	MP CAPEX [M€]	MP OPEX [M€]	MP Levelized cost [€/tonne]
1	x	x		x		x	x				1116.7	140.8	87.9	1465.0	149.9	103.8
2			x	x		x	x				1209.5	128.9	87.4	1541.6	135.2	101.7
3	x	x			x	x	x				1489.3	148.1	104.1	1792.2	148.5	115.3
4			x		x	x	x				1582.1	136.2	103.5	1868.8	133.8	113.2
5	x	x		x				x			2762.0	121.8	142.0	2815.5	122.8	144.3
6			x	x				x			2812.5	95.7	135.2	2852.2	98.0	137.4
7	x	x			x			x			3058.2	107.1	148.0	3072.0	105.8	148.1
8			x		x			x			3108.7	81.0	141.2	3108.7	81.0	141.2
9	x	x		x					x		930.3	138.7	80.4	1368.1	145.7	98.8
10			x	x					x		1023.1	126.8	79.8	1444.7	131.0	96.7
11	x	x			x				x		1302.9	146.0	96.5	1695.3	144.3	110.4
12			x		x				x		1395.7	134.1	96.0	1771.9	129.6	108.3
13	x	x		x						x	880.2	139.0	78.7	1236.7	145.6	93.9
14			x	x						x	973.0	127.1	78.1	1313.3	130.9	91.9
15	x	x			x					x	1252.8	146.3	94.8	1563.9	144.2	105.5
16			x		x					x	1345.6	134.4	94.2	1640.5	129.5	103.4

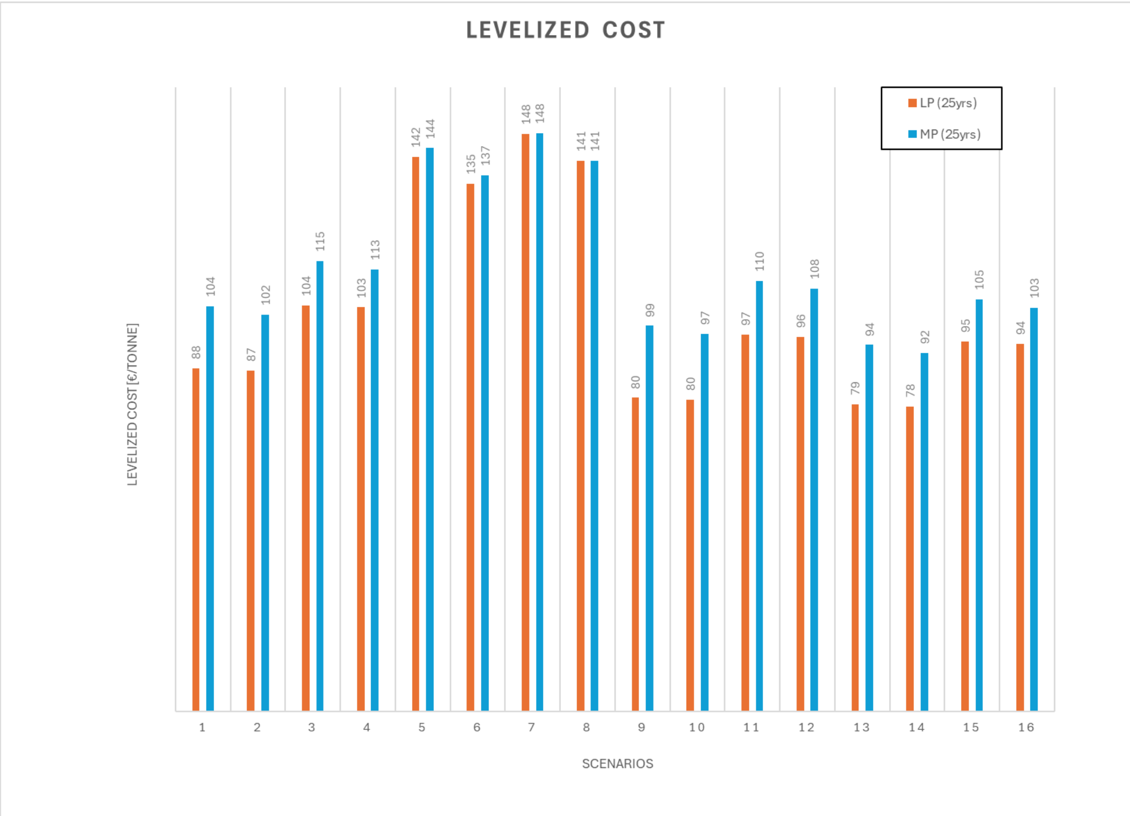


Figure 5 Levelized cost LP and MP

The levelized cost is the main criteria used when the logistic solution is selected. Also, other elements such as regularity, risk, and reliability are included in a decision table for the final evaluation. The decision table favours scenario 14 for both low pressure (LP) and medium pressure (MP). There are also other good candidates with high scores, such as scenario 2 and 13. However, for the further work on case 1, scenario 14 is selected.

