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The Status and Challenges of CO_2 Shipping Infrastructures

IEA GREENHOUSE GAS R&D PROGRAMME

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The Status and Challenges of CO_2 Shipping Infrastructures

(IEA/CON/19/257)

Key Messages

- The results from this study demonstrate that for long distance transport of low volumes of CO_2 (~1-2 Mtpa), such as in cross-border shipping from several industrial CCS clusters across Europe, shipping can provide a cost-effective option.
- Based on the four different scenarios modelled in this study, more CO_2 could be stored annually by shipping to an intermediate port, and then transporting CO_2 to a storage site via a pipeline, compared with direct delivery to the site by tanker.
- Of the four scenarios modelled here, based on a shipping distance of 1,000 km, there is little cost advantage from increasing the ship size above 10,000 tCO_2. Conversely, there is also little penalty in cost by using larger ships. However, the optimum ship size will be highly dependent on the flow rate (Mtpa). Ideally, size and capacity could be customised for each specific logistics chain.
- A comparison of the levelised cost of four different scenarios conducted in this study suggests that direct injection at a storage site from a ship is the most cost-effective solution (32 €/t CO_2). The cost advantage may vary under different scenarios.
- Transfer of CO_2 from a tanker into a floating storage injection (FSI) unit is the least cost effective solution even though it can allow continuous injection (41 €/t CO_2). Moreover, this system is unproven and less well understood compared with onshore facilities therefore direct comparison needs to be treated with caution.
- The modification of LPG tankers for CO_2, or dual purpose, will be influenced by the contrast in fluid density of the different gases. Consequently, only 50-60% of a tank capacity designed for LPG can be used for CO_2. Partially filled cargo tanks will also have a structural impact on a ship and its motion.
- Tankers specifically designed for CO_2 transportation can be optimised for maximum capacity and investment cost.
- A comparison between CO_2 delivered by sea tanker and a pipeline to an offshore storage site, based on minimum unit costs, shows that the pipeline option is cheaper over shorter distances. The break-even distance depends on the volume of CO_2 and whether tankers are pre-pressurised or non-pressurised (see Figure 9).
- A review of the legal instruments (international treaties, EU law & Norwegian Law), that relate to the movement of CO_2, shows that there are no evident showstoppers to the international shipment of CO_2.
- A decision taken at the 14th meeting of the Contracting Parties to the London Protocol on 7th – 11th October 2019 means that Contracting Parties who choose to are able to legally transship CO_2 for storage.
- An unfortunate result of having two monitoring reporting and verification (MRV) regimes for CO_2, is that ship operators will have to manage two separate reporting schemes for the fuel that they use. The European Commission has reviewed the MRV regulation and is considering potential alignment with the International Maritime Organisation Data Collection System (IMO DCS).

Background to the Study

Large-scale CO_2 storage will entail substantial transportation of CO_2 from either point-sources or hub collection points to geological formations capable of storing thousands of tonnes of CO_2 in supercritical form. In many parts of the world the most suitable storage options for large-scale capacity will be in offshore formations such as the North Sea. Consequently, it is important to build an understanding of the most suitable techno-economic solutions for the trans-shipment of CO_2 from shore facilities to offshore storage locations. This study has explored a series of options to gain a more detailed comparison of shipping CO_2 either directly by sea tanker to a storage site, or via an intermediate stage, to a shore facility in closer proximity to a storage site prior to transfer via pipeline. These options have also been compared to direct transfer via pipeline.

In contrast to natural gas, CO_2 only exists as either a solid or gas at atmospheric pressure and therefore requires pressurisation to reach a liquid state. Although CO_2 pipeline transport is typically carried out under high pressure conditions (70-100 barg), CO_2 shipment is likely to be most cost-effective under either low pressure / low temperature (Low P; -55 to -40°C, 5-10 barg) or medium temperature / medium pressure (Medium P; -30 to -20°C, 15-20 barg) conditions.

Both pressure and temperature affect a large number of the components of the supply chain including material choices, transport volumes and safety considerations. There are trade-offs between cost and operational complexity that must be considered in the selection of the most appropriate transport condition. The Medium Pressure condition is currently used for small-scale CO_2 transportation and it has been adopted for early CCS projects. However, the Low Pressure condition has been proposed as it is considered to be the most cost-effective and only viable option for ship sizes above 10,000 tCO_2.

While processing and handling of pure CO_2 streams is well-understood, the presence of impurities in the CO_2 product stream for CCS may also have a negative impact on transport and storage applications. Limitations on the amount of water, oxygen and other impurities depend on the material requirements of ship transport and injection facilities, as well as the final use of the CO_2 stream. Processes to purify the CO_2 stream are therefore an integral part of the shipping chain.

Scope of work

The objective of this study is to provide an overview of the current status of CO_2 shipping and to carry out a detailed assessment of the implications of large-scale operations on the supply chain. The study specifically includes:

- Phase and handling implications, and related constraints, for the trans-shipment of CO_2
- The infrastructure requirements for the transfer, shipment and delivery of liquefied CO_2
- Proposed vessel designs, capacity ranges, and innovations, for the marine shipment of CO_2.
- Quantification of the capital and operational costs of different marine shipment options and the evaluation of the economic viability of CO_2 transfer from shore facilities to offshore storage sites.
- A review of current regulatory and legal frameworks relevant for national (Norwegian) and international ship transport and CO_2 logistics.
- A review of those implications for monitoring, reporting and verification (MRV) of CO_2 that relate to CO_2 transport via ship and subsequent transfer to a storage site.

The scope of this study covers onshore infrastructure requirements at coastal locations, CO_2 tanker vessels and the unloading requirements. Both onshore unloading (for further transportation by pipeline) and offshore unloading (direct to storage site) are evaluated.

The infrastructure components of the CO_2 shipping chain that need to be considered (Figure 1) broadly consist of:

- Liquefaction: CO_2 is brought into the liquid state through a series of cooling and compression steps.
- Intermediate storage: buffer storage is used to bridge the gap between continuous CO_2 capture and discrete (batch) transportation by ship.
- Loading/unloading equipment: Loading/unloading equipment consists of either conventional articulated loading arms or flexible cryogenic hoses and auxiliary equipment such as cryogenic pumps and pipelines for transfer from storage to a loading arm and a return line for boil off gas.
- Ship: either a purpose-built CO_2 tanker or converted ship may be used; however, repurposing of ships does have implications if the ship was not also originally designed for carrying CO_2. Tankers specifically designed for CO_2 transportation can be optimised for maximum capacity and investment cost.
- Conditioning: CO_2 must be brought from the liquid state to a condition for further transportation or injection after shipping, typically by heating and pumping.

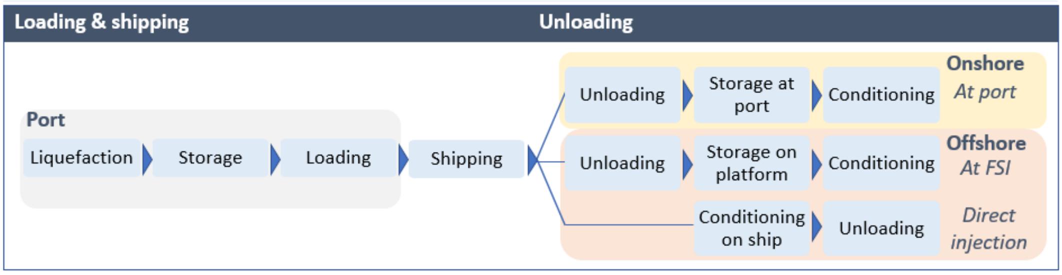

Figure 1 Overview of the components of the CO_2 shipping chain

This study also includes a comprehensive review of regulatory and legal frameworks that are the most relevant instruments at international, national and regional level affecting CO_2 transfer and transport. The extent to which international regulations may affect different countries is considered at a high-level, but a full comparison of legal framework for each region is outside the scope of this study.

The study was led by Element Energy in combination with SINTEF Industry, Brevik Engineering and IOM Law.

Findings of the Study

The onshore components and processes of the shipping chain are well understood from existing (small-scale) operations. Additional components for CCS, and for transport at larger scales, have also been established through feasibility studies and literature reports. Detailed concept designs have been prepared for ships carrying CO_2 under Medium Pressure conditions. In contrast, ships for Low Pressure CO_2 transport conditions are typically larger and with much less certain cost estimates.

Offshore unloading of CO_2 has been evaluated but is as yet unproven and less well understood compared with onshore processes. There is as yet no clear consensus on the most appropriate solution for this stage. CO_2 can either be unloaded by direct injection into the well or via temporary storage in an intermediate platform, here referred to as a Floating Storage and Injection unit (FSI).

The choice of offshore unloading solution and infrastructure has implications for the vessel design and costs of operation. In particular, the unloading solution affects the onboard equipment requirements, CO_2 injection rates and continuous versus batch-wise nature of CO_2 delivery to an injection well.

One potential option, at least in the initial stages of shipping CO_2, is to either repurpose LPG marine tankers for CO_2, or even modify tankers for dual purpose operations. The concept of repurposing tankers has been the subject of several studies. There are, however, a number of considerations which govern liquefied and low pressure gas transport that ideally favor purpose built CO_2 tankers. The contrast in fluid density has a significant influence on ship design and operation. LPG, for example, has a density of 550-700 kg/m^3 while liquid CO_2 has a density of ~1050~1200 kg/m^3 depending on temperature and pressure. This difference in density has several effects:

1. Only 50-60 % of the tank capacity may be utilised for CO_2 shipment compared to LPG due to the difference in the ship's displacement. Partial filling of the tanks results in sloshing inside the tanks which has a structural impact on the tanks and also on the motions of the ship.

2. The allowable pressure for CO_2 transport is reduced compared with LPG partly because there are higher dynamic loads from sloshing which need to be constrained. In practical terms this means a gas-carrier capable of containing LPG at pressures up to 7.5 barg will be able to contain CO_2 at ~7 barg, however the exact pressure must be calculated for each vessel.

The majority of fully pressurised LPG carriers are designed to operate with liquefied gas down to -48°C and pressures up to 7 barg. Specialized ethylene carriers are capable of transporting liquefied gas down to -104°C but at lower pressure than 7 barg. Some of the smallest LPG carriers have tanks capable of containing LPG at 17-18 barg pressure. Due to the high pressure, the tanks and the ships are small (3,000-4,000 m^3). If the different density of CO_2 is taken into account these ships may carry 2,000-2,500 tCO_2 at medium pressure.

There are also some carriers capable of carrying LPG at 10-11 barg at -48°C. For such a tanker, 8.5 barg at -47°C could be an option for CO_2 transport. Since only 50-60% of the capacity can be used, a ship with 5,500 m^3 cargo hold would only be able to transport around 3,000 tCO_2.

In practice, conversion between cargo gases is likely to be most feasible for a single conversion only. This option could provide a means to de-risk projects by providing a second use for ships after shorter-term CO_2 shipping operations.

One advantage of a CO_2 dedicated tanker design or modification is the option for direct shipment and offloading at an offshore storage site. CO_2 can either be unloaded by direct injection into a well or via a FSI. A FSI unit offers the operational advantage of continuous injection flow into a reservoir. The system can offer a temporary storage buffer which means that offloading CO_2 is less constrained by harsh weather conditions. The downside of FSI units is the requirement for higher capital investment. Direct injection without an intermediate offshore storage option means that, although the initial capital investment is lower, a batch-wise operation is required. This option is more vulnerable to weather constrained operational windows and the necessity for guaranteed CO_2 temperature and pressure conditioning to avoid hydrate formation within the reservoir. Batch-wise operations also increase the risk of cyclical loading on casing and well barrier materials caused by thermal recovery between injection cycles. There is considerable experience in offshore unloading that has been gained from the oil and gas industry. However, offshore unloading of CO_2 is currently unproven. In addition to CO_2 conditioning prior to injection, tankers may require a dynamic positioning system to ensure that they can be held in a defined position during unloading operations. Consequently, there will be an energy and environmental penalty in terms of fuel use and related emissions.

Direct injection to the well requires a gas transfer system to connect the ship to the well. For unloading to an FSI, two gas transfer systems are required, one between the ship and the FSI, and one between the FSI and the well. For both offshore unloading options, equipment for station keeping will be required for the ship and for the FSI.

The degree of risk, and therefore suitability of batch-wise injection, is expected to be specific to each reservoir and would need to be assessed on a site-specific basis. While the feasibility of batch-wise injection for CO_2 injection remains uncertain, it has been included in this study for comparative purposes.

Initial development of offshore CO_2 storage, and the transportation option adopted, could also depend on the supply and distribution of CO_2. Supply and storage agreements for relatively small quantities of CO_2 that are geographically dispersed maybe difficult to agree without some degree of flexibility. In contrast, the establishment of large-scale CO_2 supply from a few fixed points, that can be linked to a storage site, offers the prospect of optimized infrastructure and shipment solutions.

Basis for Modelled Scenarios

Ship logistics scenarios for three possible future North Sea CCS projects have been defined and used as the basis for cost estimates (Table 1). These scenarios compare two different transport conditions for onshore unloading (Low Pressure and Medium Pressure) as well as the two different offshore unloading options (Figure 1).

For each scenario, bottom-up engineering designs were prepared and ship operational profiles were estimated and then used as the basis for ship cost estimates. Cost modelling of the onshore components was carried out using a detailed factor estimation method and combined with the ship costs to estimate the capital costs of the full shipping chain.

Table 1 Ship logistic scenarios used as the basis for the cost assessment

No.	Route	Unloading type	Condition before transport	Transport condition	Condition after transport	Ship capacity / tCO_2	No. of ships
1	Rotterdam-Kollsnes	Onshore	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3
2	Rotterdam-Kollsnes	Onshore	1 barg, 20°C	Medium P	100 barg, 5°C	10,000	3
3A	Rotterdam-North Sea	Offshore to FSI	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3

3B	Rotterdam-North Sea	Offshore, direct injection	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3

Low P = 7 barg, -50°C; Medium P = 15 barg, -28°C

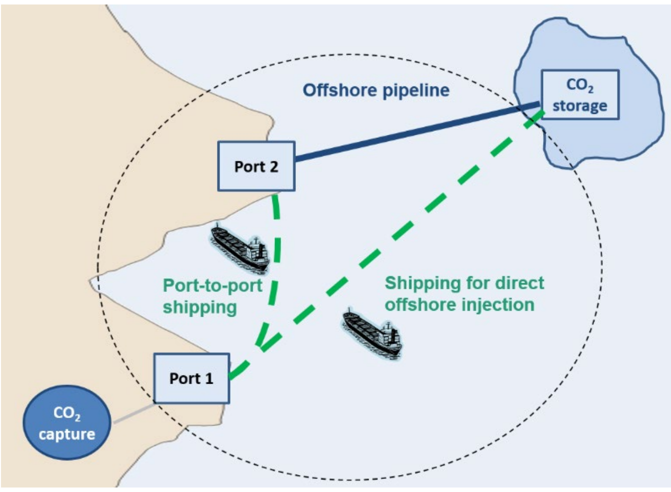

Figure 1 Illustrative summary of scenarios used in this review for cost estimation and techno-economic comparison

The four different scenarios modelled in this study (1, 2, 3A & 3B) were designed to test the implications of each option including their capital (CAPEX) and operating (OPEX) costs and the transport cost in €/tonne of CO_2. In each case the operational conditions in terms of number of ships used, shuttle deliveries per year, time for each round trip including loading and offloading CO_2 and then, ultimately, the tonnage of CO_2 stored per year. The impact of weather conditions on these operations varies. For a fixed number of ships the number of trips per ship per year is lower for offshore unloading (Scenarios 3A and 3B) than for onshore unloading (Scenarios 1 and 2) because the onshore options deliver CO_2 via pipeline to the offshore storage site. The yearly amount of pipeline injected CO_2 is reduced for the Medium Pressure scenario (2) compared to the Low Pressure condition (1), because of the higher volume of CO_2 required to be left in the ships' tanks to maintain pressure during loading and unloading.

Techno-economic modelling was based on these four different scenarios and then used for comparison with direct delivery of CO_2 by long distance pipeline.

In the direct offshore injection scenario (3B), the offloading rate is limited by the injection rate into the well, resulting in significantly longer unloading times compared with offloading to an FSI unit (3A) where continuous, regulated injection is possible. A comparison of the operational hours and annual CO2 tonnage for each scenario is presented in Figure 2.

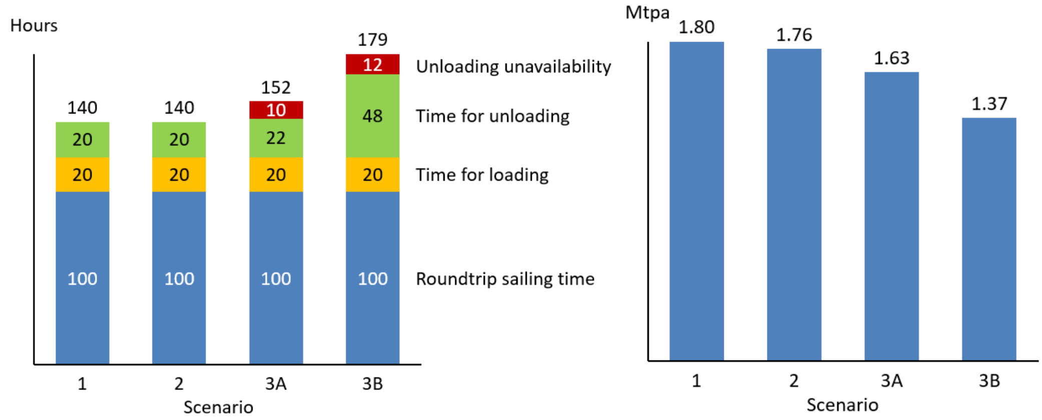

Figure 2 Total roundtrip time (left) and total injected CO_2 (right) for each shipping scenario

The CAPEX is based on the use of three ships for each scenario, shore based loading and unloading facilities, and gas conditioning, especially pressurization. For Scenarios 1 and 2 the pipeline cost from the shore based terminal to the storage site is included. The OPEX was based on the logistics for each scenario. Undiscounted costs have been compiled and presented in Figure 3.

Ship costs were calculated using a bottom-up approach based on the detailed vessel designs and logistics profiles developed for these scenarios. Onshore infrastructure costs were derived using a detailed factor estimation method. The liquefaction plant, intermediate storage, loading and unloading, ship transport and conditioning before further transport, are included in the costs. For the offshore cases, the FSI unit is included, but not the costs for injection into the reservoir.

Ships for shore-to-shore shipping only need equipment for offloading to a land-based station, while offshore-going vessels require the offloading equipment to be integrated into the ship. The offshore unloading scenarios 3A and 3B will also require extra space for an offloading system. In addition, the direct injection scenario 3B requires an on-board process plant to increase the temperature and pressure of the CO_2 before injection. Assuming 3A is not connected to a permanent mooring system the vessel is equipped with a Dynamic Positioning System (DP) in order to maintain position during offloading.

Feedback from stakeholder engagement questioned the operational limits applied in this study for the size of ships. The given Hs (mean wave height) limit of 4.5 m may be appropriate for larger ships but smaller ships may have more difficulty connecting to the offloading system under these conditions. With a lower operation limit (e.g. Hs 2.5 or 3 m) the offloading operational window will go down and higher storage capacity would be required. This factor is highly uncertain and needs to be further investigated for each offshore location with detailed calculations and dialogue with operators.

It is clearly evident from these data that Scenario 3A has the highest CAPEX and OPEX due to the inclusion of an FSI unit. This scenario has the highest overall undiscounted unit cost (€41/tCO_2 transported; Figure 3). The direct injection scenario (Scenario 3B) has the lowest CAPEX and OPEX costs but stores the least CO_2 per year (unit cost €32/tCO_2). Scenario 1 has the lowest overall unit cost, excluding transport beyond the port (€26/tCO_2). If an onshore to offshore pipeline is include the overall cost rises to (€34/tCO_2). It should be stressed that all these cost estimates are subject to some uncertainty. The transfer of CO_2 from a tanker directly to an offshore storage facility is unproven and will be influenced by site-specific conditions. Direct comparison with shore-based facilities based on mature designs should, therefore, be treated with caution.

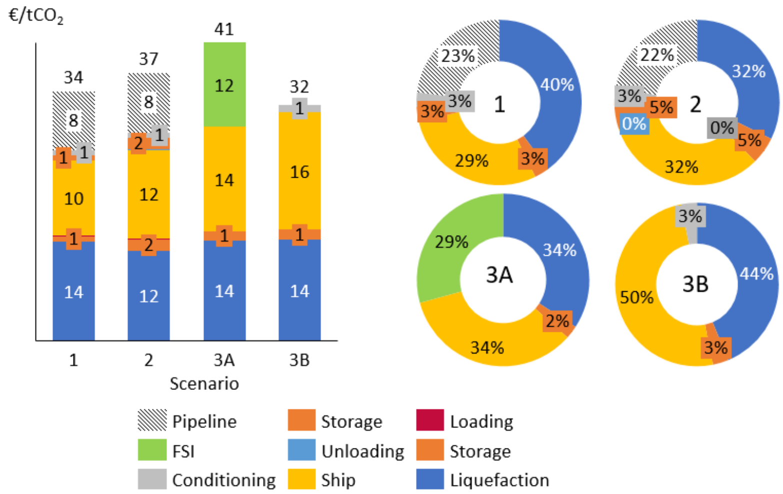

Figure 3 Unit costs (€/tCO₂) for each shipping scenario, assuming a 20 year lifetime, excluding discounting or financing. Note that loading and unloading are not visible on these charts due to the relatively small size of these cost components (0% of cost).

For the shipping scenarios to be fully comparable, a pipeline must be included between the onshore unloading site and the final offshore storage site. Inclusion of this pipeline is estimated to add a further €8/tCO_2 to the total lifetime cost of Scenarios 1 and 2, bringing the costs of onshore unloading above those of direct injection for the modelled set of transport conditions. However, it should be noted that an onshore-to-offshore pipeline is likely to be utilised by more than one project, improving the economic viability of this option.

Liquefaction accounts for 40% of the overall unit cost for Scenario 1, if the cost of the pipeline transport is included. If the CO_2 is pre-pressurised prior to liquefaction, costs of the shipping chain can be reduced to €17/tCO_2; however, although pre-pressurisation reduces the cost of the shipping chain, the cost may still be borne by an earlier stage of the CCS chain.

Economies of scale can reduce CO_2 transportation costs. Increasing pipeline delivery rates from 1.8 Mt/year to 10 Mt/year could potentially reduce the cost of CO_2 transportation to an offshore storage site by ~15% which is evident from Figure 4.

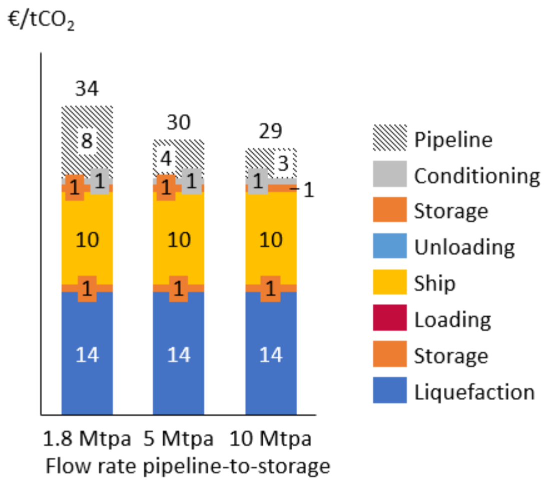

Figure 4 Effect of higher utilisation at the shore-to-offshore pipeline on the cost of an individual shipping chain under Scenario 1 (1.8 Mtpa transported by ship, representing a pipeline used by multiple projects).

The results of the techno-economic modelling based on the cost estimates for both CAPEX and OPEX derived from this study are presented in Figure 5. The modelling needs to include assumptions on the time and cost loading and offloading operations. In practice, all costs are interrelated in a complex manner consequently these model results are intended to be illustrative trends.

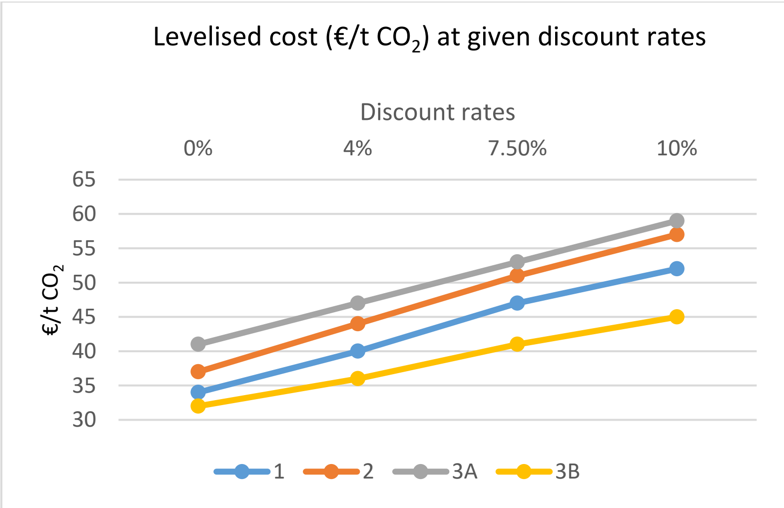

Figure 5 Levelised cost of transported CO2 for the different scenarios

The impact of ship size could influence the economic viability of offshore CO_2 storage. Ships with cargo capacities ranging from 2,000 to 30,000 tonnes were modelled assuming different operational scenarios: onshore unloading to a shore based terminal; offshore unloading using a FSI unit; and offshore unloading by direct injection. Two different cases (600 t/h and 3,000 t/h) for onshore and offshore to an FSI were modelled to test the influence of unloading rates.

For the 600 t/h unloading rate case increasing the ship size reduces the number of ships required up to a size of 20,000 tCO_2, which reduces the overall ship costs (Figure 6); however, the difference in ship cost between 10,000 and 20,000 tCO_2 is largely offset by the increase in buffer storage capacity and conditioning costs (for direct injection), resulting in little change in overall unit cost. Increasing the ship capacity to 30,000 tCO_2 increases the unit cost as the number of ships is not reduced.

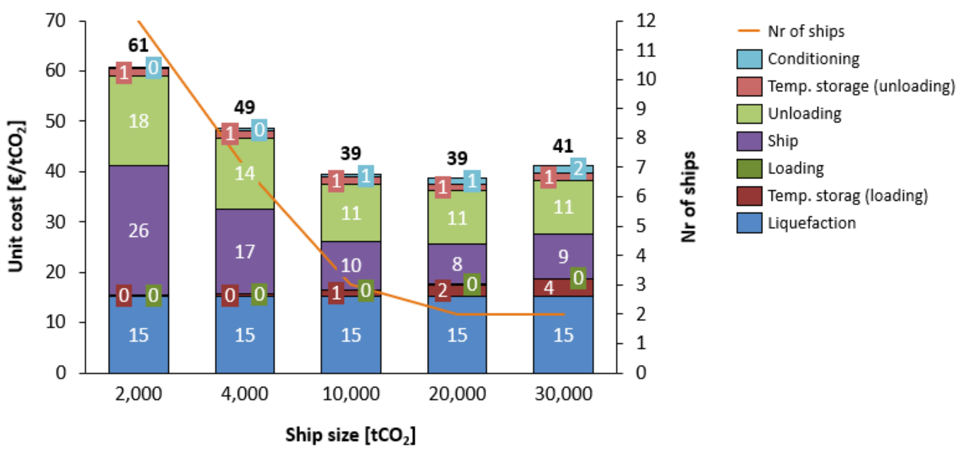

Figure 6 Unit cost of shipping for different ship sizes using the base case unloading rate (600 t/h onshore and offshore to FSI, 228t/h direct injection) for offshore unloading to an FSI (Case 3A).

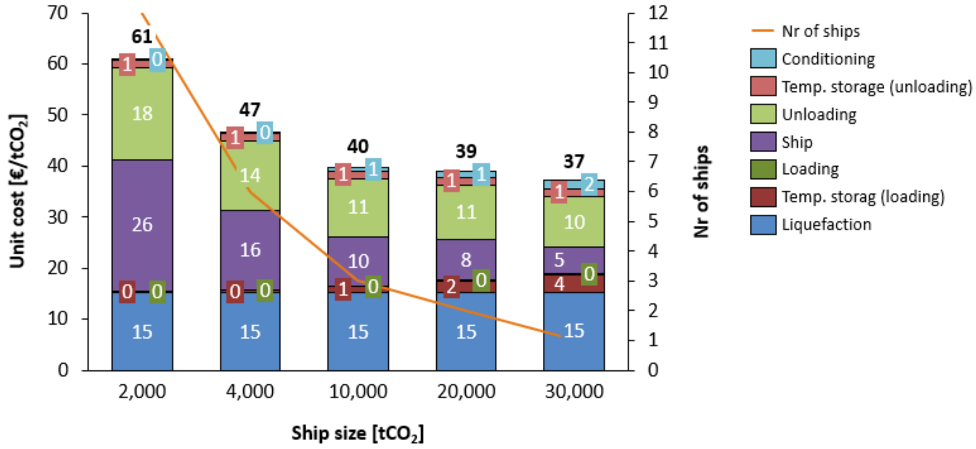

Figure 7 Unit cost of shipping for different ship sizes using an unloading rate of 3,000 t/h for offshore unloading to an FSI unit (Case 3A).

Overall, a higher loading/unloading rate only reduces the unit cost if it reduces the total trip time to such an extent that a lower number of ships are required. For a 10,000 tCO_2 ship capacity, increasing the loading and unloading rate to 3,000 t/h (Figure 7) does not reduce the number of ships required for onshore unloading and 3A (offshore to FSI) and therefore the unit cost is marginally increased (by €0.2/tCO_2). However, for these scenarios, the cost can be decreased (from €41/tCO_2 to €37/tCO_2) by increasing the ship capacity to 30,000 tCO_2 since only one ship is required (Figure 7).

For Scenario 3B (direct injection), where unloading times are a particular bottleneck in the trip time, increasing the loading and unloading rate reduces the roundtrip time for a ship capacity of 10,000 tCO_2 sufficiently that only two ships are required. This reduces the unit cost from €31/tCO_2 to €28/tCO_2, as only two ships are needed instead of three. Increasing the ship size to 20,000 tCO_2 does not reduce the number of ships and therefore increases the unit cost. Only one ship is required for a capacity of 30,000 tCO_2; however, although the cost is reduced compared to a 20,000 tCO_2 ship, it is still higher than for a 10,000 tCO_2 ship. However, achieving a high unloading rate in the case of direct injection is more challenging than in the case of unloading onshore or to liquid storage on an FSI, as the injection rate will be limited by specific reservoir conditions.

Overall, increasing the ship size and unloading rate can reduce costs if the number of ships can be reduced. However, in practice, two or more vessels may be desirable for full-scale projects to ensure redundancy.

For the scenarios modelled here, there is little cost advantage from increasing the ship size above 10,000 tCO_2. Conversely, there is also little penalty in cost by using larger ships. However, the optimum ship size will be highly dependent on the flow rate (Mtpa) and would therefore need to be considered for each specific logistics chain. Operational limits such as ease of connection to offshore assets under local conditions will also be important in choosing an appropriate ship size and will need to be assessed on a case-by-case basis. Additional benefits of larger ships include the possibility of injecting more CO_2 per chain per year and, if the number of trips can be reduced so that they can travel more slowly, increased fuel efficiency. These aspects have not been incorporated in the modelling but could affect the relative levelised costs of the chain.

A comparison between shipping and pipeline transport costs depends on flow rate and distance. Pipeline transport costs are dominated by CAPEX and therefore decrease significantly with increased annual flow rates (Figure 8). In contrast, shipping costs are dominated by OPEX and Fuel cost, which are not reduced with higher utilisation (Figure 8.

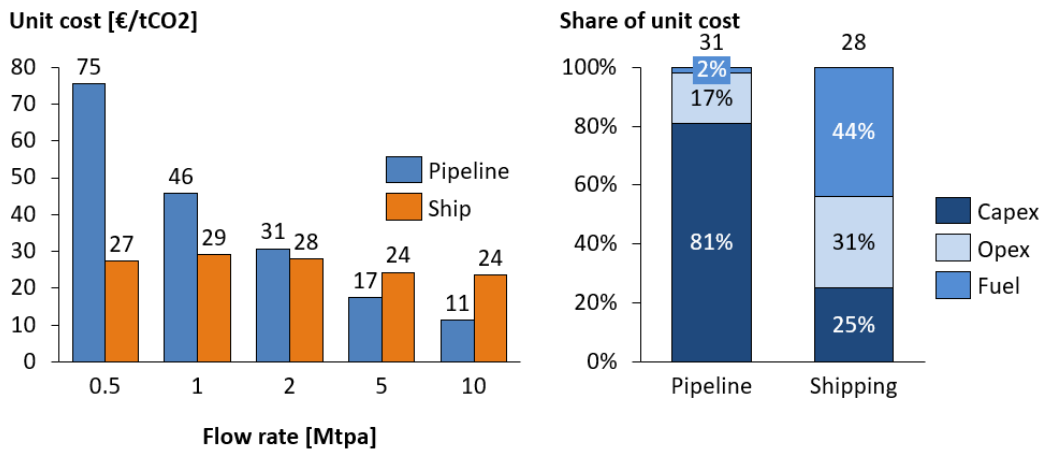

Figure 8 Unit cost of pipeline and ship transport (with onshore unloading) for different flow rates (left); share of unit cost by CAPEX, OPEX, and Fuel of shipping and pipeline transport for 1,000km distance and a 2 Mtpa flow rate.

Pipeline costs are also much more sensitive to the transport distance than shipping costs since the distance has a direct impact on the pipeline dimensions. To compare the distance at which shipping becomes more cost-effective than pipeline transport (breakeven distance), the minimum unit costs were calculated for both transport options.

For shore-to-shore transport, shipping becomes more cost effective than pipeline transport at distances above about 650km for a flow rate of 1 Mtpa, which increases to 920km for a flow rate of 2 Mtpa. If the gas is pre-pressurised prior to liquefaction, shipping costs can be reduced sufficiently so that the breakeven distances reduce to 320km and 520km, respectively.

The breakeven distances are similar for shore-to-offshore transport, with direct injection from a ship becoming more cost-effective than pipelines at distances above 660km for a flow rate of 1 Mtpa and above 990km for a flow rate of 2 Mtpa (Figure 9).

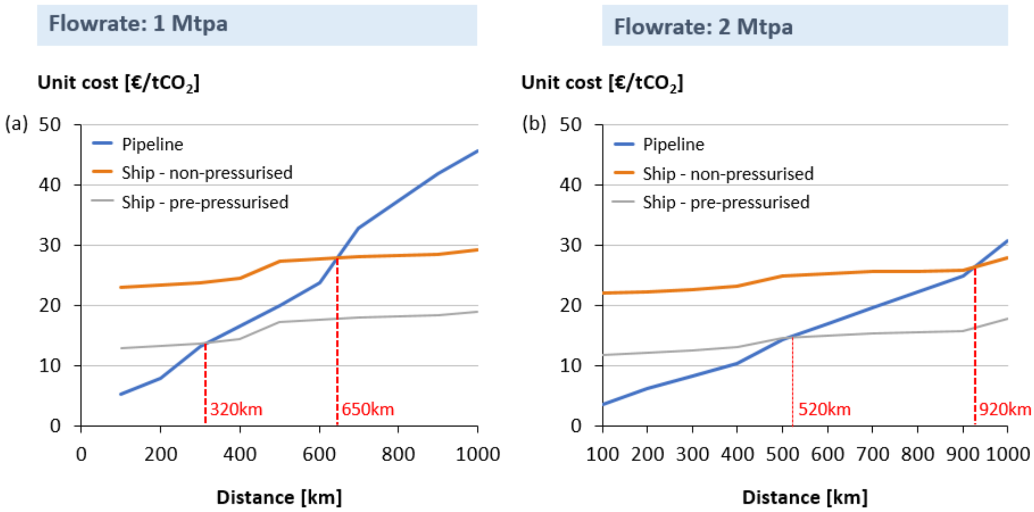

Figure 9 Unit cost of shore-to-shore shipping and pipeline transport for a range of distances for flow rates of (a) 1 Mtpa flow rate (and (b) 2 Mtpa flow rate

These results demonstrate that for long distance transport of low volumes of CO_2, such as in cross-border shipping from several industrial CCS clusters across Europe, shipping can provide a cost-effective option. Since pipeline costs are CAPEX dominated, the cost-effectiveness of this option also improves with increasing operational lifetime. The breakeven distance will therefore be lower for operational lifetimes less than 20 years and higher for lifetimes greater than 20 years.

Innovations in Marine Transportation

This study has also included an outline of potentially new innovative concepts in ship transport. They include:

- The development of autonomous electrically power container ships with remote control loading, unloading and navigation.
- Battery electric propulsion short sea transits. Conventional fossil fueled car ferries in Norway are rapidly being replaced by ferries with battery-electric drive trains. Hydrogen and biofuel propulsion is also under investigation.
- Push barge (several units linked into a single unit) solutions are well-established, as are their applications for gas logistics. Several hydrogen FOAK (first-of-a-kind) ship projects are expected to become operational in 2021-22.

Legal and regulatory requirements relevant for international shipment of CO_2

As part of the wider implications for the development of shipping large quantities of CO_2 by sea this study reviewed public international legal instruments (laws and regulations). These legal instruments are summarized in Table 2.

There is no global supranational legal entity to develop and coordinate a comprehensive legal framework. Although there has been a proliferation of public international law which can result in overlap or conflicting frameworks there do not appear to be any showstoppers that would prevent the international development of CCUS.

Table 2 Summary of key features of relevant public international legal instruments

Legal instrument	Key features
1982 United Nations Convention on the Law of the Sea (**UNCLOS**)	• Main legal framework for governing activities at sea • States have the right to exploit their natural resources but are obliged to protect and preserve the environment • Some room for interpretation regarding storage as UNCLOS does not refer to subsea • No specific provisions for ships transporting CO_2
1972 **London Convention** on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter	• Focused on dumping • CO_2 is not listed in Annexes, therefore its disposal is not prohibited or subject to special permits
1996 Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (**The London Protocol**)	• Only global agreement dealing specifically with offshore unloading and storage of CO_2 • CO_2 is regarded as waste and storage in the subsea is considered dumping, but storage of CO_2 from capture processes is excepted from general dumping prohibition • Prevents export of "*waste or other matter to other countries for dumping…*" presenting a **hurdle to establishment of international offshore storage hubs** involving cross-border elements for most of its Contracting Parties
1992 Convention for the Protection of the Marine Environment of the North-East Atlantic Convention (**OSPAR**)	• Objective to prevent and eliminate pollution for the protection of the marine environment • Applies to transport of CO_2 by ships and pipelines • Applies to storage activities but CO_2 from capture processes is a listed exception from dumping prohibition
The 1973 International Convention for the Prevention of Pollution from Ships (**MARPOL**)	• Objective to prevent pollution of the marine environment by ships from operational or accidental causes
1974 International Convention for the Safety of Life at Sea (**SOLAS**)	• Sets out minimum standards for the construction, equipment and operation of ships carrying dangerous goods (CO_2 included) • Implications for the costs and viability of CO_2 shipping through adherence to design and operation regulations
1976/1977 Convention on Limitation of Liability for Maritime Claims	• Establishes a system of limiting liability for ship owners • Does not set limitation of liability for environmental damage
2010 International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea	• Aims to ensure compensation for damage from the transport of hazardous and noxious substances • Not currently in effect but may be in future

London Protocol - Legality of CO_2 export

One of the most specific pieces of legislation is the London Protocol. In order to overcome this legal barrier, Norway proposed a resolution to adopt a second paragraph to Article 6 to specifically allow for export of CO_2 for storage. After the publication of the recommendations, the Contracting Parties Norway and the Netherlands, submitted a proposed resolution on the provisional application of the 2009 amendment to Article 6 to their fellow Contracting Parties, in preparation for the 14th meeting of the Contracting Parties 7th – 11th October 2019. Following this meeting Contracting Parties who choose to are now able to legally transship CO_2 for storage.

OSPAR

Article 5 applies to all parts of the value chain. Further, the dumping prohibition in Article 3(1), explicitly does not apply to *"carbon dioxide streams from carbon dioxide capture processes for storage"*, provided compliance with specific requirements. The conditions set out in OSPAR for storage are similar to those of the London Protocol with regard to the location of storage sites and contents of the CO_2 stream; however, these conditions should not be viewed as a hurdle for the deployment of CCS or related transport, offloading or storage of CO_2. Norway is one of the Contracting Parties to OSPAR and operates sites at Sleipner and Snøhvit. Although the transport of the CO_2 in these projects is conducted by pipelines, no additional legal hurdles are presented by OSPAR if the means of transportation were to change to shipping.

Consequently, OSPAR allows for transport, offloading and storage of CO_2, utilizing ships as means of transport and offloading.

EU legislation

The ETS Directive specifically includes in the Annex I list the *"transport of greenhouse gases by pipelines for geological storage in a storage site permitted under the CCS Directive"*. The implication of this statement is that pipelines are the only permitted means of transport for CO_2 under the ETS scheme. This wording could mean that CO_2 is excluded from shipping under the ETS Directive. However, the barrier is not absolute since Member States may apply emission allowance trading to activities and to greenhouse gases which are not listed in Annex I.

The EU MRV Regulations contain no specific provisions to address ships transporting CO_2, only the CO_2 being emitted from the operations. Consequently how CO_2 can be effectively and adequately monitored and verified under the current regime is unclear.

The EU MRV Regulation and the IMO (International Maritime Organization) DCS (Data Collection System) are both intended to quantify CO_2 emissions from shipping, and they apply in parallel, implying the ships calling at EU and EEA ports have to report under both frameworks. There are however differences between the two systems, including the geographic limitations of each framework. The EU scheme only applies within the EU and EEA area, whereas the IMO scheme covers global emissions from shipping.

An unfortunate result of having two MRV regimes, is that ship operators will have to manage two separate reporting schemes for the fuel they use. The European Commission has reviewed the MRV Regulation, considering potential alignment with the IMO DCS.

Expert Review Comments

- The report provides a good basis for an investigation of potential shipping routes. These could be found by identifying locations with a potentially significant future supply of CO_2 but without nearby storage options. The choice of ship vs pipeline transport for those locations could be worked out in detail.
- The comparison between the cost of shipping and transport by pipeline is clear and confirms previously published results. A pipeline for 1 Mtpa or 2 Mtpa over a distance of hundreds of kilometers is considered a hypothetical one. Over these distances pressure losses could be significant and could require booster stations. Perhaps, for these relatively low flow rates, transport over large distances is only feasible by ship.
- Batch-wise injection can either enhance of prevent injection impairment. The risks associated with this mode of operation have been included in the text. A reviewer recommended case specific simulations to determine the optimum injection rate. Batch-wise schemes also depend on reservoir properties.
- Heating of CO_2 prior to injection has an energy penalty, although there are technical solutions which could be applied for example using waste heat from a ship's engines and seawater.
- Clarification on availability of technologies for offloading CO_2 offshore. The text does comment that although similar offshore transfer systems are available for oil and gas they have yet to be proven for CO_2.
- The basis for the number and capacity of ships was questioned. Assumptions needed to be made so that a design could be costed for modelling and comparison purposes. The alternative would require designing separate ships for each case or operating some ships at very unfavourable transit speeds.
- One reviewer thought that it would be interesting to see how the spread of costs might be altered with increasing the tonnage of CO_2 transported each year. Although this is an interesting idea the interaction of the key components of the transport system is likely to be complex due to the change in the number and/or size of ships with flow rate. Further analysis to address this relationship is beyond the scope of this study.
- Further discussion on contractual arrangements was suggested. This is a complex subject which could be explored further in future studies
- The advantages of spherical tanks was suggested, but the authors settled for horizontal tanks because they offer a space advantage even though thicker steel is required. This option was selected so that a base case design could be developed and costed.
- The repurposing of LNG carriers, or constructing new build CO_2 vessels using similar designs to the world's largest LNG carriers was not mentioned. The challenges of repurposing tankers for fluids with different densities are explained in the report as are the benefits of designs optimized for CO_2 transport.
- The maximum downtime of 19 days, when unloading CO_2 offshore would be not be possible, was considered to be conservative. The authors considered that this assumption was justified as a theoretical maximum. Further elaboration was not possible within the scope of the study.

- The capacity sizes were questioned, although actual dimensions will not be realized until projects are developed at full scale. The modelling used to test the significance of capacity suggests that increasing capacity it is not necessarily more economic.