Table 4 LP decision table

LP																		
Criteria	**Weight (1-5)**	**Scoring scheme**	**Scenario**															
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
CAPEX	3	Low = 2, Medium = 1, High = 0	1.79	1.70	1.45	1.37	0.31	0.27	0.05	0.00	1.96	1.87	1.62	1.54	2.00	1.92	1.67	1.58
OPEX/y	2	Low = 2, Medium = 1, High = 0	0.22	0.57	0.00	0.35	0.78	1.56	1.22	2.00	0.28	0.63	0.06	0.42	0.27	0.63	0.05	0.41
Levelized cost	10	Low = 2, Medium = 1, High = 0	1.72	1.73	1.26	1.27	0.17	0.37	0.00	0.20	1.93	1.95	1.47	1.49	1.98	2.00	1.52	1.54
Regularity	2	Low = 0, Medium = 1, High = 2	1.25	1.50	1.50	1.75	1.50	1.75	1.75	2.00	0.00	0.25	0.25	0.50	0.50	0.75	0.75	1.00
Risk	1	Low = 2, Medium = 1, High = 0	1.60	1.80	1.80	2.00	1.10	1.30	1.30	1.50	0.60	0.80	0.80	1.00	0.10	0.30	0.30	0.50
Flexibility	1	Low = 0, Medium = 1, High = 2	1.00	1.00	1.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	2.00	1.00	2.00	1.00
Total	**19**	**Weighted total score**	**1.48**	**1.55**	**1.20**	**1.21**	**0.49**	**0.70**	**0.39**	**0.60**	**1.44**	**1.51**	**1.11**	**1.18**	**1.55**	**1.57**	**1.27**	**1.29**

Table 5 MP decision table

MP																		
Criteria	**Weight (1-5)**	**Scoring scheme**	**Scenario**															
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
CAPEX	3	Low = 2, Medium = 1, High = 0	1.76	1.67	1.41	1.32	0.31	0.27	0.04	0.00	1.86	1.78	1.51	1.43	2.00	1.92	1.65	1.57
OPEX/y	2	Low = 2, Medium = 1, High = 0	0.00	0.43	0.04	0.47	0.79	1.51	1.28	2.00	0.12	0.55	0.16	0.59	0.12	0.55	0.17	0.59
Levelized cost	10	Low = 2, Medium = 1, High = 0	1.58	1.65	1.17	1.24	0.13	0.38	0.00	0.25	1.75	1.83	1.34	1.42	1.93	2.00	1.51	1.59
Regularity	2	Low = 0, Medium = 1, High = 2	1.25	1.50	1.50	1.75	1.50	1.75	1.75	2.00	0.00	0.25	0.25	0.50	0.50	0.75	0.75	1.00
Risk	1	Low = 2, Medium = 1, High = 0	1.80	2.00	1.80	2.00	1.30	1.50	1.30	1.50	0.80	1.00	0.80	1.00	0.30	0.50	0.30	0.50
Flexibility	1	Low = 0, Medium = 1, High = 2	1.00	1.00	1.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	2.00	1.00	2.00	1.00
Total	**19**	**Weighted total score**	**1.39**	**1.49**	**1.15**	**1.20**	**0.48**	**0.72**	**0.39**	**0.63**	**1.32**	**1.43**	**1.03**	**1.14**	**1.52**	**1.57**	**1.28**	**1.33**

It is seen that MP comes with a 20% increase in levelized cost compared to LP, hence scenario 14 with LP is the final selection.