Conclusions

- The transport condition of CO_2 affects a large number of components of the shipping chain, including material choices, storage tank design and operation, transport volumes and safety considerations. Medium pressure conditions are currently used for CO_2 transportation but low pressure conditions may be more cost-effective.
- Onshore infrastructure for handling pure CO_2 is well-understood however, additional impurities present in the CO_2 product stream for CCS may have a negative impact on transport and storage applications. Processes to purify the CO_2 stream are an integral part of the shipping chain.
- Offshore unloading of CO_2 is currently unproven and no consensus exists for the most appropriate solution. The primary challenges to offshore unloading include increased costs of offshore processing of CO_2 for injection and potential periods of unavailability due to weather conditions.
- Batch-wise injection presents challenges for offshore unloading via direct injection but maintaining continuous flow requires the use of an intermediate FSI which is a major cost driver.
- For the scenarios modelled here, there is little cost advantage from increasing the ship size above 10,000 tCO_2. Conversely, there is also little penalty in cost by using larger ships. However, the optimum ship size will be highly dependent on the flow rate (Mtpa) and would therefore need to be considered for each specific logistics chain.
- A comparison between shipping and pipeline transport costs depends on flow rate and distance. Pipeline transport costs are dominated by CAPEX and therefore decrease significantly with increased annual flow rates.
- For shore-to-shore transport, shipping becomes more cost effective than pipeline transport at distances above about 650km for a flow rate of 1 Mtpa, which increases to 920km for a flow rate of 2 Mtpa. If the gas is pre-pressurised prior to liquefaction, shipping costs can be reduced sufficiently so that the breakeven distances reduce to 320km and 520km, respectively.
- The breakeven distances are similar for shore-to-offshore transport, with direct injection from a ship becoming more cost-effective than pipelines at distances above 660km for a flow rate of 1 Mtpa and above 990km for a flow rate of 2 Mtpa.
- For representative CCS shipping chains (port to offshore storage site) in Europe, undiscounted unit costs of €30-40/tCO_2 are projected with comparable costs for onshore unloading and direct injection when the ongoing pipeline for final transport from shore-to-storage is included. For a discount rate of 10%, the levelised costs increase to €46-60/tCO_2 depending on the shipping scenario. It should be stressed that all cost estimates in this report are subject to some uncertainty. The transfer of CO_2 from a tanker directly to an offshore storage facility is unproven and will be influenced by site-specific conditions. Direct comparison with shore-based facilities based on mature designs should, therefore, be treated with caution.
- Whilst cost is an important consideration other factors such as regulatory constraints and national policies could influence, or determine, transport options.

- Liquefaction and ship costs make up the majority of costs of the shipping chain, accounting for 52% and 37% of the undiscounted unit cost for shore-shore shipping, respectively (excluding shore-to-offshore pipeline). Liquefaction costs can be reduced if the initial CO_2 stream is pre-pressurised, but this simply transfers the cost further up the chain (to the capture plant).
- International, regional and national legal frameworks governing shipping and carriage of CO_2 are mature and present few hurdles to CO_2 shipping for CCS. The London Protocol has historically presented the main barrier to CCS but IMO developments in October 2019 represent a breakthrough in effectively removing this barrier for those parties that have ratified the amendment or wish to tranship CO_2. The ETS Directive now remains the main hurdle to CCS operations in EU and EEA EFTA countries but the barrier is not absolute and is due for revision.
- Contractual arrangements may be based on existing frameworks but specific clauses will need to be included.
- Ship operators will have to manage two reporting schemes for CO_2 emissions from fuel but these systems are under review.

Recommendations

Recommendations for future technical work to develop the CCS transport chain:

- More detailed investigation, possibly based on a site-specific case study, of operational windows for offshore facilities (relevant sea-states) particularly with regard to optimal ship size. A study could build on oil industry oceanographic expertise and related risk assessment. However, generic studies should be treated with caution because they may not necessarily related to site-specific conditions.
- Modelling of the potential for innovations in shipping to reduce the costs and GHG impact of the CO_2 shipping chain.
- Detailed assessment of the market potential for export/import of CO_2 within Europe, and/or other regions, and identification of locations where the shipment of CO_2 may be feasible.
- Inclusion of CO_2 storage infrastructure (wells etc) in shipping costs and the impact of port-to-storage options on CO_2 storage costs (e.g. due to potential effect on injectivity).
- Greater certainty on the effect different sea states have on the operational window of tankers delivering CO_2 to offshore storage sites is required. As this factor is highly uncertain further investigation for different offshore locations, with detailed calculations and dialogue with the operators, is recommended.

Recommendations to investigate the liability associated with the handling, shipment and transfer of CO_2

- The authors of the study recommend the use of specialized agreements for the transport of CO_2 for storage, rather than reusing existing contractual models that are not fit for purpose. Such contracts should take into consideration requirements for e.g. MRV (monitoring, reporting and verification) for the emission source to be eligible for allowances, and for shipping to qualify, as part of the CCS value chain. Reference could be made to the ISO standard under development for quantification and verification[1] as part of that arrangement.

[1] Currently on a Committee Draft level, ISO/CD 27920 Carbon dioxide capture, transportation and geological storage (CCS) – Quantification and verification

- More detailed analysis of contractual mechanisms, taking into account the conflicting regulatory and operational (cost) drivers related to ETS compliance.
- The development of contracting arrangements for bulk transfer of CO_2.
- Detailed study of different legal frameworks, legal contractual traditions, cost implications and ports in other regions with potential to use CO_2 shipping (e.g. Japan and South Korea).

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BREVIK engineering

IOM LAW

The Status and Challenges of CO_2 Shipping Infrastructures

Final report

for

IEAGHG

4th March 2020

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Element Energy is a leading low carbon energy consultancy working in a range of sectors including carbon capture and storage, low carbon transport, low carbon buildings, renewable power generation, energy networks, and energy storage. Element Energy works with a broad range of private and public sector clients to address challenges across the low carbon energy sector and provides insight and analysis across all parts of the CCS chain.

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While the authors consider that the data and opinions contained in this report are sound, all parties must rely upon their own skill and judgement when using it. The authors do not make any representation or warranty, expressed or implied, as to the accuracy or completeness of the report. There is considerable uncertainty around the development of industrial carbon capture and the available data are extremely limited. The authors assume no liability for any loss or damage arising from decisions made on the basis of this report. The views and judgements expressed here are the opinions of the authors and do not reflect those of IEAGHG or any of the stakeholders consulted during the course of this project.

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Glossary and terminology

barg	pressure in bars above ambient or atmospheric pressure
BLS	Bow loading system
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CIF	Cost, insurance and freight contract
CIT	Conventional integrated turret
CO_2	Carbon dioxide
DP	Dynamic positioning
EEA	European Economic Area
EEZ	Exclusive economic zone
EFTA	European Free Trade Association
ELD	The Environmental Liability Directive
ETS	Emissions Trading System
EU	European Union
EUR	Euros (€)
FOB	Freedom to board contract
FRD	HiLoad floating regasification dock
FSI	Floating Storage and Injection unit
GHG	Greenhouse gas
H	Hour(s)
Heel	The total quantity of CO_2 left in the cargo tank after unloading, (liquid and gas in equilibrium)
HiLoad DP and LNG	Standalone offloading unit with DP
Hs	Significant wave height
IBC Code	The International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk
IGC Code	International Code of the Construction and Equipment of Ships Carrying Liquified Gases in Bulk
IMO	International Maritime Organisation
Km	Kilometre

LLMC	The 1976/1977 Convention on Limitation of Liability for Maritime Claims
LNG	Liquified natural gas
Low P	Low pressure, low temperature condition, -55 to -40°C, 5-10 barg
LPG	Liquid petroleum gas
MARPOL	The 1973 International Convention for the Prevention of Pollution from Ships
Medium P	Medium pressure, low temperature condition, -30 to -20°C, 15-20 barg
MEUR	Million Euros
MRV	Monitoring, reporting and verification
Mtpa	Megatonnes per annum
NH_3	Ammonia
Nm	Nautical mile
NMC	The 1994 Norwegian Maritime Code
OPEX	Operational expenditure
OSPAR	1992 Convention for the Protection of the Marine Environment of the North-East Atlantic Convention
RAS	Rigid arm system
SAL	Single anchor loading
SEVAN	Circular form stable FSI
SOLAS	1974 International Convention for the Safety of Life at Sea
SSSA	The 2007 Ships Safety and Security Act
STL	Submerged turret loading
T	tonnes
TBL	Turret buoy loading
tCO_2	tonnes of carbon dioxide
TLP	Tension leg platform
UNCLOS	1982 United Nations Convention on the Law of the Sea

Executive Summary

Overview

Carbon capture and storage (CCS) is a vital technology with numerous applications across a future low-carbon energy system. Efficient CCS at an industrial scale depends on CO_2 capture from large point sources and transfer to secure geological storage sites. As this technology option expands, onshore pipeline networks will be necessary to deliver the volumes envisaged. However, this may not necessarily be the most favourable option offshore and shipping could offer a more flexible and economic alternative.

Although liquefied CO_2 is currently transported by sea tankers, it is a relatively modest trade and in comparatively small quantities of around 2,000 tonnes. A number of recent initiatives are developing CO_2 shipping for CCS in Europe; however, shipping of CO_2 at large scale (on the order of millions of tonnes per year) requires consideration of regulatory, technical as well as economic conditions.

Element Energy, SINTEF, Brevik Engineering and IOM Law were commissioned by IEAGHG to carry out a detailed assessment of the CO_2 shipping supply chain, specifically considering the physical equipment, related handling infrastructure, operational constraints, projected costs and legal and regulatory issues that govern the marine shipment of CO_2. The study focuses specifically on the components of the shipping chain itself, which includes both shore-to-shore and shore-to-offshore options for transporting CO_2 up to the point of unloading (both onshore and offshore). Although conditions at the capture and storage sites will have implications for the shipping chain, the processes of CO_2 delivery and storage themselves are not examined here. Equally, while onshore unloading requires further infrastructure for onward transport to the storage site (e.g. a shore-to-offshore pipeline), detailed analysis of this component is out of scope for this study and it is considered only at a high-level (illustrative costs for the purposes of direct comparison between shipping options).

Phase and handling

In contrast to natural gas, CO_2 only exists as either a solid or gas at atmospheric pressure and therefore requires pressurisation to reach a liquid state. In contrast to CO_2 pipeline transport, which is typically carried out under high pressure conditions (70-100 barg), CO_2 shipping is expected to be most cost-effective under either low pressure, low temperature (Low P; -55 to -40°C, 5-10 barg) or medium temperature, medium pressure (Medium P; -30 to -20°C, 15-20 barg) conditions.

Both pressure and temperature affect a large number of the components of the supply chain including material choices, transport volumes and safety considerations. As such, trade-offs between cost and operational complexity must be considered in choosing the most appropriate transport condition. The Medium P condition is currently used for small-scale CO_2 transportation and has been adopted as the transport pressure for early CCS projects. However, the Low P condition has been proposed to be the most cost-effective and is considered the only viable option for ship sizes above 10,000 tCO_2.

While processing and handling of pure CO_2 streams is well-understood, the presence of water, oxygen and other impurities in CO_2 from anthropogenic sources can also have a negative impact on transport and storage applications. Processes to purify the CO_2 stream before or during liquefaction are therefore an integral part of the shipping chain, with both the material requirements of ship transport and injection facilities and the final use of the CO_2 stream determining the required impurity limitations.

Infrastructure requirements

The scope of this study includes the onshore (at port) infrastructure requirements, CO_2 carrying vessels and the unloading requirements, with both onshore and offshore unloading considered.

The infrastructure components of the CO_2 shipping chain (Figure 1) broadly consist of:

- **Liquefaction:** CO_2 is brought into the liquid state through a series of cooling and compression steps
- **Intermediate storage**: buffer storage is used to bridge the gap between continuous CO_2 capture and discrete (batch) transportation by ship
- **Loading/unloading equipment:** Loading/unloading equipment consists of either conventional articulated loading arms or flexible cryogenic hoses and auxiliary equipment such as cryogenic pumps and pipelines for transfer from storage to loading arm and a return line for boil off gas
- **Ship:** either a purpose-built CO_2 tanker or converted ship may be used; however, repurposing of ships is challenging if the ship is not also originally designed for carrying CO_2
- **Conditioning:** CO_2 must be brought from the liquid state to a condition for further transportation or injection after shipping, typically by heating and pumping

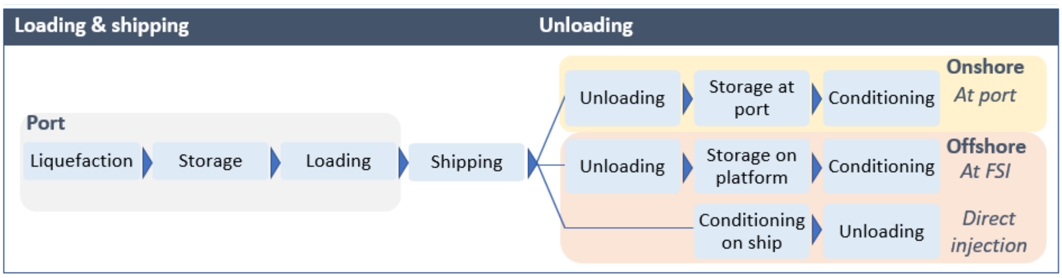


Figure 1 Overview of the components of the CO_2 shipping chain included in the detailed review and cost assessment. FSI = Floating Injection and Storage unit. Note that onshore unloading requires a shore-to-offshore pipeline for delivery to an offshore geological storage site; this component is only included at a high-level in this study.

The onshore components and processes of the shipping chain are well understood from existing (small-scale) operations. Additional components for CCS and for transport on larger scales have also been established through feasibility studies and literature reports. Whereas detailed concept designs have been prepared for ships carrying CO_2 under Medium P conditions, designs of ships for Low P CO_2 transport are typically high-level and with much less certain cost estimates.

Offshore unloading of CO_2 has been evaluated in literature studies but is as yet unproven and is much less understood than onshore processes, with no clear consensus on the most appropriate solution.

CO_2 can either be unloaded by direct injection into the well or via temporary storage on an intermediate platform, here referred to as a Floating Storage and Injection unit (FSI). The choice of offshore unloading solution and infrastructure has implications for the vessel design and costs of operation. In particular, the unloading solution affects the onboard equipment requirements, CO_2 injection rates and continuous versus batch-wise nature of delivery of CO_2 to the well. Although expensive, a key benefit of unloading via an FSI is to enable continuous injection, whereas direct injection from the ship is necessarily batch-wise with periods of inactivity between ship deliveries.

Many offshore unloading technologies suitable for CO_2 unloading are already being used in the oil and gas industry for hydrocarbon transfer (such as risers, turret solutions and others) but are not yet proven for CO_2 storage and injection. These systems differ in terms of the water depths and weather conditions that they can be used in. For FSI concepts, the potential systems also differ with regards to the suitable storage capacity that they can support and their accessibility in harsh weather. The storage capacity requirement is dependent on the CO_2 ship capacity and the need to be able to maintain continuous flow to the well during weather conditions that prevent ships connecting to the FSI. As such, the choice of solution is highly dependent on the operational requirements and the specific storage site environment.

Economic evaluation of CO_2 shipping

Ship logistics scenarios for three possible future North Sea CCS projects have been defined and used as the basis for cost estimates (Table 1). These scenarios compare two different transport conditions for onshore unloading (Low P and Medium P) as well as the two different offshore unloading options.

For each scenario, bottom-up engineering designs were prepared and ship operational profiles were estimated and used as the basis for ship cost estimates. Cost modelling of the onshore components was carried out using a detailed factor estimation method and combined with the ship costs to estimate the costs of the full shipping chain.

Table 1 Ship logistic scenarios used as the basis for the cost assessment. The shipping distance in each case is 1,000 km.

No.	Route	Unloading type	Condition before transport	Transport condition[1]	Condition after transport	Ship capacity / tCO_2	No. of ships
1	Rotterdam-Kollsnes	Onshore	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3
2	Rotterdam-Kollsnes	Onshore	1 barg, 20°C	Medium P	100 barg, 5°C	10,000	3
3A	Rotterdam-North Sea	Offshore to FSI	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3
3B	Rotterdam-North Sea	Offshore, direct injection	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3

Due to weather criterion limitations and longer unloading times for offshore unloading operations, the total roundtrip time per ship is higher than for onshore unloading (Figure 2, left). In the direct injection scenario, offloading rate is limited by the injection rate into the well, resulting in significantly longer unloading times than offloading to an FSI. For a fixed number of ships this limits the number of trips per ship per year and therefore, for a fixed number of ships, the yearly amount of CO_2 for injection is lower for offshore unloading

[1] Low P = 7 barg, -50°C; Medium P = 15 barg, -28°C

(Scenarios 3A and 3B) than for onshore unloading (Scenarios 1 and 2; Figure 2, right). The yearly amount of injected CO_2 is also reduced for the Medium P compared to the Low P condition, due to the higher volume of CO_2 required to be left in the ships tanks to maintain pressure during loading and unloading.

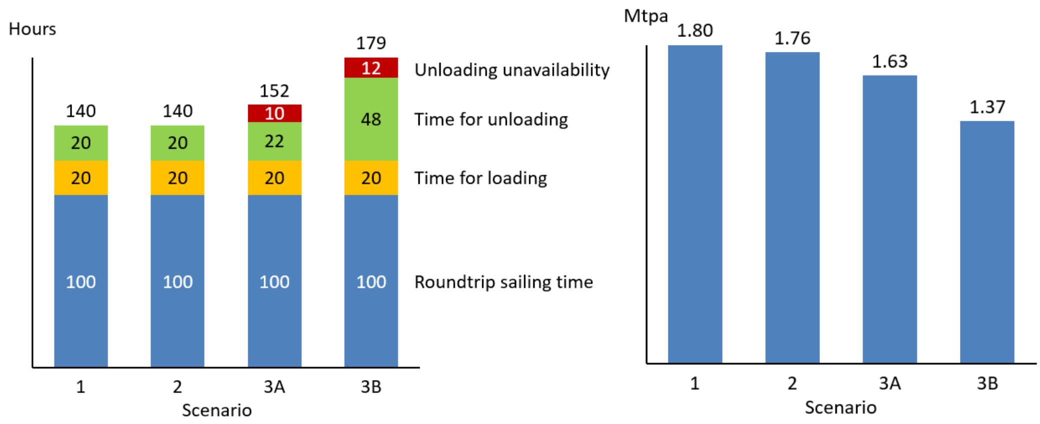


Figure 2 Total roundtrip time (left) and total injected CO_2 (right) for each shipping scenario

Considering only the shipping chain, Scenario 3A has the highest CAPEX and OPEX due to the FSI, and the highest overall undiscounted unit cost (€41/tCO_2 transported; Figure 3)[2]. Direct injection (Scenario 3B) has the lowest CAPEX and OPEX costs but stores the least CO_2 (unit cost €32/tCO_2). Scenario 1 has the lowest overall unit cost, excluding transport beyond the port (€26/tCO_2).

For the shipping scenarios to be fully comparable, a pipeline must be included between the onshore unloading site and the final offshore storage site. Inclusion of this pipeline is estimated to add a further €8/tCO_2 to the total lifetime cost of Scenarios 1 and 2, bringing the costs of onshore unloading above those of direct injection for the modelled set of transport conditions. However, it should be noted that an onshore-to-offshore pipeline is likely to be utilised by more than one project, improving the economic viability of this option.

Liquefaction accounts for 52% of the overall unit cost for Scenario 1, excluding pipeline transport. If the CO_2 is pre-pressurised prior to liquefaction, costs of the shipping chain can be reduced to €17/tCO_2; however, although pre-pressurisation reduces the cost of the shipping chain, the cost may still be borne by an earlier stage of the CCS chain.

Techno-economic modelling based on these estimated costs shows that increasing the ship size and the unloading rate can reduce costs if the number of ships can be reduced. For the flowrates considered here, increasing the size of the ship above 10,000 tCO_2 has little or only minor impact on the unit cost.

Shipping is more favourable for a project with lower CO_2 flow rates (depending on transport distance) and longer transport distances (depending on flow rate), due to the highly capital-intensive nature of pipeline costs. Liquefaction account for a large proportion of the overall shipping cost and, as such, the transport distance at which shipping becomes more cost-effective (breakeven distance) also depends on the initial pressure condition of the CO_2 delivered to the port.. For instance, for Low P shore-to-shore shipping, the breakeven distance at 1 Mtpa flow rate is 320 km for the pre-pressurised condition but 650 km for the non-pressurised condition (Figure 4).

[2] Assuming a 20 year operational lifetime.

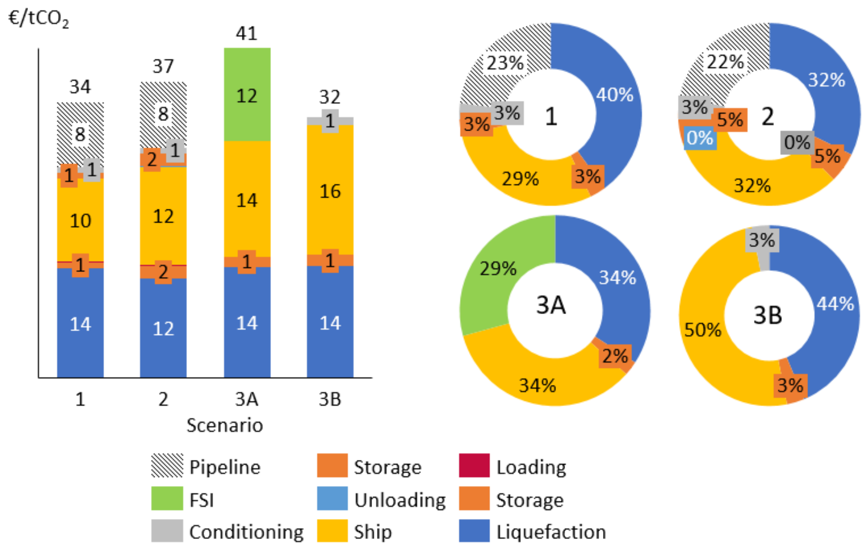


Figure 3 Unit costs (€/tCO₂) for each shipping scenario, assuming a 20 year lifetime, excluding discounting or financing. Note that loading and unloading are not visible on these charts due to the relatively small size of these cost components (0% of cost).

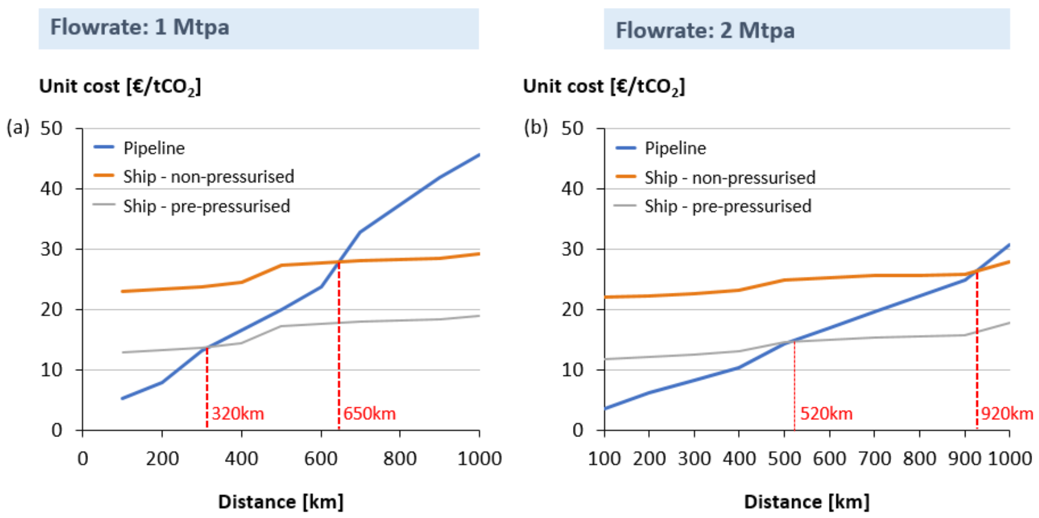


Figure 4 Unit cost of shore-to-shore shipping and pipeline transport for a range of distances for flow rates of (a) 1 Mtpa flow rate (and (b) 2 Mtpa flow rate

Regulatory implications for CO_2 shipping

Legal instruments relevant for CO_2 shipping are found in international, regional and national frameworks. Public international law, regional law and domestic law are all interlinked and one framework builds on the next. Thus, there is a need to interpret the various layers of legal instruments both separately and in combination to determine which criteria apply, as well as to identify legal gaps and issues that may potentially restrict or prevent the shipping of CO_2.

The most relevant current legal instruments at each level have been reviewed and regulatory gaps and hurdles have been identified. European Union (EU) law and Norwegian law are used as examples of national and regional frameworks with advanced provisions for CCS. Selected frameworks related to CCS-specific activities are summarised in Table 2.

Table 2 Summary of key features of selected relevant legal instruments for CO_2 shipping for CCS

Legal instrument	Key features
International Law	
1996 Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (**The London Protocol**)	• Only global agreement dealing specifically with offshore unloading and storage of CO_2 • CO_2 is regarded as waste and storage in the subsea is considered dumping, but storage of CO_2 from capture processes is exempted from general dumping prohibition • Prevents export of "*waste or other matter to other countries for dumping…*" presenting a **hurdle to establishment of international offshore storage hubs** involving cross-border elements for most of its Contracting Parties
Regional (EU) Law	
Directive 2009/31/EC on geological storage of carbon dioxide (CCS Directive	• **Main legal instrument for CO_2 storage** • Does not specifically address transport other than by pipelines therefore is **not directly relevant** • **Specifies requirement to ensure 3rd party access**
Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading (ETS Directive)	• Establishes a **scheme for greenhouse gas emission allowance trading** • Maritime sector is not covered but CO_2 transport and storage are • **Presents a barrier to CO_2 shipping for storage since only CO_2 transported by pipeline is eligible under the scheme**
Directive 2004/35/EC on environmental liability with regard to the prevention and remedying of environmental damage (ELD)	• Establishes a **liability framework against environmental damage** • Liability for incidents caused by CO_2 storage activities included after the adoption of the CCS Directive and covers transport by ship, including offloading and storage
National (Norwegian) Law	
2004 Greenhouse Gas Emission Trading Act and Regulations	• Implements the ETS Directive • Since ship transport of CO_2 is excluded from the ETS Directive, it is also excluded from Norwegian law • Ships are therefore also not required to surrender allowances for leaked CO_2

The main regulatory hurdles to CCS are the London Protocol, which prevents cross-border transport of CO_2 for storage, and the EU ETS Directive, which excludes CO_2 shipping from the greenhouse gas emissions trading scheme and therefore prevents CO_2 shipping benefitting from financial incentives of CCS. A resolution to the London Protocol was adopted on 11th October 2019 allowing a former amendment to allow for cross-border transport to be taken into use between Contracting Parties while waiting for sufficient ratifications for the amendment to become effective.. The resolution implies that this showstopper or hurdle is effectively removed from an international perspective as the early-movers do not have to wait for sufficient ratifications of Article 6 to take the amendment into use. However, the resolution does not imply project operators are automatically free to conduct these activities; it is now up to national declarations to implement the resolution and an unilateral declaration only has effect for the Contracting Party declaring pursuant to the resolution. For the amendment to Article 6 to become effective for all Contracting Parties, ratification by two-thirds of the Contracting Parties is still required.The ETS Directive does not represent an absolute barrier since EU Member States may choose to apply emissions trading to activities not currently listed in the Annex to the Directive; however, actions to extend the ETS to shipping are called for in the revised Directive to start as of 2023.

Contractual arrangements

Given the requirement in the EU CCS Directive for third-party access to be granted to CO_2 transport and storage networks, it is likely that the most natural contractual arrangement would be for the emitter to contract directly with the storage operator and for the storage operator to contract with the transporter, instead of the emitter having to contract with both the transporter and the storage operator. The choice of contracting parties will affect the type of contract to be entered into as well as the nature of any offtake guarantees included in contractual agreements.

Subject to the international and national framework on liability and limitation of such, it would typically be subject to the agreement to establish when the liability passes over at the delivery point to the ship owner or operator, and when the liability passes over at re-delivery. Metering points at CO_2 transfer would be the natural liability transfer point from a regulatory point of view, regarding who is to be held responsible of any leakage and environmental damage under the polluter-pays-principle. However, this has been identified as a cost driver and alternative contractual arrangements may be possible.

Monitoring, reporting and verification (MRV) of CO_2

Both the EU and the International Maritime Organisation (IMO) have established regimes for MRV of CO_2 in the maritime sector. Both are data collection systems establishing mandatory verification and reporting requirements, aimed at collecting emissions data to provide the basis for further policy actions to eventually reduce emissions from the shipping industry. Both operate in parallel but differ in geographic limitations; whilst the EU scheme only applies within the EU and the European Economic Area (EEA), the IMO scheme covers emissions from shipping globally. An unfortunate result of having two MRV regimes, is that ship operators will have to manage two separate reporting schemes for the fuel they use.

Recommendations

CO_2 shipping may have an important role in supporting global deployment of CCS and actions to overcome regulatory barriers must be taken to enable this. This includes revision of the ETS Directive to include shipping and increased efforts to have Contracting Parties ratify the amendment to the London Protocol in parallel with the unilateral declarations to take the amendment into use.

While this study has provided a detailed analysis of costs, operational considerations and legal frameworks for the EU case, additional research and analysis is required to further understand the global implications and variations, as well as the potential market for cross-border transport. Suggestions of further work include:

- **More detailed analysis of contractual mechanisms**, taking into account the conflicting regulatory and operational (cost) drivers related to ETS compliance.
- **More detailed investigation of availability of offshore facilities** (relevant sea-states) particularly with regard to optimal ship size.

- **Modelling of the potential for innovations in shipping** to reduce the costs and GHG impact of the CO_2 shipping chain.
- **Detailed study of different legal frameworks**, legal contractual traditions, cost implications and ports **in other regions** with potential to use CO_2 shipping (e.g. Japan and South Korea).
- **Detailed assessment of the market potential for export/import of CO_2** within Europe and/or other regions and identification of locations between which shipping of CO_2 may be feasible.
- **Inclusion of CO_2 storage infrastructure** (wells etc) in shipping cost and the impact of port-to-storage options on CO_2 storage costs (e.g. due to potential effect on injectivity).

Contents

1 Introduction

1.1 Project context

Carbon capture and storage (CCS) has been identified as a key technology that can help decarbonise power generation and energy intensive industries, as well as heat and transport when used for hydrogen production. Applying CCS across industry is integral to hitting global climate targets, with CCS expected to contribute 15-20 per cent of the required reduction in power sector emissions by 2040.[3] However CCS deployment needs to accelerate significantly if it is to play a role in combatting climate change.

To date, CCS development has primarily focused on capture and storage, with CO_2 logistics receiving little attention. Efficient CCS at an industrial scale depends on CO_2 capture from large point sources and then transfer to secure geological storage sites. As this technology option expands, onshore pipeline networks will be necessary to deliver the volumes envisaged. However, this may not necessarily be the most favourable option for offshore transport, where shipping could offer a more flexible and economic alternative.

While the levelised costs of large-scale trunk CO_2 pipelines may be lower than transport by ship, they require substantial upfront capital investment, which has been a significant challenge for previous CCS projects.[4] Recent activities in Norway[5] have shown that CO_2 shipping could be a feasible option, even for first phase CCS projects. In addition, a recent study for the UK government[6] identified a number of key opportunities that CO_2 shipping can enable, such as reducing the cost of early CCS projects, extending the economic locations for CCS and importing CO_2 from other countries.

Although liquefied CO_2 is currently transported by sea tankers it is a relatively modest trade and in comparatively small quantities (around 2,000 tonnes). The design and operation of larger scale shipping chains will need to consider regulatory, technical and economic conditions.

Element Energy, SINTEF, Brevik Engineering and IOM Law were commissioned by IEAGHG to provide a detailed analysis of the physical equipment, related handling infrastructure, operational constraints, economic evaluation and legal and regulatory issues that govern the marine shipment of CO_2.

1.2 Objectives

The objective of this study is to provide an overview of the current status of CO_2 shipping and to carry out a detailed assessment of the implications of large-scale operations on the supply chain. The study specifically considers:

- **Phase and handling implications**, and related constraints, for the trans-shipment of CO_2
- The **infrastructure requirements** for the transfer, shipment and delivery of liquefied CO_2

[3] *Energy Technology Perspectives* (2016) International Energy Agency
[4] *Lessons Learned - Lessons and Evidence Derived from UK CCS Programmes, 2008 – 2015* (2016) Carbon Capture and Storage Association
[5] https://www.gassnova.no/en/ccs-in-norway-entering-a-new-phase (accessed 29/05/2019)
[6] *Shipping CO_2 – UK Cost Estimation Study* (2018) Element Energy for Business, Energy & Industrial Strategy Department (BEIS)

- **Proposed vessel designs, capacity ranges, and innovations**, for the marine shipment of CO_2.
- **Quantifying the capital and operational costs** of different marine shipment options and evaluate the economic viability of CO_2 transfer from shore facilities to offshore storage sites.
- **Reviewing current regulatory and legal frameworks** relevant for national and international ship transport and CO_2 logistics.
- Reviewing those implications for **monitoring, reporting and verification (MRV)** of CO_2 that relate to CO_2 transport via ship and subsequent transfer to a storage site.

1.3 Scope and approach

Scope

The study specifically focuses on the infrastructure and regulatory frameworks unique to the shipping supply chain (as indicated in Figure 1-1). This includes both shore-to-shore and shore-to-offshore options for marine transport of CO_2 (onshore and offshore unloading). Here, the shipping supply chain is considered to comprise onshore and offshore components up to the point of unloading of the CO_2 (either onshore or offshore) in a condition suitable either for onward transport or delivery to storage. When comparing shore-to-shore shipping with shore-to-shore pipelines, this boundary limit is sufficient. For a direct comparison between shore-to-shore and shore-to-offshore shipping options delivering to the same offshore storage site, the additional shore-to-offshore pipeline should also be considered (as shown in Figure 1-1). Illustrative costs for this pipeline are included in this study but a detailed cost analysis of this component was outside the scope of the cost assessment.

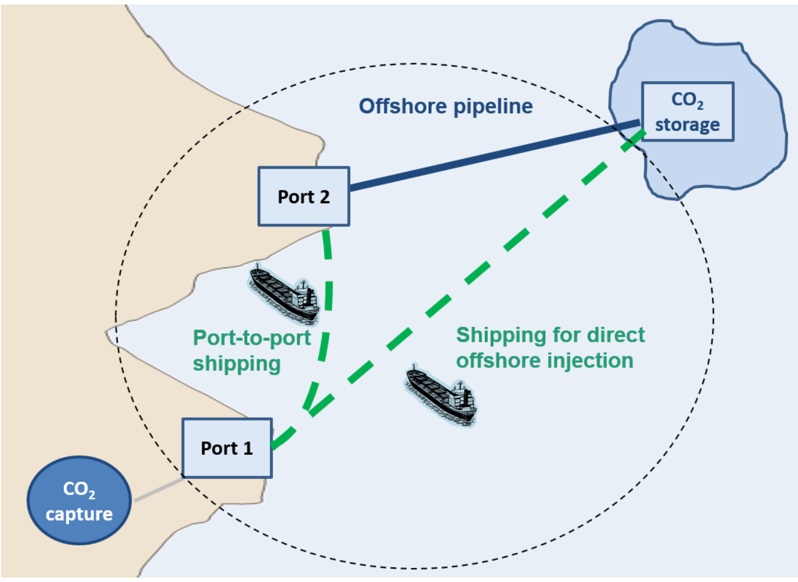


Figure 1-1 Scope of components considered in the review and cost assessment. Detailed analysis was carried out for components unique to the shipping supply chain (at port and green dashed lines); however, for the purposes of comparison between shipping options, the offshore pipeline is considered at a high-level (illustrative costs only).

The pressure condition and impurity requirements of the CO_2 as it is delivered to the port and as it is injected into the reservoir for final storage will have an effect on components of the supply chain; where relevant, these implications are included in the review but the processes of delivery and storage themselves are excluded from the scope.

The review of regulatory and legal frameworks considers the most relevant instruments at international, national and regional level. The extent to which international regulations may affect different countries is considered at a high-level, but a full comparison of legal framework for each region is outside the scope of this study.

Approach

Assessment of the status and requirements for large-scale shipping was carried out through an extensive literature review, bottom-up engineering design, techno-economic modelling and stakeholder interviews (Figure 1-2).

The infrastructure requirements, vessel designs, offshore unloading challenges, and legal and regulatory implications for CO_2 shipping were identified through detailed review of existing literature and legal instruments, building on the expertise of the study partners and drawing on experience in parallel projects.

Four shipping scenarios were defined, and a bottom-up engineering design was carried out for these scenarios, comprising vessels for CO_2 shipment and the required onshore and offshore infrastructure. Capital and operational costs were calculated based on equipment costs and operational profiles of the logistics chain.

The results of the cost assessment were used to update an existing CO_2 shipping model and the impact of operational parameters on the cost of shipping was evaluated. This included examination of the role of shipping compared to pipeline transport.

Finally, the results of the analysis were tested through interviews with 5 industry stakeholders working at the forefront of CCS logistics. An overview of the feedback received during the consultation is included in the Appendix (Section 10.1, page 92).

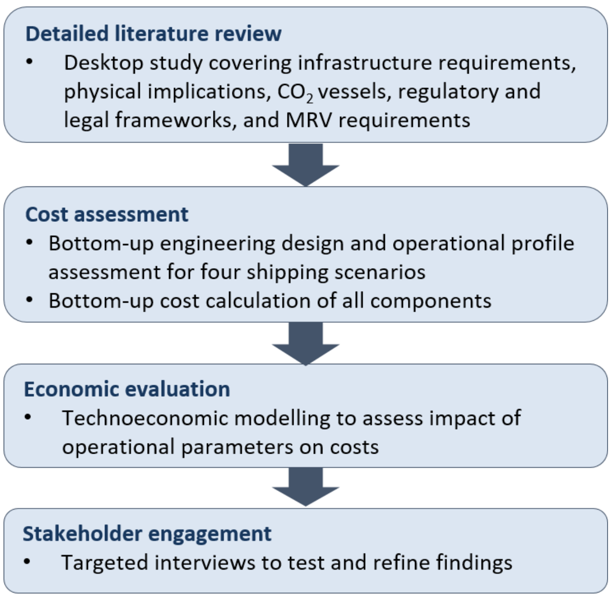


Figure 1-2 Overview of study approach

1.4 Structure of the report

Section 2 sets out the current status of CO_2 shipping, including existing operations and ongoing projects targeting ship transport for CCS.

Section 3 sets out the infrastructure and handling requirements of the CO_2 shipping supply chain, including: implications of the phase and impurity requirements of CO_2, onshore infrastructure, existing vessel designs, offshore unloading challenges and infrastructure, and conditioning requirements after transport.

Section 4 describes the basis for the cost assessment and the projected costs of large-scale CO_2 shipping for four scenarios based on possible future CO_2 shipping projects in the North Sea.

Section 5 presents the techno-economic modelling of the shipping chain, exploring the impact of ship operational parameters on the costs of the shipping chain and the role of shipping in future transport networks.

Section 6 discusses innovations in shipping with potential to reduce costs and emissions from CO_2 shipping.

Section 7 assesses the legal and regulatory frameworks relevant to CO_2 shipping at international, regional and national level. The European Union and Norway are used as examples of regional and national legal frameworks with mature provisions for CCS logistics. Contractual frameworks and implications for liability are discussed.

Section 8 describes the framework and technical aspects of monitoring, reporting and verification (MRV) of CO_2 emissions in the context of their implications for CO_2 shipping.

Section 9 provides a summary of the key findings of this study and sets out recommendations for actions and further study to support the development of CO_2 shipping.

2 The current status of CO_2 shipping

2.1 Current CO_2 shipping operations

The current trade of CO_2 in Europe is about 3 Mtpa, primarily for the food and drinks industry (about 2 Mtpa).[7] Most of the CO_2 is transported by truck or train over land. The fleet consists of both purpose-built and converted ships (see Section 10.1, page 92 for representative examples). The ships and the transported volumes are small compared to what is expected in the future CCS trade, for which a development towards larger ships/volumes and possible lower cargo pressure is expected.

One of the largest CO_2 traders is Yara International who transports most of the liquified gas by ship.[8] Yara International is an ammonia producer with production sites in Norway and the Netherlands. Their fleet of tankers sails from production sites in Norway and Netherlands to distribution and import terminals at the western coast of Europe.[7] The vessels are owned by Nippon Gases Europe Ship AS and operated by Larvik Shipping AS. Three vessels, Embla, Froya and Gerda, have a cargo capacity of 1,800 tonnes each. These vessels are converted from general cargo carriers. A fourth vessel, Iduna is a converted General Cargo Carrier/Container ship with a cargo capacity of 1,200 tonnes. The vessels carry liquified CO_2 at 15-20 bara and -30 °C.[9]

2.2 Large-scale shipping projects

Large-scale shipping of CO_2 as part of a CCS chain has been proposed for sites in the UK, including Wales,[10] and feasibility studies have been carried out for transport in Japan. The most mature CCS projects with ship-based logistics are in Europe, specifically targeting offshore storage in the North Sea.

The Full-scale CCS Project in Norway intends to develop an open access infrastructure for storing CO_2 from across Europe (Figure 2-1).[11] The transport and storage infrastructure development is being carried out by the Northern Lights consortium, comprised of Shell, Equinor and Total, and aims to be operational by 2023.[12] In the first phase of the project, CO_2 will be captured at two sites in east Norway and carried by ship to an onshore facility at Kollsnes on the west coast of Norway. A pipeline from Kollsnes to the North Sea and injection into a reservoir below the seabed will be the final link in the logistics chain. The capacity to store up to 1.5 Mtpa will be developed in Phase 1. Provided a positive financial investment decision is taken, Phase 2 could develop capacity up to a total of 5 Mtpa.

The 3D Project (DMX™ demonstration in Dunkirk), led by a consortium of 11 stakeholders, focuses on demonstration of novel capture technology but is part of a study aiming to develop a future industrial CCS cluster in Dunkirk.[13] The transport and storage aspect of the CCS chain will be supported by developments in other projects, including the Northern

[7] *Ship transport of CO_2 for Enhanced Oil Recovery – Literature Survey* (2015) Scottish Carbon Capture & Storage (SCCS)
[8] *CO_2 Ship Transport Study* (2016) Yara, Larvik Shipping and Polarkonsult
[9] DNV GL Register of Vessels
[10] *Delivering Cost Effective CCS in the 2020s: an overview of possible developments in Wales and areas linked to Welsh CCS activities via shipping* (2016) UK CCS Research Centre
[11] https://ccsnorway.com/
[12] https://northernlightsccs.eu/
[13] https://www.cere.dtu.dk/research-and-projects/framework-research-projects/3d-dmxtm-demonstration-in-dunkirk

Lights project. In practice, this is will involve CO_2 transport either by ship or pipeline from Dunkirk to Kollsnes for storage in the North Sea.[14]

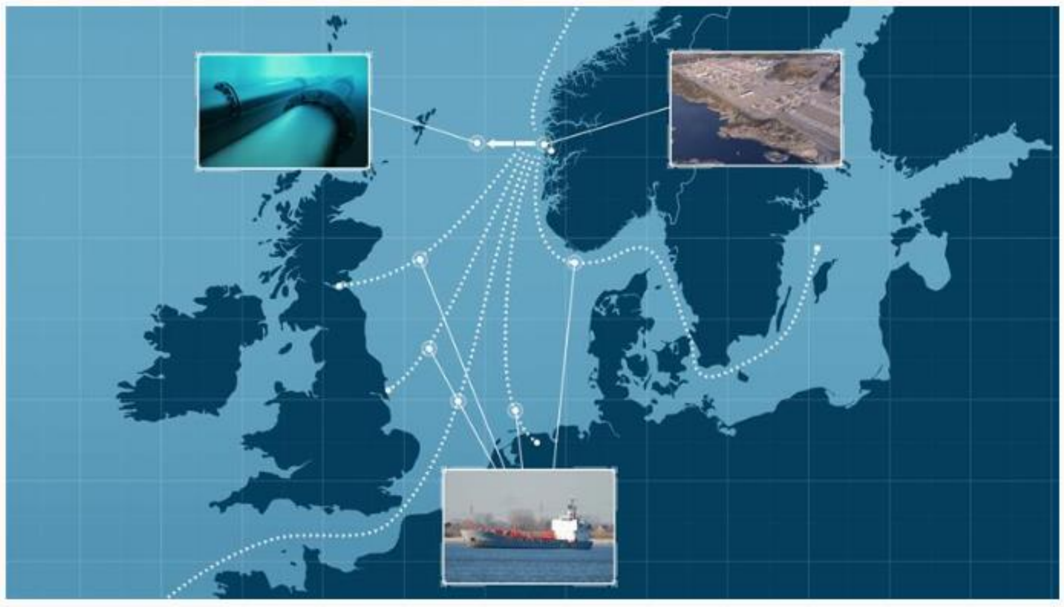


Figure 2-1 Illustration of the envisaged infrastructure network for CO2 international transport and storage network enabled by the Full-scale CCS Project in Norway[15]

The ACORN CCS and Hydrogen Project in the UK is a full chain CCS project led by Pale Blue Dot Energy and based at the St Fergus Gas Terminal in Scotland. The project aims to develop an international storage hub in the central North Sea to enable development of CCS clusters in the UK and Europe.[16] The transport infrastructure is being developed by the CO_2 SAPLING project[17] and considers both pipelines (new and existing) and shipping. It is envisaged that shipping can provide greater flexibility and reliability for storage sites, for example by allowing CO_2 to be stored at the Northern Lights site during maintenance at the ACORN site and vice versa.[18]

Finally, although not directly implementing CO_2 shipping operations, the **CO2LOS II project** is a research and development project currently underway with the aim of developing a knowledge base for CO_2 shipping. It specifically considers North Sea offshore unloading from ship to a floating offshore unit. Investigation of a 7 barg low pressure transport alternative is a key issue in this project. The project is funded by the Norwegian CLIMIT programme and a consortium of industrial partners[19] including Brevik Engineering (project owners), SINTEF; ongoing findings from this project have supported the work presented in this report.