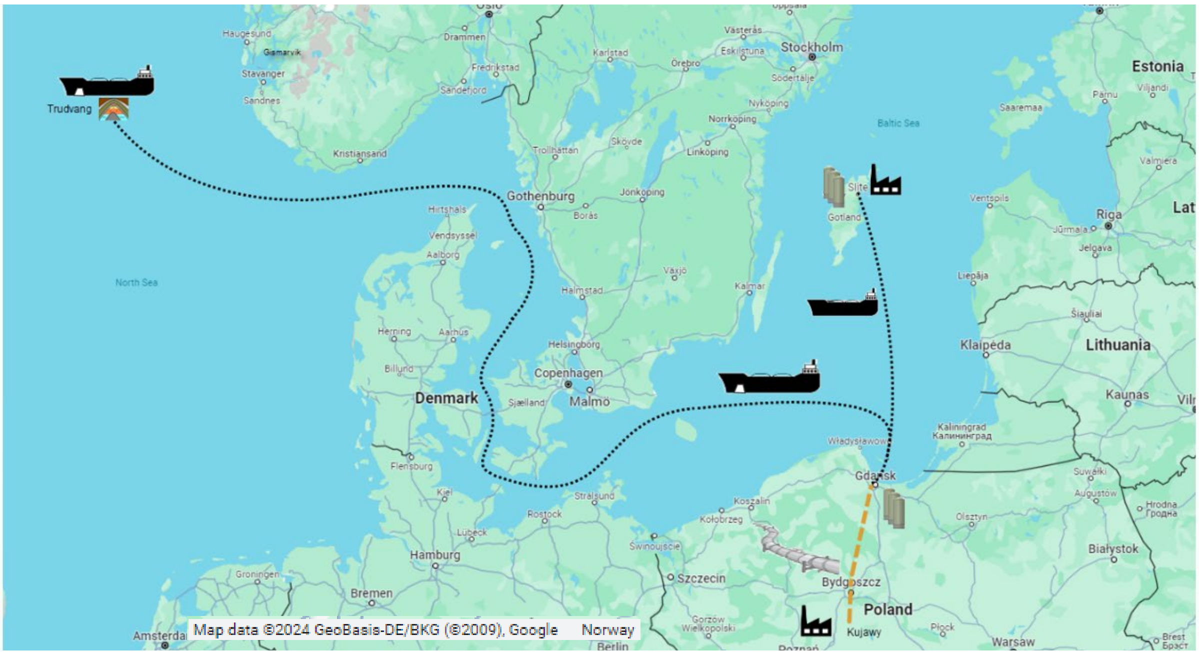


Figure 6 Logistics scenario 14

Based on a project internal poll, the CO_2 injection vessel was selected for further engineering.

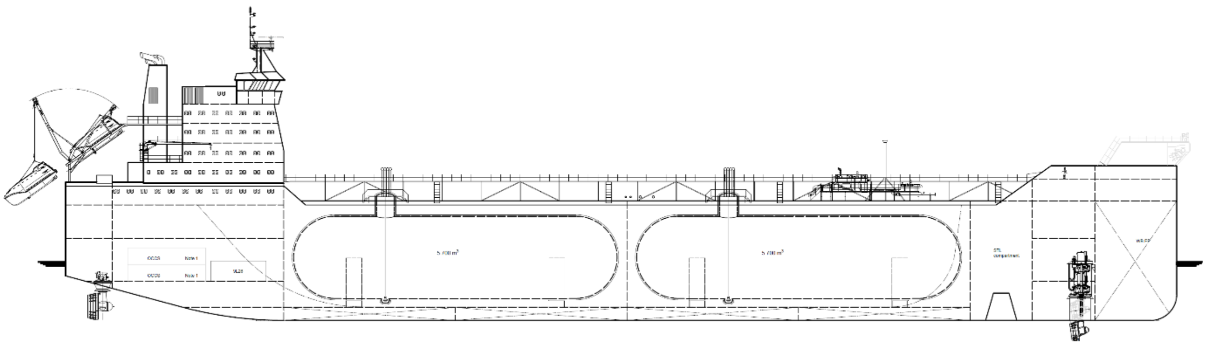


Figure 7 CO_2 injection vessel

This concept has been taken to a level where the following items are considered/developed, some with several iterations:

- Ship cargo capacity (from cost tool logistics calculations)
- Cargo tank shape and main scantlings
- Cargo block arrangement and main scantlings
- Longitudinal strength check
- Main particulars
- Hull shape and resistance
- Propulsive power requirements including Dynamic Positioning (DP)
- Operational profiles with electrical power consumers
- Propulsion and power generation

- Mooring and injection system
- Fuel selection
- Onboard Carbon Capture System (OCCS)
- Cargo system
- Brief outline specification
- General Arrangement drawing
- Structural cargo block drawings

Although considerable work has been performed, a substantial further engineering scope needs to be covered until the concept is developed to a stage where an Approval in Principle (AiP) or a full Class approval is achievable.

6 CASE 2: RETURN CARGO TRANSPORT

The concept of return cargo for CO_2 ships was investigated in one of the work packages in CO_2LOS II, with further elaboration proposed for CO_2LOS IV. Carrying return cargo can enhance earnings and reduce emissions per ton of cargo transported as there will be a shorter or no ballast voyage with no earnings. However, few compatible return cargoes for CO_2 have been identified. The ones found are propane, propylene and butane, according to the discussion in the first consortium meeting this would not be profitable. The primary reason is that the costs and risks associated with return cargo outweigh the potential increase in earnings. The main cost drivers include additional investment costs and the operational expenses of switching cargoes.

Return cargo 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.

In this context the cargo system is seen as:
Cargo tanks + all necessary piping used for the cargo + all necessary equipment needed for safe handling of the cargo.