[14] https://www.thechemicalengineer.com/news/european-consortium-launches-co2-capture-demonstration-project/
[15] Image source: http://www.gassnova.no/en/ccs-in-norway-entering-a-new-phase
[16] https://pale-blu.com/acorn/
[17] https://pale-blu.com/co2-sapling/
[18] A. James, Pale Blue Dot Energy *Acorn CCS a Smart Route to Delivering Carbon Capture and Storage in the UK* Early Career Researcher Led Webinar: CO_2 Capture and Storage Researchers' Forum 22nd October 2019.
[19] Other project partners are Equinor, Total, Gassco, Sogestran Group and Air Liquide.

3 Infrastructure and handling considerations of large-scale CO_2 shipping operations

The components of the CO_2 shipping chain are shown in Figure 3-1. The chain includes all components from the point of arrival of CO_2 at the exporting port to the point of conditioning the CO_2 for either ongoing transport or injection to storage.

CO_2 is first liquefied to bring it into a condition suitable for transport by ship and stored in liquefied form in temporary storage tanks. From the tanks, it is loaded onto the ship via a cargo handling system and then transported to the destination.

For port-to-port (shore-to-shore) shipping, the CO_2 is unloaded to temporary storage tanks at the importing port and then pumped and heated to conditions suitable for pipeline transport.

Where the CO_2 is transported directly to the storage site (shore-to-offshore), it can either be unloaded to an offshore platform before conditioning and injection, or it can be conditioned on board the ship and injected directly into the storage site.

Onshore unloading is well understood from current CO_2 shipping operations and from large-scale shipping of similar gases (such as LNG and LPG). Offshore unloading is as-yet unproven and much less understood than onshore processes, with no clear consensus on the most appropriate solution.

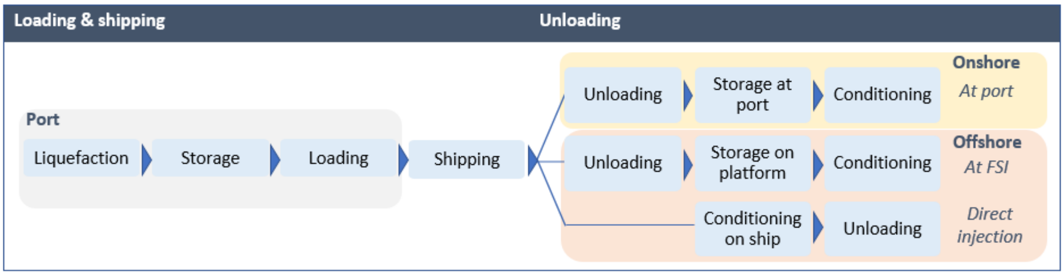


Figure 3-1 Components of the CO_2 shipping chain included in the detailed review and cost assessment. FSI = Floating Injection and Storage unit.

3.1 CO_2 phase and handling considerations

3.1.1 Effect of pressure on the CO_2 shipping chain

In order to be cost-effective, CO_2 should be in a dense form (not gaseous) for both ship and pipeline transportation. In contrast to natural gas, CO_2 only exists as either a solid or gas at atmospheric pressure and therefore requires pressurisation to reach a liquid state. For shipping, this means that CO_2 must be stored and transported using fully pressurised tanks.

Effect of pressure on tank operation and design

During operation, CO_2 is present within storage tanks in both gaseous and liquid form. To prevent damage, the pressure on a storage tank needs to be continuously maintained which in practice means that tanks are never completely filled or completely emptied.

During loading, a share of the volume is left for the gaseous phase in order to avoid hydraulic lock which otherwise can cause catastrophic equipment failure.[20,21] According to the International Code of the Construction and Equipment of Ships Carrying Liquified Gases in Bulk (IGC Code), the maximum filling level in the cargo tanks is 98%.

During unloading, pressure is maintained either by leaving a small volume of liquid for vaporisation within the tank or by transferring gaseous CO_2 between the receiving and unloading tanks. The total quantity of CO_2 left in the cargo tank after unloading, (liquid and gas in equilibrium) is called the heel. Both the maximum filling volume and the heel are determined by the transport pressure and the pressure requirement of the cargo pump.[22] Together, these factors affect the overall quantity of CO_2 that can be transferred between tanks and, ultimately, the net carrying capacity of a shipping chain.

Both the maximum allowable size and required wall thickness of CO_2 storage tanks vary with the design pressure. The wall thickness increases with increasing pressure,[23] with a limiting wall thickness of 40 mm recommended (regardless of pressure) according to the IGC Code. This limit is related both to requirements for thermal weld stress-relieving and special considerations related to testing and material quality. The maximum allowable tank size decreases with increasing pressure,[24] requiring a greater number of smaller tanks to carry the same quantity of CO_2 under high pressure conditions compared to low pressure conditions.

Choice of CO_2 transport condition

Three main pressure conditions have been considered for CO_2 shipping, with associated temperature requirements:

- **Low pressure and temperature (Low P):** -55 to -40°C, 5-10 barg (close to the triple point)
- **Medium pressure and temperature (Medium P)**: -30 to -20°C, 15-20 barg
- **High pressure and temperature (High P)**: 10 to 30°C, 45-70 barg

In addition to tank size and operation, both pressure and temperature affect a large number of the components of the supply chain including material choices, transport volumes and safety considerations. As such, trade-offs between cost and operational complexity must be considered in choosing the most appropriate transport condition.

Although CO_2 pipeline transport is typically carried out under high pressure conditions (70-100 barg), no precedents for the High P condition exist for CO_2 shipping and it is not considered likely to be suitable due to the low volumes and high costs associated with this condition.[25]

The Medium P and Low P conditions correspond to two standard transport modes of liquified petroleum gas (LPG). The Medium P condition is currently used for small-scale CO_2 transportation and, as such, has been adopted as the transport pressure for the first phase

[20] *CO_2 Ship Transport Study* (2016) Larvik Shipping, Yara and Polarkonsult for Gassco
[21] Hydraulic lock can occur due to heat ingress, which can result in rapid transient pressure spikes.
[22] The Net Positive Suction Head Required (NPSHr), the minimum pressure at the suction port of the pump to keep the pump from cavitating.
[23] In accordance with guidelines of the Pressure Vessel Handbook.
[24] In accordance with the Ship Classification Society Rules, such as those issued by DNV GL.
[25] As discussed during stakeholder engagement

of the Northern Lights project. However, many literature studies and reports consider the Low P condition to be the most cost-effective.[6]

Table 3-1 summarises the implications of the Medium P and Low P conditions across the supply chain.

Table 3-1 Summary of trade-off factors between pressure states of CO_2

Factor	Medium P	Low P
CO_2 density	1 060 kg/m³ ✗ Less CO_2 is transported per tank for a fixed volume, and larger volume capacity is required for a fixed mass	1 153 kg/m³ ✓ More CO_2 is transported per tank for a fixed volume, and smaller tanks are required for a fixed mass
Liquefaction	✓ Lower energy requirement for liquefaction (cooling and compression).	✗ Greater energy requirement for liquefaction (around 10% higher).
Transport and storage tank design	✗ Greater wall thickness is required, increasing weight and cost per volume stored and affecting workability. ✗ Storage tanks must be smaller, requiring more tanks and therefore higher capital and operational costs. ✓ Less expensive materials such as carbon steel may be used (depending on impurity levels, see next section).	✓ Wall thickness can be lower, reducing weight and cost. ✓ Storage tanks can be larger, resulting in lower operational and investment cost. ✗ Higher quality material may be required to handle the lower temperature (close to -50°C), increasing material costs, but not the installation cost.[26]
Ship design and operation	✗ Greater number of tanks increases required ship size, increasing cost. ✗ Higher fuel consumption due to increased weight of tanks	✓ Lower number of tanks reduces required ship size, reducing cost. ✓ Lower operational and investment cost due to lower weight of tanks
Heel	✗ 4%, greater impact on transport capacity.	✓ 1.6%, lower impact on transport capacity.
Water content limit	✗ More strict requirements to avoid hydrate formation than Low P	✓ Less strict requirements – up to 100 ppmv.
Dry ice formation	✓ Little dry ice formation in the event of a pressure drop	✗ As the condition is close to the triple point, the margins for formation of dry ice are smaller with implications for required control systems and relief valve streams.

[26] DNV GL rules accept manganese steel for pure CO_2 down to -48 °C.

Factor	Medium P	Low P
Safety margin	✓ Risks and safety requirements are well understood, and operation is far from triple point.	× Safety concerns due to proximity to the triple point, but with safety measures (control system and valves) in place it is expected to be safe.

3.1.2 Purity requirements

Depending on the CO_2 emission source, the type of fuel and the capture method used, the CO_2 product stream may contain several impurities which may have a negative impact on transport and storage applications. For example, the presence of water in the CO_2 stream poses issues of hydration, freezing and corrosion, whereas other impurities (such as H_2S, N_2 and others) can also affect phase behaviour and induce solidification.

The impurity limitations depend not only on the requirements of ship transport itself, but the final use of the CO_2 stream, for example:

- CO_2 pipeline transport mainly requires the removal of water and oxygen in order to prevent corrosion and other defects in the pipelines
- For enhanced oil recovery, very low oxygen contents are permitted since oxygen could react with the hydrocarbons within the oil field

Some water is removed during the compression stages of liquefaction, but it is likely that the water content will remain higher than the required limit and additional purification may be needed. The water content of the CO_2 is even more important for ship transport than for pipeline transport due to the higher risk of hydrate formation at the lower pressures and temperatures used. Dehydration technologies are known and available and it is likely to be more cost-beneficial to reduce the water content than to use water resistant materials during the transport. Further removal of water is expected to be achieved with the use of known methods such as triethylene glycol or solid bed desiccants.

Several methods to remove oxygen may be considered including catalytic oxidation of carbon monoxide, catalytic oxidation of propane, catalytic oxidation of methanol, cryogenic distillation, oxidation of coal, catalytic oxidation of hydrogen and chemisorption of oxygen on copper.[27] The catalytic oxidation of hydrogen or cryogenic distillation are considered the most promising technologies. Other impurities may be removed by distillation.

Several CO_2 specifications and recommendations for impurity limitations have been published. The most cited CO_2 quality recommendation was suggested in the DYNAMIS project in 2008.[28,29] In 2012 and 2013, the National Energy Technology Laboratory (NETL) issued Quality Guidelines outlining recommended impurity limits to be used for carbon steel pipelines and onshore storage in reservoirs.[30] The limits in these guidelines may also be viable for ship transport but, as the pressures and temperature are different, the limitations for the impurities may need to be more stringent. Impurities can have an effect on the

[27] Abbas *et al.* (2013) Energy Procedia vol. 37 p. 2389–2396
[28] DYNAMIS, Project No. 019672, DYNAMIS CO_2 quality recommendations; Towards Hydrogen and Electricity Production with Carbon Dioxide Capture and Storage. 2009, DYNAMIS Consortium 2006-2009.
[29] de Visser, E., et al. (2008) International Journal of Greenhouse Gas Control **2**(4): p. 478-484.
[30] NETL Quality Guidelines for Energy System Studies, CO_2 impurity design Parameters, DOE/NETL-341/011212. (2012) and (2013).

thermodynamics, requiring a higher compression energy for liquefaction compared to pure CO_2.

The current recommendations for CO_2 specification for the Norwegian full-scale project are for less than 30ppm water, and less than 10ppm each for oxygen, sulfur dioxides and nitrous oxides.[31]

3.2 Onshore infrastructure

3.2.1 Liquefaction

The technology for liquefaction of pure CO_2 is not novel. However, the corresponding process for liquefaction of anthropogenic CO_2 is more complex due to the presence of impurities. The main challenge for large-scale CO_2 liquefaction lies in complying with the impurity limitations set by the transport/storage infrastructure operator while limiting the loss of CO_2.[32]

CO_2 liquefaction is carried out using a combination of process stages of compression and cooling. There are two main methods for liquefying CO_2:

- **Internal cooling loop (compression only):** CO_2 is compressed to 70 barg and then decompressed to the transport pressure;
- **External cooling loop (compression and cooling):** CO_2 is compressed to the transport pressure and cooled with an external cooling loop, for example using cold NH_3.[33]

Internal cooling loop systems are simpler but typically less efficient than external cooling loop systems. Liquefaction can also be carried out using a combined internal and external cooling method, in which CO_2 is compressed to 20 barg, cooled by an external cooling loop (NH_3) and then decompressed to the transport pressure. This method is primarily relevant for transport pressures lower than 15 barg.

The choice of liquefaction method depends on factors including:

- The state of the CO_2 before liquefaction (either pre-pressurised, at 70-100 bar, or non-pressurised, at 1-2 bar)
- The required transport condition
- The temperature of available cooling water
- Availability/desirability of an external refrigeration system (e.g. using ammonia)

Water removal is an essential part of the liquefaction process, with water removed down to the water content specification. Dehydration occurs through condensation at the cooling stages followed by duplex[34] regenerative adsorption columns to achieve <50 ppm water content. Impurities such as N_2 and Ar can be removed through distillation after liquefaction and prior to the final expansion to the storage pressure.[7]

The main energy drivers are compression of the CO_2 and pumping for the cooling circuit. The overall energy requirements for the liquefaction processes range from 110-123

[31] These recommendations are based on input from stakeholders in the project.
[32] CO_2 may be lost during purification steps if small amounts of CO_2 are removed with the impurities.
[33] Cold NH_3 is prepared through compression and decompression. Although there are potential health and safety implications of using large quantities of NH_3, it has been used extensively in industry for decades with extensive knowledge of handling considerations to minimise risk.
[34] Two drying columns are used, one in use and another in regeneration.

kW/tCO_2.[35] Compared to the energy for compression for pipeline transportation, the liquefaction processes need 11-14% more energy for comparable purification duty and service availability. Several literature studies have considered methods to increase the efficiency and thereby reduce the energy cost for the liquefaction process.[36,37,38]

3.2.2 Intermediate buffer storage

Onshore intermediate buffer storage is required in the CO_2 shipping chain to bridge the gap between the continuous process of CO_2 capture and the batch-wise process of ship transportation. Buffer storage is typically carried out in pressure vessels. It is possible for saline aquifers to be used, but it is very challenging and is therefore not considered further in this report. Whereas permanent onshore storage of CO_2 has experienced difficulties with health and safety regulators and public acceptance,[39] intermediate storage of CO_2 at process sites do not experience the same challenges. This is due to the lower volumes stored as well as the possibility to inspect vessels compared to underground storage.

The total capacity of the buffer storage is an important parameter and is dependent on the ship size and logistics cycle. The buffer storage should hold at least the same volume of the produced CO_2 at the source as the capacity of one ship. It has been discussed in the literature whether some extra capacity should be included in the buffer storage to account for delays or unexpected issues since, if the storage reaches capacity, the capture plant would be required to temporarily shut down and/or CO_2 would be need to be vented. Literature estimates for buffer storage vary from 100-150% of the ship carrying capacity.

Pressure vessels for buffer storage can be horizontal, spherical or vertical tankers, depending on the available area. Spherical vessels will have the advantage of reduced wall-thickness and therefore reduced steel quantity but construction may be more expensive and the tanks will take up more space, Horizontal tankers are most common, convenient and space effective, especially for small volumes where the tankers may be transported by road. At process sites where space is limited, vertical vessels are the most common.

As discussed in section 3.1.1, the size of the tanks is determined by the cargo system design pressure, and the material choice is dependent on the design temperature and the impurity levels. While carbon steel may be used for temperatures above -50 °C, lower temperatures and higher impurity contents will require more sophisticated alloys. For example, nickel steel or carbon steel with manganese may be suitable candidates. Loading and unloading

Equipment for onshore loading and unloading of liquefied gases are proven technologies and are currently in use for several gases worldwide. Conventional articulated loading arms developed for other cryogenic liquids such as LPG and liquefied natural gas (LNG) are suitable for CO_2. During loading and unloading, gases are transferred to the pipelines using a pump located close to the buffer storage tanks. A second line is required to transfer the heel volume between the loading and unloading tanks, and any boil-off gas produced during loading is returned to the liquefaction plant.

Alternative options for loading and unloading include flexible cryogenic hoses and insulated pipelines but these are considered to be less reliable with higher risk of failure and leakage.[40]

[35] Aspelund, A. et al. (2006) Chemical Engineering Research and Design, 84(9): p. 847-855.
[36] Alabdulkarem, A. et al. (2012) Applied Thermal Engineering 33-34: p. 144-156.
[37] Lee, Y., et al. (2017) International Journal of Greenhouse Gas Control 67: p. 93-102.
[38] Engel, F. and A. Kather, (2018) International Journal of Greenhouse Gas Control72: p. 214-221.
[39] Brunsting, S., et al (2011) Energy Procedia, 4: p. 6376-6383.
[40] Knowledge sharing report – CO_2 Liquid Logistics Shipping Concept (LLSC). Overall Supply Chain Optimization (2011) T. Vermeulen.

Loading and unloading equipment contributes only a small proportion of the total cost of the CO_2 shipping chain. However, the loading time is a significant parameter since it contributes to the overall journey time per ship which ultimately determines the number of ships required to deliver a specified flow rate.

3.3 Vessels for CO_2 shipping

3.3.1 CO_2 ship design

The main drivers of ship design and cost are the design requirements of the tanks and the equipment requirements of the unloading condition (onshore or offshore).

For a fixed cargo capacity, the ship size will vary with the tank size and number of tanks. The tanks are not a part of the ship structure and must be fitted within the cargo spaces of the vessel. Tanks must also be appropriately spaced to allow for inspection. In general, large diameter tanks are more space efficient and provide a more favourable ratio between storage capacity and steel weight and hence require smaller ships to carry the same weight of cargo. However, geometrical constraints of the vessel must be taken into account for decision on the optimal relation between ship and tank design.

For offshore unloading, additional space will be required for unloading equipment and, in the case of direct injection, for on-board conditioning equipment (see Section 3.4 for further details).

A number of vessel designs for the Medium P and Low P condition have been proposed and are described in the following sections.

Ships for Medium P CO_2 transport

The Medium P condition is a more mature concept than the Low P condition since small scale ships with capacities below 2,000 tCO_2 are presently in operation. A number of detailed concept designs have been prepared for larger capacity ships as part of the Norwegian full-scale project.[8,41,42] The concepts are well-defined and demonstrated to be feasible. Costs are available for these designs, informed by equipment vendors and experience of shipyard costs.

The proposed designs use a double parallel tank lay-out with 2 by 2 horizontal tanks and, in some cases, with an additional tank in the bow (see Figure 3-2 and Figure 3-3). Due to structural restrictions related to the tank diameter, 10,000 tCO_2 is considered to be the upper limit for Medium P ships with this layout. Other ship layouts may allow for larger cargo quantities but this would require new designs, which adds a significant premium to the cost of the subsequent shipping chain and is technically challenging.

[41] *CO_2 ship transport study – Concept study report* (2017) Brevik Engineering
[42] *Concept study of CO_2 transport by ship as part of the Norwegian CCS Demonstration Project* (2017) Polarkonsult, Praxair, Larvik Shipping

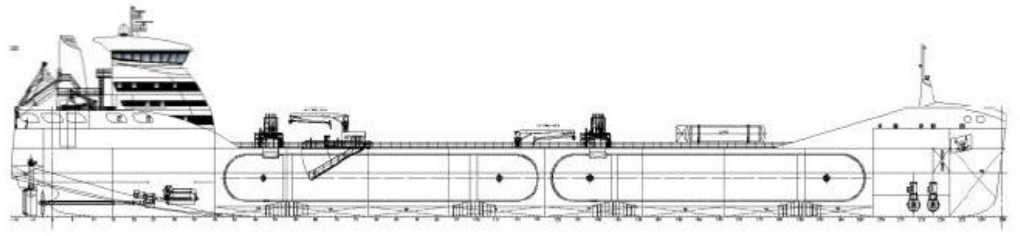


Figure 3-2 New build concept for a 10,000 tCO_2 carrier based on a four tank, twin layout[42]

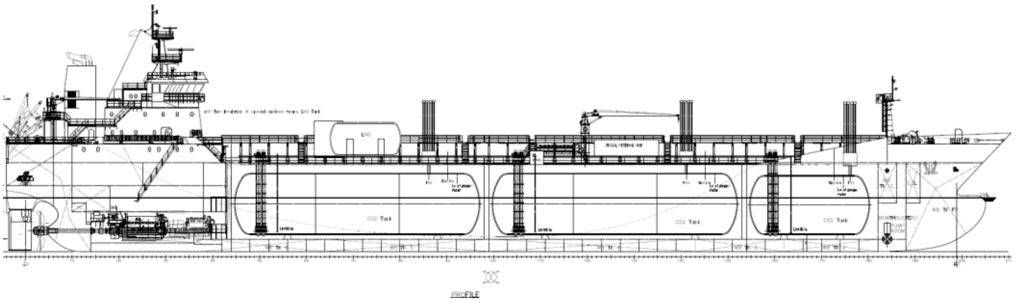


Figure 3-3 Concept based on existing ship model for a 10,000 tCO_2 carrier. The concept may also be applied as conversion of a cargo ship [41]

Low pressure CO_2

Designs for Low P CO_2 transport are typically based on LPG ships operating at similar temperature and pressure conditions, with tanks arranged in pairs horizontally. However, due to the different characteristics of CO_2, technical solutions for LPG cannot be directly transferred to CO_2 shipping (see also Section 3.3.2). There are no low-pressure CO_2 vessels in operation today, therefore the technical maturity of the proposed designs is limited, focusing on high-level concepts and with much less certain cost estimates.

Low P designs are characterised by the possibility of installing larger tanks compared to medium pressure alternatives. With larger tanks the total number of tanks can be reduced, and the ship can be smaller, reducing the construction cost. Conversely, larger capacity ships are also possible for the Low P condition. Using conventional designs, up to 20,000 – 30,000 tCO_2 capacities are possible[40,43] and considered likely to be used in near-term ship transport.[44] Using non-conventional design concepts, capacities of over 100,000 tCO_2 have been proposed in the literature.[43] The largest ship design concept arranged a large number of small tanks vertically (91 x 1000 m^3), offering more flexibility in the arrangement of tanks than conventional designs and promising the potential to better adjust capacity to a given ship size.

Spherical tanks are a well-proven concept and suitable for transporting CO_2; however, most studies indicate that this will be a more expensive solution than cylindrical tanks onboard a ship. Alternative designs such as multi-lobe tanks are used in gas carriers primarily for lower pressure than will be required for CO_2. Further technology development is expected.

[43] Yoo et al. (2013) International Journal of Greenhouse Gas Control vol. 12, p 323-332
[44] As discussed during stakeholder consultation.

Examples of early concepts for low pressure transport are shown in Figure 3-4, Figure 3-5 and Figure 3-6.

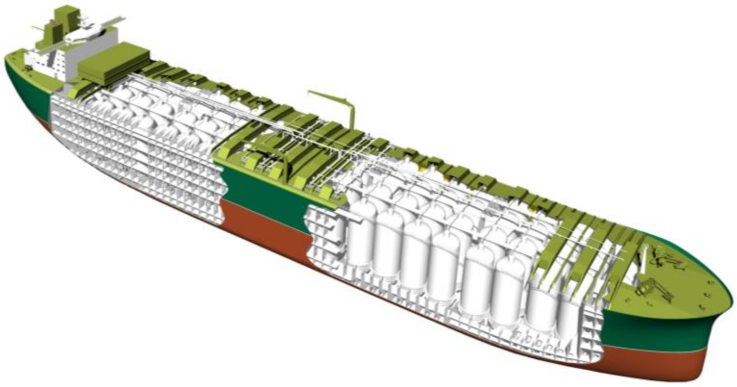


Figure 3-4 Brevik Green Tanker Concept design for Low P transport. Design intended for combined trades of CO_2 and crude oil transport, intended for EOR projects[45]

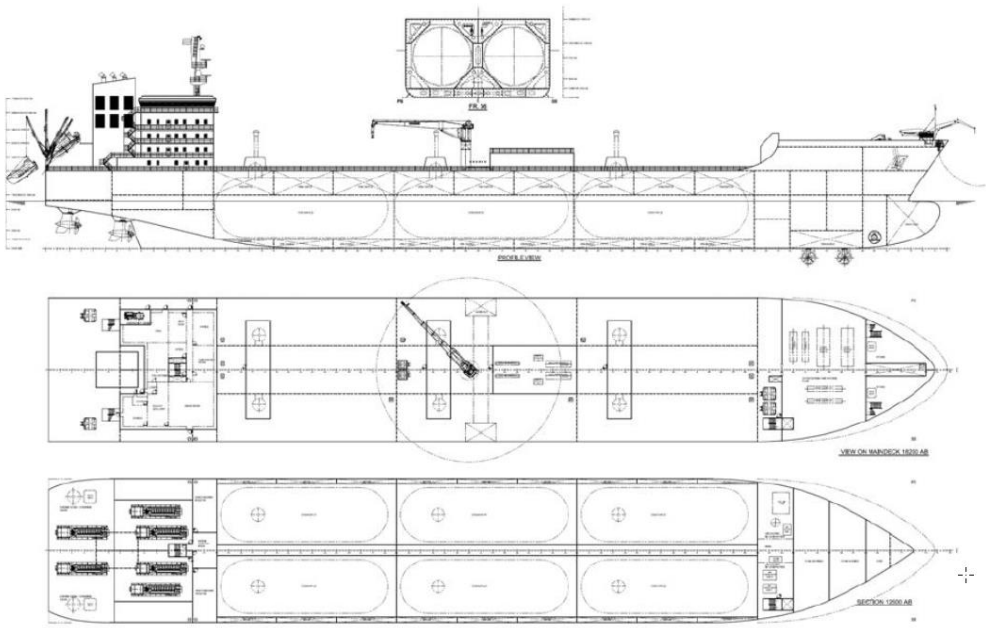


Figure 3-5 Ulstein Sea of Solutions concept design for Low P CO_2 transport based on semi-refrigerated LPG ship design, with total capacity 23,000 m³ (26,500 tCO_2).[40]

[45] Green Tanker Concept (2008) Brevik Engineering

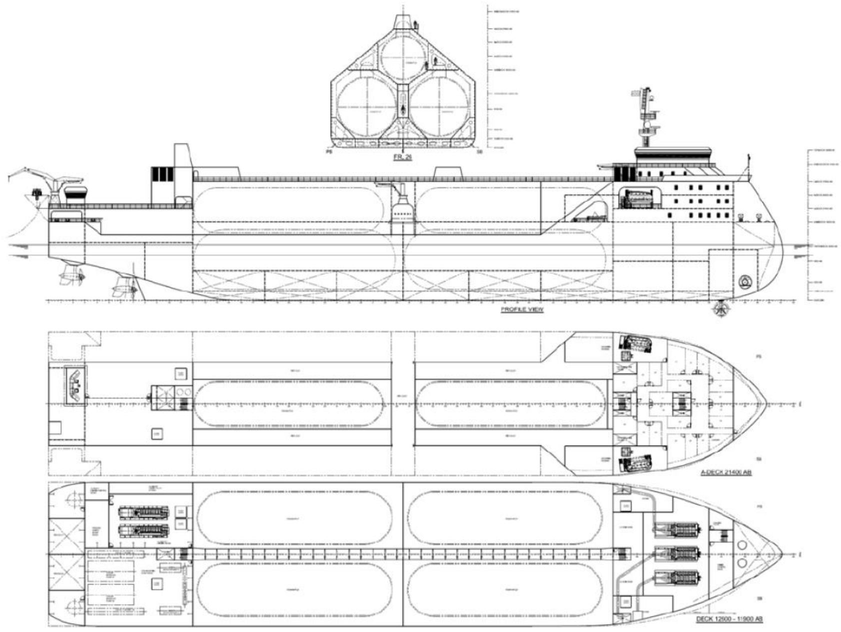


Figure 3-6 Ulstein Sea of Solutions concept with capacity of 35,000 tCO_2. [40]

3.3.2 Re-use and multi-use of ships

Newbuild vs retrofit

In addition to commissioning newbuild CO_2 tankers, conversion of existing ships is attractive as a means of reducing the time from investment decision to operation, and for reducing CAPEX for projects with a short depreciation period. There is a precedent for conversion among smaller CO_2 carriers, since the Nippon Gases Europe AS-owned ships currently in operation (Froya, Gerda and Embla, see Appendix Section 10.1) are all converted general cargo ships. As such, conversion may be an option also for larger ships.

However, there are several drawbacks to retrofit including:

- **The donor ship's hull and cargo holds are not optimised for the CO_2 tanks**. The cargo capacity may therefore be significantly smaller than a purpose-built CO_2 carrier of the same size. As a result, the OPEX per unit of transported CO_2 may be significantly higher.
- **The geometry of the cargo holds may require smaller CO_2 tanks to be fitted**, increasing the total number of tanks for a fixed volume and therefore increasing cost.
- **Using an older ship will lead to a shorter operational life** for CO_2 transportation.

A commercially successful conversion requires a minimum of modifications and maximum use of installed systems in the donor ship. The most likely donor candidate would be a bulk carrier where CO_2 tanks can be installed in the cargo holds. Altering the watertight bulkheads or carrying out major modifications of the deck will lead to an extensive conversion scope which is most likely not commercially feasible.

A bulk-carrier up to 125 metres in length will normally have three cargo holds whereas larger ships will normally have 4 or more cargo holds. If the existing ship layout allows for major deck modifications to be avoided then three or four cargo tanks may be fitted; otherwise, six or eight tanks may be required in order to avoid major structural modifications.

Repurposing of ships for CO_2 transport

Several studies have investigated the use of existing fully pressurized LPG and ethylene carriers for transport of CO_2 (see Section 10.3 for further details).[46] However, this option is considered to have limited potential if the ships are not also originally designed for carrying CO_2 since there are significant operational challenges.

For example, LPG has a density of 550-700 kg/m^3 while liquid CO_2 has a density of ~1050~1200 kg/m^3 depending on temperature and pressure. This has several effects:

1. **Only 50-60 % of the tank capacity may be utilised** compared to LPG due to the difference in the ship's displacement. Partial filling of the tanks results in sloshing inside the tanks which again have a structural impact on the tanks and on motions of the ship.

2. **The allowable pressure is reduced** compared with LPG. In addition, comes the higher dynamic loads from sloshing which further reduces the maximum allowable pressure. In practical terms this means a gas-carrier capable of containing LPG at pressures up to 7.5 barg will be able to contain CO_2 at ~7 barg, however the exact pressure must be calculated for each vessel.

The majority of fully pressurised LPG carriers are designed to operate with liquified gas down to -48°C and pressures up to 7 barg. Specialized ethylene carriers are capable of transporting liquified gas down to -104°C but at lower pressure than 7 barg. Some of the smallest LPG carriers have tanks capable of containing LPG at 17-18 barg pressure. Due to the high pressure, the tanks and the ships are small (3,000-4,000 m^3). Accounting for the different density of CO_2, these ships may carry 2,000-2,500 tCO_2 at medium pressure.

There are also some carriers capable of carrying LPG at 10-11 barg at -48°C. For such a tanker, 8.5 barg at -47°C could be an option for CO_2 transport. Since only 50-60% of the capacity can be used, a ship with 5,500 m^3 cargo hold would only be able to transport around 3,000 tCO_2.

In practice, converting between cargo gases is likely to be most feasible for a single conversion only. This option could provide a means to de-risk projects by providing a second use for ships after shorter-term CO_2 shipping operations.[47]

3.4 Offshore Unloading

3.4.1 Considerations and challenges

For offshore storage, transport of CO_2 directly to the well for offloading and injection may be an attractive alternative to shore-to-shore shipping followed by subsequent pipeline transport.

CO_2 can either be unloaded by direct injection into the well or via temporary storage on an intermediate platform, here referred to as a Floating Storage and Injection unit (FSI).[48] The main advantages of offloading to an FSI are the ability to provide a continuous injection flow to the reservoir while still providing rapid unloading of the ship. For direct injection, unloading

[46] Reviewed in *Feasibility study for ship-based transport of ethane to Europe and back hauling of CO_2 to the USA* (2017) IEAGHG
[47] As discussed during stakeholder consultation
[48] Possible future naming convention for a CO_2 offshore temporary storage facility

is necessarily batch-wise and the unloading rate is limited by the injection rate at the well,[49] leading to much longer unloading times compared to unloading to an FSI. Direct well injection from ship also requires conditioning equipment to be installed on each ship instead of just one system on the FSI. Conditioning of the CO_2 to the corresponding temperature and pressure for the reservoir is necessary to avoid hydrate formation and large temperature changes in the well.

However, the construction and operation of an FSI will be a major cost driver. The FSI is a manned facility with a storage capacity exceeding the cargo carrying capacity of one ship in the logistics chain.

Most of the technologies required for offshore unloading are already being used in the oil and gas industry but offshore unloading of CO_2 is currently unproven. Irrespective of whether the CO_2 is unloaded directly to the well or via an FSI, general challenges include:

- **There will be periods with sea-states which will not allow ships to connect for offloading**. Harsh weather conditions can prevent ships connecting to offshore unloading systems. This requires higher buffer storage across the whole value chain and/or higher acceptance of venting CO_2 to air when storage capacities are reached.
- **Due to being an off-grid operation, conditioning of CO_2 for injection is expected to be significantly more expensive** offshore than onshore.
- **Offshore conditioning, vessel unloading and station keeping requires energy** which will normally be generated using fossil fuel which increases the greenhouse gas impact of the logistics cycle compared to a shore-to-shore solution.

Batch-wise vs continuous injection

Continuous injection is considered the best option for maintaining a stable injection pressure, temperature and flow. However, batch-wise injection is the only feasible option for direct injection from the ship to the well.

Batch-wise injection is characterised by intermittent injection of CO_2 at low temperatures (close to negative) and at high rates. Batch-wise injection is discussed in several studies related to CO_2 ship transport and storage, and the following risks have been discussed:

- **Possible impairment of injectivity due to salt precipitation and hydrate formation in the near-well zone:** Studies show that batch-wise injection can either enhance or prevent injection impairment.;[50] It is recommended to perform case specific simulations as the optimum injection rate and batch-wise scheme depend on reservoir properties..
- **Damage to casings and well barrier materials**: where cold cargoes are unloaded episodically with thermal recovery between injection cycles, casings and well barrier materials could expand and contract, causing them to crack or de-bond at interfaces. To avoid leakage paths through wells it is therefore important to understand within which temperature intervals it is safe to operate.[51]

[49] The maximum injection rate will depend on the properties of the well itself rather than the injectivity of the reservoir or an increase in the bottom hole pressure. The injection rate during batchwise injection could be between 30-40 kg/s
[50] Marielle Koenen TNO Netherlands, part of ALIGN CCUS project, February 2019
[51] SINTEF, Study of Thermal Variations in Wells During CO2 Injection, 2014.

- **Possible hydraulic fracturing of the reservoir rock and possibly the caprock**: due to both higher injection pressure and low temperature of the injected CO_2, leading to loss of containment.
- **Risk of formation of back-flow:** frequent thermal and pressure cycling of the injection well and shutdown of the well risks formation of back-flow in the lower part of the well.[52] It is assumed the challenge can be mitigated to a certain extent by heating the CO_2 before injection. However, heating of CO_2 prior to injection should be minimised as this requires large amounts of energy.
- **Reduced yearly storage potential:** with batch-wise injection the well will be out of operation for periods between arrival and connection of ships, reducing the yearly potential storage volume for a given number of wells.

The degree of risk and therefore suitability of batch-wise injection is expected to be specific to each reservoir and would need to be assessed on a case-by-case basis. While the feasibility of batch-wise injection for CO_2 injection remains uncertain, it is important to include this option as it may provide significant cost savings by not requiring an intermediate floating offshore storage and injection facility (FSI).

3.4.2 Offshore unloading infrastructure

Direct injection to the well requires a gas transfer system to connect the ship to the well. For unloading to an FSI, two gas transfer systems are required, one between the ship and the FSI, and one between the FSI and the well. For both offshore unloading options, equipment for station keeping will be required for the ship and for the FSI.

Concepts suitable for each of these processes in CO_2 transport are summarised in the following sections, and described in detail in Sections 10.4, 10.5 and 10.6.

Concepts in floating storage and injection units (FSIs)

Presently a floating offshore unit purpose-built for CO_2 storage and injection to a reservoir below the seabed does not exist. However, several concepts are already proven for oil and gas operations. These systems differ in terms of the water depths that they can be deployed in, suitable storage capacity and accessibility in case of harsh weather.

Here, storage size is characterised as: small (less than 15,000 tCO_2), medium (15,000-50,000 tCO_2) and large (greater than 50,000 tCO_2).

The key features of each concept are summarised in Table 3-2 and described in detail in Section 10.4. A decision tree for choosing suitable FSIs for different conditions is given in Figure 3-7.

[52] Ministry of Petroleum and Energy, Feasibility study for full-scale CCS in Norway

Table 3-2 Summary of key features of floating storage and injection unit (FSI) concepts

Concept	Key features	Water depth	Storage size
Ship-shape	• Well-known and often used • Space efficient • Turret is preferred in harsh weather, can be spread moored in benign weathers • Higher motions than other concepts • Weather-vaning unit, if turret is used • Can be a conversion rather than new-build	All	All
Spar	• Platform with cylindrical hull • May have cylindrical hull and truss or cell of multiple cylinders. • Low motion design • Current designs used for production and do not have storage – requires re-design	Deep	Small
Circular form stable units (SEVAN)	• Large diameter cylinder • Low motions • No weather-vaning (shape same for all weather directions) • Spread moored (see next section)	All	Large
Semi-submersible unit	• Well-known for production without storage • Low motions • No weather-vaning • Spread moored	All	Small
Tension Leg Platform (TLP)	• Mooring consists of tension legs between the platform and seabed • Low vertical motions allowing for (low cost) steel risers	Up to Medium	Small
Jack-up Platform	• Buoyant hull • Can be moved between locations • No vertical motions when jacked-up	Shallow/ Medium	Small
Fixed platform	• Legs connect to the seabed (e.g. concrete or steel) • Not possible/Very difficult to move • No vertical motions allowing for (low cost) steel risers • Good in harsh weather	Up to Medium	All

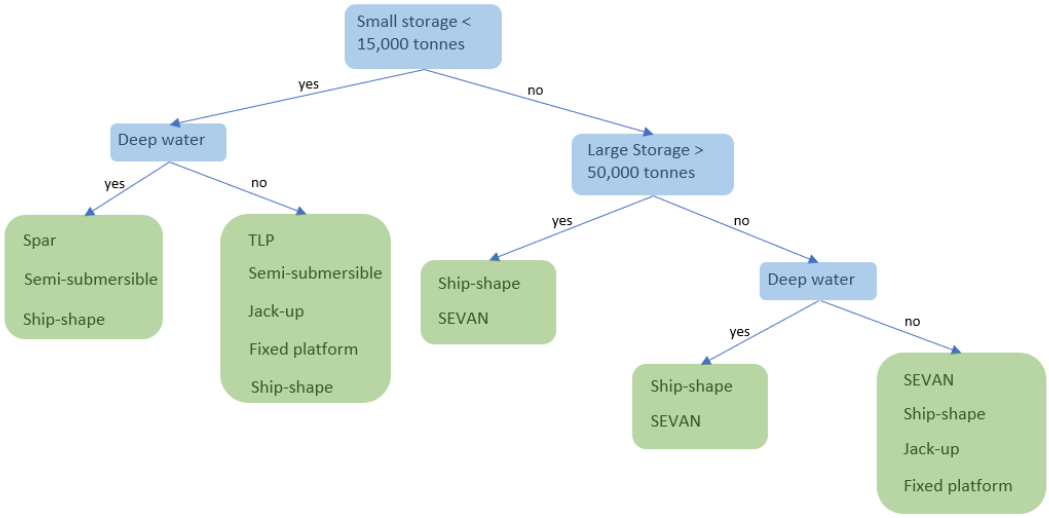


Figure 3-7 Decision tree for choosing an appropriate FSI type

Concepts in Station keeping solutions

Table 3-3 summarises the key features of two different station keeping solutions available without gas transfer (described in detail in Section 10.5). The spread mooring system can be both permanent or temporary (months to years) depending on the type of system that is used. Dynamic positioning is usually only for shorter, temporary mooring (hours to months).

Table 3-3 Summary of key features of station keeping concepts

Concept	Suitable for	Key features
Spread mooring	FSI	• Conventional, well-proven method for mooring • Offloading must be directly through a riser • Challenging for ship-shaped vessels in harsh weather because the unit is not allowed to weather-vane.
Dynamic positioning (DP)	Ship	• Vessel kept in position with thruster force • Bow thrusters not used in transit, aft thrusters used during transit • Easy to use – integrated in the ship, flexible and low connection time • Consumes more fuel than other station keeping options • Expensive system both investment and operational cost.

Concepts in gas transfer systems

Table 3-4 summarises the key features of concepts for gas transfer systems suitable for either transfer between the ship and the FSI and either the ship or FSI and the well. A decision tree for selecting a suitable gas transfer system is given in Figure 3-8. The tree can be used for multiple purposes i.e. transfer from FSI, direct injection from ship or offloading to an FSI. If you have a need for storage, an assumption of a permanently moored FSI is made. If there is no need for storage the assumption is that a shuttle tanker is used.

Table 3-4 Summary of key features of concepts for gas transfer systems for offshore CO_2 unloading

Concept	Suitable for	Key features
Conventional integrated turret (CIT)	FSI only	• Integrated into FSI – space consuming • Allows for weather-vaning • Well-known and often used for Floating Production Storage and Offloading (FPSO) units • Can hold many risers and have a possibility of a more complex mooring system. • Good in harsh weather
Submerged turret loading (STL)	Ship and FSI	• Connected to the FSI or ship, with a temporarily integrated turret, during unloading. • Submerged and pulled into the vessel during unloading – possible to disconnect. • Fewer risers and fewer mooring configurations possible than for a CIT • Less space consuming and cheaper than a CIT • Allows for weather-vaning • Good in harsh weather
Turret buoy loading (TBL)	Ship	• Surface piercing buoy anchored to seabed or tower standing on seabed (depending on water depth) • Offloading through hose to well or FSI. • Need aft thrust on ship to keep position. • Allows for weather-vaning • Only for calm weather
Single anchor loading (SAL)	Ship	• Base is placed on the seabed, riser placed on seabed when not used. • Simpler system than the STL with same purpose. • Need aft thrust on ship to keep position • Offloading hose attached to bow of vessel • Allows for weather-vaning • Good for harsh weather
Bow loading system (BLS)	Ship	• Well-known loading system for larger oil shuttle tankers • Vessel connects via hose in bow to the FSI • Compatible with SAL • Vessel requires DP system for station keeping
Yoke system	Ship and FSI	• Steel frame connected to floating buoy or tower on seabed • Offloading via hose • Limited use in harsh weather
Rigid arm System (RAS)	FSI only	• Floating buoy with rigid frame • Offloading via hose • Good for permanent loading for larger FSIs in non-harsh weather environments.

Concept	Suitable for	Key features
HiLoad DP and LNG	Ship	• Stand-alone offloading unit with DP • No connection to the seabed (water depth independent) • Good for harsh weather • No redesign of ship is required • Only one unit built for oil industry.
HiLoad floating regasification dock (FRD)	Ship	• Floating dock with conditioning equipment • Includes soft-yoke mooring • For shallow draughts and non-harsh weather environments. • No redesign of ship is required
Side-by-side	FSI only	• Unloading by mooring vessel on side of FSI • Uses offloading arm – no hoses • Calm weather only

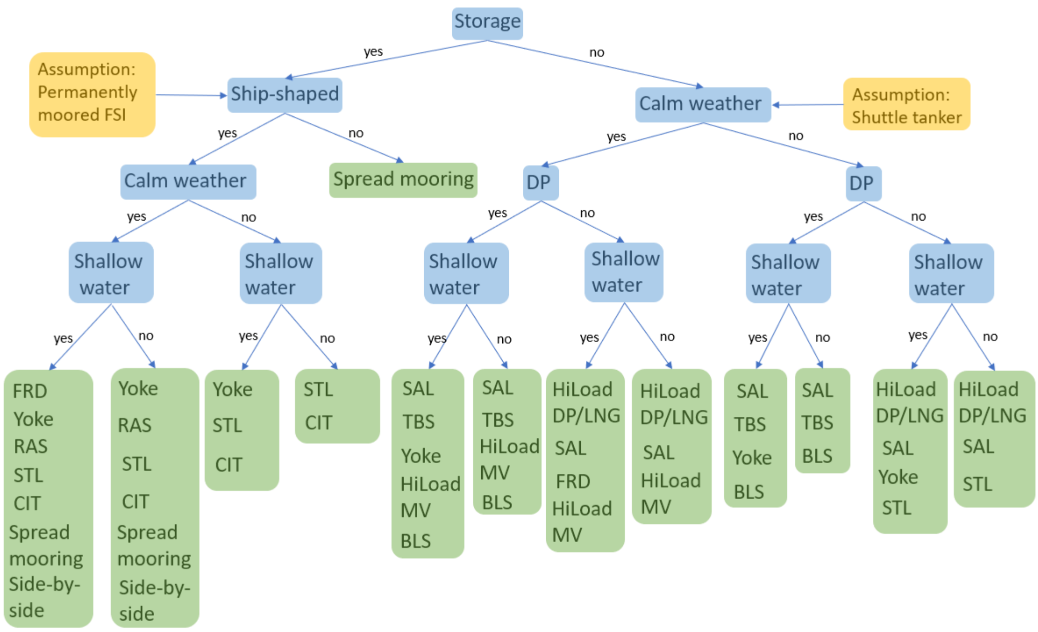


Figure 3-8 Decision tree for choosing a gas transfer system

3.4.3 Operational considerations

Availability for offloading

The availability for offloading – defined as the assumed time per year that it is possible for a ship to connect to an offloading system[53] – is dependent on the weather conditions at the site and the offloading system that has been chosen. For example, under the conditions at the North Sea site considered in our analysis (see Section 4), a significant wave height (Hs)

[53] Based on statistical data from a given site.

of 4.5 m is considered limiting which results in an availability of approximately 92%.[54] However, each site needs to be assessed on a case-by-case basis.