The conclusion is that the second alternative with separate cargo systems for CO_2 and return cargo seems to be the most promising. The reasons for this are:

• Long cleaning time needed to change cargo when carrying the return cargo in the same cargo system. The time needed for cleaning has been estimated to 7 days.
• Few alternative cargoes which could be carried in the same cargo system have been identified as mentioned above.

The chosen case is transport of liquid CO_2 from the CO_2 hub in Wilhelmshaven to the CO_2 hub in Gismarvik and stone aggregates as return cargo from Jelsa, Dirdal or Tau to Germany's North Sea coast. This will be a ship with one dedicated cargo system for liquid CO_2 and one cargo system for bulk. One of the challenges for such a ship is that the design of the cargo system will have to follow two different codes, IGC for the CO_2 cargo system and IMSBC, for the bulk cargo. This case is chosen as the return cargo trade is already ongoing today and the planned CO_2 hub in Gismarvik is close to the quarries from where the stone aggregates are shipped and the planned CO_2 hub in Wilhelmshaven is close to where the stone aggregates are delivered.

The ship concept in this case is designed to carry CO_2 and bulk material in separate compartments. The trade involves transport of CO_2 from Germany across the North Sea to Norway for offloading and further transport to storage. The ship then sails to a nearby port to load aggregate (crushed stone). The ship then sails back to a port at Germany´s North Sea Coast and offloads the cargo.

The economic rationale for this concept and trade is to carry cargo both ways, as opposed to making the return voyage empty. In addition, ships carrying heavy cargoes such as crushed stone or CO_2 are designed with some "spare room" in the hull to create the required buoyancy. The draft of the ship is limited by port restrictions on draft. The idea is to take advantage of this extra space to create cargo holds for a second type of cargo. For the CO_2 transport, the concept has four cylindrical tanks in a row with a total cargo capacity of 16 900 tonnes. For the aggregates, the concept has bulk cargo holds on each side of the cargo tanks with a total capacity of 18 300 m^3.

The cost estimate is based on the longest sailing route: Wilhelmshaven – Gismarvik – Jelsa – Emden – Wilhelmshaven.

Table 6 Roundtrip sites and distances

Roundtrip sites and distances km	dual cargo	single cargo
Jelsa - Load aggregate	57	
Emden - unload aggregate	700	700
Wilhelmshaven - load CO2	150	
Gismarvik - unload CO2, return to Jelsa	700	700
sum	1607	1 400

The single cargo column shows distances used in a comparison of one dual cargo ship vs two single cargo ships as explained further below.

Figure 8 Dual cargo concept trade route

Table 7 CAPEX and OPEX sums and unit costs

CAPEX, OPEX and unit costs total estimates		Dual cargo		CO2 carrier	Bulk carrier	Sum
CAPEX						
ship	M€	105		47	49	96
terminal 1		51		41		41
terminal 2		51		41		41
CAPEX sum	M€	206		128	49	177
OPEX	M€/yr	13.2		10.6	7.6	18.2
Unit cost per tonne cargo	€/tonne	16.2		32.4	9.0	17.1

Estimated total costs for the two scenarios are shown in the table above. The costs of the single cargo CO_2 carrier and the bulk carrier is added for comparison with the dual cargo carrier. The comparison shows as expected that the dual cargo carrier has higher CAPEX and lower OPEX than the two carriers in the single cargo scenario. That's because the fewer annual roundtrips for the dual cargo ship requires relatively higher ship and terminal capacity than in the single cargo scenario. OPEX is higher in the single cargo scenario because it costs more to run two ships to carry the same annual cargo mass flow as in the single ship scenario.

The costs of the two scenarios are compared by calculating and comparing a levelized unit cost based on a real discount rate of 10% and 25 discount periods. The unit costs are almost the same for the two scenarios. The dual cargo concept has a lower TRL than the single cargo concept. In addition, there are operational and commercial risks outside the scope of this analysis which are higher for the dual cargo scenario. The conclusion of this preliminary cost analysis is that in this case, the dual cargo concept is not competitive. Even if the cost estimates in this analysis are very uncertain, it's hard to imagine that better cost data change so much in favour of the dual cargo scenario that it would change this conclusion.

Life-cycle emissions, however, favour the dual-cargo concept, with approximately 40% lower emissions per tonne of transported cargo, mainly due to avoiding empty return voyages. Despite this advantage, the dual-cargo solution's lower technology readiness level and operational complexity mean it cannot be considered competitive from a cost and risk perspective. The dual carrier has significantly lower emissions per tonne cargo transported than the two single carriers. Although the levelized cost has the same dynamics – lower cost for the dual carrier – the difference between the two options is very small. The small difference gives weight to the *low TRL* argument, meaning that the dual carrier option is unlikely to be selected. This shows the importance of including emissions in the early-phase assessments, as the cost tool now allows for. A 40% reduction in emissions was found for this case, and this could be an argument *for* selecting the dual carrier option.

7 CASE 3: CO_2 TRANSPORT FROM JAPAN TO INDONESIA

The purpose of this case study was to assess long distance transport of CO_2 in Asia. However, the generic approach makes it applicable to other regions. The specific cases study was centred around an emitter located at the Port of Nagoya in Japan. The import terminal, from which the CO_2 is foreseen transported via an offshore pipeline to permanent storage in the Sunda Basin, is located near Jakarta in Indonesia, 5 700 km away.

Figure 9 Case 3 overview, Google Maps ©

The initial Base Case transport volume was 1 Mt CO_2 per year. Assuming that CCS is gradually implemented, the CO_2 volumes will increase, and therefore ramp-up scenarios to 3 and then further to 6 Mt CO_2 annually was included.

The CCS Cost Tool developed in the CO_2LOS III and further refined in the current project phase was used for the parametric study. The goal of the parametric study was to identify suitable ship sizes that could transport 1, 3, and 6 Mt CO_2 annually from the export terminal at Nagoya Port in Japan to the import terminal near Jakarta, Indonesia. A constraint in the current study was the upper limit on ship sizes to 50 000 t. This was partly due to expected limitations in ship draft in Japanese ports and the approach that the ship sizes selected could be used for both the Base Case and the ramp-up scenarios. In addition, it was assumed that due to the roundtrip time, the operational risk is reduced if more than one ship is in operation. Based on the above assumptions on maximum ship size and CO_2 volumes a parametric study was undertaken to identify suitable operating condition, ship size(s), and sailing speed. The study identified LP at 6.5 barg as the most cost-effective operating pressure of the long-distance transport case, However, there are currently no CO_2 cargo ships in operation applying this operating condition. Another result was that a sailing speed of 12 kn gave a good trade-off between time used for roundtrip, cost, and CO_2 emissions due to fuel consumption. The duration of the roundtrip, assuming an average speed of 12 kn, was approximately 22 days. The parametric study also resulted in the selection of two ship sizes, 24 000 and 45 400 t. The full-chain cost from source to but not including permanent storage was then calculated for all scenarios, please note that the cost of permanent storage is not included. The overall technical and cost results are provided in the table below.

Table 8 The results of the economic assessment of the whole chain

	1 Mt		3 Mt		6 Mt	
Ship size	24000	45400	24000	45400	24000	45400
Operating condition	LP		LP		LP	
Sailing speed	12	12	12	12	12	12
No of ships	3	2	8	5	16	9
No of roundtrips per year per ship	14	12	16	14	16	15
Ship OPEX per ship M€/year	9.2	12.2	9.5	12.2	9.5	12.2
Ship CAPEX per ship, M€	81.7	133.5	81.7	134.5	81.8	134.5
Total ship OPEX. M€/year	27.7	24.3	76.0	60.8	152.1	109.70
Total Ship CAPEX, M€	245.2	267.0	653.9	672.5	1308.0	1210.5
Terminal OPEX cost export/import, M€/year	5.6	8.8	6.8	10	8.6	11.8
Terminal CAPEX cost export/import, M€	127.20	207.2	127.2	207.2	127.2	207.2
Levelised cost of ship transport, EUR/t	54.7	52.2	49.4	45.0	49.4	40.5
Levelised cost of terminals, EUR/t	19.6	33.3	7	11.0	3.8	5.8
Levelized cost of conditioning for transport, EUR/t	21.4	21.4	21.4	21.4	21.4	21.4
Levelized cost of conditioning for pipeline, EUR/t	1.2	1.2	1.2	1.2	1.2	1.2
Levelized cost of pipeline to storage, EUR/t	14.7	14.7	6.1	6.1	3.8	3.8
Levelized cost of onshore collection pipeline, EUR/t			2.6	2.6	1.5	1.5
Total levelized cost full-chain, EUR/tCO_2 transported	**111.6**	**122.8**	**87.7**	**87.3**	**81.1**	**74.2**

A general observation that can be made based on the results is that the total levelized chain costs decrease with increased CO_2 volume handled. This is expected and normally observed for CAPEX heavy systems as economies of scale comes into effect. Furthermore, it can also be observed that whether it is the alternative with the smaller or larger ship that is the most cost effective depends on the CO_2 volume handled. For the Base Case, 1 Mt annually, it is the smaller ship configuration that seems to be more cost efficient. For the 6 Mt annually ramp-up scenario, it is the larger ship configuration that results in the lowest cost. While, for the 3 Mt ramp-up scenario the different in cost between the two configurations are negligible. Here, the trade-off between the terminal and ship costs evens itself out.

For loaded voyages of up to ~11 days, boil-off is not a major concern. For unloaded voyages with a small heel (~3%), calculations are complex and excluded from this study. Mitigation options include increasing heel, designing tanks for higher pressure, or installing a small re-liquefaction unit.