Sufficient storage capacity must be included on the FSI to both allow the ship to fully unload (at least the same capacity as the ship) but also have sufficient additional capacity to enable continuous injection to be maintained during periods of unavailability. The additional amount required is dependent on the minimum allowable injection rate, the storage tank filling level at which the minimum injection rate is instated, the number of wells, and the maximum period of unavailability for receipt of new cargo supplies. These parameters are operational, sea environment and well-specific and will vary with chosen sites and operational philosophy.

Harsh vs benign Waters

Compared to harsh environment cases (such as sites in the North Sea), simpler technological solutions and potential cost savings in several areas may be achieved where transport and offloading are performed on inland seaways or in benign waters.

Normally a ship will be designed for unrestricted trade, however if the ship is intended for a fixed trade with a limited maximum distance to safe port or anchorage, modified requirements to arrangement, equipment or scantlings apply.[55] The zones, areas and seasonal periods as defined in the International Convention on Load Lines, 1966, Annex II.

Table 3-5 Service area notations[56]

Service area notations	*Seasonal zones (nautical miles)*		
	Winter	*Summer*	*Tropical*
R0	250	No restrictions	No restrictions
R1	100	200	300
R2	50	100	200
R3	20	50	100
R4	5	10	20
RE	Enclosed waters		

For an FSI in benign waters, the choice of loading systems to ship, mooring and injection system may be simpler and cheaper solutions than for harsh environment cases. Typically spread mooring and balcony risers can be used instead of a turret solution for a ship shaped unit.

As for a ship, the choice of location/operational area will also have an impact on the structural dimensions required. The significant wave height, Hs, for the 100-year design limit for benign waters for a ship-shaped offshore unit (i.e. FSI) are 8 to 10 m.[57] Rules for benign waters are less strict with respect to scantlings of the structural steel than those for harsh conditions. This means a reduced steel weight of the design which will give lower cost for the FSI.

The availability will also be higher for a benign weather site compared to a harsh weather site. For example, availability for two different significant wave heights at the Haltenbanken

[54] Average availability based on wave statistics from 50 years.
[55] Rules of Classification of Ships, Pt 1 Ch 2. Høvik: DNVGL (2018)
[56] DNVGL-OS-C102. Høvik: DNVGL
[57] According to DNVGL-OS-C102

area in the Norwegian Sea (harsh weather site) and the N'Kossa area outside Congo (benign weather site) are shown in Table 3-6. The limiting criteria for bow loading system (harsh weather solution) is a significant wave height, Hs, of 4.5 m and for side-by-side offloading (benign weather solution) the Hs is 2.0 m.

Table 3-6 Availability at Harsh and Benign sites for given limiting criteria. Note: The values are only valid for given sites

Site/Hs	4.5 m	2 m
Harsh	91.62 %	44.20 %
Benign	100 %	87.36 %

3.5 Conditioning for delivery to pipelines and offshore unloading

Injection state of CO_2

The conditions considered optimal during transport are not optimal injection conditions. For transport, lower density CO_2 and liquid phase state are preferred for convenience of pumping and storing in tankers. At the reservoir and injection facility, high pressure and temperatures above 10°C are preferred to avoid hydrates, temperature changes within the well and in the injection riser. To avoid chances of two- phase flow and hydrates at the riser and reservoir inlet, a temperature at 5°C and above in inlet to the riser (due to little heat exchange effect in the well) is assumed to be needed. The condition needed at the inlet of the riser and reservoir inlet is very site specific, and it is difficult to project the condition needed for a general basis.

Conditioning of CO_2

The processes for conditioning CO_2 after ship transport are fundamentally the same for both onshore and offshore unloading. Prior to CO_2 injection or pipeline transport, the CO_2 must be pumped and heated to reach the injection specifications. Large amounts of heating are required; for example, pumping from 6.5 bar to 150 bar has been estimated to require 4-5kWh/tCO_2. Use of warm (>15ºC) sea water or waste heat, such as from the ship's engine or FSI operation, could make the design of the heating process easier and more economical.[58] Fuel oil can be used if the waste heat or warm sea water is not available. However, this increases the energy demand significantly and causes some CO_2 emissions.

A possible route to pump and heat the transported CO_2 to 100 bar and 5°C before injection is shown in Figure 10-27, Appendix.

[58] Aspelund, A., Gas purification, compression and liquefaction processes and technology for carbon dioxide (CO_2) transport (2010) in Developments and innovation in CCS technology, Cambridge, Woodhead Publishing Ltd.

4 Projected costs of large-scale CO_2 shipping

4.1 Approach

The approach to the cost assessment is outlined in Figure 4-1. Full details of all assumptions and methodology are given in section 10.8.

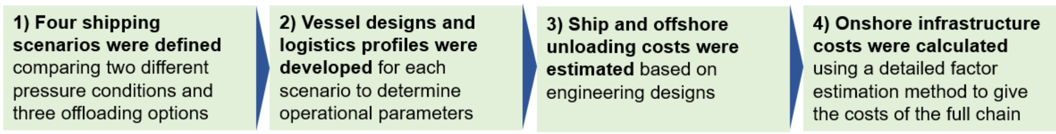


Figure 4-1 Approach to cost assessment

Since costs for each of the components of the shipping chain are highly case-specific with regard to location, storage and transport conditions, and operational profiles, four ship logistics scenarios were defined (Table 4-1) and used as the basis for the cost assessment. Scenarios 1 and 2 consider shore-to-shore transport and (onshore) unloading, comparing the Low P and Medium P conditions. Scenario 3 considers offshore unloading and is split into two offloading options: 3A “Offloading to FSI” and 3B “Direct injection”. The routes chosen (Figure 4-2) are based on ongoing CCS projects with operations in the North Sea,[59] and all use a comparable transport distance of 1,000 km. A ship size of 10,000 tCO_2 was used for all scenarios since this is the upper limit for the Medium P condition using conventional design to ensure comparability between scenarios. The chosen offshore site is characterised by medium (100-300 m) water depth and harsh weather conditions.

Ship costs were calculated using a bottom-up approach based on the detailed vessel designs and logistics profiles developed for these scenarios. Onshore infrastructure costs were derived using a detailed factor estimation method. Included in the costs are the liquefaction plant, intermediate storage, loading and unloading, ship transport and conditioning before further transport. For the offshore cases, the FSI is included, but not the injection and reservoir. The battery limits for the shipping chain considered in the detailed cost assessment of the 4 cases are shown in Figure 10-28, Figure 10-29 and Figure 10-30 in the Appendix.

All costs are in €2018 price basis and assume Nth of a kind (NOAK) components and vessels (see Appendix for discussion). The methodology for ship cost estimates is the same as used for the Norwegian Full-Scale CCS project,[60] which is accepted at better than ± 30%. Onshore infrastructure costs are based on equipment costs included in the Aspen In-Plant cost estimator with an estimated uncertainty of ±40%. Onshore and offshore infrastructure costs were based on the respective locations (Rotterdam, Kollsnes and North Sea site) and ship and FSI crew costs were based on Norwegian labour costs. The condition after transport was set to 100 barg and 5°C for each scenario, assumed to be appropriate for both pipeline transport and for injection to geological storage.

For the onshore unloading scenarios, illustrative costs for a shore-to-offshore pipeline between Kollsnes and the North Sea site (250 km) were calculated in line with previous reports (see Appendix, page 117 for details) and include the cost of booster compression to 250 barg.[6,61]

[59] As described in Section 2.2, page 4.
[60] CAPEX is based on a 3-level SFI breakdown; OPEX costs are based on bottom up estimation.
[61] *Brine production cost-benefit analysis tool* (2017) Element Energy for Energy Technologies Institute

Table 4-1 Ship logistic scenarios. The shipping distance in each case is 1,000km.

No.	Route	Unloading type	Condition before transport	Transport condition[62]	Condition after transport	Ship capacity / tCO_2	No. of ships
1	Rotterdam-Kollsnes	Onshore	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3
2	Rotterdam-Kollsnes	Onshore	1 barg, 20°C	Medium P	100 barg, 5°C	10,000	3
3A	Rotterdam-North Sea	Offshore to FSI	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3
3B	Rotterdam-North Sea	Offshore, direct injection	1 barg, 20°C	Low P	100 barg, 5°C	10,000	3

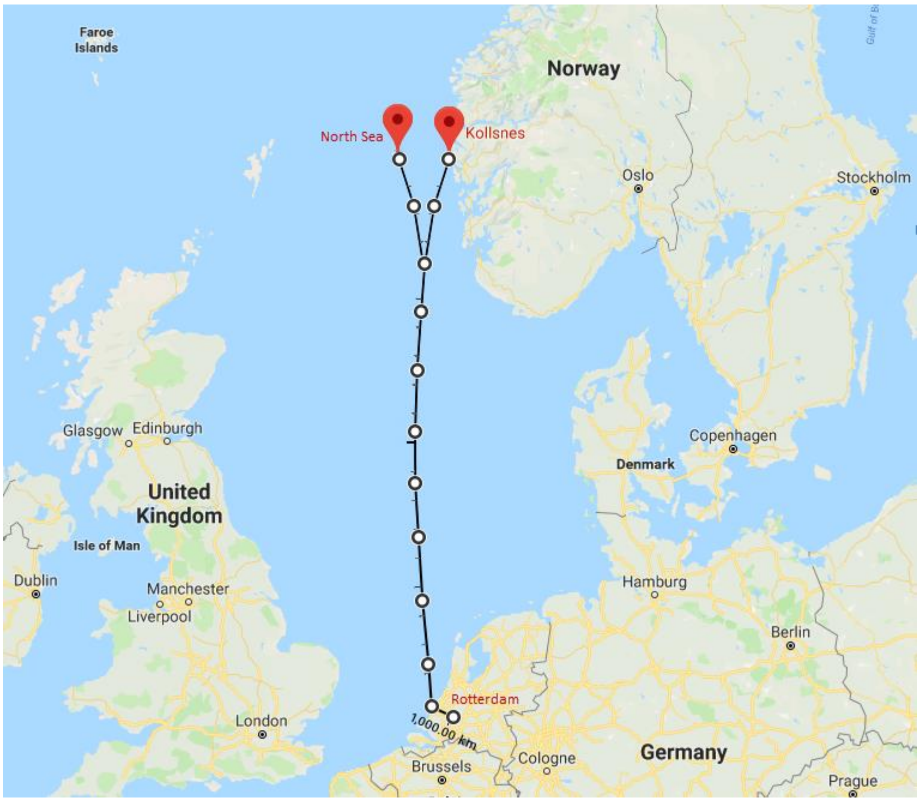


Figure 4-2 Map of chosen shipping routes. Map data ©2019 Google Maps.

[62] Low P = 7 barg, -50°C; Medium P = 15 barg, -28°C

4.2 Ship design and logistics profiles

Vessel specifications

Different CCS scenarios will require different vessel properties. The ship sizes and equipment assumptions used for the cost estimation are listed in Table 4-2.

With a Medium P vessel the tanks have to be smaller compared to a Low P vessel due to the pressure. This means that the number of tanks will be increased compared to a Low P solution with the same cargo volume. As such, the vessel in Scenario 2 is larger than for Scenario 1 because it has 4 tanks instead of 2 tanks.

Low P Scenarios 1 and 3 will, compared to Scenario 2 require a smaller displacement vessel with other geometric properties due to reduced weight and larger diameter of tanks.

Ships for shore-to-shore shipping only need equipment for offloading to a land-based station, while offshore-going vessels require the offloading equipment to be integrated into the ship. The offshore unloading scenarios 3A and 3B will require extra space for an offloading system, as a minimum a bow loading system (BLS). In addition, the direct injection scenario 3B requires an on-board Process Plant to increase the temperature and pressure of the CO_2 before injection. Assuming 3A is not connected to a permanent mooring system the vessel is equipped with a Dynamic Positioning System (DP) in order to maintain position during offloading.

Offshore unloading is generally subject to operational limits related to wave heights. Vessel sizes significantly smaller than typical shuttle tankers operating in the North Sea will be subject to larger motions which may affect the regularity of the operations.

Table 4-2 Main parameters of ships for different operational scenarios. Lpp = Length between perpendiculars; B = Breadth; T = Draught; D = Depth

Scenario	Pressure [barg]	# of tanks [-]	L_{pp} [m]	B [m]	T [m]	D [m]	Assumptions
1	7 barg	2	124.10	18.07	8.45	12.95	
2	15 barg	5	139.25	22.00	8.00	12.95	
3A	7 barg	2	130.09	18.05	8.45	12.95	BLS, DP
3B	7 barg	2	130.09	18.05	8.45	12.95	BLS, Process Plant

Floating Storage and Injection unit

When deciding the size of the FSI a number of criteria needs to be fulfilled. The most important criteria are:

- Size of arriving CO_2 vessels
- Offloading limitations of CO_2 vessel
- Minimum injection rate for the well

The storage capacity of the FSI must be at least equal to the cargo capacity of the transport ship in order to ensure that the arriving vessel is able to unload its full cargo. In addition, it is important that the storage capacity is sufficient to ensure continuous injection to the wells during weather conditions where it is not possible to connect the arriving vessel to the FSI for unloading.

The offloading system used for unloading from the arriving vessel to the FSI (BLS) has an Hs limit for connection of 4.5 m. By using statistical wave data for the chosen offshore location,[63] a maximum expected continuous period of unavailability of 19 days is estimated. This means that the theoretical maximum period for which new cargo cannot arrive is 19 days.

Assuming a reduced rate of injection that may be used in such cases is 15% of the max injection rate and also assuming that this minimum rate is instated when the FSI storage is down to 50% filling, the required storage capacity of the FSI is estimated to be 31,000 tCO_2. Reducing the minimum injection rate and accepting close down of operations in rare occasions would significantly reduce the buffer capacity.

Following the decision tree in Section 3.4.2 (Figure 4-3), a ship-shaped FSI was chosen because it is the most scalable solution to different storage sizes. The ship-shaped design is well-proven with many built units on the North Sea. It is also possible to use an existing FPSO unit or tanker for conversion into an FSI; however, this was not considered here.

Based on the ship-shaped FSI choice, STL and CIT are possible solutions for gas transfer from the FSI to the storage site (Figure 4-4, left). The STL solution was chosen because it is a simpler and cheaper solution than an integrated turret but still fulfils the requirements. With a limited need for risers, as in this project, the STL is the best choice. Another benefit with the STL is that it requires less space on-board the FSI than the integrated turret.

The cost calculations were based on a set of main dimensions for a new-build ship shaped FSI with the calculated storage capacity, as listed in Table 4-3. A tank configuration with 3 pairs (total of 6 tanks) of tanks with length 38 m each along the length of the FSI is assumed. Full details of the cost assessment assumptions are given in Section 10.8.2, page 114. The cost estimates may be considered on the conservative side taking into account that the facility will be a first of kind.

During stakeholder engagement, it was commented that the assumed operating limit may be too high for the size of ships used in this study. The given Hs limit of 4.5 m may be appropriate for larger ships but smaller ships may have more difficulty connecting to the offloading system under these conditions. With a lower operation limit (e.g. Hs 2.5 or 3 m) the offloading availability will go down and higher storage capacity would be required. This factor is highly uncertain and needs to be further investigated for each offshore location with detailed calculations and dialogue with the vendors.

[63] 92% availability for the chosen storage site, based on 50 years average data.

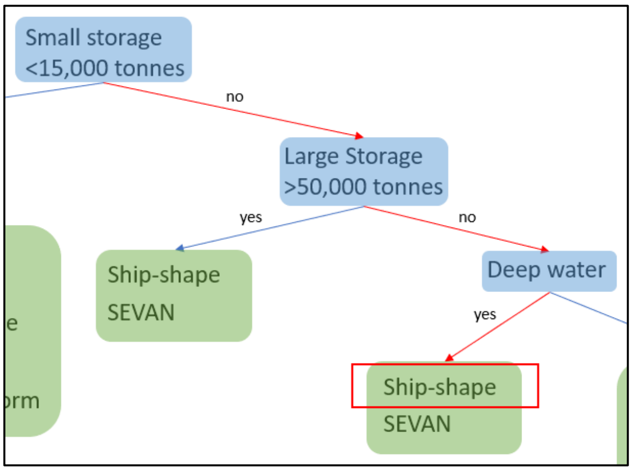


Figure 4-3 Decision FSI type

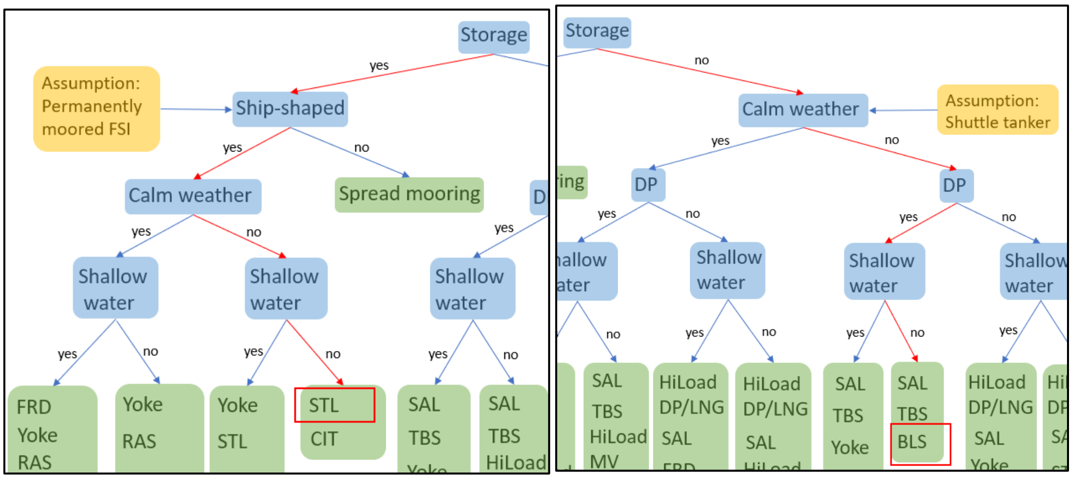


Figure 4-4 Decision gas transfer from FSI to storage (left) and ship to FSI (right)

Table 4-3 Main dimensions for ship-shaped FSI in Scenario 3A. Lpp = Length between perpendiculars, B = Breadth, T = Draught, D = Depth, C_b = block coefficient.

# of tanks [-]	Storage tCO_2 [t]	L_{pp} [m]	B [m]	T [m]	D [m]	C_b [-]	Lightship weight [t]	Displacement [t]
6	31,190	174.90	31.50	10.80	16.50	0.86	17,946	52,255

Direct injection gas transfer system

Based on given scenarios, the HiLoad DP/LNG, SAL or STL are options (Figure 4-5). SAL is the easiest and cheapest option of the three. It may be possible to use a shuttle tanker without DP, which reduces the CAPEX and OPEX compared to a shuttle tanker with DP system.

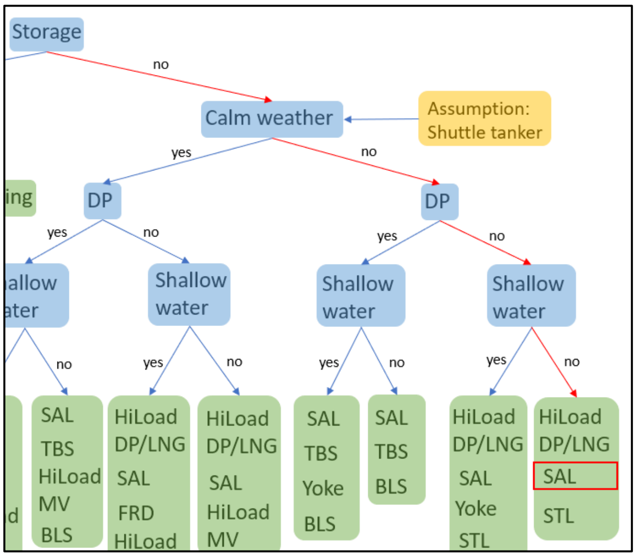


Figure 4-5 Decision gas transfer system direct injection

Vessel cost assessment

Vessel cost estimates for each scenario are detailed in Table 4-4. OPEX costs were calculated including costs of energy, crew, maintenance, shore support/administration, pilot and port fees.

Table 4-4 Vessel cost estimates for each scenario. All ship costs, including offloading and conditioning equipment for the offshore unloading scenarios, are included.

Scenario	CAPEX per ship (€m)	OPEX per ship per year (€m/y)	FSI CAPEX (€m)	FSI OPEX per year (€m/y)
1	**37**	**13**		
2	**50**	**14**		
3A	**49**	**16**	**176**	**10**
3B	**48**	**14**		

Logistics profiles

Total round-trip times were calculated for each scenario based on ship speed, connection and disconnection time to and from loading and unloading equipment, loading and unloading rate, and unavailability (offshore unloading only). The modelled parameters are detailed in Figure 10-31, page 116 (Appendix). For each scenario, two wells are assumed for the storage site.

Due to weather criterion limitations and longer unloading times for offshore unloading operations, the total round-trip time per ship is higher than for onshore unloading. For a fixed number of ships this limits the number of trips per ship per year and therefore the yearly amount of CO_2 for injection is lower for Scenarios 3A and 3B than for Scenarios 1 and 2 (Figure 4-6).

Scenario 3A with offshore unloading to FSI is based on an unloading rate of 600 t/h limited by the chosen capacity of on-board cargo pumps. In Scenario 3B with 2 wells with an assumed maximum injection rate of 114 t/h the total injection is limited to 228 t/h. The prolonged unloading time needed for offshore unloading with direct injection results in a reduced injected yearly amount of CO_2. Unloading may be a bottleneck for the scenario 3B logistics chain.

When weather limitations cause a halt in the logistics chain for offshore unloading, there is a need for a buffer storage capacity on the loading side. As such, an offshore unloading logistics chain should be designed with a relatively larger buffer storage on loading side compared to a shore unloading scenario.

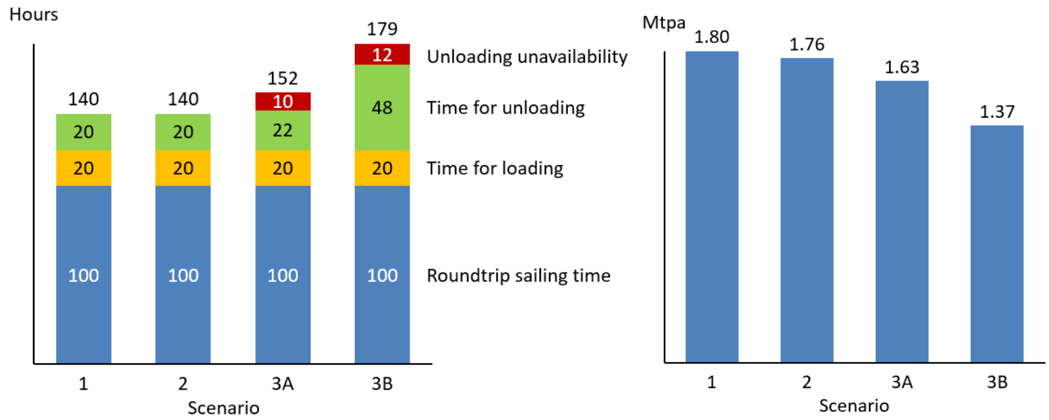


Figure 4-6 Time for one round-trip (left) and maximum yearly amount of CO_2 available for injection (right) for selected scenarios of CCS transport by ship. When calculating transport capacity a general allowance has be made for weather (weather margin) reducing transit speed and increasing docking time.

4.3 Onshore infrastructure

The CAPEX for the land facilities is estimated based on a bottom-up approach in which equipment costs are derived and multiplied by an installation factor (see Section 10.8.3, page 114 for details). CAPEX includes 20% contingency. OPEX is calculated based on consumption of electricity, manning, cooling water (where relevant), and maintenance.

Liquefaction

A combined internal and external cooling loop using NH_3 was assumed for both transport conditions. The compressors for NH_3 and CO_2 are the main cost drivers, and they are based on carbon steel. For OPEX, the electricity and maintenance are the main cost drivers, in addition to manning. For the liquefaction, the manning is approximately 4 % of the OPEX. The arriving CO_2 stream is assumed to be low in impurities (amine capture technology at the capture plant is assumed) and therefore dehydration is assumed to be the only purification step. Other capture technologies will give higher impurity contents and therefore incur higher purification costs. A molecular sieve drying system in assumed for dehydration.

The non-pressurised CO_2 case assumes that the liquefaction plant is integrated with or close to the capture plant. If the CO_2 is pre-pressurised when delivered to the liquefaction plant (for example, if delivered from a remote capture plant by pipeline) then the liquefaction costs are significantly reduced (Table 4-5); however, although the cost of the additional compression is saved for the shipping chain, it will still be incurred by the capture plant.

Table 4-5 Summary of estimated costs for liquefaction, based on 1.8 Mtpa flow rate and a combined internal and external cooling loop liquefaction system

Transport condition	Condition before transport	CAPEX (MEUR)	OPEX (MEUR/y)
Low P	Non-pressurised	70	21
Low P	Pre-pressurised	29	6.9
Medium P	Non-pressurised	64	18.5
Medium P	Pre-pressurised	13	3.2

Intermediate buffer storage

The buffer storage is based on carbon steel horizontal storage tankers located in Rotterdam (Table 4-6). For Low P, the maximum size of each vessel is 5,000 m^3. For the onshore case, storage capacity equal to the ship capacity is assumed (storage factor of 1) so two tankers are needed. For the offshore cases (3A and 3B), a storage factor of 1.5 is assumed, requiring three tankers. For transport at 15 bar, a smaller storage vessel is required, and the maximum capacity was set to 1,000 m^3. If stainless steel is used the cost for storage is over three times the cost of carbon steel for the Low P condition. It is therefore important to keep the temperature to a level that carbon steel can handle.

Table 4-6 Estimated costs of onshore buffer storage for each scenario

Scenario	Transport condition	Storage factor (multiple of ship capacity)	CAPEX (€m)	OPEX (€m/y)
1	Low P	1	13.0	0.7
2	Medium P	1	27.7	1.4
3A	Low P	1.5	19.5	1
3B	Low P	1.5	19.5	1

Loading/unloading

The cost of a pump is included for loading and unloading. This pump gives rather a small cost compared to the other cost items of the CO_2 transport chain (0.4 MEUR CAPEX and 0.02 MEUR per year OPEX). The primary equipment for unloading and loading is included in the shipping cost.

Conditioning

After transport, the CO_2 needs to be heated and compressed or pumped to higher pressure. It is assumed that the CO_2 needs to reach 100 bar, but that depends on the distance to reservoir and reservoir properties. Heating of the CO_2 may be possible with sea water, however heating above sea water temperature is more challenging offshore as it requires an additional heat source. Heating and compressing onshore is not a big issue, and in liquid phase the CO_2 may be pumped, which is less energy demanding than compressing gases.

4.4 Costs for the full CO_2 shipping chain

The CAPEX and OPEX for the full chain in each scenario are shown in Figure 4-7. The transport cost per tonne of CO_2 injected is shown in the tables below. The volume injected is different in each case (see Figure 4-6), which is important when calculating the total cost per tonne.

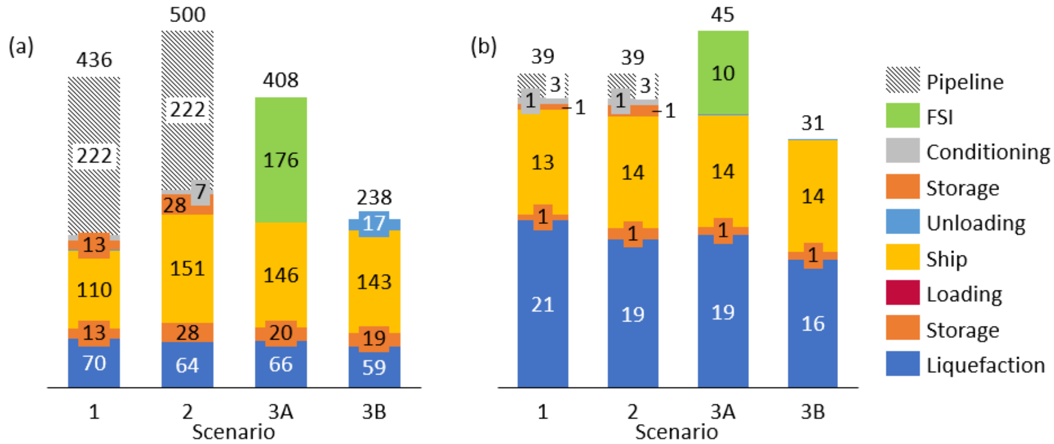


Figure 4-7 (a) CAPEX (€m) and (b) OPEX (€m per year) for the full CO_2 shipping chain for each scenario; Scenario 1 = Low P, onshore unloading, Scenario 2 = Medium P, onshore unloading, Scenario 3A = Low P, offshore unloading to an FSI and Scenario 3B = Low P, direct injection.

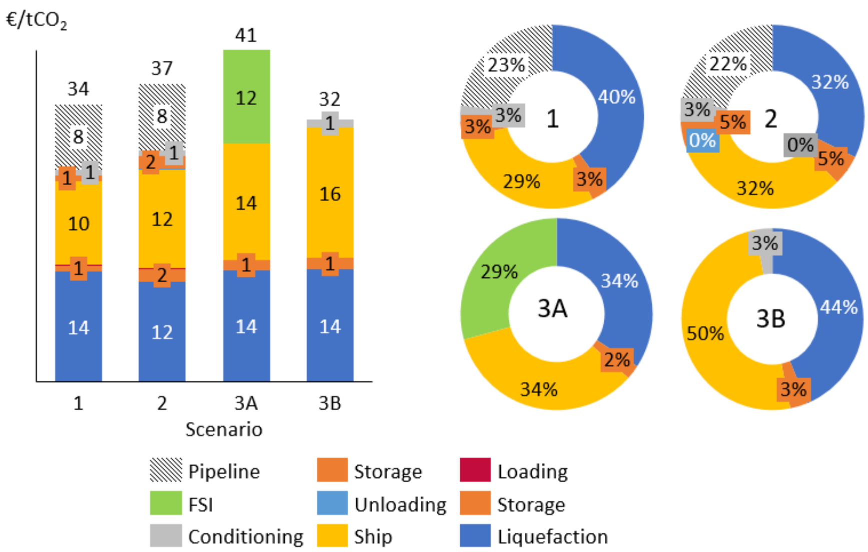


Figure 4-8 Unit costs (€/tCO_2) for each shipping scenario, assuming a 20 year lifetime, without discounting or financing. Note that loading and unloading are not visible on these charts due to the relatively small size of these cost components (0% of cost).

Considering only the shipping chain (excluding the cost of the pipeline in Scenarios 1 and 2), Scenario 3A has the highest CAPEX and OPEX due to the FSI, and the highest overall undiscounted unit cost (€41/tCO_2; Figure 4-8). Direct injection (scenario 3B) has the lowest

OPEX costs and relatively low CAPEX costs but stores the least CO_2 (unit cost of €32/tCO_2). Scenario 1 has the lowest overall unit cost, excluding transport beyond the port.

Adding the cost of a shore-to-shore pipeline to Scenarios 1 and 2 adds €8/tCO_2 to the undiscounted cost of the onshore unloading scenarios, bringing the cost of Scenario 1 to above that of Scenario 3B. However, it should be noted that the pipeline cost is highly dependent on the degree of utilisation; it is likely that future importing ports will receive shipments of CO_2 from multiple projects, therefore transporting higher volumes of CO_2 and reducing the levelised costs (Figure 4-9). The relative costs of the different shipping options are therefore highly case-specific.

For all scenarios, liquefaction and ship costs make up the majority of the costs (Figure 4-8, right). The ship cost accounts for more of the cost for the direct injection scenario (3B), in line with the additional equipment requirements.

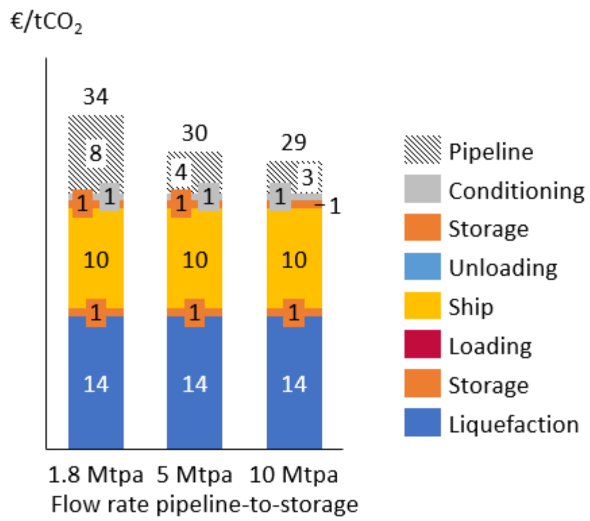


Figure 4-9 Effect of higher utilisation at the shore-to-offshore pipeline on the cost of an individual shipping chain under Scenario 1 (1.8 Mtpa transported by ship, representing a pipeline used by multiple projects).

Effect of initial CO_2 condition

If the CO_2 is pre-pressurised prior to liquefaction, the overall costs reduce by €9-10/tCO_2 for each scenario. However, although pre-pressurisation reduces the cost of the shipping chain, it should be noted that this cost may simply transferred to a different part of the CCS chain. Increasing the operational lifetime to 40 years decreases the costs by €3-6/tCO_2, with the highest reduction for Scenario 3A (reduced to €35/tCO_2).

Effect of financing

The levelised cost for each scenario was calculated for three discount rates, representing the range of effective costs of CO_2 transported if a project is Government funded (4% discount rate) or commercially funded (rates of 7.5 % and 10%). The results are summarised in Table 4-7.

Table 4-7 Levelised costs (EUR/tCO_2) for each scenario at varying discount rate. Costs are calculated assuming 2 years construction and 20 years operation.

			Levelised cost (EUR/t) at given discount rate			
Scenario	**CAPEX (€m)**	**OPEX (€m/y)**	**0%**	**4%**	**7.5%**	**10%**
Shipping chain only						
1	214	36	26	29	32	35
2	278	36	28	32	37	40
3A	408	46	41	47	53	59
3B	238	32	32	36	41	45
With shore-to-offshore pipeline						
1	436	39	34	40	47	52
2	500	39	37	44	51	57

5 Techno-economic modelling

As part of a cost assessment study for the UK Government, Element Energy built a detailed CO_2 shipping cost model covering all infrastructure elements of the CO_2 shipping supply chain.[64] This model uses specific cost and operational data to calculate detailed costs for a shipping or pipeline project scenario, as specified by the user (Figure 5-1). The cost and performance dataset used in this model was based on literature studies with varying degrees of technical maturity, with particular uncertainties in the offshore unloading components.[65]

In this study, more detailed cost and performance estimates have been developed based on engineering results described in Section 4. The updated model was then used to explore the impact of key operational parameters on the costs of CO_2 shipping and to identify the cases where ship transport might be more cost-effective than pipeline transport.

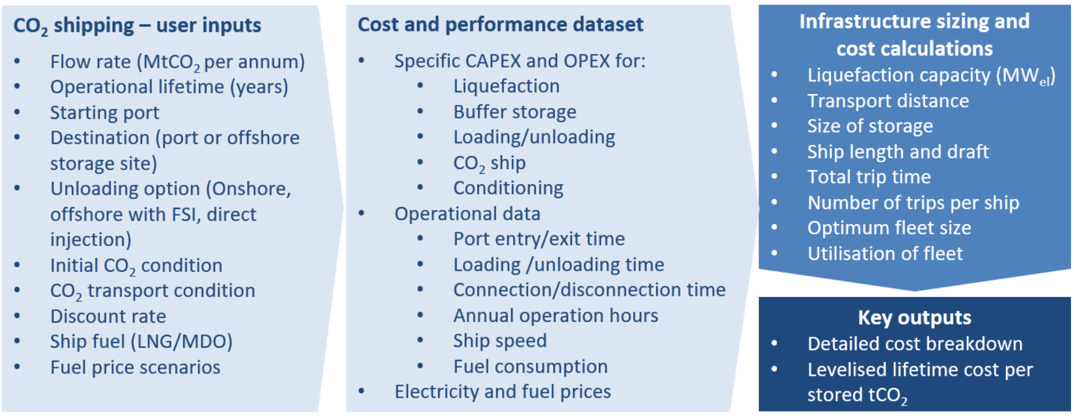


Figure 5-1 High-level overview of CO_2 shipping cost model methodology

5.1 Methodology

Full details of all data updates are described in Section 10.9, Appendix (page 117). An overview of modelled components is given in Table 5-1. Briefly, all infrastructure cost components were updated to the new data based on the results of Section 4, with modifications to map the new costs to the model structure.

In order to allow modelling of the impact on costs of varying operational parameters (such as flow rate, distance, ship size), simplifications in cost allocation and dependence on operational parameters have necessarily been applied. For example:

- The ship costs used in the model are estimated using a fitting curve to account for economies of scale of increasing ship capacity (tCO_2); these fitting curves were updated to incorporate the new data rather than using the new costs directly.
- The costs of gas transfer systems, conditioning equipment and gas transfer systems were treated separately from the cost of the ship.
- The storage on the FSI was treated separately to the FSI itself.

[64] Available for download from https://www.gov.uk/government/publications/shipping-carbon-dioxide-co2-uk-cost-estimation-study
[65] See *Shipping CO_2 – UK Cost Estimation Study* (2018) Element Energy for BEIS for full details.

- Many components are modelled as linear functions of flow rate, capacity or loading rates

In practice, these costs are interrelated in a more complex manner that is difficult to capture and design factors will result in non-linearities. However, the modelling results are intended to be illustrative of trends only and not representative of true project costs.

Table 5-1 Overview of components included in the modelling

Parameter	Components	Cost scaling
Liquefaction	Liquefaction plant	Linear with **flow rate**[66]
Buffer storage (loading)	Onshore buffer storage	Linear with **storage capacity**
Loading	Pumping to ship	Linear with **loading rate**
Ship	Base ship only	With **ship capacity**, following curve fitting
Unloading	**Onshore:** pumping from ship **Offshore:** gas transfer system (BLS), DP, FSI, SAL	**Pumping:** Linear with **unloading rate** **FSI:** fixed and variable (with flow rate) components **SAL:** fixed cost **Gas transfer:** fixed cost per ship
Buffer storage (unloading)	**Onshore:** as for loading **Offshore:** storage tanks on FSI	Linear with **storage capacity** **FSI storage fixed** up to 30,000tCO_2 ship capacity
Conditioning	Conditioning equipment	**Onshore:** Linear with **flow rate** **Offshore:** Linear with **ship capacity** Applied once per ship for direct injection, applied once for onshore and FSI

5.2 Techno-economic analysis results

5.2.1 Cost estimate consistency

To ensure consistency with the more detailed assessment, the model was used to calculate costs for the four scenarios described in Section 4 (Figure 5-2). The model results show good alignment with the detailed cost assessment, with minor discrepancies that primarily arise from the slightly different ship cost assumptions and simplifications in scaling of the liquefaction plant costs. As a result of the model structure, there are also some differences in the way in which costs have been distributed between the infrastructure components. For example, the DP system of the ships is included in the unloading cost component in the model, whereas it was included in the ship costs in Section 4.

The calculated unit costs[67] of shipping for the 4 scenarios are within ±€1/tCO_2 of those estimated in Section 4 (Figure 5-3). In-line with the results of Section 4, liquefaction is the most expensive component of the shipping chain when the CO_2 is initially non-pressurised.

[66] Scaling factor of 0.8 applied below 1 Mtpa, factor of 1 above 1 Mtpa.
[67] Unit costs are undiscounted and assume a 20 year lifetime.

Fuel costs (electricity and ship fuel) and OPEX dominate the unit cost, with CAPEX making up less than a third of the unit costs

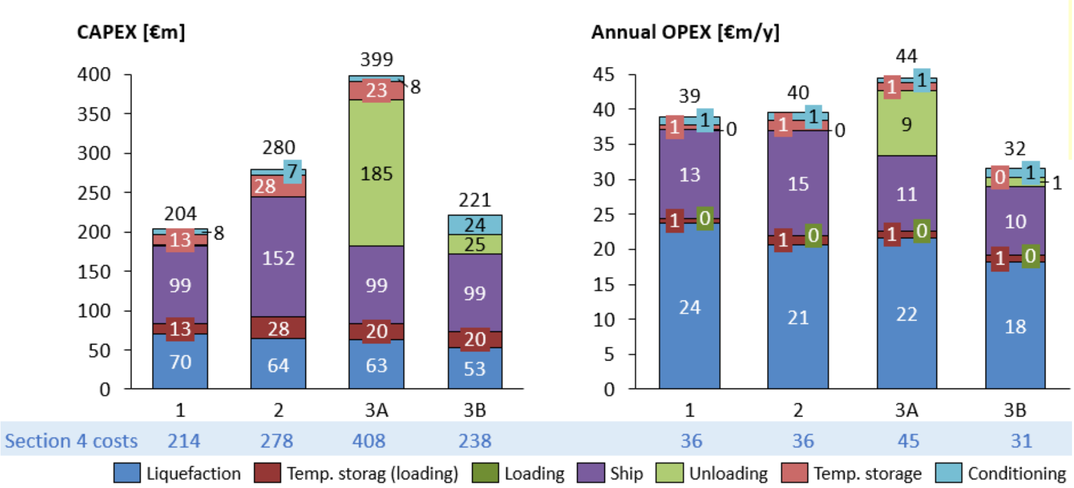


Figure 5-2: CAPEX and annual OPEX as calculated by the model for the four scenarios described in Section 4

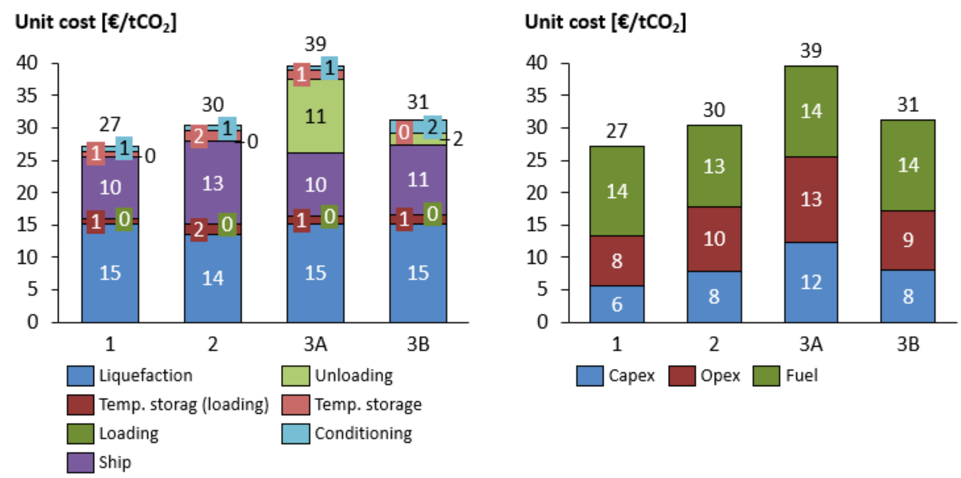


Figure 5-3: Unit cost of ship transport as calculated by the model for the four scenarios described in Section 4, divided into shipping chain components (left) and CAPEX, OPEX, and Fuel (right)

5.2.2 Impact of ship size and unloading rate on costs

Ship costs account for one third to just over half of the cost of the shipping chain. A larger ship capacity can reduce the number of ships required for transporting a fixed volume of CO_2, which reduces the total number of trips and subsequently the fuel costs. Ships larger than 10,000 tCO_2 may also be more favourable in practice for offshore unloading scenarios, especially in harsh weather conditions.[68] However the need for intermediate storage capacity (and cost) will increase proportionally with the size of ship. In addition, for a fixed unloading rate, larger ships will spend much of their time unloading rather than transporting CO_2. This is particularly relevant for direct injection operations in which the unloading rate is limited by the well capacity to receive CO_2 rather than the cargo pumps. Very large ships

[68] As discussed during stakeholder consultation; see also Section 10.1.

may also experience port constraints and may require modifications to existing ports or specialised jetty design.

The impact of varying the ship size and increasing the loading rate on the cost of ship transport was modelled for each of the Low P transport scenarios. The flow rates and distance (1,000 km) were fixed to those defined in Section 4.

Ship size

For the base case unloading rates (600 t/h for onshore and offshore to an FSI, 228 t/h for direct injection) increasing the ship size reduces the number of ships required up to a size of 20,000 tCO_2, which reduces the overall ship costs (Figure 5-4); however, the difference in ship cost between 10,000 and 20,000 tCO_2 is largely offset by the increase in buffer storage capacity and conditioning costs (for direct injection), resulting in little change in overall unit cost. Increasing the ship capacity to 30,000 tCO_2 increases the unit cost as the number of ships is not reduced further.