The 5 700 km sailing distance at 12 knots results in a ~22-day roundtrip. Operating with the minimum number of ships would require very large intermediate storage and excess capacity to manage delays. While one large vessel could theoretically handle the Base Case (1 Mt/year), at least two ships are recommended for reliability. The calculated terminal costs for a single-vessel approach exceed the cost of an additional ship.

Impurity behaviour under LP conditions (~-50 °C) and long transport times is poorly understood, and no specifications currently exist for these conditions. Extended voyage duration (~22 days) may affect impurity behaviour and specification requirements.

8 CASE 4: CO-LOADING OR SINGLE LOADING

Four cases were analysed to compare co-loading (CL) and single loading (SL) transport concepts. As a starting point, a worst-case configuration for co-loading was assumed, in which the storage site or hub is located between two or more export terminals. The opposite situation — export terminals located relatively close to each other, with a long distance to the storage site — was also considered. The analysed cases include scenarios with three export terminals and two export terminals. In addition, two cases compare co-loading configurations using one versus two ships operating on the same roundtrip. Time spent in port was treated as a key variable, as it directly affects roundtrip duration and, consequently, ship size and intermediate terminal storage requirements.

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.

The results indicate a tendency for co-loading to be more favourable when the distance between the export terminals and the import terminal or storage site is large, leading to a higher SL-to-CL roundtrip distance ratio. However, the increased operational complexity associated with co-loading must also be considered. Given the simplified modelling approach and uncertainties in several input parameters, the results should be interpreted with caution.

The life cycle emissions assessment shows that ship operation is the dominant contributor to emissions, accounting for approximately 78–87% of total CO_2 emissions, while emissions related to ship construction are comparatively minor. From an emissions perspective, transport-related emissions represent only a small fraction (approximately 1.8–3.5%) of the total CO_2 volumes transported to permanent storage.

The analysis further shows that levelized costs increase with increased port time due to longer roundtrip durations and the resulting need for larger vessels to maintain annual transport capacity. This supports the cost tool's approach to ship sizing based on continuous operation without spare capacity, which generally produces cost-effective solutions under the assumed parameters. Cost sensitivities to port time and ship size are lower than anticipated. Co-loading scenarios exhibit greater CAPEX sensitivity than single-loading scenarios, mainly due to faster growth in roundtrip time as port time increases. While a single large vessel in a co-loading scenario typically has lower vessel OPEX than multiple smaller vessels in a single-loading scenario, the longer roundtrip times require larger terminal capacities, increasing terminal OPEX. These opposing cost drivers tend to balance each other, reducing overall cost sensitivity.

Finally, the analysis is subject to design constraints within the cost tool, and a simplified modelling approach was therefore applied, requiring minimal manual adjustments. Given the uncertainties in input values and the exclusion of operational and commercial risks—such as scheduling flexibility, port accessibility, and contractual complexity—firm conclusions should be avoided. In practice, such factors may favour single-loading solutions.

9 METHODOLOGY OF BOIL-OFF-RATE AND HOLDING TIME CALCULATION

This study develops a one-dimensional (1D) methodology for calculating Boil-off Rate (BOR) and equilibrium holding time of IMO Type C cargo tanks carrying liquefied CO_2 (LCO_2). The work forms CO_2LOS IV Work Package 7 and is intended to reduce uncertainty in CO_2 transport by ship through a consistent, practical calculation framework that can be used across different design stages.

The study addresses the following key objectives:

- Development of a heat-transfer analysis methodology for IMO Type C tanks installed onboard vessels
- Development of a methodology for BOR calculations for IMO Type C tanks
- Development of a methodology for equilibrium holding time calculations for IMO Type C tanks

The methodology provides a structured link from external conditions and tank configuration to heat ingress, BOR, and ultimately the holding time. The calculation framework is organized into four main steps: condition definition, heat transfer analysis, BOR calculation, and equilibrium holding time calculation.

Figure 10 Steps for BOR and Holding Time Calculation

- First, environmental and loading conditions are defined in accordance with IGC Code requirements and relevant ship draught conditions.
- Second, a heat transfer analysis is performed to determine total heat ingress into the cargo tank from ambient air and seawater.
- Third, this total heat ingress is combined with cargo properties to calculate the BOR.
- Finally, ISO 21014:2019 and CO_2 saturation data are used to determine the equilibrium holding time.

At the heart of the methodology is a 1D steady-state heat transfer model that accounts for conduction, convection, and radiation between the external environment and the tank. The study identifies three principal heat transfer pathways for IMO Type C tanks: heat transfer through the insulated tank surface, through the saddle/support structures, and through the dome/opening area. Total heat ingress is obtained by summing contributions from these pathways.