Loading and unloading rate

Overall, a higher loading/unloading rate only reduces the unit cost if it reduces the total trip time to such an extent that a lower number of ships are required. For a 10,000 tCO_2 ship capacity, increasing the loading and unloading rate to 3,000 t/h does not reduce the number of ships required for Scenarios 1 (onshore unloading) and 3A (offshore to FSI) and therefore the unit cost is marginally increased (by €0.2/tCO_2). However, for these scenarios, the cost can be decreased by increasing the ship capacity to 30,000 tCO_2 since only one ship is required (Figure 5-5).

For Scenario 3B (direct injection), where unloading times are a particular bottleneck in the trip time, increasing the loading and unloading rate reduces the roundtrip time for a ship capacity of 10,000 tCO_2 sufficiently that only two ships are required. This reduces the unit cost from €31/tCO_2 to €28/tCO_2, as only two ships are needed instead of three. Increasing the ship size to 20,000 tCO_2 does not reduce the number of ships and therefore increases the unit cost. Only one ship is required for a capacity of 30,000 tCO_2; however, although the cost is reduced compared to a 20,000 tCO_2 ship, it is still higher than for a 10,000 tCO_2 ship. However, achieving a high unloading rate in the case of direct injection is more challenging than in the case of unloading onshore or to liquid storage on an FSI, as the injection rate will be limited by specific conditions of the reservoir.

Summary

Overall, increasing the ship size and unloading rate can reduce costs if the number of ships can be reduced. However, in practice, two or more vessels may be desirable for full-scale projects to ensure redundancy.

For the scenarios modelled here, there is little cost advantage from increasing the ship size above 10,000 tCO_2. Conversely, there is also little penalty in cost by using larger ships. However, the optimum ship size will be highly dependent on the flow rate (Mtpa) and would therefore need to be considered for each specific logistics chain. Operational limits such as ease of connection to offshore assets under local conditions will also be important in choosing an appropriate ship size and will need to be assessed on a case-by-case basis. Additional benefits of larger ships include the possibility of injecting more CO_2 per chain per year and, if the number of trips can be reduced so that they can travel more slowly, increased fuel efficiency; these aspects have not been incorporated in the modelling but could affect the relative levelised costs of the chain.

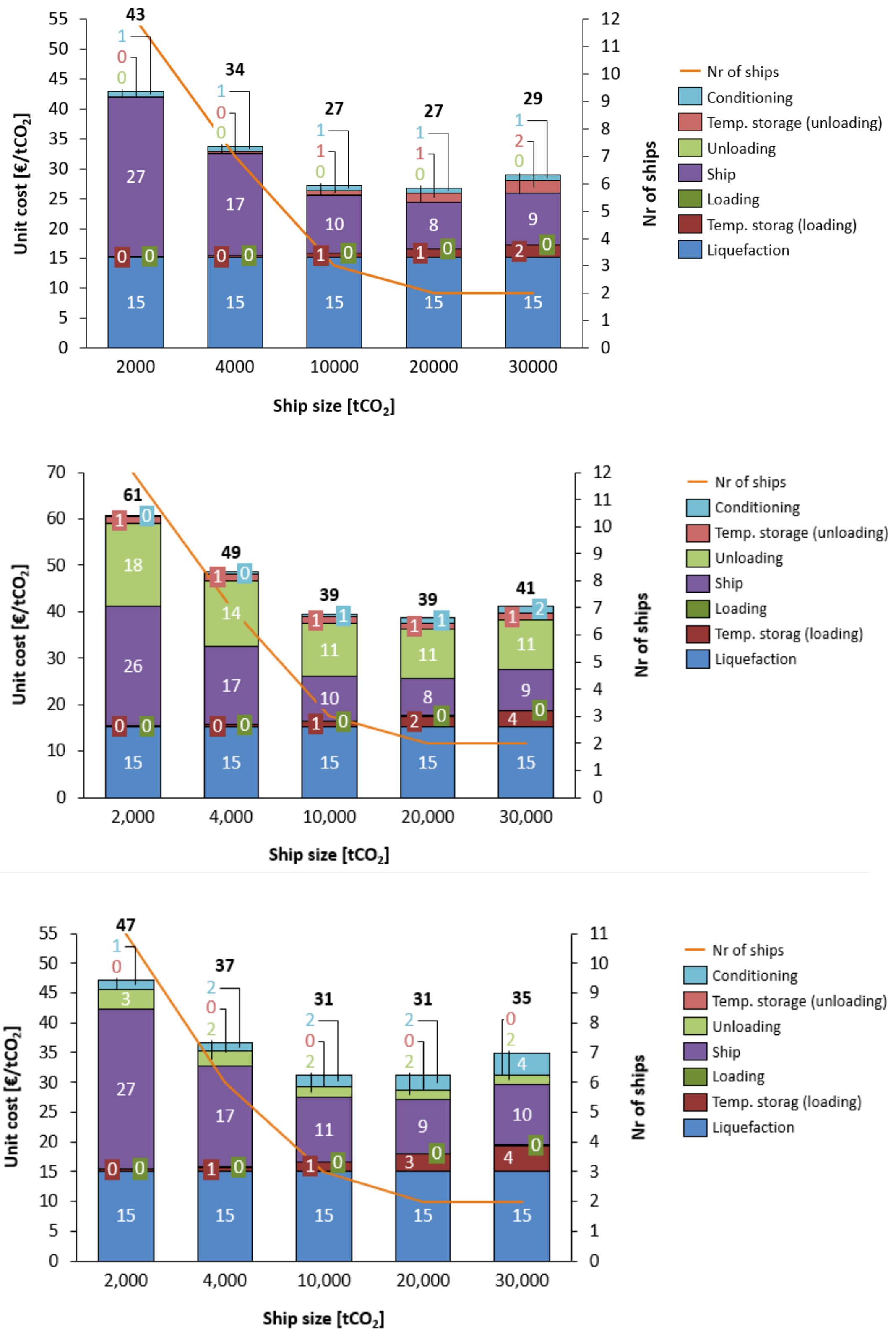
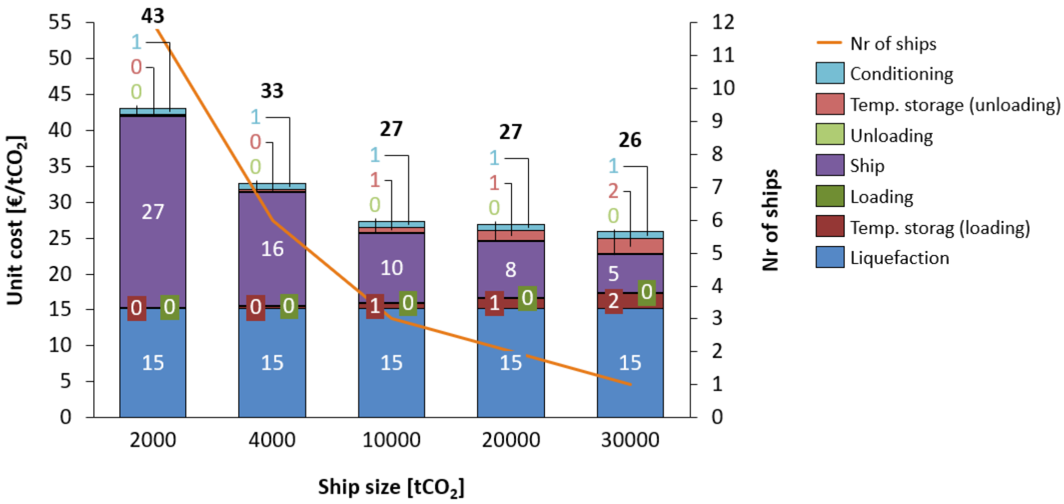
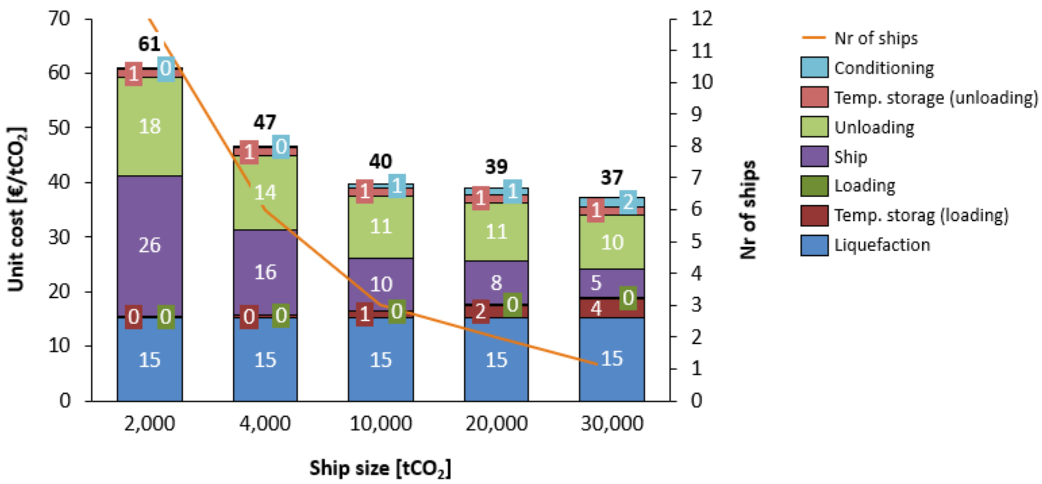


Figure 5-4: Unit cost of shipping for different ship sizes using the base case unloading rate (600 t/h onshore and offshore to FSI, 228t/h direct injection) for (top) onshore unloading, (middle) offshore unloading to an FSI and (bottom) offshore unloading by direct injection.





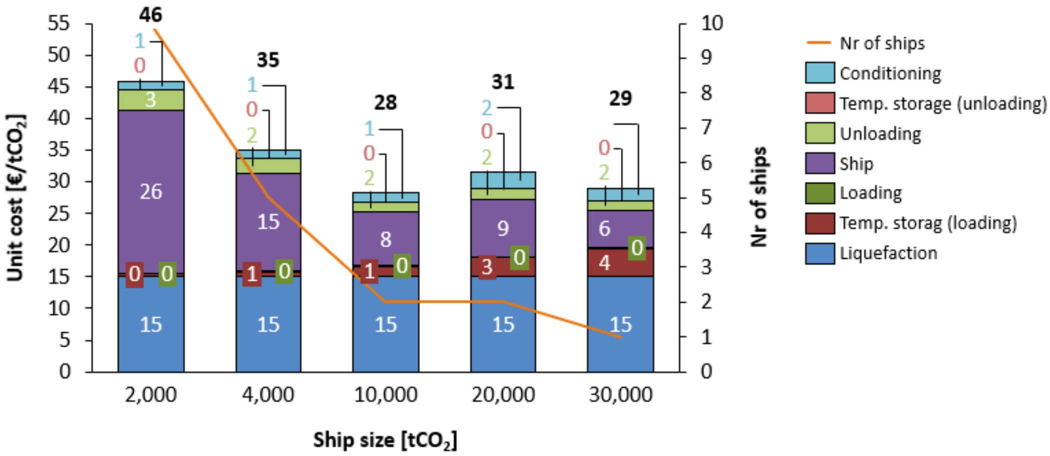


Figure 5-5: Unit cost of shipping for different ship sizes using an unloading rate of 3,000 t/h for (top) onshore unloading, (middle) offshore unloading to an FSI and (bottom) offshore unloading by direct injection.

5.2.3 Comparison of shipping to offshore pipelines

Pipeline transport costs are dominated by CAPEX and therefore decrease significantly with increased annual flow rates (higher utilisation) as the cost is distributed among a larger number of tCO_2 (Figure 5-6). In contrast, shipping costs on the other hand are dominated by OPEX and Fuel cost, which are not reduced with higher utilisation (Figure 5-6, right).

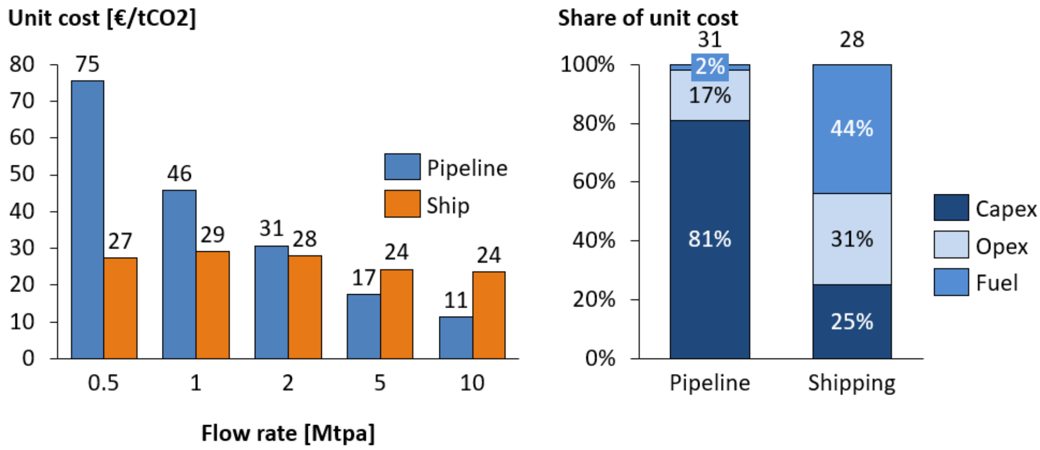


Figure 5-6: Unit cost of pipeline and ship transport (with onshore unloading) for different flow rates (left); share of unit cost by CAPEX, OPEX, and Fuel of shipping and pipeline transport for 1,000km distance and a 2 Mtpa flow rate

Pipeline costs are also much more sensitive to the transport distance than shipping costs since the distance directly impacts the infrastructure sizing (larger CAPEX for longer pipelines). To compare the distance at which shipping becomes more cost-effective than pipeline transport (breakeven distance), the minimum unit costs were calculated for both transport options.[69]

For shore-to-shore transport, shipping becomes more cost effective than pipeline transport at distances above about 650km for a flow rate of 1 Mtpa, which increases to 920km for a flow rate of 2 Mtpa (Figure 5-7). If the gas is pre-pressurised prior to liquefaction, shipping costs can be reduced sufficiently so that the breakeven distances reduce to 320km and 520km, respectively.

The breakeven distances are similar for shore-to-offshore transport, with direct injection from a ship becoming more cost-effective than pipelines at distances above 660km for a flow rate of 1 Mtpa and above 990km for a flow rate of 2 Mtpa (Figure 5-8).

These results demonstrate that for long distance transport of low volumes of CO_2, such as in cross-border shipping from several industrial CCS clusters across Europe, shipping can provide a cost-effective option.[70] Since pipeline costs are CAPEX dominated, the cost-effectiveness of this option also improves with increasing operational lifetime.[6] The breakeven distance will therefore be lower for operational lifetimes less than 20 years and higher for lifetimes greater than 20 years.

[69] Shipping costs were calculated by choosing the lowest cost option, with the optimal ship capacity and number of ships.
[70] For example, the transport distance between Dunkirk and Kollsnes is approximately 1,200km, whereas Rotterdam to St Fergus is 880 km.

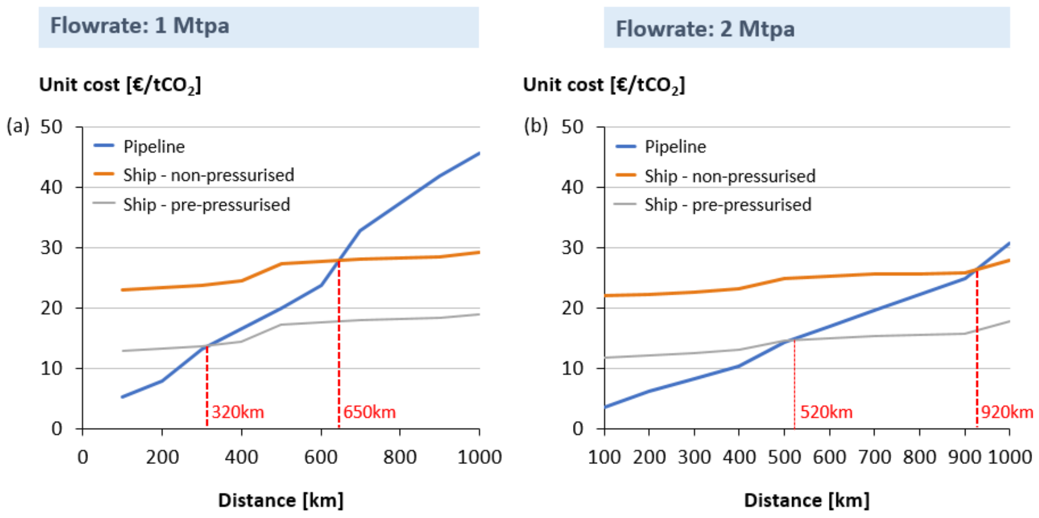


Figure 5-7: Unit cost of shore-to-shore shipping and pipeline transport for a range of distances for flow rates of (a) 1 Mtpa flow rate (and (b) 2 Mtpa flow rate.[71]

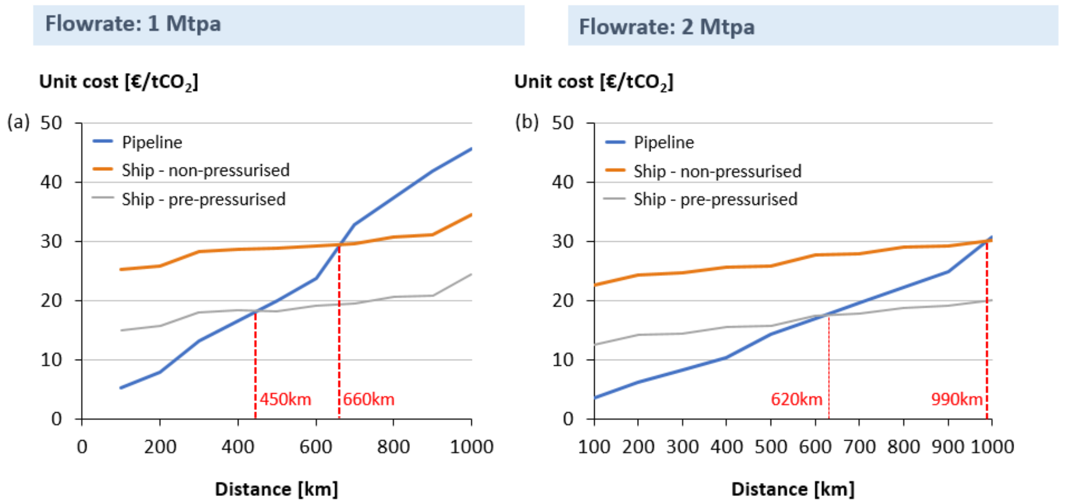


Figure 5-8 Unit cost of shipping with direct injection and pipeline transport for a range of distances for flow rates of (a) 1 Mtpa and (b) 2 Mtpa[71]

[71] The modelling boundary condition is the same for both pipelines and ships in the analysis. Compression to the transport condition is included. The difference in the cost of compression between the pre-pressurised and non-pressurised condition for pipeline costs is less than 1%.

6 Innovations in shipping

Ship costs are primarily OPEX-driven, with crew and fuel accounting for a large proportion of the overall lifetime costs of a shipping operation. In addition, the marine sector is a growing contributor to global greenhouse gas emissions, accounting for 2.5% of emissions which is expected to increase significantly in the absence of mitigation strategies. Minimising the amount that CO_2 transport contributes to global emissions is an important goal.

Innovations in shipping, such as autonomy, zero emission propulsion and on-board CCS can reduce costs and emissions from the marine sector, and potentially from future CCS transport chains.

6.1 Autonomy

There are several ongoing initiatives in autonomous shipping. The ship closest to operations is likely theYara Birkeland, an 80 m container ship presently under construction[72] The ship will have an eco-cruising speed of 6-7 knots and is expected to require only 200 kW thrust, which allows it to be fully electrified, with power supplied from a 7 MWh battery pack. All operations including loading, unloading and navigation will be autonomous, albeit with a supporting remote-control room. The ship is set to be in operation in 2020. After a test period, expected to be 2 years, the ship will navigate without on-board crew.

The ship will replace expensive road transport of containers. Removing the crew reduces the hourly operations cost and means that travelling at a slower transit speed has a less negative impact on cost compared to a fully crewed ship.

Figure 6-1 Yara Birkeland concept design[72]

Autonomy is expected to develop hand-in-hand with electrification and evolve from smaller short-sea vessels in short trades to larger vessels operating longer routes. For electric propulsion, vessels operating with long periods for loading and offloading will be favourable with respect to charging batteries. However, crew costs make up a higher proportion of ship costs for small ships compared to large ships. For example, for a 3,000 t CO_2 carrier, the

[72] https://www.yara.com/news-and-media/press-kits/yara-birkeland-press-kit/

direct crew cost amounts to around 45 % of OPEX. Autonomy has the potential to eliminate all crew costs however some cost of remote operations (control centre) will still be incurred.

Developing autonomous CO_2 logistics will require:

- **Approval by class and maritime organisations for the relevant cargo**. Container ships in general carry "low risk" cargo whereas CO_2 is regarded as "medium to high risk cargo".
- **Bi/multilateral acceptance** of the technology.
- **Reliable high-speed data transfer between ship and control centre** (5G coverage or equivalent). Whether this will be required for the whole route is yet to be defined.
- **Development of autonomous gas handling equipment** onshore and interfaced to the ship.

6.2 Zero emission shipping options

Different options for zero emission shipping are presented in Figure 6-2.

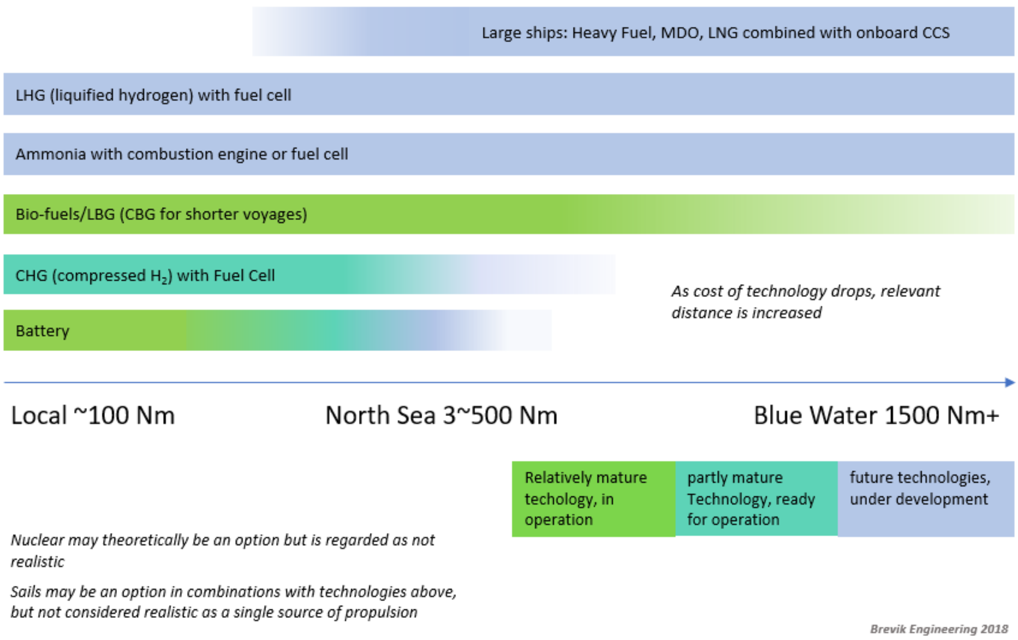


Figure 6-2 Options for zero emission shipping and their relative maturity

Zero GHG emission - short sea

Battery Electric Propulsion is proven to be cost effective for short sea transits. Conventional fossil fuelled car ferries in Norway are rapidly being replaced by ferries with battery-electric drive trains. Present plans include 73 ferries by 2022, increasing to 200 ferries (all Norwegian costal car-ferries) by 2030.[73] Battery packs are now installed in large

[73] www.vegvesen.no.

ROPAX ships enabling arrival and departure including 10-15 nautical miles of the passage to run on batteries.

The challenge for ferries is the short periods in port for charging. The batteries are therefore technically more sophisticated than Electrical Vehicles (EV) batteries used in land transport. The production volumes are also small compared to production of EV batteries. Present marine battery application (5-700 USD/kWh) are therefore significantly more expensive than EV applications (2-250 USD/kWh). For applications where super-fast charging is not required, EV battery technology can be used in ships. The price difference between EV and marine applications is expected to converge in future which accelerates implementation of marine battery applications. With the option for relatively long charging- and discharging-periods, “cheaper” battery applications are suitable for CO_2 logistics. Battery electric solutions are expected to be implemented for longer and longer trades solely due to cost efficiency without government incentives.

Hydrogen Electric Propulsion involves producing power from fuel cells run on hydrogen, normally in combination with a relatively small battery pack for power load equalization. A fuel-cell hydrogen system can only be regarded as a zero-emission technology when the hydrogen is produced without greenhouse emissions: such as from electrolysis with power form clean sources, industrial process with a surplus of hydrogen or from natural gas with CCS. The cost of storing hydrogen is significantly more expensive than natural gas. Hydrogen is mostly relevant for situations where the requirement for charging, speed and sailing distance excludes batteries. Due to the cost, risk and volume of storage, compressed hydrogen concepts are less suitable for blue water (long distance) trades.

Bio-fuels as both gas and liquids can replace their equivalent gas and liquid fossil fuels. Biogas is approximately twice the price of natural (fossil) gas.

Zero emission - blue water

Ammonia may in the future be used as a source of energy both in combination with fuel cells and used as fuel in conventional “gas turbines”. The advantage of ammonia compared to hydrogen is the relatively low pressure required to keep the substance liquid.

Liquified Hydrogen requires refrigeration to very low temperatures below -253°C. As such, the cost of equipment and energy consumption is high. Containing a liquid at this low temperature is also challenging. However, despite the challenges, there are several ongoing projects exploring the option of liquified hydrogen as ship cargo and as fuel for long haul shipping.

On board capture of CO_2 was explored by DNV in 2013.[74] The study suggested the use of state-of-the-art amine technology on a very large crude carrier, to scrub the fuel gas. The conclusion was that it was feasible, but that the energy consumption of the ship would increase drastically. The CCS technology has developed since 2013 and the concept should be revisited.

6.3 Future logistics concepts and technologies

Push barge solutions are well-established, as are their applications for gas logistics. Several hydrogen FOAK ship projects are expected to become operational in 2021-22. Further adoption of hydrogen will be a commercial issue. Autonomy is technically expected to reach

[74] IEAGHG 2013-IP20/DNV Press-release 11. FEB 2013.

operational stage by 2021-22, however further adoption beyond the pilot stage will depend on maritime regulations.

Virtual Pipeline

The concept of using a virtual pipeline will avoid the need for expensive CO_2 storage at the export terminal and possibly also at the import terminal. In a virtual pipeline, CO_2 is transferred directly from liquefaction plant to a floater ship or barge. When the ship is fully loaded it is replaced by a new ship. The same principle in reverse order may also be adapted at the import terminal. A logical set up would be to operate with 3 or more ships: one loading, one unloading and one or several in transit. The logistics concept is common for transport of bulk materials on inland waterways and sheltered waters, usually with barges, but is also relevant for transport in rough sea environments.

Virtual Pipeline with push barge

Push barge solutions have evolved from tugboats pushing a standard barge to customized barges and pushing vessels which fit together. Connection between a barge and a pusher can form a stiff or semi rigid link where the barge and the pusher are hinged. Only the semi-rigid solution can be used in an open sea environment.[75] Zero emission pushers are under development based on hydrogen.[76]

Figure 6-3 Push barge from Kanfer shipping[75]

Virtual Pipeline with autonomy

As for tankers and container ships, part or full autonomy would cut OPEX compared to manned units. As CAPEX drops, a scenario could be to equip the barges with navigation capabilities, turning them into fully battery-operated autonomous drones. The long battery charging period could benefit from periodically low-cost electricity.

[75] http://kanfershipping.com/home/
[76] https://plugboats.com/worlds-1st-hydrogen-river-boat-emission-free/

7 Implications of legal and regulatory frameworks on CO_2 shipping

7.1 Introduction

Large-scale shipping of CO_2 for storage requires consideration of legal and regulatory frameworks governing both shipping operations and CO_2 handling considerations. Here, the most relevant current legal instruments at international, national and regional level are presented, including identification of regulatory gaps and hurdles. European Union law and Norwegian law are used as examples of national and regional frameworks with advanced provisions for CCS. Variations in national law across other regions are complex and outside the scope of this study.

Included in the review are legal and regulatory framework of transport of CO_2 by ship, including observations on transfer, and especially the offloading of the CO_2 from the ship to either a port or an offshore injection site, as identified as the alternative ship logistics scenarios in Table 4.14. The objective of the analysis is to assess whether the alternative logistics scenarios are affected or hindered by the various legal frameworks, either at international, regional (EU) or national levels. Special requirements of hazardous and noxious cargos and to what extent such requirements relates to CO_2 transport are also assessed.

Liability and contractual issues, including limits of operational and regulatory boundaries between a shipper and a storage operator are also examined, including how different legal entities might interact. How contractual arrangements might be set up to benefit smooth contractual relationships, being mindful of existing and pending legal requirements, is also considered.

Although the analysis is comprehensive and considers a wide range of legal instruments and schemes, we have not addressed or assessed every legal instrument relating to shipping in general. Further, we have not addressed regulatory framework onshore relating to either capture facilities or ports handling CO_2. Although some instruments applicable to shipping in general are dealt with briefly for the sake of good order and to illustrate the complexity of shipping regulation, we have not dealt with instruments or provisions of general character in detail as these are not seen as paramount to CO_2 transportation and because ship transportation is viable subject to these rules independent of CO_2 transportation. Finally, we have limited our observations on storage to the degree relevant to understand the part of the value chain and the limits and boundaries of the regulatory framework addressing either one of or both transport and storage. Thus, this report does not provide an exhaustive list of instruments and analysis relevant to shipping of CO_2. It has to be taken into consideration that shipping of CO_2 has been conducted as part of the food and beverage industry's value chain for many years, c.f. the observations made on the operations of Yara in Norway and the Netherlands on page 5 of this report. For many legal instruments, a change of destination or purpose for the CO_2 does not imply a new set of criteria in relation to shipping.

7.2 Regulating shipping

7.2.1 Introduction

In the sphere of climate and environment, including activities that may affect the climate and environment, no nation is completely free to independently implement a framework with no regards to its neighbouring countries or potentially the world as a whole. Shipping is such an activity, with ships moving around and regularly crossing state lines, posing a risk for emissions, leakages and spillage in both internal or national waters as well as international waters. The consequence of an accident or faulty operation is not only suffered at the location of the incident but has the potential of affecting large areas at sea and shorelines in multiple neighbouring countries. Thus, legal instruments relevant for CO_2 shipping are found in international, regional and national frameworks. These take various forms such as conventions, treaties, directives, acts and regulations.

Public international law, regional law and domestic law are all interlinked and one framework builds on the next. The complexity of legal frameworks and the interrelations between international, regional and national law represents potential challenges, especially as CO_2 storage activities for some jurisdictions and aspects are not yet fully covered by or incorporated into legislation. The different layers of frameworks apply to different sets of stakeholders, with public international law as a main rule first and foremost applying to states and national frameworks regulating the behaviour of the residents of the state and activities conducted in that state's territory. This layering of frameworks results in parallel frameworks for the same activities, which may or may not result in gaps, conflicting rules and challenges interpreting the content of the rule and to a certain extent streamlining of frameworks between sovereign states. Thus, there is a need to interpret the various layers of legal instruments both separately and in combination to determine which criteria apply, as well as to identify legal gaps and issues that may potentially restrict or prevent the shipping of CO_2.

Before we present the various instruments under international, regional and national law being subject to analysis in this study, we will introduce the different categories of framework and how they relate to each other. This is to offer up some basic features of the frameworks and a backdrop to which the analysis is taking into consideration.

7.2.2 Overview of legal frameworks

Public international law

Public international law as a default binds states and not private parties. The framework consists of agreements between states, as laid out in e.g. treaties, conventions, protocols, international custom, general principles of law, judicial decisions and legal teachings.[77] There are few legal instruments or treaties that bind all states or nations, as each state has sovereignty to decide which agreements to enter into.

The states generally subject themselves to the instruments by ratification.[78] After ratification, it is the responsibility of the States to ensure compliance by reflecting these principles in national legislations. However, either whole instruments or certain provisions within the instruments are in some cases considered generally applicable principles or rules of customary law, implying that the states are subjected to the principles or rules regardless of ratification. Most commonly, such rules or principles are found in either the area of human rights and the protection and preservation of the environment

Relevant to CCS are the e.g. the generally applicable principles that it is *"the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction"*[79] and that *"[i]nternational matters concerning the protection and improvement of the environment should be handled in a cooperative spirit by all countries, big and small, on an equal*

[77] M. Evans (2014) *International Law*. Fourth Edition p. 91
[78] M. Evans (2014) *International Law*. Fourth Edition p. 170
[79] Stockholm Declaration of the United Nations Conference on the Human Environment, Principle 21, https://www.jus.uio.no/english/services/library/treaties/06/6-01/stockholm_decl.xml (Accessed 9 July 2019)

footing.'[80] Further, for environmental damages, the polluter-pays principle[81] is a widely accepted principle that states that the party performing a polluting activity is responsible for the eventual damages caused.

There is no global supranational legal entity to develop and coordinate a comprehensive legal framework. This has contributed to a proliferation of public international law which can result in overlap or conflicting frameworks.[82] However, for the scope of this study, we have not observed any showstoppers to CCUS due to conflict between international legal instruments.

Bodies such as the United Nations and the International Maritime Organization are responsible for the development of overreaching international legal frameworks. The International Maritime Organization (IMO) is a specialized agency and standard-setting authority subject to the United Nations, with responsibility for the safety, security and environmental performance of shipping.[83]

Within this study, relevant framework related to offshore and marine activities was reviewed, of which there are two broad categories: global rules and regional rules. In this study, we will analyse both categories, in which UNCLOS[84] is an example of the former and OSPAR[85] is an example of the latter.

Regional law – European Union law

The EU is a political and economic union, consisting today of 28 Member States[86] that operate as a single market (also known as the "Internal" or "Common" Market). The EU aims to enhance economic cooperation, stability and growth between its countries, by securing free movement of goods, capital, services and labor ("the four freedoms"). Through the Agreement of the European Economic Area (The EEA Agreement), the single market also includes three EEA European Free Trade Association (EFTA) States – Iceland, Liechtenstein and Norway.[87]

EU legal framework is one of the most comprehensive and systematic regional public international frameworks. The EU establishes a supranational legal system for its Member States founded upon principles of democracy which recognizes the sovereignty of each of its Member States. The EU institutions are granted powers through the founding treaties which are negotiated and ratified by each Member State[88] also referred to as primary legislation. The EU Member States are obliged to implement all legally binding EU acts and shall adopt all measures of national law necessary to do so.[89]

EU's secondary legislation is based on the principles and objectives of the treaties, and is separated into different types of legal acts, including:[90]

[80] Stockholm Declaration of the United Nations Conference on the Human Environment, Principle 24, https://www.jus.uio.no/english/services/library/treaties/06/6-01/stockholm_decl.xml (Accessed 9 July 2019)
[81] The polluter pays-principle is set out in e.g. the Treaty on the Functioning of the European Union (Article 191(2) TFEU).
[82] For example, see P. Sands and J. Peel (2013) *Principles of International Environmental Law.* Third Edition. p. 105-107
[83] IMO website; http://www.imo.org/en/About/Pages/Default.aspx (Accessed 24 May 2016)
[84] The United Nations Convention on the Law of the Sea (UNCLOS) of 1982
[85] The 1992 Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)
[86] https://europa.eu/european-union/about-eu/countries_en
[87] The European Free Trade Association Website, https://www.efta.int/eea/eea-agreement (Accessed 9 July 2019)
[88] Treaty on European Union (TEU) and Treaty on the Functioning of the European Union (TFEU)
[89] TFEU Art. 291
[90] TFEU Art. 288

- **Regulations** are legally binding and directly applicable across the EU in all of its entity,[91] without needing to be transposed into national law. Regulations are designed to ensure uniform application of EU law in all Member States, superseding national laws that are incompatible with substantial provision.[92]
- **Directives** are legally binding but allow the national authorities freedom to choose the form and method of implementation. Member States are obliged to adopt transposing acts and at the same time to bring their national laws into line with the objectives of the directive. As opposed to regulations, directives are generally not directly enforceable[93] until their transposition into national law (commonly within 2 years of the Directive being adopted).
- **Decisions** are binding but only to those to whom they are specifically addressed (for example, Member States, national or legal persons). Like directives, decisions must be adopted as transposed acts at national levels before becoming applicable.
- **Recommendations** and **Opinions** seek to ensure uniformity by providing guidance as to the interpretation and content of EU law. However, they do not confer any rights or obligations on those to whom they are addressed and are not binding.[94]

Secondary legislation either sets minimum standards, which can be met or exceeded Member States,[95] or sets exhaustive regulation of the given field, precluding any differing national measures.[96] The degree to which the Member States have discretion to deviate depends upon the interpretation of the specific legislative text in question.[97]

For the three EEA EFTA states, the implementation of EU legislation follows different procedures. The EEA EFTA States have not transferred any legislative competences to the EU or to the joint EEA bodies and are therefore constitutionally unable to accept binding decisions or acts directly. In order for an EEA relevant Union act to be adopted by the EFTA States, all three states have to agree and approve the act. Upon agreement,[98] the legislation is incorporated into the Annexes to the EEA Agreement and the same rules for the implementation of the Union acts applies as for the EU.[99]

National law

It is the responsibility of individual States to ensure compliance with overarching international and regional law. The guiding principles must be integrated into national law in order for the rules to become applicable within national jurisdictions and binding upon citizens.[100]

Recognizing the principle of sovereignty, the national authorities have the exclusive right to develop and adopt national legislation.[101] Compliance must however be ensured in order for the State to avoid sanctions. One example of how international law is implemented into

[91] https://europa.eu/european-union/eu-law/legal-acts_en
[92] http://www.europarl.europa.eu/unitedkingdom/en/education/teachingresources/howeuworks/legalsystem.html
[93] See case law, e.g. *Van Duyn* and *Ratti* cf. P. Craig, *et. al.* (2015). *EU Law - text, cases and materials.* OUP, Sixth edition, p. 200-204.
[94] http://www.europarl.europa.eu/unitedkingdom/en/education/teachingresources/howeuworks/legalsystem.html
[95] Member States can set more exacting standards and maintain more stringent regulatory provisions than those prescribed, if these are otherwise compatible with EU law
[96] P. Craig, *et. al.* (2015). *EU Law - text, cases and materials.* OUP, Sixth edition, p. 626
[97] P. Craig, *et. al.* (2015). *EU Law - text, cases and materials.* OUP, Sixth edition, p. 626-627
[98] http://www.efta.int/media/documents/eea/1113623-How-EU-acts-become-EEA-acts.pdf
[99] http://www.eftasurv.int/about-the-authority/the-authority-at-a-glance-/ (Accessed 31 July 2019)
[100] R. Jennings and A. Watts (2011) *Oppenheim's International Law.* Ninth Edition. Volume 1. p. 13
[101] Stockholm Declaration of the United Nations Conference on the Human Environment, Principle 21, https://www.jus.uio.no/english/services/library/treaties/06/6-01/stockholm_decl.xml (Accessed 9 July 2019)

national legislation is the reflection of the polluter pays principle in the Norwegian Pollution Control Act (see Information Box below).[102]

Since national authorities are often given discretion to set stricter requirements than those set out in both general public international law and the EU framework, the legal situation may in fact vary greatly from country to country. This is often the case for EU environmental legal framework. The EU CCS directive[103] may serve as an example. CCS as such is not made mandatory, but if the Member States should choose to allow for and initiate CCS projects, the minimum requirements in the directive are applicable. This has led to countries such as Germany to transpose the directive into national law limiting the legality of CO_2 storage to pilot, research and demonstration projects and further limiting the annual storage capacity both for single projects and for Germany as a whole.[104]

Polluter pays principle in the Norwegian Pollution Control Act

Subject to public international law, national authorities are responsible for implementing the polluter pays principle into their national framework. In Norway, the principle is included and elaborated on in the Pollution Control Act. Section 2 nr. 5 of the Act provides that *"[t]he costs of preventing or limiting pollution and waste problems shall be met by the person responsible for the pollution or waste."*

Accordingly, the responsibility as set out by international law to cover costs to prevent or limit pollution is transferred from the State to the responsible party under national law. Regardless, the Norwegian State remains liable for the pollution or waste towards its fellow nations and will carry the cost and responsibility of cleaning up the pollution or correcting the damage if for example the polluting company goes bankrupt and ceases to exist.[105]

7.3 Public international law

The most relevant public international legal instruments for shipping and the maritime environment, as well as the CCS specific regulatory framework have been reviewed for the purpose of this study. Some of the key features of the instruments reviewed are summarised in Table 7-1, and in the following sections.

[102] Act of 13 March 1981 No.6 Concerning Protection Against Pollution and Concerning Waste
[103] Directive 2009/31/EU
[104] I. Havercroft *et al.* (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues.* Second Edition p. 61
[105] P. Sands and J. Peel (2013) *Principles of International Environmental Law.* Third Edition p. 229

Table 7-1 Summary of key features of relevant public international legal instruments

Legal instrument	Key features
1982 United Nations Convention on the Law of the Sea (**UNCLOS**)	• Main legal framework for governing activities at sea • States have the right to exploit their natural resources but are obliged to protect and preserve the environment • Some room for interpretation regarding storage as UNCLOS does not refer to subsea • No specific provisions for ships transporting CO_2
1972 **London Convention** on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter	• Focused on dumping • CO_2 is not listed in Annexes, therefore its disposal is not prohibited or subject to special permits
1996 Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (**The London Protocol**)	• Only global agreement dealing specifically with offshore unloading and storage of CO_2 • CO_2 is regarded as waste and storage in the subsea is considered dumping, but storage of CO_2 from capture processes is excepted from general dumping prohibition • Prevents export of "*waste or other matter to other countries for dumping…*" presenting a **hurdle to establishment of international offshore storage hubs** involving cross-border elements for most of its Contracting Parties
1992 Convention for the Protection of the Marine Environment of the North-East Atlantic Convention (**OSPAR**)	• Objective to prevent and eliminate pollution for the protection of the marine environment • Applies to transport of CO_2 by ships and pipelines • Applies to storage activities but CO_2 from capture processes is a listed exception from dumping prohibition
The 1973 International Convention for the Prevention of Pollution from Ships (**MARPOL**)	• Objective to prevent pollution of the marine environment by ships from operational or accidental causes
1974 International Convention for the Safety of Life at Sea (**SOLAS**)	• Sets out minimum standards for the construction, equipment and operation of ships carrying dangerous goods (CO_2 included) • Implications for the costs and viability of CO_2 shipping through adherence to design and operation regulations
1976/1977 Convention on Limitation of Liability for Maritime Claims	• Establishes a system of limiting liability for ship owners • Does not set limitation of liability for environmental damage
2010 International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea	• Aims to ensure compensation for damage from the transport of hazardous and noxious substances • Not currently in effect but may be in future

7.3.1 The 1982 United Nations Convention on the Law of the Sea (UNCLOS)

The United Nations Convention on the Law of the Sea of 1982 (UNCLOS) is the main legal framework under international law for governing activities at sea and to some extent seen as an incorporation of generally recognized principles of international law.[106] It entered into force in 1994 and established the rights and obligations of coastal states as an overreaching international agreement.[107] To date, 168 countries and the European Union have joined the Convention.[108]

UNCLOS recognises and emphasises the sovereignty of coastal states *"to exploit their natural resources pursuant to their environmental policies"*.[109] It divides the sea into maritime zones for which international law recognizes different rights and obligations. The territorial sea extends 12 nautical miles (nm) out of the coast, for which a state's sovereignty extends to the airspace over and the seabed below.[110] The exclusive economic zone (EEZ) extends out to 200 nm,[111] over which a state has control of all economic resources.

Each sovereign State enjoys the right to regulate transport and storage activities within its EEZ but foreign ships are allowed the right of innocent passage through the territorial sea. However, there is a right and duty for port State control,[112] which may interfere with an undisturbed passage. The implications for CO_2 shipping for CCS are that transport and storage activities that occur solely within one State's EEZ would be under the jurisdiction of that State. If CO_2 is transported out of one State's EEZ and into the EEZ of another State for storage, then jurisdiction over the transport and storage activities that occur within the other State's EEZ passes to that State. However, under the right of innocent passage, a ship may pass through another State's waters on route to a storage site so long as there is no threat to the maritime environment.

UNCLOS requires the states to implement a framework for *"the prevention, reduction and control of pollution of the marine environment from vessels flying their flag"*[113] and further to collaborate with other states to establish an international framework with the same purpose. There is further an obligation for the states to establish *"routeing systems designed to minimize the threat of accidents which might cause pollution of the marine environment."*[114] UNCLOS contains no specific provisions for ships transporting CO_2. As a consequence, such activities are permitted subject to the provisions of the convention and need to be conducted pursuant to the same care for prevention, reduction and control of pollution as shipping in general. Thus, UNCLOS does not present a barrier to CO_2 shipping.

Subject to UNCLOS Part XII, each state has the general obligation to *"protect and preserve"* the marine environment[115] and must take measures to prevent, reduce and control pollution

[106] P. Sands and J. Peel (2013) *Principles of International Environmental Law.* Third Edition pp. 344, 350, and OSPAR Convention Preamble. https://www.ospar.org/convention/text (Accessed 9 July 2019)
[107] https://hub.globalccsinstitute.com/publications/offshore-co2-storage-legal-resources/united-nations-convention-law-sea-unclos
[108] The United Nations Division for Ocean Affairs and Law of the Sea (2019), https://www.un.org/depts/los/reference_files/chronological_lists_of_ratifications.htm
[109] Article 193, drawing upon Principle 21 of the 1972 Stockholm Declaration
[110] UNCLOS Articles 3, c.f. 1 No.. 1 and 2, and Article 2 No. 2
[111] Article 57
[112] **Port State Control** is defined by IMO as *"the inspection of foreign ships in national ports to verify that the condition of the ship and its equipment comply with the requirements of international regulations and that the ship is manned and operated in compliance with these rules."* http://www.imo.org/en/OurWork/MSAS/Pages/PortStateControl.aspx . See Chapter 7.3.6 for further details.
[113] Article 211(2)
[114] Article 211(1)
[115] Article 192

of the marine environment from any source, individually and jointly with other States. The definition of pollution of the marine environment is broad (see Appendix, Section 10.10.1 for details). Shipping, offloading and storage may all ultimately result in pollution to the marine environment, which implies an obligation to reduce the environmental impact of these activities. However, this does not present a barrier for ship transport of CO_2.

Under UNCLOS, there is a requirement for the member states to adopt regulatory framework to *"prevent, reduce and control pollution"* resulting from "dumping".[116] UNCLOS does not specifically address storage of CO_2 but has a relatively vague definition of the term "dumping" identical to that in the London Convention (see 7.3.2 below), namely *"(i) any deliberate disposal of wastes or other matter from vessels, aircraft, platforms or other man-made structures at sea"* and *"(ii) any deliberate disposal of vessels, aircraft, platforms or other man-made structures at sea."* This definition leaves room for interpretation and questions whether CO_2 storage is included. However, Article 216 in Section 6 on enforcement, emphasizes that the framework on prevention, reduction and control of pollution by dumping shall be enforceable *"with regard to dumping within its territorial sea or its exclusive economic zone <u>or onto its continental shelf</u>."*[117] Although still not clear with regards to injection of CO_2 in the subsea bed, it is our understanding that CO_2 storage would be included, as this definition came prior to any storage activities offshore and no change of wording has been initiated since the introduction of this article. Our understanding is therefore that UNCLOS comprises CO_2 offloading and storage in a similar manner as shipping, as activities to be implemented subject to the obligation to protect and preserve the marine environment, regardless if the offloading is conducted at a port for further transport and later storage, or offshore to FSI or direct injection. (See Appendix Section 10.10.1 for more detailed discussion). As for shipping, we have not observed any hurdles for offloading or storage.

7.3.2 The 1972 London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

The London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the "London Convention") is one of the first global treaties to protect the marine environment from human activities. Its objective is to *"promote the effective control of all sources of marine pollution and to take all practicable steps to prevent pollution of the sea by dumping of wastes and other matter."* States are obliged to implement measures both individually and collectively to meet this objective.[118]

The London Convention prohibits dumping from vessels, aircraft, platforms and other man-made structures, for which "vessels and aircrafts" encompasses *"waterborne or airborne craft of any type whatsoever."* including *"air cushioned craft and floating craft, whether self-propelled or not."*[119] Thus, the inclusion of ships as well as offloading facilities are implied.

The London Convention regulates the disposal of wastes and other matter at sea through a systematic listing of substances in the Annexes, often referred to as a "black list" (substances subject to an absolute prohibition) and a "grey list" (substances subject to a special permit).[120] CO_2 is not specifically listed and is therefore not prohibited or subject to a special permit. Further, exemptions to the definition of dumping imply that incidental storage of CO_2 through enhanced oil recovery might not be regulated by the London

[116] Article 210
[117] Our underlining.
[118] London Convention Article II
[119] London Convention Article (2)
[120] P. Sands and J. Peel (2013) *Principles of International Environmental Law.* Third Edition p. 367

Convention.[121] The London Convention therefore does not represent a hurdle to CO_2 shipping activities.

It is worth noting though that the London Convention represents a stricter set of obligations for its Contracting Parties than UNLCOS. This implies that the provisions of the London Convention prevail, if a state is signatory to both instruments.

7.3.3 The 1996 Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

Introduction and background

In 1996, a number of the Contracting Parties to the London Convention adopted a Protocol to the Convention (the "London Protocol"). The objective of the London Protocol is to *"prevent, reduce and where practicable eliminate pollution caused by dumping or incineration at sea of wastes or other matter"*, c.f. Article 2. To achieve this objective, the Parties to the London Protocol *"shall prohibit the dumping of any wastes or other matter with the exception of those listed in Annex 1",* c.f. Article 4.1.1.[122] The London Protocol thus shifted the approach of the London Convention from prohibiting dumping of only specific, listed waste materials to prohibiting all dumping, *except for* listed wastes.[123]

The London Protocol is the only global agreement dealing specifically with offshore offloading and CO_2 storage and that explicitly allows for sub-seabed storage of CO_2. The London Protocol imposes a set of principles such as the precautionary principle and the polluter-pays principle, minimum required actions and omissions and opens up for more stringent measures to be implemented. It does not present any hurdles or barriers to CCS deployment in the London Protocol for transport, offloading and storage per se. However, as we will examine in greater detail below, there is an observed hurdle related to export prohibition and thus to the establishment of cross-border storage hubs.

Transport, offloading and storage provisions

CO_2 is included under the definition of waste in Article 1.8 being a *"material and substance of any kind, form or description."*[124] The definition of dumping in Article 4.1.3 includes *"any storage of wastes or other matter in the seabed and the subsoil thereof from vessels, aircraft, platforms or other man-made structures at sea."*[124] This implies the inclusion of CO_2 storage from ships as well as floating installations. CO_2 storage in offshore reservoirs is regarded as dumping of waste and subject to the restrictions of the London Protocol; however, following an amendment in 2006, storage of CO_2 for CCS is included in the listed exceptions.[125]

Whether offloading activities are included in the definition of dumping is not clear from the wording. Regardless, it is our understanding that offloading as such is regulated by the London Protocol. Subject to Article 10, Contracting Parties, meaning contracting States, are obligated to implement the requirements of the London Protocol to *"vessels […] loading in its territory the wastes […] which are to be dumped […] at sea"*[126] and *"vessels, […] and platforms or other man-made structures believed to be engaged in dumping […] at sea*

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[121] Article III
[122] I. Ombudstvedt and A. Gimnes Jarøy (2019) 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14 21st -25th October 2018, Melbourne, Australia. Available at: https://www.ssrn.com/index.cfm/en/
[123] R. C. Smyth and S. D. Hovorka (2017) *Best Management Practices for Offshore Transportation and Sub-Seabed Geologic Storage of Carbon Dioxide* p. 19. DOI: 10.1109/OCEANS.2012.6404971
[124] Our underlining
[125] Resolution LP.1(1) Amendment to include CO_2 sequestration in sub-seabed geological formations in Annex 1 to the London Protocol.
[126] Article 19.1.2

[…].[127] (see Appendix, Section 10.10.1 for discussion), Thus, CO_2 offloading and storage are both exempt from direct prohibition. The reason it would be of interest to establish whether offloading is included in the definition of "dumping" is to figure out what legal consequences and criteria apply to the CO_2 and if e.g. the activity would face issues like the export prohibition we are analysing below. Interpreting the terms based on the technologies being used, it may however, be reasonable to assume there is no "one size fits all". In a situation of onshore offloading for later injection via pipeline, it would seem logical having offloading as part of the transport part of the value chain. This would fit with the experience from Yara and Linde Group, transporting CO_2 for onshore offloading and later use, without hindrance from the London Protocol. However, if the CO_2 is transported by ship for direct injection, the offloading activity is so closely linked to the definition of dumping, it is more logical to interpret the activity to be an integrated part of the storage.

Export prohibition

Article 6 prevents export of *"waste or other matter to other countries for dumping or incineration at sea"*. As CO_2 is considered "waste" and storage is considered "dumping", the London Protocol effectively prevents the establishment of international storage hubs offshore in the 51 Contracting Parties.[128] Export of CO_2 for the purposes of onshore storage, is not prevented by the London Protocol, nor is transport for use in enhanced oil recovery (CO_2-EOR), as this is not considered dumping under the London Protocol.[129]

The London Protocol is to a large extent technology neutral and does not treat export by ship differently than pipelines.[130] The export prohibition is thus not a specific hurdle or barrier related to export by shipping of CO_2. However, the prohibition represents a challenge under public international law and restricts the possibility for commercial deployment of CCS.

In order to overcome this legal barrier, Norway proposed a resolution to adopt a second paragraph to Article 6 to specifically allow for export of CO_2 for storage. This provides that *"[e]xport of CO_2 for disposal in accordance with Annex I may occur, provided an agreement or arrangement has been entered into by the countries concerned."* The amendment was adopted in 2009; however, ratification of the amendment is needed by two thirds of the Contracting Parties in order for the provision to enter into force and this has not yet been achieved.[131]

As a result, various legal options under public international law have been proposed to overcome the export prohibition and accommodate for cross-border CCS despite the delay in ratifications (see Appendix, Section 10.10.1 for detailed discussion). Based on published analysis, IOM Law recommended that while waiting for a sufficient number of ratifications, provisional application of the 2009 amendment between States that have already ratified should be sought.[132] This solution allows for the ratifying Parties to take the provisions immediately into use, ensuring that the strict obligations set forth in the London Protocol

[127] Article 19.1.3
[128] http://www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx
[129] Article 1(4)(3)
[130] c.f. wording *"vessels, aircraft and platforms or other man-made structures"* in article 10. (Our underlining.)
[131] To date, only six out of the 53 Parties to the London Protocol have ratified the 2009-amendment, namely Norway, the UK, the Netherlands, Iran, Finland and Estonia http://www.imo.org/en/About/Conventions/StatusOfConventions/Documents/Status%20-%202019.pdf p. 558
[132] VCLT Article 25 provides the option of giving the amendment immediate effect through provisional application if *"the negotiating States have in some other manner so agreed"*.

continue while not undermining efforts to ratify the amendment and thus preserve diplomatic relations.[133]

After the publication of the recommendations, the Contracting Parties Norway and the Netherlands submitted a proposed resolution on the provisional application of the 2009 amendment to Article 6 to their fellow Contracting Parties, in preparation to the 14th meeting of the Contracting Parties 7th – 11th October 2019. The proposal was adopted on 11th October with the effect for all of the Contracting Parties to the London Protocol, implying that the Contracting Parties wanting to take the amendment into use may do so after depositing a declaration on provisional application of the 2009 amendment. This is in accordance with the recommendation made on provisional application mentioned above. However, the Contracting Parties agreed to extend the access to the amendment to Contracting Parties who have ratified and those who have not alike, implying the showstopper to export CO_2 for storage is removed from an international perspective.[134] Now, it is up to national declarations to implement the resolution.

7.3.4 The 1992 Convention for the Protection of the Marine Environment of the North-East Atlantic Convention (OSPAR)

Introduction and background

OSPAR is a regional treaty to which the Contracting Parties are Belgium, Denmark, the European Union, Finland, France, Germany, Iceland, Ireland, the Netherlands, Norway, Portugal, Spain, Sweden and the United Kingdom of Great Britain and Northern Ireland.[135] Pursuant to Article 1, it applies within the internal waters of the Contracting Parties, in accordance with international legal boundaries as set out by UNCLOS.

The OSPAR convention's objective is to prevent and eliminate pollution for the protection of the marine environment, relying on general principles of public international law such as the precautionary principle and the polluter-pays principle.[136]The Contracting Parties are obligated to *"take all possible steps to prevent and eliminate pollution"* and to *"take the necessary measures to protect the maritime area against the ad-verse effects of human activities".*[137] specifically applies to pollution by dumping or incineration and pollution from offshore sources, including offshore installations or pipelines.[138]

Transport and storage

OSPAR contains general provisions that have implications for transport offloading and storage of CO_2 (see Appendix Section 10.10.1 for details). Ships transporting CO_2 are subject to the general obligation to prevent and eliminate pollution,[139] which applies to non-deliberate disposal, such as CO_2 leakages during transport, rather than offloading and storage in particular. No specific provision is made for the transport of CO_2. However, in our opinion, the obligation would apply to both transport and offloading activities, meaning that the activities must be undertaken with careful considerations to the marine environment in which they are conducted.

[133] M. Gran and I.Ombudstvedt (2018) 14th International Conference on Greenhouse Gas Control Technologies, p. 10. Available at: https://www.ssrn.com/index.cfm/en/.
[134] LC 41/6, 2 August 2019, Pre-session public release
[135] https://www.ospar.org/site/assets/files/1290/ospar_convention_e_updated_text_in_2007_no_revs.pdf
[136] Article 2(2)(a) and (b)
[137] Article 2(1)(a)
[138] as defined, cf. Article 5 in accordance with the provisions provided for in Annex III.
[139] Article 5

OSPAR applies to storage and the Contracting Parties are obligated to prevent and eliminate pollution by "dumping or incineration of wastes or other matter[140]OSPAR uses the same definition as UNCLOS for "dumping",[141] implying the legal boundaries in OSPAR between transport, offloading and storage would be subject to interpretation and technical consideration. However, we have not gone into further detail on this, due to the fact that Article 5 applies to all parts of the value chain. Further, the dumping prohibition in Article 3(1), explicitly does not apply to *"carbon dioxide streams from carbon dioxide capture processes for storage"*, provided compliance with specific requirements.[142] The conditions set out in OSPAR for storage are similar to those of the London Protocol regarding the location of the storage site and contents of the CO_2 stream; however, these conditions should not be viewed as a hurdle for the deployment of CCS or transport, offloading or storage of CO_2. Norway is one of the Contracting Parties to OSPAR and operates sites at Sleipner and Snøhvit. Although the transport of the CO_2 in these projects is conducted by pipelines, no additional legal hurdles are presented by OSPAR if the means of transportation were to change to shipping.

Consequently, OSPAR allows for transport, offloading and storage of CO_2, utilizing ships as means of transport and offloading.

7.3.5 The 1973 International Convention for the Prevention of Pollution from Ships (MARPOL)

Introduction and background

The International Convention for the Prevention of Pollution from Ships (MARPOL) of 1973 is the main international instrument regulating prevention of pollution of the marine environment by ships from operational or accidental causes. MARPOL is built up by six annexes, which entered into force at different times between 1983 and 2005.[143]

The general objective of the MARPOL Convention is to prevent pollution of the marine environment by the discharge of harmful substances or effluents containing such substance from ships.[144] Interpretation of the implications of the definition of "discharge" and applicability for CCS projects differs (see Appendix for detailed discussion). In our opinion, there is a distinction between deliberate disposal (as covered by the London Convention and defined as dumping) and unplanned, accidental or operational pollution (as covered by MARPOL and defined as discharge). These are not conflicting but are complementing each other meaning that both conventions are needed to regulate the activities of the CCS value chain.

All Contracting Parties are bound by the first two Annexes of MARPOL, something which due to the large number of Contracting Parties has earned the principles and regulations in these Annexes the status of "generally accepted international rules and standards", implying that the provisions are enforceable against all states (and thus ships flying any state's flag), not only those which have ratified MARPOL.[145] MARPOL comprises provisions regarding to ships entitled to fly the flag of or which operates under the authority of a Party to the Convention, cf. Article 3 nr. 1 (a)(b). However, in combination with UNCLOS, MARPOL has addressed problems related to ships' owners and flag states not operating under sufficiently stringent regulation or taking enough care of e.g. maintenance, training and safety by

[140] Article 3
[141] Article 1(1)
[142] as are set out in sections (i)-iv) of Article 3(2)(f) in Annex II
[143] http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx
[144] MARPOL, Article 1(1)
[145] P. Birnie *et al.* (2009) *International Law & the Environment*. Third edition. p. 404

strengthening the rights and jurisdiction of the costal and port states by relying on these states' fully recognised right to regulate conditions of entry to or passage through their internal waters.[146] In view of what has been stated in the previous paragraph relating to generally accepted international rules and standards, one could interpret this to imply a right for the port state, meaning the state which controls the port in which the ship docks, to inspect any ship entering its port, regardless of origin, and thus not limited to ships flying the flag of a contracting State to MARPOL.

Of specific relevance to ship transport of CO_2 is the provision for the prevention and control of pollution Noxious Liquid Substances in Bulk (see Appendix for definition).[147] There are 250 substances listed as noxious liquid substances included in the International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk (IBC Code), including CO_2.[148] The list is included as Appendix II to Annex II, and thus enforceable globally. The IBC Code, imposes standards for safe carriage of dangerous chemicals and noxious liquid substances in bulk by sea, which would include CO_2 transported to a storage site by ship. More specifically, the IBC Code prescribes the design and a construction standard and further identifies the equipment to be carried to minimize the risks to the ship, its crew and to the environment.[149, 150]

Both ships and reception facilities[151,152]must follow the requirements for design, construction, equipment. In our opinion, these requirements do not represent hurdles for CO_2 shipping. Also, there is a long-standing history of shipping of CO_2 as part of e.g. food industry's value chain, although in more modest quantities than would be the case for CO_2 storage. A change of destination or purpose for the CO_2 does not imply a new or more onerous set of criteria for the ship operator.

7.3.6 The 1974 International Convention for the Safety of Life at Sea (SOLAS)

The International Convention for the Safety of Life at Sea (SOLAS) of 1974[153] is an international treaty which aims to promote the safety of life at sea (IMO 2018). [154] It applies to ships entitled to fly the flag of the 165 contracting States. [155] However, SOLAS has picked up on the port State control mechanism,[156] as defined above in 7.3.1.This control was increased additionally in 1993, when IMO following a disaster off the Shetland Islands amended SOLAS to allow costal States to require ships to report their presence when entering into environmentally sensitive areas and other designated zones.[157]

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[146] P. Birnie et al. (2009) International Law & the Environment. Third edition. p. 405, c.f. Chapter 7.3.1 on UNCLOS. MARPOL is emphasizing the costal and port States' right to control through Article 5, allowing for any ships required to hold a certificate subject to the technical standards of MARPOL to be inspected in the port State.
[147] http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx
[148] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/ChemicalPollution/Pages/IBCCode.aspx
[149] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/ChemicalPollution/Pages/Default.aspx
[150] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/ChemicalPollution/Pages/IBCCode.aspx
[151] C.f. Annex II Regulation 7(1)
[152] C.f. Annex II Regulation 7(1)(a)
[153] https://www.ifrc.org/docs/idrl/I456EN.pdf
[154] http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx
[155] http://www.imo.org/en/About/Conventions/StatusOfConventions/Documents/Status%20-%202019.pdf p. 17.
[156] http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx
[157] P. Birnie *et al.* (2009) *International Law & the Environment*. Third edition. p. 415-416

The main objective of the SOLAS is to specify minimum standards for the construction, equipment and operation of ships, in line with the IMO International Code for the Construction and Equipment of Ships Carrying Liquified Gases in Bulk (IGC Code) (see Appendix for definition of dangerous goods, under which CO_2 is included).[158] In our opinion, these rules apply to transport of CO_2 as well. (See Appendix for detailed analysis). The IGC Code will in principle also apply to floating storage regasification units, but the application of the IGC Code rules to offloading units remains unclear.[159]

Although provisions regarding the design and operation of the ships will have impacts for the final costs and viability of CO_2 shipping,[160] the requirements are first and foremost related to design and construction and therefore do not represent hurdles for CO_2 shipping. As for MARPOL, the long history of transporting CO_2 for e.g. food industry supports this conclusion. A change of destination or purpose for the CO_2 does not seem to imply a new set of criteria under SOLAS, however being mindful of the unclear situation regarding offloading.

7.3.7 The 1976/1977 Convention on Limitation of Liability for Maritime Claims (LLMC)

The Convention on Limitation of Liability for Maritime Claims (LLMC) was adopted in 1976 and replaced the International Convention Relating to the Limitation of the Liability of Owners of Seagoing Ships of 1957.[161]

The LLMC establishes a system of limiting liability for ship owners for claims related to e.g. loss of life and personal injury as well as property claims, including damage to ships, docks, and offloading facilities.[162] Delays, infringements and other types of claims that may arise in the operation of ships are also included.[163] Ship owners of ships constructed for the carriage and offloading of CO_2 are entitled to limit their liability under the 1996 LLMC. [164] It could potentially also be argued that ships (including FPSOs) being employed to inject CO_2 could be subject to the LLMC, given their ability to sail and thus might be what is being referred to as "seagoing" (see Appendix for further discussion of scope of application and analysis of the term "ship"). Further, Article 11 constitutes a limitation fund to be distributed amongst the claimants in portion to their established claims.

In our opinion, liability eligible to limitation under LLMC for ships used for transporting CO_2 comprises for example damage to the port in which it loads or offloads the CO_2, personal injury occurring during either loading, transport or offloading (see Appendix for details of limitation of liability). Further, it would comprise potential loss caused to e.g. the storage operator for delays in deliveries, such as may be experienced in demonstration projects in which there are few emission sources delivering CO_2 to the storage facilities. Delays in deliveries may cause an interrupted supply of CO_2 resulting in interrupted operations (which again might lead to both a loss of income and considerable costs related to stopping and restarting the injection operations). Such losses may end up far exceeding what the ship owner or operator are capable of covering and it is thus reasonable the ship operator is eligible to limitation under LLMC for such losses.

[158] Under provisions of SOLAS Chapter VII
[159] I. Havercroft *et al.* (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues.* Second Edition p. 258
[160] *Shipping CO_2 – UK Cost Estimation Study* (2018) Element Energy for BEIS p. 54
[161] http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/Convention-on-Limitation-of-Liability-for-Maritime-Claims-%28LLMC%29.aspx
[162] LLMC Article 2(1)(a)
[163] Article 2
[164] V. Weber and M. N. Tsimplis (2017) The International Journal of Marine and Coastal Law doi:10.1163/15718085-12341419, p. 153

The LLMC does not include a definition of the term “loss”, which could indicate that it is a cap on the ship operator and owner’s responsibility for both direct and indirect loss caused by delays or damage to port, offloading facilities and injury. There also seems to be room for limiting the ship operator and owners’ liability related to removing leaked CO_2.[165] This does not include a right to limit claims related to environmental damage caused by the cargo.

The general limits of liability are based on gross tonnage of the ship.[166] The criteria in LLMC do not represent hurdles for CO_2 transport or storage, rather they are of benefit to operators, as the right to limit the ship owner’s liability would also apply to claims related to loss and claims occurring during loading, transport and offloading of CO_2. As for MARPOL and SOLAS, it has to be taken into consideration the long-standing history of shipping of CO_2 as part of e.g. food industry’s value chain. A change of destination or purpose for the CO_2 does not imply a new set of criteria under LLMC.

7.3.8 The 2010 International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (HNS Convention)[167]

The International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea (the HNS Convention)[168] is an international agreement originally adopted at an international conference in 1996. However, neither the HNS Convention nor the subsequent 2010 Protocol have received sufficient ratifications to enter into force.[169] However, the HNS Convention is a regime which may become applicable in the future.[170]

The objective of the HNS Convention is to compensate damages caused by spillage of hazardous and noxious substances during maritime transportation, based on the model of the 1992 International Convention on Civil Liability for Oil Pollution Damage, which covers pollution damage caused by spills of crude oil from tankers.[171]

It applies to any damage, including contamination of the environment, within the territory of a State Party, including the territorial sea and the EEZ.[172] The HNS Convention is part of the IMO liability regime that determines liability to third parties for pollution by contamination arising from ship transport, as well as for preventive measures, property damage, personal injury, and loss of life.[173] Ships used for CO_2 transport and offloading are covered by the provisions as long as CO_2 falls under the definition of *“hazardous or noxious substances”*, and it could be argued that the HNS Convention would apply to injection of CO_2 by a FPSO. (We refer to the chapters on the London Protocol and LLMC above, and the appendix for further elaboration and analysis of the term ship and the distinction between transport, offloading and storage).

[165] Article 2(1)(b)
[166] https://www.jus.uio.no/english/services/library/treaties/06/6-07/liability-maritime-claims-consolidated.xml#treaty-header1-3
[167] Originally adopted in 1996, it has been amended by a 2010 Protocol and the consolidated text is referred to as the International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea, 2010. Consolidated text available at https://www.hnsconvention.org/the-convention/
[168] https://www.hnsconvention.org/wp-content/uploads/2019/05/2010-HNS-Convention-English.pdf
[169] https://www.hnsconvention.org/status/, http://www.imo.org/en/OurWork/Legal/HNS/Pages/HNSConvention.aspx
[170] V. Weber and M. N. Tsimplis (2017) The International Journal of Marine and Coastal Law doi:10.1163/15718085-12341419
[171] https://www.hnsconvention.org/the-convention/
[172] Article 3(a)(b)
[173] HNS Convention Article 4

The HNS Convention covers claims for damages caused by noxious and hazardous substances such as loss of life or personal injury, loss of or damage of property, loss or damage by contamination to the environment.[174] Included is also the costs of preventive measures further loss or damage caused by preventive measures.[175] However, claims falling under the HNS Convention will be subject to limitation , cf. Article 9, unless it is *"proved that the damage resulted from the personal act or omission of the owner, committed with the intent to cause such damage, or recklessly and with knowledge that such damage would probably result".*

Compensation following incidents covered by the HNS Convention are subject to a two-tier system, as set out by the conditions of Chapter III. The 1st tier is insurance and 2nd tier a compensation fund.

According to Article 12, insurance of the ship owner is made compulsory. This shall cover the sums fixed by applying limits of liability (See Appendix for details).

The HNS Convention further establishes the International Hazardous and Noxious Substances Fund (the HNS Fund)[176] which aims *"to provide compensation for damage in connection with the carriage of hazardous and noxious substances by sea"".* The HNS Fund shall pay compensation *"to any person suffering damage if such person has been unable to obtain full and adequate compensation for the damage under the terms of chapter II",* pursuant to the specific provisions of Article 14. Thus, compensation for damages by drawing from the Fund is secondary to the liability of the owner under chapter II of the HNS Convention, as a second tier of compensation in cases where the insurance is insufficient.[177]

The HNS Fund is divided into a general fund for different sectors, as separate funds for oil, LNG and LPG.[178] We have been asked to assess whether a separate fund should be included for CO_2, similarly to the special funds for oil, LNG and LPG In our opinion this would likely not be necessary or particularly helpful to transportation of CO_2 since CO_2 is already covered by the general fund and the risk and extent of damage in cases of CO_2 cargo leakages is much lower than for hydrocarbon spillages. Establishment of a CO_2 fund would also come with transaction costs that would be undesirable.

If the 2010 HNS Convention comes into force, it is expected to replace the Environmental Liability Directive (ELD) and the LLMC for the establishment of a liability regime for HNS cargoes in the EU.[179] (See sections 7.3.7 and 7.4.7 on the LLMC and ELD). Thus, a comparison between the two liability regimes is relevant to this study's assessment of implications for ship transport of CO_2 concerning liabilities. The compensation limits provided for by the LLMC are significantly lower than provided for by the HNS Convention.[180] A difference is also that the fund established by the LLMC provides for direct compensation payment compared to the secondary safety net as established by the liability regime under the HNS Convention.

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[174] Chapter II, cf. Article 1 nr. 6(a)-(c).
[175] Article 1 nr. 6(d)
[176] Article 13
[177] I. Havercroft *et al.* (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues.* Second Edition p. 260
[178] Article 16(2)
[179] V. Weber and M. N. Tsimplis (2017) The International Journal of Marine and Coastal Law doi:10.1163/15718085-12341419 p. 149
[180] I. Havercroft *et al.* (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues.* Second Edition p. 260

7.4 EU law

7.4.1 Introduction

The EU has produced an impressive amount of secondary legislation that aims to protect and regulate activities at sea, with the overall objective to preserve the equal treatment of operations and protection of the marine environment. In recent years, the EU has also established and developed safety requirements for shipping, including establishing the European Maritime Safety Agency (EMSA),[181] and thus has become a more active and visible stakeholder in regulating the maritime environment.[182] Currently, the EU is also an important provider of a comprehensive and CCS specific legal framework. There are a wide range of instruments, regulating the full life cycle of shipping. Consequently, the EU Member States and thus stakeholders operating within the EU, have gradually been subjected to a more complex set of requirements. Some examples are given in the Appendix (Section 10.10.2), and the relevant instruments are summarised in Table 7-2.

Table 7-2 Summary of relevant legal instruments in EU Law

Legal instrument	Key features
Regulation (EC) No 1013/2006 on shipments of waste	• Aims to protect the environment • Limited current relevance as most Member States have ratified the London Protocol
Regulation (EU) No 1315/2013 on Union guidelines for the development of the trans-European transport network	• Focus on having a resource-effective transport network through optimisation of infrastructure and interconnection • Positive effect on CCS projects and objectives • Shipping of CO_2 falls under remit of Projects of Common Interest
Directive 2009/20/EC on the insurance of shipowners for maritime claims	• Implements a requirement to obtain insurance • Applies to large-scale shipping of CO_2 since applies to commercial ships over 300gt
Directive 2009/31/EC on geological storage of carbon dioxide (CCS Directive)	• **Main legal instrument for CO_2 storage** • Does not specifically address transport other than by pipelines therefore is **not directly relevant** • **Specifies requirement to ensure 3rd party access**
Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading (ETS Directive)	• Establishes a **scheme for greenhouse gas emission allowance trading** • Maritime sector is not covered but CO_2 transport and storage are • **Presents a barrier to CO_2 shipping for storage since only CO_2 transported by pipeline is eligible under the scheme**

[181] EMSA was established by Regulation (EC) No 1406/2002181 to provide the necessary support to ensure the convergent and effective implementation of the port State control system as established in public international law and to ensure a high, uniform and effective level of maritime safety and prevention of pollution by ships
[182] T. Falkganger *et al.* (2017) *Scandinavian Maritime Law. The Norwegian Perspective*. 4th edition p.82

Directive 2004/35/EC on environmental liability with regard to the prevention and remedying of environmental damage (ELD)	• Establishes a **liability framework against environmental damage** • Liability for incidents caused by CO_2 storage activities included after the adoption of the CCS Directive and covers transport by ship, including offloading and storage

7.4.2 Regulation (EC) No 1013/2006 on shipments of waste[183]

The Regulation (EC) No 1013/2006 on shipments of waste (SWR) was implemented to protect the environment, taking international obligations and requirements that the EU has signed on to into account.[184] The SWR is considered to have only incidental effects on international trade.[185]

The SWR takes its definition of the term waste from the 2006 Directive on Waste,[186] as *"any substance or object in the categories set out in Annex I which the holder discards or intends or is required to discard."*[187] CO_2 could fall under two of these categories.[188]

In Article 1, the applicability of the SWR is limited to shipments of waste:

(a) *between Member States, within the Community or with transit through third countries;*

(b) *imported into the Community from third countries;*

(c) *exported from the Community to third countries;*

(d) *in transit through the Community, on the way from and to third countries.*

As most EU Member States have ratified the London Protocol, the SWR is currently of limited relevance to transport of CO_2 by ship. Transport of CO_2 for storage is, however, not included in the list of activities excluded from the scope of the SWR,[189] implying that from the time that either some or all states are permitted to transport CO_2 under the London Protocol, the SWR will apply to such activities for EU Member States. Given the recent developments for the London Protocol (see 7.3.3 above) and the plans to establish European storage hubs in e.g. the North Sea through the Northern Lights infrastructure, one could expect the SWR to be applicable to several Member States transporting CO_2 for storage in the future. Further, the SWR applies if an EU Member State, also being a London Protocol Contracting Party, should import CO_2 from a State that is not a Contracting Party to the London Protocol. What is worth noting, however, is that the SWR is applicable for transport of other wastes. We have not noted that the SWR poses hurdles for such other types of wastes. We have not observed provisions that would pose direct hurdles for

[183] Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste
[184] such as the Stockholm Convention of 22 May 2001 on persistent organic pollutants (see SWR Recital 6) and the BASEL Convention to prohibit the import of hazardous waste or of waste listed in Annex II to that Convention (see SWR Recital 9)
[185] SWR Recital 1
[186] Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste
[187] SWR Article 1(1)(a)
[188] *"production or consumption residues not otherwise specified below"* (Q1) and "*any materials, substances or products which are not contained in the abovementioned categories"* (Q16).
[189] Article 1(3)(a)-(g)

transport of CO_2 either, which is consistent with the EU Commission's own statement on the SWR's limited effect on international trade.

7.4.3 Regulation (EU) No 1315/2013 on Union guidelines for the development of the trans-European transport network[190]

The Regulation (EU) No 1315/2013 on Union guidelines for the development of the trans-European transport network is an instrument contributing to important EU objectives [191] with the objective of regulating a trans-European transport network.[192] Pursuant to Article 2(2), such a network includes maritime transport. The purpose of establishing and regulating a trans-European transport network is to *"strengthen the social, economic and territorial cohesion of the Union and contribute to the creation of a single European transport area which is efficient and sustainable, increases the benefits for its users and supports inclusive growth"*.[193] Focus is on having resource-effective transport network, trough e.g. optimisation of infrastructure and interconnection,[194] something which is highly relevant for CCS projects.

An important element of the Regulation, is "projects of common interest" (PCI).[195] PCIs are eligible for funding under the Connecting Europe Facility (CEF), [196] which supports development and deployment of *"high performing, sustainable and efficiently interconnected trans-European networks in the fields of transport, energy and digital services"*.[197] In 2018, for the first time, three CCS projects were found eligible[198] and allocated funds under CEF. One of these projects is the Feasibility Study for Acorn CO_2 SAPLING Transport Infrastructure Project, which comprise both pipeline and ship transport of CO_2 for storage in an offshore storage hub.[199]

Regulation No 1315/2013 contains no observed hurdles for transport of CO_2 by ship. Rather, due to the inclusion of maritime transport and CCS in the PCI scheme, this Regulation represents an incentive to further develop transport networks including both pipelines and ships. We have not observed any hurdles to shipping of CO_2 or the establishment of a transport network involving ships in this Regulation. Rather, the focus on efficiency and enhanced accessibility and connectivity seems positive and workable for CO_2 transporters and the stakeholders interested in using ship transportation for their projects.

7.4.4 Directive 2009/20/EC on the insurance of ship owners for maritime claims[200]

Since the HNS Convention is not currently in force, there is no international obligation to have insurance.[201] However, in recognition of the negative consequences of not having

[190] Regulation (EU) No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU
[191] for example as presented in the Commission White Paper entitled "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system", see Recital (2)
[192] Article 1
[193] Article 4
[194] Article 5
[195] defined in Article 3(b) as *"any project carried out pursuant to the requirements and in compliance with the provisions of this Regulation"*, which thus comprise shipping of CO_2.
[196] Article 7(5), c.f.. https://ec.europa.eu/energy/en/topics/infrastructure/projects-common-interest/funding-projects-common-interest Accessed 21 July 2019
[197] https://ec.europa.eu/inea/en/connecting-europe-facility Accessed 21 July 2019
[198] Article 7 of the Regulation provides for criteria to be eligible for status as PCI, c.f. Article 4 and Chapters II and III.
[199] https://pale-blu.com/co2-sapling/ Accessed 21 July 2019
[200] Directive 2009/20/EC of the European Parliament and of the Council of 23 April 2009 on the insurance of shipowners for maritime claims
[201] I. Havercroft et al. (2018) Carbon Capture and Storage Emerging Legal and Regulatory Issues. Second Edition p. 260

proper insurance coverage, or other forms of financial security, the IMO has adopted guidelines on ship owners responsibilities in respect of maritime claims,[202] and has invited signatories to IMO to implement the guidelines under their jurisdictions. Directive 2009/20/EC on the insurance of ship owners for maritime claims implements these guidelines within the EU and, through its adoption, it implements a requirement to obtain insurance[203] with the aim of ensuring better protection for victims and eliminating substandard ships from operating in Europe.[204]

Directive 2009/20/EC applies to commercial ships over 300 gross tonnage (gt) but does not apply to State-owned or operated ships used for non-commercial public service. It has been proposed that this exception might be applicable for ships transporting CO_2. In our opinion, this would most likely be applicable only if full-scale CCS projects are commissioned without industry involvement.[205] However, despite the obvious public service element in mitigating climate change by capturing and storing CO_2, the assumption should be that a CCS value chain is operated by commercial stakeholders. Thus, as a general rule, Directive 2009/20 applies to CCS operations.

This Directive does not present a hurdle to transport of CO_2 by ship, as the obligation to obtain insurance applies to ships in general. Further, beyond provisions related to port control and inspections,[206] requirements to demonstrate adequate insurance through insurance certificates[207] and penalties for non-compliance,[208] there are no provisions regulating shipping operations as such. The existence of this Directive is, however, an additional argument against the need to establishment of an separate fund pursuant to the HNS Convention (see Chapter 7.3.8),[209] as this Directive imposes mandatory insurance to cover damages, which is similar to tier 1 of the compensation scheme under the HNS Convention. The fund is supposed to kick in if insurance is inadequate to cover the damages and as pointed out in our analysis of the HNS Convention, the extent of the damage caused by CO_2 may be far less than for e.g. LNG, implying the insurance is more likely to cover the damages.

7.4.5 Directive 2009/31/EC on geological storage of carbon dioxide (CCS Directive)[210]

The EU CCS Directive of 2009 is the main legal instrument for CO_2 storage.[211] The CCS Directive was adopted as part of EU's climate and energy package, a set of binding legislation to ensure that the EU meets its climate and energy targets.[212]

[202] Resolution A.898(21), adopted on 25 November 1999, available at http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Assembly/Documents/A.898(21).pdf Accessed 19 October 2019
[203] Article 4
[204] Recital (4)
[205] For example, as a consequence of industry being unable to find viable business models and Member States not seeing any other option
[206] Article 5
[207] Article 6
[208] Article 7
[209] at least for EU/EEA Member States
[210] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006
[211] Directive 2009/31/EC.
[212] European Commission (Undated).

The CCS Directive applies within the territory of the EU/EEA Member States, including their continental shelves, within the meaning of UNCLOS.[213] This includes the Member States' EEZ.[214] Thus, the CCS Directive applies to CO_2 storage onshore as well as offshore.

Transport of CO_2

The objective of the CCS Directive is to provide a legal framework for *"environmentally safe geological storage"* of CO_2.[215] The CCS Directive focuses on storage and does not specifically address transport of CO_2 other than by pipelines. It is therefore not directly relevant for CO_2 shipping but it has important implications for the ETS Directive (Section 7.4.6 below), contractual arrangements (Section 7.6) and monitoring, reporting and verification (Section 0).

With regard to transboundary transport of CO_2, Article 24 of the CCS Directive underlines that: *"the competent authorities of the Member States concerned shall jointly meet the requirements of this Directive and of other relevant Community legislation."* This wording seems purposely open-ended and requires minimal amendments if the scope of the Directive should sometime in the future be widened to include ship transportation.

Third-party access

We have included a brief summary of the requirement to grant third-party access to infrastructure as this will be of relevance in Chapter 5.6 on contractual arrangements. Under Article 21, Member States are required to ensure third-party access to infrastructure for transport and storage,[216] of CO_2 being produced and captured. This has to be read in the light of general principles of efficient and economically viable resource management. For example, developing and managing storage sites is costly and may inflict damage or stress to the local marine environment. It thus makes little sense to develop another storage site in proximity to an existing one if there is still capacity to take CO_2 from more than one emission source. The same applies to transport infrastructure; tying into an existing pipeline may potentially reduce both costs and the footprint of a project.

Member States are obliged to apply *"the objectives of fair and open access,"* with transport and storage capacity as limiting factors.[217] Further, there are requirements in relation to technical specifications and the owner or operator of the storage site or transport network needs may prevail, and *"the interests of all other users of the storage or the network or relevant processing or handling facilities who may be affected"* have to be taken into account before granting access.

Due to the limited scope of the CCS Directive, the requirement of third-party access does not apply to ship transportation. However, as for trans-border transportation, the wording is open-ended and refers only to "transport networks."[218] In our opinion, the CCS Directive should be read in correlation with new developments and regulations, such as the EU Regulation 1315/2013 for trans-European transport networks and the inclusion of CCS in the PCI scheme. The fact that both the CCS Directive and the ETS Directive (section 7.4.6 below) exclude CO_2 transport by ship is thus something that might be outdated and ready for revision.

[213] Article 2 nr. 1.
[214] Recital (18)
[215] CCS Directive Article 1
[216] More precisely *"transport networks and to storage sites,"*
[217] CCS Directive Article 21(2)
[218] CCS Directive Article 21(1)

7.4.6 Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading (ETS Directive)[219]

The EU emissions trading system (EU ETS) is a cornerstone of the EU's policy to combat climate change and a key tool for reducing greenhouse gas emissions cost-effectively.[220] It sets out a "cap and trade" system that puts a price on CO_2 emissions and allows for emissions being traded across the Union within the total emission limit (the "cap"). The ETS Directive requires surrendering of allowances for CO_2 emissions from industries or installations included in scheme. In this way, the ETS Directive is the main European instrument to incentivize emissions reductions and achieve the targets set out in the Paris Agreement.

The ETS only covers certain industry sectors as listed in the Directive's Annex I. The maritime sector is currently not covered by the ETS but offshore installations are. Originally, the ETS applied only to major manufacturing industries such as power plants, oil refineries, iron and steel plants, and various factories making such goods as cement, glass, lime, brick, ceramics, pulp and paper.[221] Eventually, aviation was included as well as (in 2009) CO_2 storage and transport activities.

Allowances for CO_2 permanently stored

Pursuant to Article 12 nr. 3a,[222] if emissions are captured and permanently stored, the emitter will not be under the obligation of surrender emission allowances. However, the ETS requires that the operator surrenders emissions trading allowances for any leaked emissions, provided the requirement of verification of "permanent storage". The obligation to surrender emissions allowances lies upon the Member States to ensure[223], through implementation of the requirements of the Directive into national legislations.

The ETS Directive specifically includes in the Annex I list the *"transport of greenhouse gases by pipelines for geological storage in a storage site permitted under the CCS Directive"*. This statement implies that pipeline transportation is required to secure an unbroken value chain from capture to storage and that this is the only method of transportation that would be accepted to consider the stored CO_2 as eligible under the ETS scheme. Thus, transport by ship is excluded from the scope, as for the CCS Directive.

It has been argued that the exclusion of shipping from the ETS Directive presents a barrier to large-scale CO_2 shipping that requires reform.[224] However, the barrier is not absolute since Member States may apply emission allowance trading to activities and to greenhouse gases which are not listed in Annex I.[225]

The exclusion is, however, the cause of unpredictable conditions for both industry and authorities, as they would need to go through extra steps to achieve the same incentives as

[219] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC
[220] https://ec.europa.eu/clima/policies/ets_en
[221] Truxal (2008)
[222] *"[a]n obligation to surrender allowances shall not arise in respect of emissions verified as captured and transported for permanent storage to a facility for which a permit is in force in accordance with Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide".*
[223] Article 21
[224] A. O'Brien (2018) http://urn.nb.no/URN:NBN:no-69680 p. 15
[225] Pursuant to Article 24 nr.1, and "taking into account all relevant criteria, in particular the effects on the internal market, potential distortions of competition, the environmental integrity of the EU ETS and the reliability of the planned monitoring and reporting system, provided that the inclusion of such activities and greenhouse gases is approved by the Commission,"

projects utilising pipelines. The lack of inclusion of shipping further results in a lack of an established and standardized framework for monitoring, reporting and verification (see Section 0). This again, is part of emphasizing the identified hurdle which ultimately may all be part of preventing the four freedoms (see Section 7.2.2) and also discriminate between offshore and onshore projects.

Considering that the shipping industry is one of the largest emission sources, with 13 % of the total EU greenhouse gas emissions from the transport sector,[226] and following EU's 2013 strategy to reduce emissions from the maritime sector, it has been said that it is quite probable "that the ETS will be extended to include shipping by sea and/or surface transport," as such actions are called for in the revised ETS Directive[227] to start as of 2023.[228]

Since shipping of CO_2 is more flexible than pipeline transportation in terms of scaling up, and given the emergence of projects and studies, such as the Norwegian Northern Lights[229] and the Acorn CO2 SAPLING Transport Infrastructure Project, such a revision would thus be timely, appropriate and welcome to facilitate an industry ready to deploy.

7.4.7 Directive 2004/35/EC on environmental liability with regard to the prevention and remedying of environmental damage (ELD).[230]

Introduction and background

The Environmental Liability Directive (ELD) was adopted in 2004 with the purpose of establishing an environmental liability framework for the prevention and remediation of environmental damage.[231] As part of this goal, ELD emphasises and furthers the polluter-pays-principle.[232] The ELD covers three categories of "environmental damage", namely (a) "damage to protected species and natural habitats", (b), "water damage" and (c) "land damage."[233] Water damage is defined as any damage that *"significantly adversely affects the ecological, chemical and/or quantitative status and/or ecological potential of the waters concerned".*[234]

The ELD applies to environmental damage caused by any of the occupational activities listed in Annex III as well as to *"any imminent threat of such damage occurring by reason of any of those activities"*.[235] In the event of water damages, the ELD established a liability regime under which operators of listed activities in Annex III are held liable. Fault or negligence are not a prerequisite to be held liable,[236] implying a strict liability for the operator. Thus, the liability is strict.