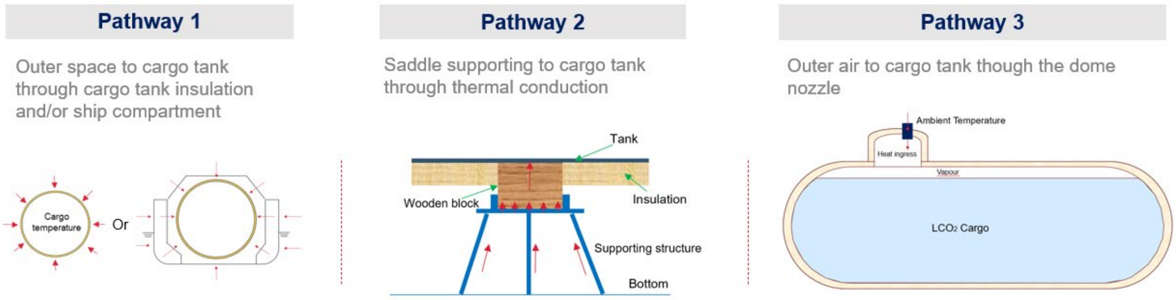


Figure 11 Heat Transfer Pathway

A key contribution of the study is the introduction of three levels of heat transfer methodology—simplified, detailed, and hybrid—each aligned with a different project phase and the available level of design detail. The simplified methodology assumes the tank is directly exposed to ambient air and considers only conduction, enabling rapid heat ingress estimates for concept design using minimal inputs such as tank dimensions, insulation properties, and basic geometric areas. The detailed methodology, recommended for detailed design, uses realistic cargo hold arrangements and includes all three pathways with conduction, convection, and radiation, but requires vessel-specific data such as hull structure, support geometry, and insulation layout. The hybrid methodology is tailored for basic design, combining elements of both to improve realism compared to the simplified approach while keeping data requirements low.

This methodology framework offers several advantages. It provides a unified, stepwise method that connects heat transfer analysis, BOR, and holding time in a way that is consistent with Classification Society rules and international standards, which supports comparability across projects and stakeholders. It offers a multi-fidelity structure so that concept, basic, and detailed design analyses can all be performed using the same underlying logic, avoiding discontinuities when moving from early screening to refined design.

10 LIQUID CARBON DIOXIDE (L CO_2) TANK INTERNAL COATING OR CLADDING

This chapter addresses corrosion risks associated with liquefied carbon dioxide (LCO_2) cargo tanks and evaluates internal surface protection measures, with a particular focus on protective coatings and corrosion-resistant alloy (CRA) cladding. The work was carried out as Work Package 8 (WP8) within the CO_2LOS IV project and aims to support safe, reliable, and cost-effective ship transport of LCO_2 under realistic operating conditions.

While dry CO_2 is not corrosive, the presence of water and impurities such as SO_2, NO_x, O_2, and H_2S can lead to the formation of acidic phases, significantly increasing corrosion rates in carbon-manganese steels commonly used for Type C cargo tanks. Laboratory data from the literature indicate that corrosion rates in liquid CO_2 can be substantially higher than in supercritical CO_2, even at low water contents (50–100 ppm). When impurities are present, calculated corrosion allowances for a 30-year design life can exceed those currently applied in marine tank design, indicating that corrosion may become a critical integrity and safety issue if not adequately mitigated.

The primary corrosion control strategy remains strict control of water content and impurities in the CO_2 stream. However, achieving very low impurity levels through purification and drying is technically challenging and costly. Consequently, this work evaluates alternative or complementary mitigation measures in the form of internal protective coatings and CRA cladding.

Protective epoxy-based coatings, particularly phenolic-modified epoxy systems, can provide a corrosion barrier if properly selected, applied, and qualified. The work in this WP has included coating procedures, inspection requirements, and qualification testing to address risks related to low-temperature brittleness, thermal and pressure cycling, permeation, and adhesion loss. While coatings may be viable, their long-term performance in large Type C tanks and practical application in shipyard environments remain areas of uncertainty.

CRA cladding is identified as a more robust long-term solution. Investigating integral clad plates, weld overlay cladding, and linings, concludes that roll-bonded bi-metal clad plates offer the most attractive balance between corrosion resistance, structural integrity, manufacturability, and lifecycle cost. Clad plates provide excellent corrosion protection through a thin CRA layer while retaining the mechanical performance of carbon-manganese steel. Weld overlay cladding is technically feasible but may introduce fabrication complexity and cost, while linings are generally unsuitable for pressurised Type C tanks.

Cost comparisons indicate that, over the operational life of an LCO_2 carrier, coatings or clad plates can be economically competitive with repeated CO_2 drying and purification, particularly when corrosion risk and inspection requirements are considered.