As part of the liability regime under ELD, the operator is obliged to take the necessary preventive measures *"where environmental damage has not yet occurred but there is an imminent threat of such damage occurring".*[237] Where environmental damage has occurred,

[226] https://ec.europa.eu/clima/policies/transport/shipping_en
[227] S. Truxal (2008) International Trade Law and Regulation, 14(6), pp. 117-121.
[228] See Directive (EU) 2018/410 of the European Parliament and the Council Paragraph 4 of the Receital
[229] Equinor (2017) Statoil evaluating new CO2 storage project on the Norwegian continental shelf https://www.equinor.com/en/news/co2-ncs.html
[230] DIRECTIVE 2004/35/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage
[231] Article 1
[232] Recital()2
[233] Article 2 (1)
[234] Water Framework Directive 2000/60/EC, see Article 2 (b)
[235] Article 3(1)(a)
[236] http://ec.europa.eu/environment/legal/liability/pdf/Summary%20ELD.pdf
[237] Article 5

the operator shall take the necessary remedial measures,[238] as well *as "all practicable steps to immediately control, contain, remove or otherwise manage the relevant contaminants and/or any other damage factors in order to limit or to prevent further environmental damage and adverse effects on human health or further impairment of services"*.[239] The remedial measures are identified in accordance with Annex II. It is the operators' responsibility to bear the costs for the preventive and remedial actions.[240]

The environmental damage comprised by Annex III includes : *"[t]ransport by road, rail, inland waterways, sea or air of dangerous goods or polluting goods"*[241] as well as *"[t]he operation of storage sites pursuant to [the CCS Directive]"*.[242] The inclusion of liability for incidents caused by CO_2 storage activities were included under in the scope of ELD after adoption of the CCS Directive.[243] Thus, it is our understanding that the ELD applies to CO_2 transport by ship, including offloading and storage. Comparatively, transport of CO_2 by pipelines is not included in Annex III. As a result, whilst the liability for the ship transport of CO_2 is strict, the liability for transportation through pipelines is fault-based.[244] Arguably, this difference could be seen as a disincentive to and discrimination against CO_2 transportation by ship.

In order to avoid conflict with other liability frameworks of international law, incidents that come under the maritime conventions listed in Annex IV are excluded from the scope of the ELD.[245] This includes the HNS Convention. Thus, in the future, the HNS Convention is expected to take over a large portion of the strict liability regime under the ELD after its entry into force.[246] However, the ELD applies *"without prejudice to the right of the operator to limit his liability"* pursuant to LLMC.[247] Ship owners transporting CO_2 will therefore be able to limit their liability under the provisions of the LLMC, which covers injuries or loss of life or *"the raising, removal, destruction or the rendering harmless of a ship which is sunk, wrecked, stranded or abandoned"*[248] but not environmental damage as a consequence of leakages of CO_2, as the operator may not limit his liability for environmental damage under LLMC (See Chapter 7.3.7 above).

Despite being applicable to CO_2 transport, offloading and storage, we have not observed criteria in ELD represent hurdles for such activities. Similarly, as for SOLAS, MARPOL and LLMC, the long-standing history of shipping of CO_2 as part of the food and beverage industry's value chain, has to be taken into consideration. A change of destination or purpose for the CO_2 does not imply a new set of criteria under ELD but will result in the requirements for offloading and storage being applicable to the operations.

Although the strict liability for shipping compared to pipelines may represent a disincentive as well as discriminating between technologies, we are not recommending an amendment to correct this. Ships are in subject to a higher risk for damage than pipelines and, at least in Europe, there are requirements to obtain insurance subject to Directive 2009/20/EC (see

[238] Article 6(1)(b), cf. Article 7
[239] Article 6(1)(a)
[240] Article 8
[241] See paragraph 8 referring to Directive 93/75/EEC
[242] Paragraph 14
[243] I. Havercroft *et al.* (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues.* Second Edition p. 259
[244] V. Weber and M. N. Tsimplis (2017) The International Journal of Marine and Coastal Law doi:10.1163/15718085-12341419 p. 167, I. Havercroft *et al.* (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues.* Second Edition p.250
[245] Article 4 paragraph 2
[246] V. Weber and M. N. Tsimplis (2017) The International Journal of Marine and Coastal Law doi:10.1163/15718085-12341419 p. 153
[247] Article 4, paragraph 3
[248] LLMC Article 2

Chapter 7.4.4 above) in order for the ship owners to cover potential damage. Thus, the different approach to ship transportation versus pipeline transportation seems appropriate.

7.5 Norwegian law

7.5.1 Introduction

Norway is an EEA EFTA State, with the EU CCS Directive being successfully implemented into the Norwegian national legal framework. Entering into force in 2014, CCS specific provisions are incorporated in parallel into the original Petroleum Act[249] and Regulations[250] as well as a new set of CO_2 Storage Regulations.[251] Thus, establishing a two-track system where CO_2 storage related to petroleum activities are regulated through the petroleum framework,[252] whilst the CO_2 Storage Regulations govern industrial CO_2 storage activities.[253] Further, a requirement to report and pay allowances pursuant to ETS applies to both tracks, depending on the emission source, and is incorporated in the Greenhouse Gas Emissions Trading Act (see Section 7.5.7below). The Norwegian CO_2 storage activities at the natural gas fields of Sleipner and Snøhvit have been permitted and regulated in pursuant to the petroleum activities. Both activity types are subject to the general provisions of the Pollution Control Act[254] and Regulations[255] (see Section 7.5.4 below), as well as offshore HSE-Regulations,[256] for ensuring the health, safety and environment during operation.

In Norway, CO_2 storage has been conducted for more than 20 years since 1996 at the Sleipner field.[257] The shipping of CO_2 for storage purposes has not yet happened in Norwegian waters. However, shipping of CO_2 such as for the food industry has been conducted for several years[258] and, provided a positive budgetary decision is reached for the Norwegian full-scale demonstration project, one option is for industrial onshore emissions of CO_2 to be transported by ship to its storage site.

Norway has a wide range of maritime acts and regulations in addition to having relevant provisions in a number of other instruments, demonstrating its longstanding tradition of shipping. For all practicable purposes, Norway has coordinated much of its legislative efforts with the other Scandinavian countries and these countries have to a large extent almost identical Maritime Codes.[259] Further, Norway has needed to take requirements from general public international law and EU law into account when regulating maritime operations,[260] resulting in a framework with many parallels to a wide range of nations.

The most relevant instruments developed in Norway for shipping and the maritime environment as well as some of the CCS specific regulatory framework to the extent relevant for transport and offloading of CO_2 by ship are summarised below and in Section 10.10.3.

[249] Act 29 November 1996 No. 72 relating to petroleum activities
[250] Regulations to Act relating to petroleum activities..
[251] Regulations relating to exploitation of subsea reservoirs on the continental shelf for storage of CO_2 and relating to transportation of CO_2 on the continental shelf.
[252] Petroleum Act Section 1-6 c) and i)
[253] Storage Regulations Section 1-3 paragraph 3
[254] Act of 13 March 1981 No. 6 Concerning Protection Against Pollution and Concerning Waste.
[255] https://tema.miljodirektoratet.no/en/Legislation1/Regulations/Pollution-Regulations/
[256] Regulation No. 158 of 12 February 2010 relating to health, safety and the environment in the petroleum activities and at certain onshore facilities, with amendments,
[257] Norwegian Petroleum (2019) https://www.norskpetroleum.no/en/environment-and-technology/carbon-capture-and-storage/
[258] https://www.yara.com/news-and-media/news/archive/2015/new-liquid-co2-ship-for-yara/
[259] T. Falkganger *et al.* (2017) *Scandinavian Maritime Law. The Norwegian Perspective*. 4th edition p. 26
[260] T. Falkganger *et al.* (2017) *Scandinavian Maritime Law. The Norwegian Perspective*. 4th edition p. 82 and 87

Table 7-3 Summary of relevant legal instruments in Norwegian Law

Legal instrument	Key features
1994 Norwegian Maritime Code	• One of the most central instruments for regulation of shipping in Norway • Incorporates many of the internationally agreed obligations • Both vessels for transport and vessels for storage are subject to it
2007 Ships Safety and Security Act	• Regulates and safeguards health, property and environment • Incorporates MARPOL and SOLAS • Ships and vessels for storage are subject to it
1981 Pollution Control Act and Regulations	• Aims to protect the outdoor environment against pollution • Transport of CO_2 is not specifically mentioned but ships loading, transporting and unloading CO_2 are be subject to these instruments
Petroleum Act and Regulations	• Provisions are applicable to all activities associated with subsea petroleum deposits, including exploration, exploration drilling, production, transportation, utilisation and decommissioning • Applies to CO_2 stored and also other parts of the CCS value chain as long as related to petroleum activities, like e.g. Sleipner • Refers directly to transport by pipeline but does not cover ship transport • FSIs are covered
2014 Storage Regulations	• Relate to exploitation of subsea reservoirs on the continental shelf and the transportation of CO_2 on the continental shelf • It applies to CO_2 stored as part of industrial CCS • Refers directly to transport by pipeline but does not cover ship transport • FSIs are covered
2004 Greenhouse Gas Emission Trading Act and Regulations	• Implements the ETS Directive • Since ship transport of CO_2 is excluded from the ETS Directive, it is also excluded from Norwegian law • Ships are therefore also not required to surrender allowances for leaked CO_2

7.5.2 The 1994 Norwegian Maritime Code (NMC)

The 1994 Norwegian Maritime Code (NMC)[261] is one of the most central instruments for regulation of shipping in Norway. It is first and foremost aimed at regulating relations between private stakeholders engaged in shipping and transport of goods and passengers, and regulates e.g. freight agreements, ship building, liability, dispute resolution, and safety.

[261] The Norwegian Maritime Code, 24 June 1994 No. 39

The NMC incorporates many of the internationally agreed obligations[262] and is updated and amended accordingly.

As a default, there is freedom to contract in Norway, meaning that the parties may choose whether to contract and what the contract should entail, unless otherwise provided for by for example statutory law. Limitations to such contract of freedom may be found in the NMC Chapter 13, which contains a framework applicable to contracts of carriage by sea. Chapter 13 is a manifestation of the Nordic collaboration on the Maritime Codes, by emphasizing application for *"domestic trade in Norway and in trade between Norway, Denmark, Finland and Sweden."*[263] It further regulates contracts of carriage in the case of e.g. the agreed loading port is in a member state to the International Convention for the Unification of Certain Rules of Law Relating to Bills of Landing,[264] emphasizing the importance of public international instruments for shipping. Section 254 states that provisions in contracts that either breach Chapter 13 or Section 501(7)[265] of the NMC, are invalid. The provisions regulate issues like e.g. handling of dangerous goods,[266] payment of freight,[267], breach of contract,[268] delivery,[269] liability,[270] bills of landing,[271] and disputes.[272]

The NMC does not contain a specific definition of the term "ship". Although "ship" may be a term which usually leaves no doubts as to whether or not a specific construction is considered a ship, characteristics of the vessels, such as the ability to float, move and what purpose the vessel is meant for, should all be taken into consideration,[273] and may lead to a situation in which a vessel that looks like a ship may fall outside the defined term. The NMC contains some piecemeal and somewhat indirect definition of the term ship, including regulating minimum size and requirements for being registered in the official Ship's Register,[274][275] limiting against certain offshore mobile platforms,[276] and by claiming applicability to hovercrafts.[277] From these provisions, literature interpretations and finally the NMC implementation of international obligations under instruments which have defined ships and which we have analyzed for the purpose of this report, we draw the conclusion that both vessels for transport and for stationary uses, like offloading and injection, are subject to the NMC.

We have not observed any hurdles for CO_2 transport in the NMC.

7.5.3 The 2007 Ships Safety and Security Act (SSSA) [278]

The scope of the Ships Safety and Security Act (SSSA) is to regulate and safeguard life, health, property and the environment, including pollution prevention. It incorporates many of

[262] E.g. the right to limit liability following LLMC, cf. NMC Chapter 9
[263] NMC Section 252(1)
[264] NMC Section 252(2)(1)
[265] Which relates to statutory time bars for claims for damages for damage or loss
[266] Section 257
[267] Section 260
[268] Sections 261 and 264
[269] Sub-chapter IV
[270] Sub-chapters V and VI
[271] Sub-chapter VII
[272] Chapter VIII
[273] T. Falkganger *et al.* (2017) *Scandinavian Maritime Law. The Norwegian Perspective*. 4th edition p. 50
[274] NMC Section 11
[275] **"The Ship Register"** encompasses the Norwegian International Ship Register (NIS) and our domestic register, the Norwegian Ordinary Ship Register (NOR) with its subdivision, the Shipbuilding Register (BYGG). https://www.sdir.no/en/shipping/registration-of-commercial-vessels-in-nisnor/
[276] NMC Section 507
[277] NCM Section 6
[278] The Norwegian Ships Safety and Security Act, 16 February 2007 No. 9

the international obligations Norway is subject to, such as MARPOL and SOLAS. MARPOL with its relevant Annexes are further implemented through the subsequent 2012 Regulations on environmental safety for ships and mobile facilities.[279]

The term ship is not directly defined in SSSA, implying a wide range of vessels being included. Although initially not included in the scope of SSSA, the translation of Section 2 found at the website of the Norwegian Maritime Authority states that *"offshore units used in the exploration for or exploitation, storage or transport of submarine natural resources and mobile offshore units supporting such activities"* may be included by special regulations.[280] A natural interpretation of the wording "*or exploitation, storage or transport of submarine natural resources"* may first indicate only to be applicable to offshore petroleum activities and other activities involving submarine natural resources. However, our understanding is that offshore storage of CO_2 falls under the *wording "exploitation […] of submarine natural resources",* submarine natural resources referring to the pore space utilized for storage. Vessels used for transport and offloading of CO_2 may therefore be subject to regulations pursuant to the SSSA, despite not being regulated by the ACT itself.

An example of such subsequent regulation is the Regulations on environmental safety for ships and mobile facilities.[281] These regulations refer to MARPOL's definition of ships, which includes mobile facilities such as FSIs (see the analysis in Section 7.3.5). These Regulations implement the MRV Regulations of IMO and the EU (see Section 8).[282]

We have not observed any specific requirements to CO_2 shipping in SSSA, nor provisions representing hurdles to the industry. Further, we have not observed any deviations from the international obligations under which Norway is subject to in SSSA or subsequent regulations.

7.5.4 1981 Pollution Control Act and Regulations

The Act of 13 March 1981 No.6 Concerning Protection Against Pollution and Concerning Waste (the "Pollution Control Act")[283] aims to protect the outdoor environment against pollution.[284] The Petroleum Control Act Section 6, has a broad definition of pollution, which includes amongst other things "*the introduction of solids, liquids or gases to air, water or ground"* (For the full definition, see the Appendix Section 10.10.3, page 127).

Generally, the Act imposes a duty to avoid pollution that is not lawful[285] or permitted by a decision.[286] A permit is required for *"any activity that may lead to pollution"*.[287]

The scope of the Act includes the Norwegian Economic Zone *"if the source of pollution is a Norwegian vessel or installation".*[288] Specifically, the Act also applies *"to exploration for and production and utilization of natural subsea resources on the Norwegian part of the continental shelf, including decommissioning of facilities,"*[289]

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[279] Regulation on environmental safety for ships and mobile facilities (Unofficial/own translation), 30 May 2012 No. 488, Forskrift om miljømessig sikkerhet for skip og flyttbare innretninger
[280] https://www.sdir.no/contentassets/a7a1a5cc4998405286e99c6fbccc5c8a/ship-safety-and-security-act.pdf?t=1563709612413 Accessed 21 July 2019
[281] Regulation on environmental safety for ships and mobile facilities (Unofficial/own translation), 30 May 2012 No. 488, Forskrift om miljømessig sikkerhet for skip og flyttbare innretninger
282 Section 12 and 12a of the Regulations
[283] https://www.regjeringen.no/en/dokumenter/pollution-control-act/id171893/
[284] Section 1
[285] Pursuant to section 8 or 9
[286] Made pursuant to section 11, c.f. Section 7
[287] Subject to the provisions of chapter 3
[288] Section 3(2)(3)
[289] Section 4, cf. Section 3 (2)(3)

For pollution from *"roads, railways, etc., harbours and airports",* the Act applies *"to the extent decided by the Pollution Control Authority"*.[290] Pollution from ship transport of CO_2 is not specifically mentioned, although Section 3's mention of "vessel or installation" should be interpreted in the same way as for other Norwegian legal instruments, implying that ships loading, transporting and offloading CO_2 would be included. Further, as a consequence of the area of application of the Act and the fact that CO_2 "may lead to pollution" and cause damage or nuisance to the environment if released, activities which might result in the release of CO_2 are subject to the Pollution Control Act, with more detailed regulations issued by the Pollution Control Authority (the "Pollution Control Regulations"). Subsequently, the requirement under the Pollution Control Act and Regulation to apply for a discharge permit applies to the entire CCS value chain, unless otherwise specified. After implementation of the CCS Directive, a new Chapter 35 of part 7A was included in the Regulations to further regulate CO_2 storage activities.

Part 6 of the Pollution Regulations specifically addresses pollution to the marine environment from shipping activities, and emphasizes the pollution control framework's application for ship transportation. The provisions apply to ships, being *"any seagoing vessel, irrespective of whether the vessel has propulsion machinery of its own. This does not cover offshore units."*[291] An offshore unit is defined as *"an installation or other facility used in the petroleum activity, irrespective of whether the construction is fixed or mobile[…]"* These installations, which thus includes the FPSO used for injection, are carved out of the Part 6, as they are regulated by the Petroleum Act and Regulations, as well as the Storage Regulations and the separate part 7A of the Pollution Control Regulation. Part 6 contains regulation of composition and use of chemical dispersants and shoreline-cleaning agents to clean up oil pollution, [292] handling of waste from ships,[293] incineration,[294] dredging and dumping at sea, [295] as well as discharge of sewage.[296] Thus, several of Norway's obligations pursuant to public international law and instruments are included here.

CO_2 offloading and storage as such are not regulated pursuant to Part 6. However, Part 6 would apply in parallel for the operation of the ship transporting CO_2. Whether the offloading operation is regulated by these provisions would, as for previous analysed legal instruments, depend on which logistic scenario being chosen; while offloading to an onshore facility would be regulated as part of the ship transport, the offloading and direct injection offshore, would on the other hand be regulated outside of Part 6.

Unless specifically addressed by other regulations, the provisions of the Pollution Control Regulation Part 6 apply. For example Chapter 20 on waste handling would apply in parallel with other frameworks. Here, the definition of "ships" is widened compared to some of the other Chapters, to apply to "*a seagoing vessel of any type operating in the marine environment, including hydrofoil boats, air-cushion vehicles, submersibles and floating devices*." Thus, ships for transport and offloading of CO_2 would be included.

Despite having a comprehensive framework for both shipping and ships, we have not found any provisions regulating CO_2 transport in particular. Further, and consequently, we have not observed more onerous obligations for ships transporting CO_2 than for other ships.

[290] Section 5 first paragraph
[291] The official translation of Section 21-1(1). Similar definitions apply for the other chapters of Part 6
[292] Chapter 19
[293] Chapter 20
[294] Chapter 21
[295] Chapter 22
[296] Chapter 23

Finally, we have not found deviations in the pollution control framework compared to the international obligations Norway has signed on to.

7.5.5 Petroleum Act and Regulations

When implementing the provisions of the CCS Directive in 2014, amendments were made to the Petroleum Act and Regulations. The Act was amended to allow for third-party access to CO_2 transport and storage infrastructure.[297] Further, an entire new chapter (4a) was added to the Petroleum Regulations addressing CO_2 storage in particular, changes were made in the definitions to include CO_2 storage in general,[298] and an appendix was added to provide provisions and criteria for characterization of the storage site and complex.[299]

According to the Regulations to the Act relating to petroleum activities (the "Petroleum Regulations"),[300] its provisions are applicable to the "petroleum activities" defined as *"all activities associated with subsea petroleum deposits, including exploration, exploration drilling, production, transportation, utilisation and decommissioning, including planning of such activities, but not including, however, transport of petroleum in bulk by ship."*[301] Thus, the CO_2 stored at Sleipner and Snøhvit is included by the definition due to the fact that the CO_2 is stripped from the natural gas being produced at the field and then reinjected in a subsea reservoir.

Transportation[302] is defined to include the *"shipment of petroleum by pipeline as well as the construction, placing, operation and use of a facility for the purpose of transportation."*[303] Thus, the definition specifically only includes transportation by pipelines. The definition of "facility"[304] includes movable units such as for offloading, however not supply or support vessels or ships transporting petroleum in bulk.[305] However, the displacement of such movable facilities is not included, as explicitly stated in the preparatory works.[306]

The reason for exclusion of transport of petroleum in bulk by ship, supply and support vessels, and the displacement of movable facilities is because shipping is regarded as a general transport activity, sufficiently regulated by other acts and regulations as applicable according to Norwegian shipping law.[307,] Similar interpretation should apply for transport of CO_2. Not having an explicit exclusion of transportation of CO_2 in bulk by ship should not be interpreted as including such activities but should be read in correlation to the Storage Regulations (see next section), as these parallel sets of regulations are intended to entail the same framework. Since the Storage Regulations exclude transport of CO_2 by ship, the Petroleum Act and Regulation should also not apply to either ship transportation or offloading of CO_2 to for example onshore facilities.

[297] Petroleum Act Section 4-8
[298] Petroleum Regulations 21 n)
[299] Petroleum Regulations Appendix I
[300] Translated version available at https://www.npd.no/en/regulations/regulations/petroleum-activities/.
[301] As defined in the Petroleum Act (Act 29 November 1996 no. 72 relating to petroleum activities as defined in section 1-6 (Section 2, second paragraph)
[302] Petroleum Act Section 1-6 c)
[303] Petroleum Act Section 1-6 h)
[304] Defined as an *"installation, plant and other equipment for petroleum activities, however not supply and support vessels or ships that transport petroleum in bulk. Facility also comprises pipeline and cable unless otherwise provided"* Petroleum Act Section 1-6 d)
[305] U. Hammer *et al.* (2009) *Petroleumsloven* p. 92 jf. Ot.prp. nr. 43 (1995-96) p. 30, https://www.stortinget.no/no/Saker-og-publikasjoner/Stortingsforhandlinger/Lesevisning/?p=1995-96&paid=4&wid=c&psid=DIVL224&pgid=c_0181 (accessed 19 October 2019)
[306] U. Hammer *et al.* (2009) *Petroleumsloven* p. 92 jf. Ot.prp. nr. 43 (1995-96) p. 30 https://www.stortinget.no/no/Saker-og-publikasjoner/Stortingsforhandlinger/Lesevisning/?p=1995-96&paid=4&wid=c&psid=DIVL224&pgid=c_0181 (accessed 19 October 2019)
[307] U. Hammer *et al.* (2009) *Petroleumsloven* p. 90-92

The framework applies to the storage part of the value chain regardless of the means of transportation, following the system of the CCS Directive. The framework for storage has been analysed under other studies and falls outside the scope of the current study. The implications of ship transportation not being regulated by the petroleum framework and the framework thus following the system of the CCS Directive will be analysed jointly with the implications for similar considerations for the Storage Regulations in further detail in Chapter 7.5.7 below.

7.5.6 2014 Storage Regulations

The Regulations relating to exploitation of subsea reservoirs on the continental shelf for storage of CO_2 and relating to transportation of CO_2 on the continental shelf (the "Storage regulations")[308] apply for *"surveying and exploration for subsea reservoirs for storage of CO_2, as well as exploitation, transportation and storage of CO_2,"*[309] other than those that are *"part of the petroleum activities"*.[310]

The provisions of chapter 6 govern the transport of CO_2. As defined, transport includes the *"shipment of CO_2 via pipeline as well as construction of a pipeline, placement, operation and use of a facility for transport,"*[311] Thus, as for the petroleum-related CO_2 storage, the definition does not include ship transportation. As a facility, ships may still be included as such, as "facility" is defined as *"installations, plants and other equipment for exploitation of subsea reservoirs for storage of CO_2, but excluding supply and utility vessels or vessels that transport CO_2 in bulk. Facility also includes pipelines and cables unless otherwise determined".*[312] The definition would therefore include FSIs and other vessels if used to inject CO_2. However, as for the Petroleum Act, ships transporting CO_2 would be excluded since ship transport is sufficiently governed by general shipping legislation.

As for the petroleum framework, the Storage Regulations apply to the storage part of the value chain regardless of the means of transportation, following the system of the CCS Directive. The implications of ship transportation not being regulated by the Storage Regulations and thus following the system of the CCS Directive will be analysed jointly with the implications for similar considerations for the petroleum framework in further detail in Chapter 7.5.7 below.

7.5.7 The 2004 Greenhouse Gas Emission Trading Act and Regulations

The Act of 17 December 2004 No. 99 Relating to Greenhouse Gas Emission Allowance Trading and the Duty to Surrender Emission Allowances (the "Greenhouse Gas Emission Trading Act")[313] is the Norwegian instrument implementing the EU ETS Directive for the purpose to limit emissions of greenhouse gases by the establishment of an emission trading system, cf. Section 1.

[308] Laid down by Royal Decree on 5 December 2014 pursuant to Section 3 of Act No. 12 of 21 June 1963 relating to scientific research and exploration for and exploitation of subsea natural resources other than petroleum resources. Submitted by the Ministry of Petroleum and Energy. EEA references: EEA Agreement Annex XX Chapter III No. 21 (Directive 2009/31/EC).Corrections: 20 Jan 2015 (Section 6-2).Last translated October 31th 2017 https://www.npd.no/en/regulations/regulations/exploitation-of-subsea-reservoirs-on-the-continental-shelf-for-storage-of-and-transportation-of-co/
[309] Section 1-3, paragraph 1
[310] Section 1-3, paragraph 3
[311] Section 1-6 v)
[312] Defined as *"installations, plants and other equipment for exploitation of subsea reservoirs for storage of CO_2, but excluding supply and utility vessels or vessels that transport CO_2 in bulk. Facility also includes pipelines and cables unless otherwise determined,"* Section 1-6 i)
[313] https://www.regjeringen.no/en/dokumenter/greenhouse-gas-emission-trading-act/id172242/

Pursuant to Section 3, the Greenhouse Gas Emission Trading Act applies to stationary industrial activities or facilities and aviation activities, and detailed provisions on type of emissions (e.g. CO_2 and NO_x), activities and industries are delegated to specific Regulations. Such specific and detailed provisions are provided in the Greenhouse Gas Emission Trading Regulations. This approach, including the details in Regulations rather than the Act itself, to law-making leaves the Norwegian authorities more flexibility when adapting to future changes in the ETS Directive. The responsibility to ensure compliance with the provisions is on the operator of comprised activities,[314] and a discharge permit is required.[315] The pollution control authorities will control and verify the reports on greenhouse gas emissions submitted by each operator.[316]

Pursuant to the Greenhouse Gas Emission Trading Regulations,[317] CO_2 emissions from activities subject to the emission allowance requirements includes capture, storage and transport by pipelines of greenhouse gases for storage, provided approval by the competent authorities pursuant to the relevant Petroleum Act and Regulations and Storage Regulations. Subsequently, the transport of CO_2 for storage by ship is not specifically mentioned, which follows naturally from the incorporation of the ETS Directive. Nevertheless, CO_2 emissions from other activities than those explicitly mentioned may be subject to the emissions trading system and rules subject to regulation prescribed by the King.[318]

Thus, the result of shipping being excluded from the EU ETS and CCS Directives is that the Norwegian designated legal framework for CO_2 capture, transport and storage also excludes it. This does not imply that shipping of CO_2 is not regulated and that it could proceed without constraints or, conversely, that it is prohibited. It does, however, imply that the CCS value chains involving transportation of CO_2 by ship are not eligible under the emission trading scheme. Consequently, such value chains are cut off from an incentive of 25.10 EUR per ton CO_2 captured, transported and stored.[319] The exclusion further implies that leakage of CO_2 during transport is not subject to a duty to report or compensate through purchase of an equal amount of allowances. Thus, the only duties to compensate would be to the company contracting the ship to transporting the CO_2 for loss of cargo and any potential environmental damage caused by the leakage.

Although unfortunate and a hurdle to deployment of CCS, the exclusion of ship transport under the ETS is not an absolute barrier. Subject to the ETS Directive's Article 24, Norway is entitled to apply for an inclusion of ship transportation. Further, the Greenhouse Gas Emissions Trading Regulations may be amended to include such activities given the approval from the EU.[320]

7.6 Contractual arrangements

7.6.1 Introduction

Due to the long-standing tradition of transporting goods by ship, there is also a long-standing tradition of contractual arrangements for these activities. There are a number of

[314] Section 4, in accordance with the provisions of section 13.
[315] Pursuant to Section 11 of the Pollution Control Act
[316] Pursuant to Section 16
[317] Section 1-1 (26-28)
[318] Section 3(3)
[319] CO_2 price from «Markets Insider"; https://markets.businessinsider.com/commodities/co2-european-emission-allowances Accessed 7 November 2019
[320] Greenhouse Gas Emissions Trading Act Section 3

standardized contracts for shipping and further there are a number of well-known principles on how different legal entities interact.

The scope of this study does not allow for an in-depth analysis of existing contracts for shipping of goods to draw out the principles and present any proposed contract outline transport of CO_2. Further, there are no known standardised contracts for transport of CO_2 for storage to draw from. Finally, different legal traditions in different countries complicate a potential task of presenting an outline and would require a separate study. As an example, in the UK, contracts need to be as precise as possible due to the limited degree of freedom for interpretation to fill gaps. By contrast, in Norway, a contract may be far less precise or specific due to the parties' and court's room to use documentation from the negotiating phase, as well as background and supplementary law to fill the same gaps.[321] See for example section 7.5.2 regarding the provisions related to contracts in the NMC.

Thus, in this section, the focus is on presenting high-level observations that should be considered when entering into a contract to transport CO_2. As this study is focused on CO_2 transport, considerations relating to the storage operator's responsibility towards the emission source for potential future leakages are not included. Further, spot markets are not dealt with since, at least currently, it is not likely the transporter will agree to a charter contract priced based on spot markets.

We have not gone further into detail on commercial considerations. In general, the commercial considerations of contracts, are harder to predict and prescribe, as this will be dependent on a case by case assessment, involving a number of variables. Who the contracting parties are will be of importance, as well as the technical variations in the project (for example, the location of the storage site, the distance between the delivery and redelivery points, the amounts of CO_2 being captured for subsequent storage, whether or not transport is conducted by ships alone or by, for example, ships and pipeline in combination), the number of emission sources accessing the transport capabilities of the same vessel or operator, whether or not the ship transportation would be included in the emission trading scheme and a number of other things.

7.6.2 Contractual principles

Reusing existing contractual models for transport of CO_2

The three most common standard contractual models applicable to shipping are voyage charter, time charter and bareboat charter. The first of the three is the most common one, and implies a contract for a cargo of a specific type and quantity to be transported between named ports by a named vessel. The second is a type of contract that allows the customer, or charterer, to hire a named vessel for a specific period of time without constraints regarding type of cargo or ports. The third type of contract applies to vessels the charterer will equip and man himself,[322] and which may transport any type of cargo to the locations determined by the charterer. All of these types of contracts could be deemed appropriate for CO_2 transport.

Given the long history of transporting CO_2 for e.g. food industry, it is to be expected that these activities have either been subject to general agreements for transport of goods (like the ones referred to in the previous paragraph) with potential special amendments or annexes to take the properties of the CO_2 into consideration or that agreements similar to the transport of e.g. LNG have been used. Due to different business models for e.g.

[321] T. Falkganger *et al.* (2017) *Scandinavian Maritime Law. The Norwegian Perspective*. 4th edition p. 34
[322] *Shipping CO_2 – UK Cost Estimation Study* (2018) Element Energy for BEIS p. 56

LNG/LPG and CCS, the contracts may however not be directly applicable.[323] However, a lot of the principles laid out in these contracts may be re-used for transport of CO_2 for storage. A number of the contractual requirements will be based on standard principles which, depending on jurisdiction, may or may not be necessary to include, hence the observation made in Chapter 7.6.1.

Parties and third-party access

Provided that the CCS Directive is amended to include ship transport of CO_2, there might be a future requirement to grant third-party access to transport networks made up by ships, implying the customer of the transport services may be forced to accept the ship operator taking third party volumes as well if there is excess capacity in the ship's tanks. An important limitation to the imposed obligation to grant third-party access is the requirement to *"respect the duly substantiated reasonable needs of the owner or operator of the storage site or of the transport network and the interests of all other users of the storage or the network …who may be affected"*.[324] The implication of this is a need for coordination between the owner of the transport network and the storage site. There is no point for a ship operator to grant third-party access to available capacity on the ship to a new emission source capturing its CO_2, if there is no capacity to receive or store the CO_2. Consequently, a natural contractual arrangement would be for the emitter to contract directly with the storage operator and for the storage operator to contract with the transporter, instead of the emitter having to contract with both the transporter and the storage operator. On this basis, we find reason to recommend contracts being entered into between transporter and storage operator and that the storage operator contracts directly with the emission source.

The choice of contracting parties will further affect the type of contract to be entered into. While a voyage charter contract could be a natural fit for a contract between the emitter and transporter, a time charter or bareboat charter would potentially be more appropriate for a contract between a storage operator and the transporter.

If the emitter is the charterer, it could be natural to include an off-take guarantee clause in the contract as the failure to deliver the agreed amount of CO_2 would potentially result in losses for the ship operator. Further, if the reduced or failed delivery is a more permanent problem, the ship operator should be able to free that capacity for other emitters. However, if the storage operator charters the ship, the offtake guarantee would be entered into between the emitter and storage operator.

There might be a situation in which the storage site has capacity to take more CO_2 and the emitter is ready to capture and deliver but there are no available ships to transport it. The CCS Directive obliges the Member States to ensure the operator *"makes any necessary enhancements as far as it is economic to do so or when a potential customer is willing to pay for them, provided this would not negatively impact on the environmental security of transport and geological storage of CO_2."*[325] Provided the storage operator is the charterer, the operator might subsequently be required to offer its potential customer to commission the building of a new ship or contracting with a new ship owner on the emitter's expense to allow for the third-party access.

Structural changes to the vessel

For petroleum operations, a relatively common feature of contracts between the ship owner and the charterer, is that the charterer is entitled to either make structural changes to the

[323] *Shipping CO_2 – UK Cost Estimation Study* (2018) Element Energy for BEIS p. 4
[324] CCS Directive Article 21(2)(d)
[325] Article 21(4)

ship itself or require the ship owner to do so.[326] For CCS, this is a feature that should be included in any given contract between the ship owner or operator and the company contracting them since there are probably not that many ships available that are already equipped to load, transport and unload CO_2[327] and it is likely that modifications will be needed if an existing ship is commissioned for this use. If new ships are built for purpose, subsequent changes may also be needed, if for example there are changes in the offloading facilities or the CO_2 is to be transported from a different emitter (provided the charterer is the storage operator) or more emitters having different port and loading facilities being added to the transportation route.

A clause capturing the need for flexible transportation routes and pick-up locations should also be included. Provided the storage operator is the charterer, the operator may receive access requests from third parties. Provided the emitter is the charterer, there probably still needs to be a mechanism for third-party access and thus flexibility to add volumes from other emitters if the transporter has capacity.

Liability

Subject to the international and national framework on liability and limitation of such, it would typically be subject to the agreement to e.g. establish when the liability passes over at the delivery point to the ship owner or operator, and when the liability passes over at re-delivery. From a contractual perspective, it may be beneficial to have a metering point at both delivery (emitter) and re-delivery (storage operator) point in addition to having metering equipment on the ship. Consequently, there is a natural point of transfer of liability which allows for the parties on both sides of the transfer point to control the amount of CO_2 being transferred and contractually be free of liability for CO_2 being lost after transfer. Normally, as long as the CO_2 has passed the metering point at the ship, the ship owner or operator would be liable for any unintended release of CO_2 as well as potential damage caused by the released CO_2. Similarly, after the CO_2 has passed the storage operator's metering point, the transporter no longer has custody and is thus no longer responsible for the handling, leakage or potential damages caused by the CO_2. It would be a natural part of the contract to agree on who is to report and pay for the allowances for leaked CO_2. This is also explicitly stated in the NMC Section 274, which also defines the period of responsibility for the ship operator to be while the goods are in the ship operator's custody *"at the port of loading, during the carriage and at the port of discharge."*

Such a transfer point would also be the natural starting point from a regulatory point of view, regarding who is to be held responsible of any leakage and environmental damage under the polluter pays principle. Similarly, if shipping is included in ETS, either by amendment to the Directive or by national application, there would be reporting requirements. In further development of the legal framework for CO_2 shipping, considerations should be made with respect to the cost-benefit of rigid metering requirements.

The reporting requirement has been identified as a potential cost driver for the ship operator transporting CO_2, having to include metering equipment on the ship. In a value chain with more than one transport operator, this may be additionally challenging and expensive. A fiscal metering station as used in the oil and gas industry would typically cost in the region of €2m, and incurs an additional annual calibration cost. Such costs may raise the threshold regarding minimum volumes for commercially viable CCS

[326] S. Lazaridis (2011) Maritime Offshore Contracts: Compendium p. 23
[327] I. Havercroft *et al.* (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues.* Second Edition p. 261

For other types of transport, with more than one mode of transportation (rail, sea and road for example), it is common to enter into an agreement for multimodal transport, implying there is one carrier contracting with the customer and whom is liable toward the customer against any loss or damage to the goods transported, regardless of there the goods are lost or damaged. This would from a contractual perspective work and imply less administration for the emitter or storage operator. However, it is less certain this would work from a regulatory point of view, if the activity is included in ETS. Most likely, such inclusion would imply a reporting duty for each stakeholder in the chain. Further, such arrangements would still create challenges between the different modes of transport, establishing who is responsible towards the main carrier for the loss of CO_2. In our opinion, such arrangements are easier to manage if the goods being transported are objects rather than liquid CO_2. If a container of goods are damaged or lost at sea, it would be easy to prove it was not the truck transporting the container to the dock who lost it. If the CO_2 is delivered to a truck by the emission source and 100,000 tons are gone before being injected, it would be impossible to prove who lost it if there is more than one transport operator and none of them had measuring equipment.

One could consider other types of contracts too. For maritime transport, there are two main types of contracts, namely Freedom to Board (FOB) contracts and Cost, Insurance and Freight (CIF) contracts. The former represents a type of contract in which the seller delivers at the railing for the ship and the buyer is responsible for all risk. The latter contract holds the seller responsible for the transport, and freight charges. It has been proposed that the CIF contract as described above could be used for CCS, implying that the ship owner or operator would not carry any risk[328] This is opposed to the general principle of the aforementioned NMC Section 274. Although solving the metering issue from a contractual point of view, we are not certain this will solve the issues raising under ETS and requirements for reporting. Following the CCS Directive Article 16(1), the reporting duty in case of leakage from a storage site rests with the operator. It is likely that competent authorities, if opting for the exemption pursuant to Article 24 of the ETS Directive, will implement requirements regarding such reporting for the transport operator.

In relation to other types of damages,[329] there is a long-standing history of dealing with these issues. Traditionally, liability for ship operations in the petroleum industry is sorted under two models; a classic model built on a tort law mind set and a more modern model based on distribution of risk. Both of these models are well known in the petroleum industry. However, there is an increasing tendency to choose the latter.[330]

Overall, we recommend specialized agreements for the transport of CO_2 for storage, rather than reusing existing contractual models not fit for purpose into use. Such contracts should take into consideration requirements for e.g. MRV for the emission source to be eligible for allowances and for shipping to qualify as part of the value chains. It would be natural to consider referring to the ISO standard under development for quantification and verification[331] as part of that arrangement.

7.7 Summary of legal and regulatory implications

Ship transportation utilizes one of the largest resources on the planet, one which touches all continents, carries pollution, and one for which damage occurring in one location can affect

[328] I. Havercroft *et al.* (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues.* Second Edition (2018) p. 261
[329] Meaning e.g. damage to loading and unloading facilities, crew, the ship etc.,
[330] S. Lazaridis (2011) Maritime Offshore Contracts: Compendium p. 50
[331] Currently on a Committee Draft level, ISO/CD 27920 Carbon dioxide capture, transportation and geological storage (CCS) – Quantification and verification

the climate and environment in locations even large distances away. Large areas of the ocean are beyond national jurisdiction and, as a consequence, legal framework for shipping is composed of a complex set of instruments pursuant to both international and national law. Some public international legal documents in particular impose obligations on individual nations to implement framework for certain minimum requirements to protect and preserve the ocean.

Ship transportation of CO_2 as a commodity has been carried out for many years, meaning that regulations relating to safety and handling of CO_2 by ship are well-established and, for which, a change of purpose does not present a barrier. However, transporting CO_2 for the purpose of permanent geological storage is exposed to additional regulatory frameworks that have an influence on the development of requirements for CO_2 shipping. These include implications of national jurisdiction, environmental legislation and specific CO_2 storage regulations in addition to safety and liability considerations.

This study has analysed a number of instruments under public international law, EU law and national law (in particular Norwegian law) to map the current regulatory framework for ship transportation of CO_2 and to identify potential hurdles.

However complex, there were few observed hurdles to large-scale CO_2 shipping and no hurdles to transportation of CO_2 in particular. However, two hurdles to ship transportation for CCS were observed, one pursuant to EU law and one pursuant to public international law:

- Although not limited to ship transportation, export of waste for offshore dumping (which includes CO_2 for storage) has been prohibited by the **London Protocol**, Article 6. Although amended in 2009, to allow for export of CO_2 for the purpose of storage in particular, the amendment has not become effective. In October 2019, however, this prohibition was addressed by the Contracting Parties, agreeing to provisionally applying the amendment from 2009 while awaiting sufficient ratification to make the amendment effective and thus allow such activities.
- The EU framework for emissions trading, pursuant to the **ETS Directive**, has excluded ship transportation from its scheme, resulting in CCS value chains utilizing ship transportation not being eligible under the scheme and therefore prevented from accessing an important financial incentive to engage in such activities. The ETS hurdle is not absolute, as the EU Member States may seek to include such activities pursuant to Article 24 of the ETS Directive. However, due to the lack eligibility under the ETS scheme, there is for example no uniform EU standard for quantification and verification throughout the value chain including ships, implying a certain lack of predictability for the stakeholders wanting to include ship transportation in its value chain. ISO standards currently being developed under the project ISO TC 265 may contribute to fill this gap.

7.7.1 Actions to address regulatory barriers

Emissions trading scheme

As identified, transport by ship is outside the scope of application for ETS, which thus leads to a situation in which the Member States' only option to realise projects including shipping is to apply for an exemption pursuant to the ETS Directive Article 24. Although this removes the absolute barrier to such a value chain, it results in both unpredictability and lack of focus on setting detailed transnational guidelines for MRV, which consequently may prevent or slow down cross-border collaboration and the establishment of storage hubs. As expressed by some authors, there is however no reason why similar rules should not apply to transportation of CO_2 by ship, as the only reason for scope exclusion was that ship transportation was not envisioned upon drafting of the legal texts.[332] In our opinion, the inclusion of CCS in the PCI scheme, and the fact that some of the projects accepted as PCI projects involve transportation of CO_2 by ship, further supports that the ETS Directive should be revisited and considered amended to include such activities. However, a revision of the ETS Directive to include ships, would trigger revisions of other EU legislation as well, such as the CCS Directive.

In order to adopt new or amend EU legislation, the European Parliament and the Council both need to agree on a legislative proposal from the Commission.[333] This is according to the Ordinary Legislative Procedure of the EU,[334] which applies to a wide range of areas such as including transport and the environment.[335] The Commission initiates its legislative proposals based on its work programme and follows procedures of public consultations which allow for citizens, businesses and organizations to express their views and impact the policies of the EU.[336] Although the Commission formally has the legislative initiative, proposals may also be requested from the Commission by the European Parliament, acting by a majority of its Members.[337] Thus, in order to trigger the adoption of EU legislation amendments, proposals must formally be required by the Members of the European Parliament should the Commission by its own initiation fail to enact.

The inclusion of ship transport for ETS, either by amendment of the ETS Directive or by applying for an exemption under ETS Directive Article 4, would imply the need to reliable and standardized methods to quantify and verify the amounts of CO_2 being received, delivered and potentially leaked by the transport operator. This may be provided for directly in formal legal framework, like for example the MRV Regulations. It could also be provided for in best practices and industry developed standards. Also very often industry standards or best practises are referred to in formal legal framework or there is an opening for industry to utilize such standards to meet performance based requirements.[338] Currently, there is an ongoing project under the International Organization of Standardization named ISO TC265 Carbon dioxide capture, transportation, and geological storage. The scope of the project is *"[s]tandardization of design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the field of [CCS]".*[339] One of the standards being developed under this project, is a standard for quantification and verification of CO_2 being captured, transported and stored.[340] In our opinion, it would be a natural starting point looking to this project to find needed methods to quantify the CO_2 being successfully transported by ship, not only because it is developed by technical experts in the field but also because the mentioned document is covering the entire value chain. This would potentially increase the chances of similar approach to quantification and verification throughout the value chain and significantly reduce challenges related to documentation and reporting.