Overall, the work in this WP concludes that corrosion mitigation is essential for LCO_2 cargo tanks where water and impurity control cannot be fully guaranteed. Bi-metal clad plates are identified as the preferred solution for new tanks, while coatings may be considered for specific cases where risks can be adequately managed. Further validation through manufacturing experience, inspection data, and long-term operational feedback is recommended to refine corrosion control strategies for LCO_2 ship transport.

11 MATERIAL QUALIFICATION FOR LOW TEMPERATURE OPERATING CONDITIONS ASSESSMENT OF IGC-COMPLIANT MATERIALS

This chapter primarily examines material suitability for low temperature operation at –55 °C L CO_2. The study considers CVN test data available for existing low temperature steels at -60° C. The work evaluates whether commercially available carbon steels are suitable for use in low-temperature CO_2 transport tanks, specifically for liquid CO_2 at −55°C and, later in the study, for medium-pressure tanks operating between −35 °C and −25 °C. The work combines a detailed materials assessment with an Engineering Critical Assessment (ECA) of fracture tolerance. The materials assessment examines extensive Charpy V-notch (CVN) impact data for base materials and weldments, primarily for FH36 steel at −60 °C, and uses this information to estimate fracture toughness through BS 7910 master-curve correlations. The ECA determines the minimum fracture toughness needed to ensure structural integrity under extreme loading and fatigue conditions defined by the IGC Code.

The results show that FH36 and equivalent low-temperature grades have excellent performance at the required temperatures. Typical CVN transition temperatures around −65 °C and high impact energies at −55 °C demonstrate that these steels remain ductile well below the design temperature. Although the CTOD fracture toughness values estimated from Charpy data tend to be conservative, experience with modern thermomechanically rolled steels indicates that actual CTOD performance is likely higher.

The study finds that weldments, rather than the base metal, govern the overall fracture resistance of the tank structure. Heat-affected zones often show the lowest toughness, and the presence of imperfections such as porosity, lack of fusion, coarse grains or residual stresses can further reduce performance. Nevertheless, weld trial data demonstrate that adequate weld toughness can be achieved even at −60 °C, provided that welding procedures, consumables and heat input are carefully controlled.

Based on the collected data, FH36 and similar LT-grade steels can meet the requirements of both the IGC Code and IACS UR W1 at −55 °C. Steel mills also report significant development progress and the ability to supply LT grades with excellent low-temperature toughness, often exceeding the minimum requirements, at thicknesses up to 50–60 mm.

Higher-strength steels up to 690 MPa yield were also considered. The results show that as strength increases, fracture toughness—particularly in weldments—decreases. For 690 MPa grades, the predicted CTOD values at −55 °C are very low, meaning that these steels should only be used if actual CTOD testing confirms sufficient toughness. In contrast, the medium-pressure tank case, operating at higher temperatures, provides a more favourable environment. At −35 °C to −25 °C, fracture toughness roughly doubles compared with −55 °C, and this temperature margin widens the range of acceptable steels, making it realistic to include higher-strength grades if weld toughness is verified.

Overall, the study concludes that FH36 and equivalent low-temperature steels are suitable for −55 °C liquid CO_2 tanks, provided weld quality is well controlled. For medium-pressure tanks, a broader range of materials—including higher-strength steels—can be considered. The study recommends that critical materials should be validated through direct CTOD fracture toughness testing rather than relying solely on Charpy-based estimates. It also emphasises the importance of strict welding control, including appropriate heat input, selection of low-temperature welding consumables and high-quality non-destructive testing.

In summary, the necessary materials for safe construction of low-temperature CO_2 tanks are available today, but weld performance is the key determinant of overall safety, and project-specific testing remains essential for reliable design.

12 ABBREVIATIONS AND DEFINITIONS

AiP	Approval in Principle
BOG	Boil-Off Gas
BOR	Boil- Off rate
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CO2e	CO2 equivalent
CO_2LOS IV	CO_2 Logistics by Ship Phase IV
CRA	Corrosion Resistant Alloy
CTOD	Crack Tip Opening Displacement
DNV	Det Norske Veritas
DP	Dynamic positioning
EU	European Union
IGC	International Gas Carrier
IMO	International Maritime Organization
IMSBC	The International Maritime Solid Bulk Cargoes Code
LC	Levelized cost
LCA	Life Cycle Assessment
LCO2	Liquid CO_2
LNG	Liquid Natural Gas
LP	Low Pressure
LT steel	Low temperature steel
MGO	Marine Gas Oil
MP	Medium Pressure
Mt/y	Million tons per year
na	Not Applicable
OCCS	Onboard Carbon Capture and Storage
OPEX	Operating Expenditure
PRV	Pressure Release Valve
SAL	Single Anchor Loading
TRL	Technological Readiness Level
WP	Work Package

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