[332] Weber (2017) p. 169 supports this statement
[333] Article 289 (1) Union (TFEU).
[334] As further defined in Article 294 TFEU
[335] http://www.europarl.europa.eu/about-parliament/en/powers-and-procedures/legislative-powers
[336] https://europa.eu/european-union/eu-law/decision-making/procedures_en#review-and-adoption
[337] Article 225 TFEU
[338] I. Ombudstvedt and A. Gimnes Jarøy (2019) 14th International Conference on Greenhouse Gas Control Technologies p. 4-5
[339] https://www.iso.org/committee/648607.html
[340] ISO/CD 27920 Carbon dioxide capture, transportation and geological storage (CCS) – Quantification and Verification.

8 Monitoring, reporting and verification (MRV) of CO_2

Both the EU and the IMO work towards reducing greenhouse gas emissions from ships. The IMO is a body under which its member states negotiate public international instruments subject to national ratification and implementation, containing performance-based criteria and principles that partly shape the EU or national frameworks directly.

As a result of their efforts, mandatory requirements of monitoring, reporting and verification (MRV) of CO_2 in the maritime sector are set out as a first step to reduce CO_2 emissions from the shipping industry. Under the two bodies, two separate regimes have been introduced: the EU MRV Regulation and the IMO Data Collection System on fuel consumption (the "IMO DCS"). Both are data collection systems establishing mandatory verification and reporting requirements, aimed at collecting emissions data to provide the basis for further policy actions to eventually reduce emissions from the shipping industry.[341, 342]

EU Regulation 2015/757 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC (EU MRV Regulation)

The EU MRV Regulation lays down *"rules for the accurate monitoring, reporting and verification of carbon dioxide (CO_2) emissions and of other relevant information from ships arriving at, within or departing from ports under the jurisdiction of a Member State, in order to promote the reduction of CO_2 emissions from maritime transport in a cost effective manner"*.[343] It was adopted on the basis that international maritime shipping remains the only means of transportation not included in the EU's commitment to reduce greenhouse gas emissions through the ETS.[344]

As part of the EU 2013 strategy for progressively integrating the maritime sector into the EU's policy for reducing greenhouse gas emissions,[345] the EU MRV Regulation requires all ships above 5,000 gross tonnage calling at EU and EEA ports to collect robust and verified CO_2 emission data, including the emissions from these ships in ports.[346] The MRV Regulation entered into force and started monitoring as of 1 January 2018. Technical rules and templates for the submission of monitoring plans, emissions reports and documents of compliance are included in the supplementary Regulation 2016/1927.

The MRV Regulations contain no specific provisions to address ships transporting CO_2, only the CO_2 being emitted from the operations. According to the definition of "CO_2 emissions" as *"the release of CO_2 into the atmosphere by ships",* cf. Article 3(a), the MRV requirements regarding transported CO_2 (as for LNG) do not address CO_2 releases of the cargo or injections of the CO_2 into the sea. Rather, it covers the CO_2 emissions from the combustion of fuels.[347] As a consequence, questions and concerns are raised on how CCS projects utilizing shipping as means for transportation can be effectively and adequately monitored and verified under the current regime.

[341] https://www.dnvgl.com/maritime/insights/topics/EU-MRV-and-IMO-DCS/index.html
[342] COM(2019)38 p. 2
[343] Article 1
[344] Paragraph 3 of the preamble of Regulation 2015/757
[345] COM (2013) 479, cf. COM(2019) 38 p. 2
[346] https://ec.europa.eu/clima/policies/transport/shipping_en
[347] Article 4

IMO Data Collection System on fuel consumption

In 2016, following the entry into force of the Paris Agreement and the adoption of the EU MRV Regulation,[348] the IMO Data Collection System ("DCS") on fuel consumption of ships was established under Regulation 22A of MARPOL VI, adopted by resolution MEPC.278(70).[349] It was established as part of IMO's actions and followed the actions of the EU to address shipping emissions.[350] The mandatory data collection system is intended to be the first in a three-step process in which analysis of the data collected would provide the basis for an objective, transparent and inclusive policy debate in the Marine Environment Protection Committee (MEPC).[351]

The IMO DCS entered into force on 1 March 2018 and the collection of data started on January 1 2019. Subsequently, from calendar year 2019, each ship of 5,000 gross tonnage and above shall collect specific data,[352] according to the methodology included in the IMO's Ship Energy Efficiency Management Plan (SEEMP).[353] The submitted data shall include the technical characteristics of the ship, its fuel oil consumption, distance travelled and hours underway.[354] Similarly to the EU MRV Regulation, the IMO DCS under MARPOL Annex VI aims to prevent air pollution from ships and contains no specific provisions for ships transporting CO_2.

Summary

The EU MRV Regulation and the IMO DCS are both intended to quantify CO_2 emissions from shipping,[355] and they apply in parallel, implying the ships calling at EU and EEA ports have to report under both frameworks.[356] There are however differences between the two systems,[357] including in the geographic limitations of the frameworks; whilst the EU scheme only applies within the EU and EEA area, the IMO scheme covers emissions from shipping globally.[358]

An unfortunate result of having two MRV regimes, is that ship operators will have to manage two separate reporting schemes for the fuel they use.[359] As stated in the revised ETS Directive of 2018, the European Commission should regularly review IMO actions to assess its actions to address shipping emissions.[360] Accordingly, the European Commission has reviewed the MRV Regulation, considering potential alignment with the IMO DCS.[361] A proposal followed in February 2019 to amend the EU MRV Regulation to take appropriate account of the global data collection system (COM(2019) 38 final),[362] amending some of the provisions to allow for the same application of the provisions.[363] Further action from the IMO or the Union is called for and expected to start from 2023, including preparatory work and stakeholder consultation.[364] Meanwhile, a reminder is made of the possibility for Member

348 COM(2019)38 p. 2
349 http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/278(70).pdf
350 https://ec.europa.eu/clima/policies/transport/shipping_en
351 http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Data-Collection-System.aspx
352 Specified in Appendix IX to the Annex of the Resolution
353 As required in MARPOL Annex VI
354 Annex IX of MEPC.278(70)
355 International Chamber of Shipping p. 12 http://www.ics-shipping.org/docs/default-source/resources/ics-guidance-on-eu-mrv.pdf?sfvrsn=10
356 https://ec.europa.eu/clima/policies/transport/shipping_en
357 Six fundamental differences are outlined in http://www.ics-shipping.org/docs/default-source/resources/ics-guidance-on-eu-mrv.pdf?sfvrsn=10
358 https://www.dnvgl.com/maritime/insights/topics/EU-MRV-and-IMO-DCS/index.html
359 International Chamber of Shipping p. 2 the unfortunate result that ship operators will have to manage two separate reporting schemes for the fuel they use.
360 Directive 2018/410 paragraph 4 of the preamble
361 https://ec.europa.eu/clima/policies/transport/shipping_en
362 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CONSIL:ST_6117_2019_INIT&from=EN
363 COM(2019) 38 final p. 7
364 Directive 2018/410 paragraph 4 of the preamble https://ec.europa.eu/clima/policies/transport/shipping_en

States to apply for emissions trading and surrender for activities pursuant to Article 24 nr.1 of the ETS Directive.

9 Conclusions and Recommendations

This study provides a detailed assessment of the CO_2 shipping supply chain, including the physical infrastructure, operational constraints, projected costs and legal and regulatory issues. Although currently unproven on large-scale, the technology required for large-scale shipping for CCS exists and both technical and legal hurdles can be overcome to realise the opportunities that CO_2 shipping presents.

The key messages of this study are:

- **The transport condition of CO_2 affects a large number of components of the shipping chain**, including material choices, storage tank design and operation, transport volumes and safety considerations. Medium pressure conditions are currently used for CO_2 transportation but low pressure conditions may be more cost-effective.
- **Onshore infrastructure for handling pure CO_2 is well-understood** however, additional impurities present in the CO_2 product stream for CCS may have a negative impact on transport and storage applications. Processes to purify the CO_2 stream are an integral part of the shipping chain.
- **Offshore unloading of CO_2 is currently unproven** and no consensus exists for the most appropriate solution. The primary challenges to offshore unloading include increased costs of offshore processing of CO_2 for injection and potential periods of unavailability due to weather conditions.
- **Batch-wise injection presents challenges for offshore unloading via direct injection** but maintaining continuous flow requires the use of an intermediate FSI which is a major cost driver.
- **For representative CCS shipping chains in Europe, undiscounted unit costs of €30-40/tCO_2 are projected** with comparable costs for onshore unloading and direct injection when the the ongoing pipeline for final transport from shore-to-storage is included. For a discount rate of 10%, the levelised costs increase to €46-60/tCO_2.
- **Liquefaction and ship costs make up the majority of costs** of the shipping chain, accounting for 52% and 37% of the undiscounted unit cost for shore-shore shipping, respectively (excluding shore-to-offshore pipeline). Liquefaction costs can be reduced if the initial CO_2 stream is pre-pressurised, but this simply transfers the cost further up the chain (to the capture plant).
- **Increasing the ship capacity and/or the unloading rate reduces costs only if the number of ships in the chain can be reduced.** For the flow rates and transportation distance considered here, increasing the ship size above 10,000 tCO_2 does not significantly reduce the costs of the overall chain (up to €1-2/tCO_2 reduction in undiscounted unit costs). Under the conditions modelled, 10,000 tCO_2 is the cost-optimal solution with a 600 t/h unloading rate; with a higher unloading rate (3,000 t/h), 30,000 tCO_2 ship capacity is marginally cost-optimal. However, consideration of operational parameters such as local weather conditions and transportation speed will also be required in choosing an appropriate ship size.
- **The breakeven distance at which shipping becomes cost-competitive with pipelines depends on the flow rate and pressurisation state of the inlet CO_2 stream.** For both onshore and offshore (direct injection) unloading, long-distance transport of low volumes of CO_2 by ship can provide a cost-effective option, such as in cross-border shipping from industrial CCS clusters across Europe. For the

onshore unloading scenario modelled here, the breakeven distance at 1 Mtpa flow rate is 320km if the CO_2 is pre-pressurised prior to liquefaction but 650km if the CO_2 is non-pressurised. For direct injection, the breakeven distances under the same conditions are 450km and 660 km.

- **International, regional and national legal frameworks governing shipping and carriage of CO_2 are mature** and present few hurdles to CO_2 shipping for CCS. **The London Protocol** has historically presented the main barrier to CCS but IMO developments in October 2019 represent a breakthrough in effectively removing this barrier for those parties that have ratified the amendment. **The ETS Directive** now remains the main hurdle to CCS operations in EU and EEA EFTA countries but the barrier is not absolute and is due for revision.
- **Contractual arrangements may be based on existing frameworks** but specific clauses will need to be included.
- **Ship operators will have to manage two reporting schemes for CO_2 emissions from fuel** but CO_2 leakage from cargo and injection into the seabed are not covered.

While this study has provided a detailed analysis of costs, operational considerations and legal frameworks for the EU case, additional research and analysis is required to further understand the global implications and variations, as well as the potential market for cross-border transport. Suggestions of further work include:

- **More detailed analysis of contractual mechanisms**, taking into account the conflicting regulatory and operational (cost) drivers related to ETS compliance. Since there is currently no framework in place for quantification, verification and reporting of CO_2 transported by ship for CCS, the consequences of including shipping in the ETS need to be considered.
- **More detailed investigation of unavailability of offshore facilities** (relevant sea-states) particularly with regard to optimal ship size.
- **Modelling of the potential for innovations in shipping** to reduce the costs and GHG impact of the CO_2 shipping chain.
- **Detailed study of different legal frameworks**, legal contractual traditions, cost implications and ports **in other regions** with potential to use CO_2 shipping (e.g. Japan and South Korea).
- **Detailed assessment of the market potential for export/import of CO_2** within Europe and/or other regions and identification of locations between which shipping of CO_2 may be feasible.
- **Inclusion of CO_2 storage infrastructure** (wells etc) in shipping cost and the impact of port-to-storage options on CO_2 storage costs (e.g. due to potential effect on injectivity).

In addition, recommended actions to address regulatory barriers include:

- **Increased efforts to have Contracting Parties ratify the amendment to the London Protocol**, removing the barrier to export of CO_2 for storage for all contracting parties regardless of individual state declaration.
- **Increase efforts to expand the ETS to include shipping,** enabling streamlining of national policy across the EU.

10 Appendix

10.1 Summary of feedback received during stakeholder consultation

Overall feedback received during stakeholder consultation was positive. All participants were interested in the study and the findings. Our approach to the cost modelling was considered appropriate and the scale of the costs was considered reasonable. The legal and regulatory challenges were accurate and comprehensive of those experienced by the stakeholders. Key aspects of the feedback gathered during the engagement used to refine our analysis is summarised in Table 10-1.

Table 10-1 Summary of feedback received during stakeholder consultation

Element	Feedback
Ship logistics and cost assessment	• 10,000 tCO_2 ships may to be too small for offshore unloading under harsh weather conditions such as in the North Sea, due to difficulties with connecting/disconnecting for unloading • If small ships are used for large-scale transport, then there may be issues with the number of ships operating at any one time (multiple projects/routes) • Up to 70,000 tCO_2 ships are being developed for the Med P condition but are an innovative design – not necessarily comparable for the case modelled in this study
	• Unloading rate of 600 t/h may be too low – may be able to achieve 2,000 to 3,000 t/h
	• Choice of unavailability factor is reasonable based on wave heights chosen but could potentially be lower e.g. shuttle tankers can have overlap and can plan well to minimise this
	• To fully compare different unloading options, the boundary limit needs to be the same – all need to go up to the injection point (including pipeline in onshore unloading case)
Assessment of infrastructure and handling requirements	• Suitability of a storage site for continuous vs batch-wise injection is site-specific (assessed on a case-by-case basis)
	• Agreement that there are difficulties with multi-cargo ships – would need to be designed from the beginning and it is not envisaged that regular switch between cargoes would be done
	• High pressure (up to 45 barg) unlikely to be suitable for ship transport due to loss of volume
Legal and regulatory	• Consideration of international storage networks outside of the EU is less advanced and, in some cases, may be subject to additional legal hurdles. For example: ○ In Japan, foreign vessels cannot conduct transport of cargo between Japanese ports unless they have a permit or are covered by treaty

	○ Carriage of CO_2 by foreign vessels in Japanese waters is prohibited, even for demonstration purposes

10.2 CO_2 carriers currently in operation

Figure 10-1 Coral Carbonic. Image ©2019 Brevik Engineering.

Table 10-2 Coral Carbonic data[365]

Coral Carbonic	
Owner	Coral Carbonic Scheepvaart
Build	1999
Length overall (m)	79
Dead weight tonnage	1786
Capacity	1.25 kt CO_2
CO_2 condition:	-40^{0}C /18 barg

[365] BV Register of Vessels. Retrieved from www.veristar.com/portal/veristarinfo/generalinfo/register.

Figure 10-2 Froya. Image ©2019 Brevik Engineering.

Table 10-3 Froya/Gerda/Embla data[365]

3 ships: Froya/Gerda/Embla	
Owner	Nippon Gases Europe AS
Build	2004/5 converted in 2013
Length overall (m)	83
Dead weight tonnage	3480
Capacity	1.77 kt CO_2
CO_2 condition:	-30^{0}C /19 barg

Figure 10-3 Iduna. Image ©2019 Brevik Engineering.

Table 10-4 Iduna data[365]

Iduna (IMO 7431698)	
Owner	Nippon Gases Europe AS
Build	1975 converted in 1999
Length overall (m)	81
Dead weight tonnage	2645
Capacity	1.2 kt CO_2
CO_2 condition:	-30^{0}C /20 barg

10.3 LPG and Ethylene carriers suitable for CO_2 transportation

The list of identified carriers is presented in Table 10-5.

Included on the list is a series of vessels built at Zhonghua Shipyard. These ships were originally acquired by Ship owner IM Skaugen as 6 CO_2 capable LPG carriers designed for containing liquid gas at 7 barg down to -104°C. The ships have cargo tanks with a volume of 8,500 to 10,200 m^3. One of these ships is the Norgas Sonoma, Figure 10-4

Figure 10-4 Norgas Sonoma[366]

Figure 10-5 Coral Pavona[367]

[366] https://www.tu.no/artikler/modell-blir-ny-industri/257386
[367] https://www.anthonyveder.com/fleet/coral-pavona/

Table 10-5 List of potential LPG carriers suited for CO_2 transport[368]

Vessel Name	Type	Builder	Built Date	Capacity (cu m)	Tank Temp (C)	Tank Pressure (kgf sq m)	Owner Company
Donau	LPG Carrier	Meyer Werft	01/09/85	30200	-50	7.0	Exmar LPG BVBA
Norgas Napa	Ethylene/LPG	Zhonghua Shipyard	01/10/03	10208	-104	7.0	Teekay LNG Partners
Norgas Shasta	Ethylene/LPG	Zhonghua Shipyard	01/08/03	10208	-104	7.0	Norgas Carriers
Norgas Alameda	Ethylene/LPG	Zhonghua Shipyard	01/05/03	8556	-104	7.0	Norgas Carriers
Norgas Orinda	Ethylene/LPG	Zhonghua Shipyard	01/10/02	8556	-104	7.0	Norgas Carriers
Norgas Petaluma	Ethylene/LPG	Zhonghua Shipyard	01/03/03	8556	-104	7.0	GasMar AS
Norgas Sonoma	Ethylene/LPG	Zhonghua Shipyard	01/01/03	8556	-104	7.0	SGPC
Jemila	LPG Carrier	A.E.S.A.	01/03/83	8040	-48	8.0	Sonatrach Petroleum
Gaz Venezia	LPG Carrier	I.N.M.A.	01/12/95	7434	-48	7.5	Naftomar Shpg & Trad
Mores	Ethylene/LPG	I.N.M.A.	01/02/94	7414	-104	7.5	Lumaship S.r.l.
Virgen del Carmen B	LPG Carrier	I.N.M.A.	01/12/92	7350	-48	7.5	Transgas Shpg. Lines
Coral Palmata	Ethylene/LPG	Cant.Nav.Pesaro	01/06/94	7164	-104	7.0	Anthony Veder
Coral Pavona	Ethylene/LPG	Cant.Nav.Pesaro	01/07/95	7164	-104	7.0	Anthony Veder
Gas Optimal	LPG Carrier	Ast.De Mallorca	01/01/85	7115	-48	8.0	Nautilus Marine
PGC Strident Force	LPG Carrier	Higaki Zosen	01/06/99	6527	-48	7.0	Paradise Gas Carr.
Queen Phenix	Ethylene/LPG	HyundaiHI (Ulsan)	01/10/96	6481	-104	8.0	Daiichi Tanker Co.
Happy Bride	LPG Carrier	Hyundai HI (Ulsan)	01/04/99	6270	-48	7.0	Ultragas Aps
Tanja Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/05/99	6270	-48	7.0	Lauritzen Kosan
Tilda Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/02/99	6270	-48	7.0	Lauritzen Kosan
Syn Atlas	Ethylene/LPG	Cant. Nav. Morini	01/02/93	6073	-104	7.0	Synergas S.r.l.
Tenna Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/09/98	5900	-48	7.6	Lauritzen Kosan
Tessa Kosan	LPG Carrier	Hyundai HI (Ulsan)	01/01/99	5900	-48	7.6	Lauritzen Kosan
Gaschem Weser	LPG Carrier	Malaysia S.Y. & Eng	01/12/99	5734	-48	9.5	Hartmann Schiff.
Gaschem Hunte	LPG Carrier	Kodja Bahari	01/09/00	5730	-48	9.5	Hartmann Schiff.
Blue Dream	LPG Carrier	Meyer Werft	01/06/81	5647	-48	7.5	Arvina Trade Ltd.
Zuma Rock	LPG Carrier	Meyer Werft	01/01/75	5450	-48	8.3	Petrobulk Shipping
Gaschem Jade	LPG Carrier	J. Pattje	01/10/92	5322	-48	10.5	Hartmann Schiff.
Gaschem Jumme	LPG Carrier	J. Pattje	01/05/93	5322	-48	10.5	Hartmann Schiff.
Melina	LPG Carrier	Lindenau	01/09/84	5253	-48	11.2	Hellenic Petroleum
Habas	LPG Carrier	Usuki Zosensho	01/06/84	5060	-48	7.0	Habas Petrol

10.4 Floating storage and injection unit concepts

Ship-shape

A ship-shaped unit is a well-known technology for floating storage. The ship-shaped design is proven at different sizes. The ship-shaped unit needs to be moored either to a turret/buoy or with a spread mooring system. The turret is a flexible but expensive solution. When moored on a turret the unit will weathervane and always have the bow towards the weather. If the injection requires low motions the ship-shaped unit performs worse than a

[368] IEAGHG Technical Review 2017-TR1, Feasibility Study for Ship Based Transport of Ethane to Europe and Back Hauling of CO2 to the USA.

spar/SEVAN/semi concept. The ship-shaped unit is very space efficient, there will be almost no unused space.

The storage tanks can be in longitudinal position situated inside the hull. The process area can also be on the topside of the hull. The ship-shaped solution does not necessarily need to be a new-build, it can also be a conversion of a tanker/FPSO/FSO or similar.

In the northern Norwegian Sea at a water depth of 350- 450 m the Skarv field is located. As a storage and production unit the field has a FPSO permanently moored, see Figure 10-6. The produced gas is exported via a pipeline and the oil is offloaded by shuttle tankers. The development is relatively new and started production in 2012.[369]

Figure 10-6 Skarv, Ship-shaped FPSO[369]

Spar

A spar platform consists of either only a long cylindrical hull or a shorter cylindrical hull with a truss construction at the bottom. The truss spar saves steel weight but still have the low motion advantages of a spar unit. The existing spar have a hull height that is between about 170- 220 m which is almost the same as the water depth.[370] The spar concept is considered as a deep-water concept rather than a medium water depth unit. The built production units are used only for production and export via pipeline i.e. without storage. The concept has been used for storage since 1970s. These units were moored at the seabed. If the floating spar concept should be used the tanks and topside needs to be designed for storage. The hull also needs to be modified for shallower water depths then the units built today.

The storage tanks will be placed in the cylindrical hull and will be vertically oriented. With vertical oriented tanks the steel weight will increase due to higher pressure in the bottom of the tank. The process equipment may be on the topside of the spar.

The largest spar platform built is the Aasta Hansteen spar in the Norwegian Sea. The unit is shown in Figure 10-7. The platform is located at 1,300 m water depth. The decision was between a SEVAN and a spar platform, but the choice fell on a Spar unit because of the low motions. The low motions opened up to use of steel catenary risers (SCR) which is the first

[369] https://www.akerbp.com/en/our-assets/production/skarv/
[370] Spar Ref 2014. Retrieved from Technip : technip.fr

time these types of risers are used in Norway. Aasta Hansteen is the first Spar on Norwegian Continental Shelf.[371]

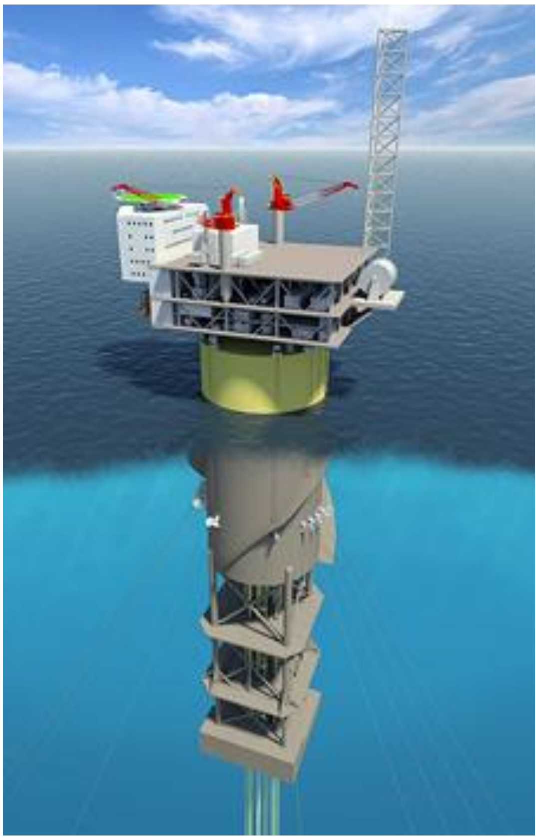

Figure 10-7 Aasta Hansteen, Spar production unit[372]

Circular form stable units (SEVAN)

The SEVAN FPSO concept consists of a large diameter cylinder but compared to the spar concept the SEVAN FPSO has a lower draught (about 15 m). The diameters of the built units vary from 60 to 90 m, and the displacement of the 70 m in diameter at 15 m draught is about 64,400 tonnes. This type of unit is designed for larger storage needs. The shape will be the same for all weather directions, which means that no weather-vaning is needed and therefore no turret.[373] The unit will be spread moored.

The tanks will be stored in the hull in vertical position with the process equipment on deck. If the tanks are placed inside the hull the SEVAN will be a space effective solution. A picture of a SEVAN design can be seen in Figure 10-8.

[371] Offshore Magazine. (2019, 01 01). Field Development. Retrieved 08 27, 2019, from Offshore Magazine: https://www.offshore-mag.com/field-development/article/16764040/worlds-largest-spar-platform-opens-deepwater-production-offshore-midnorway
[372] https://www.norwayexports.no/construction-on-worlds-largest-spar-platform-started/
[373] https://sevanssp.com/

Figure 10-8 SEVAN FPSO[373]

Semi-submersible unit

A semi-submersible unit consists of four legs, a ring pontoon and a deck box. The semi concept is a well-known concept at medium water depths. The storage is situated in the deck box and at the deck. The semi concept has big open deck area where the process equipment can be placed. The semi concept has low motions compared to a ship-shaped unit. The semi-submersible does not have any need for turret, because it will not weather-vane. The unit will be spread moored.

The semi concept is not the most space efficient concept, because the hull is not used for CO_2 storage. For large storage volumes the unit needs to be very large, for displacement requirements and not for space.

At the Troll field there are two different types of semi-submersible units. Troll B has a concrete hull while the Troll C has a steel hull. Troll B is the first semi with concrete hull and is operating at a water depth of 325 m. The platform is connected to a pipeline via Troll A.[374] Troll C platform is shown in Figure 10-9 below.

Troll C is located at 340 m water depth. Production from west Troll field and Fram field is going through Troll C platform before exported. The gas is exported via Troll A while the oil is exported through Troll II pipeline.

[374] https://www.norskolje.museum.no/wp-content/uploads/2016/02/3467_321daaaf2b0644d897762f3bb73224cc.pdf

Figure 10-9 Troll C, Semi-submersible production unit[374]

Tension Leg Platform (TLP)

Similar to the semi-submersible platform the Tension Leg Platform, has four legs, a ring pontoon and a deck box. The mooring consists of tension legs between the platform and the seabed. The tension legs are pipes connecting to the lower parts of the hull, often the columns, to the seabed. These are often made of steel and dampens the vertical motion of the platform which may allow for use of steel risers. Steel risers are beneficial from a cost perspective. The platform is still allowed to move in horizontal directions (Oil and Gas).

In 1992 a TLP was installed at the Snorre field in the North Sea. The platform is still in use and produces oil, which are exported by a pipeline via Statfjord B to Statpipe. [374]

The storage tanks can be placed as longitudinal oriented tanks on the deck. The TLP has the same space efficiency and capacity as a semi-submersible unit. An example of a TLP platform can be seen in Figure 10-10.

Figure 10-10 Tension Leg Platform (TLP)[375]

Jack-up Platform

A jack-up platform has a buoyant hull and a number of legs. The platform elevates by lowering the legs and jack-up the hull. A jack-up platform can be moved to different locations. When installed the unit has no vertical motions. The unit is best suited for up to medium water depths. The storage volumes are flexible but is best suited for up to medium storage volumes.

One of the largest jack-up platforms built today is the Maersk Invincible, shown in Figure 10-11. It is a drilling jack-up which can operate in water depths up to 150 m. It is designed for year-round operation in the North Sea. The total leg length is 207 m. The rig has three legs. The variable deck load is 10,000 tonnes in operation, but the rig is equipped with e.g. drilling equipment and living quarters with accommodation for 180 people, which can be replaced by storage.[376]

Figure 10-11 Maersk Invincible, Jack-up Platform[376]

[375] https://oilstates.com/production-platform-systems/tension-leg-spar-platforms/
[376] http://maersk-drilling-cms.prod.umw.dk/media/1654/cr-md003-drilling-brochures-2019-invincible-ju-v1-web.pdf

Fixed Platform

A fixed platform stands with the legs on the seabed. The legs can consist of e.g. concrete legs or a steel framework. The fixed platform is very difficult to move. When installed the platform is good in harsh weather, since the platform is standing on the sea bed there are no vertical motions which enables the use of steel risers. The unit is best in up to medium water depths. The unit have flexible storage capabilities.[377]

The concrete platforms are gravity-based, which means that they are kept in place by gravity and are more cost effective than the steel platforms in shallower waters. The steel framework, also called jacket, has legs that are drilled 60- 120 m into the seabed which functions as mooring.[378]

The largest fixed platform built by man is the Troll A platform, shown in Figure 10-12. It is situated at 300 m water depth 60 km outside Bergen in the North Sea. The platform is 427 m high and weighs 656,000 tonnes. It is made of steel and concrete and was installed in 1995. Production started in 1996. The platform is connected to a pipeline which erases the need of storage. The platform is designed for 70 years operation. The field is planned to produce gas until year 2060.[379]

A jacket type platform in the North Sea is the Edvard Grieg platform. The water depth where the platform is located is 110 m. The platform is connected to shore by a pipeline, no storage is needed.[380]

[377] https://www.oilandgasiq.com/drilling-and-development/news/what-are-fixed-platforms
[378] William C. Lyons, G. J. (2016). Standard Handbook of Petroleum and Natural Gas Engineering (Third Edition). Gulf Professional Publishing.
[379] https://www.offshore-technology.com/projects/troll-phase-three-development-north-sea/
[380] https://www.norskpetroleum.no/en/facts/field/edvard-grieg/

Figure 10-12 Troll A, Fixed Platform[374]

10.5 Concepts in station keeping

Spread Mooring

Spread mooring is a conventional well-proven way of mooring a unit. Typically, the mooring lines are connected to the unit by mooring winches and to the seabed by anchors. The anchor lines can consist of either chain, wire- or polyester rope or a mixture of them. On the seabed it is preferred to have a chain mooring line. If the station keeping consists of spread mooring the offloading must be done directly through a riser. When a unit is spread moored it is not allowed to weather-vane. This means that the solution is best suited for equilateral, or close to, shaped units. It is possible for spread mooring of ship-shaped units as well, but it is best for calm weather. The mooring lines can either be catenary or taut, a taut system is pre-tensioned until the lines are taut, see figure below. In Figure 10-13, the catenary mooring system is shown to the left and the taut mooring system is shown to the right.

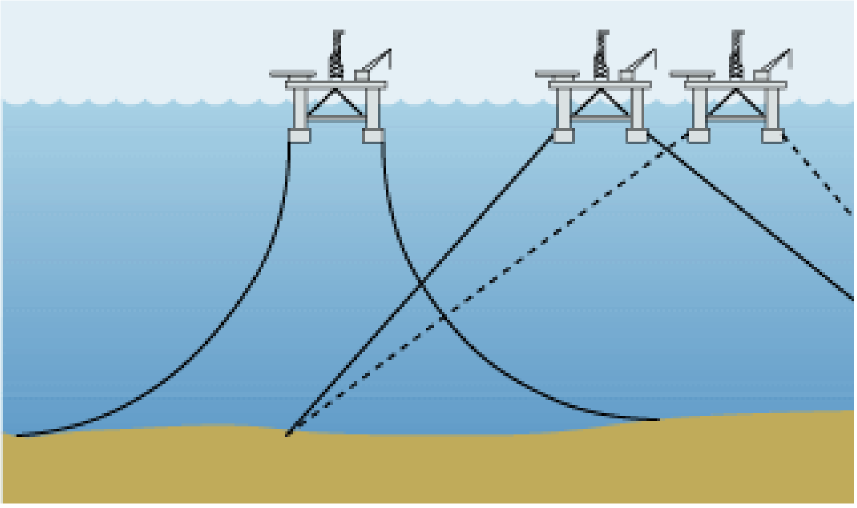

Figure 10-13 Catenary (left) and taut (right) mooring system[381]

Dynamic Positioning (DP)

Dynamic positioning is a system where the vessel is kept in position with thruster force during the offloading operation. The vessel is often positioned with the bow towards the wind and waves.

The thrusters are typically positioned in the stern and bow of the vessel. The bow thrusters are often retractable and not used in transit. The aft thrusters are used as main propulsors in transit condition. There may be retractable thruster in the aft as well, as shown in Figure 10-14 below. The forward thrusters can be either retractable thrusters or tunnel thrusters. The retractable thrusters are often retracted during transit and in harbours. When retracted the thrusters does not increase the draft of the vessel. The retractable thrusters can usually operate 360°. The tunnel thrusters are positioned in transverse direction in the front of the ship. The tunnel thrusters can only operate in transverse direction relative to the vessel. These are often cheaper and require less space than the retractable thrusters.

The DP system is easy to use, because the station keeping is integrated in the ship. On the down side the DP consumes more fuel than other station keeping solutions. The DP station keeping is a very flexible solution with low connection time.

The vessel needs to be connected to an offshore unloading buoy or similar to unload the CO_2 directly into the reservoir. For unloading to FSI a conventional hose solution e.g. Bow Loading System can be used.

[381] https://www.offshore-mag.com/home/article/16756208/installation-and-handling-of-steel-permanent-mooring-cables

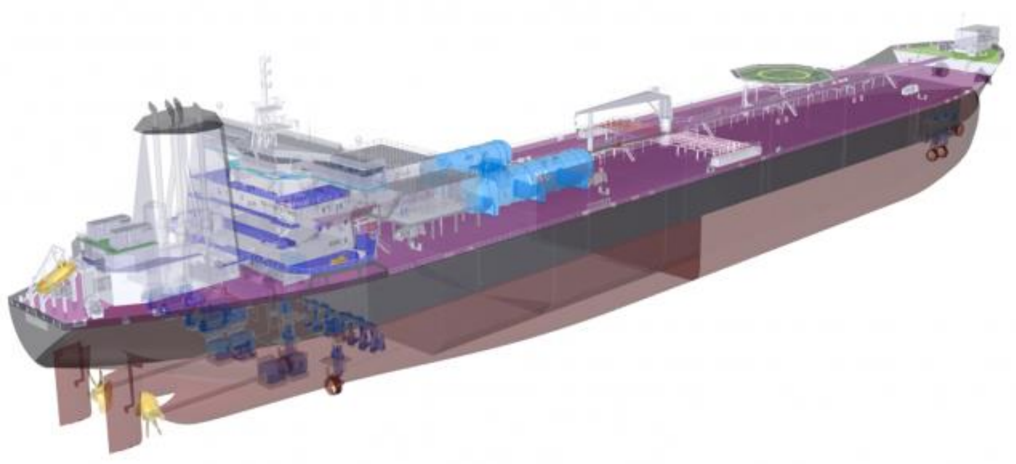

Figure 10-14 Typical arrangement of thrusters for a DP system. There are retractable thrusters in the bow and aft parts. A tunnel thruster can be seen in the most forward part of the bow.[382]

10.6 Concepts in Gas Transfer Systems

Conventional Integrated Turret (CIT)

Conventional Integrated Turret is a solution that is integrated into the FSI. It is a well-known and often used technology for FPSOs. The unit is larger than a Submerge Turret Loading (STL) and is more expensive. The conventional turret can hold more risers and is more flexible regarding mooring.

Figure 10-15 Conventional Integrated Turret (CIT) system.[383]

Submerged Turret Loading (STL)

The Submerged Turret Loading buoy is permanently moored to the seabed and is attached to the riser system. The buoy is submerged and pulled into the vessel when it arrives to the field. The vessel is not in need of a DP system, which reduces the fuel consumption during the offloading. The connection can be made in significant wave heights (Hs) of 5- 7 m

382 https://www.tu.no/artikler/forste-ute-med-a-omdanne-problemet-til-ressurs-bruker-oljedamp-som-drivstoff/415961
383 https://clubofmozambique.com/news/sofec-wins-turret-mooring-system-supply-contract-for-enis-flng-project-in-mozambique/

depending on size of vessel and disconnect can be done in every weather. The mooring system can be designed up to Hs 19 m, which is considered harsh weather. The vessel needs to be designed for or modified to attach the turret inside the bow part of the hull.[384]

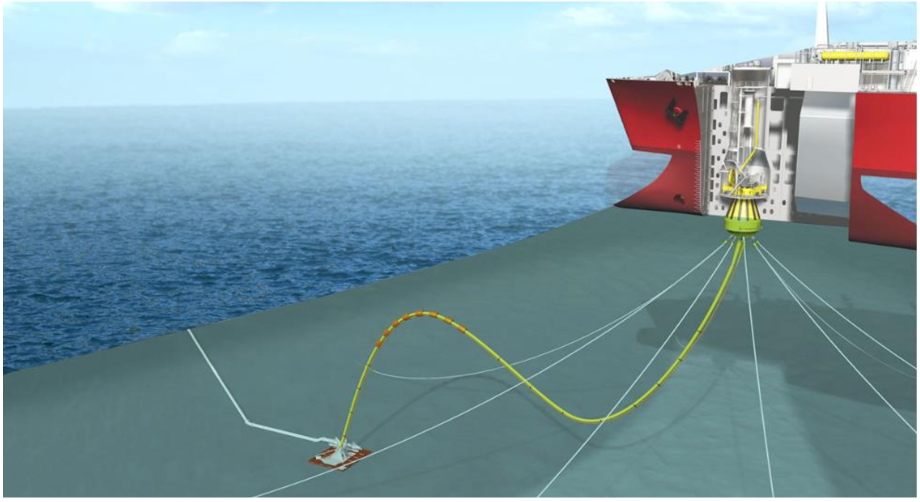

Figure 10-16 Submerged Turret Loading (STL) system.[384]

Turret Buoy Loading (TBL)

The Turret Buoy Loading can either be a surface piercing buoy anchored to the seabed or a tower standing on the seabed depending on water depth. The vessel is connected to a buoy by one large-diameter line, typically 40 - 100 m long depending on environment conditions. The vessel can use its existing mooring equipment and does not have to be modified. The offloading can be done with a floating hose.[385] The system is designed for calm waters because there is a risk of collision between the vessel and the buoy in harsh weather. The system is less robust than the STL and the SAL. [384]

Figure 10-17 Turret Buoy Loading. [384]

Single Anchor Loading (SAL)

[384] https://www.nov.com/
[385] https://www.bluewater.com

The Single Anchor Loading base is placed on the seabed. Attached to the base is the hose string and a polyester rope for mooring. The offloading hose is connected to the bow of the vessel. The mooring line includes clump weights for added damping. The vessel is free to weather-vane around the base. The connection to the system can be done in Hs up to 4.5 m and disconnect up to Hs 7 m. Only the bow needs to be modified for connection to the offloading hose.[384]

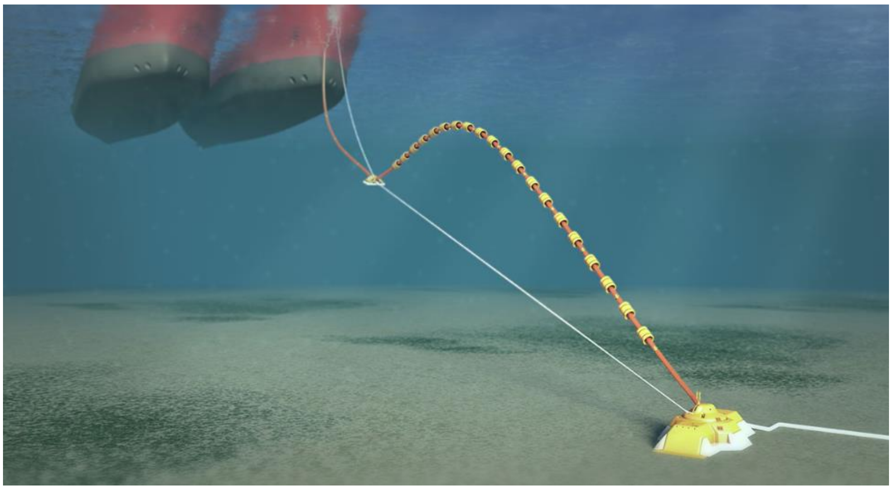

Figure 10-18 Single Anchor Loading (SAL) system. [384]

Bow Loading System (BLS)

Bow Loading system is a well-known loading system for shuttle tankers. The shuttle tanker connects to the FSO or other offshore storage unit by a hose in the bow. The tanker needs a DP system for station keeping. The system is often used world-wide, including the North Sea. The BLS consists of standardized components which are compliable with e.g. the SAL system.

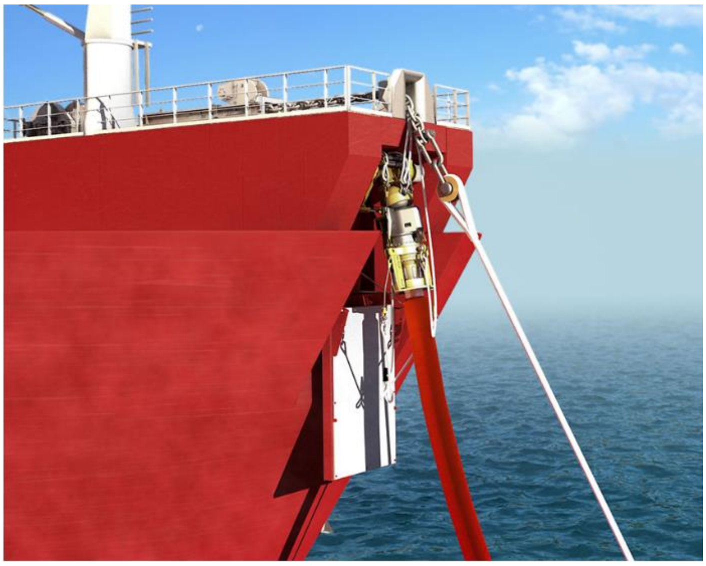

Figure 10-19 Bow Loading system (BLS). [384]

Yoke System

The Yoke System has a steel frame connected to a floating buoy or a tower at the seabed. The buoy connection consists of hinges while the vessel end consists of a pendulum structure. The pendulum structure consists of two pendulums that provide a restoring force when the vessel moves relative to the buoy. This means that the vessel needs to be designed to support this structure. The restoring forces sets the limit of how harsh weather the system can operate in. The offloading can be done with a hose (Bluewater Energy Services BV, 2019).[385]

Figure 10-20 Yoke System. [385]

APL has an own system, which they call Soft Yoke System, with a tower that is placed on the seabed where the frame is placed near the bottom of the tower and is connected to the vessel by two chains. This system reduces the bending moments and allows for high sea states in shallow waters. [384]

Figure 10-21 Soft Yoke System. [384]

Rigid Arm System (RAS)

The Rigid Arm System includes a floating buoy with a rigid triangle shaped frame which connects the buoy with the vessel. The frame keeps the vessel at the same distance from the buoy at all times. The offloading is performed via a hose. The vessel needs to be designed to support the rigid frame. The system is good for permanent loading for larger FSOs. [385]

Figure 10-22 Rigid Arm System[385]

HiLoad DP and LNG

The HiLoad DP is an offloading system with DP which can connect to a shuttle tanker without modification to the tanker. The system is stand-alone unit that connects to the tanker. The solution is water depth independent because there is no connection to the seabed. The offloading is performed with a hose from the tanker via the HiLoad DP system to the FSI. The system is approved for harsh weather.[386] The connection and offloading can be done in sea states up to Hs 4.5 m. One unit has been built for oil transfer. With further development of the concept it will most likely be possible to use for CO_2 transfer.

[386] http://www.remora.no/

Figure 10-23 HiLoad DP system[386]

The HiLoad LNG is based on the HiLoad DP technology and further developed for gas transfer. Like the Hiload DP the Hiload LNG attach to the ship and takes over control. The connection can be done in Hs up to 3.5 m. There is no need for re-design of the shuttle tanker because this is a stand-alone unit that connects to the vessel.[387] The HiLoad LNG will be situated on the FSI site all the time, further investigation of where to store the unit when harsh weather approaches. The system is designed for gas transfer, it needs to be re-designed for CO2 liquid transfer.

Figure 10-24 HiLoad LNG[387]

HiLoad Floating Regasification Dock (FRD)

The Floating Regasification Dock is a floating dock solution with regasification equipment. The concept includes a soft-yoke for mooring. It is designed for water depths between 25 and 60 m. The FRD is designed for 100-year condition with Hs up to 6 m. The regasification

[387] http://www.hiloadlng.com

may be replaced with CO_2 process equipment. Further investigations of this must be done. Due to the docking solution no re-design of the vessel needs to be performed. [387]

Figure 10-25 HiLoad Floating Regasification Dock[387]

Side-by-side

Side-by-side offloading is done by mooring e.g. a shuttle tanker on the side of an FPSO. The offloading is done by an offloading arm without need for floating hoses. The loading arm has a restricted motion envelope which makes the operation most suitable for benign weather areas.[388] Side-by-side offloading can be done both with turret and spread moored FPSO. When a FPSO is moored by a turret it is weather-vaning, which makes the offloading a bit more difficult than for the spread moored FPSO, due to the increasing yaw motion. The shuttle tanker is moored to the FPSO with several mooring lines and between the units are fenders to prevent collision. The number of mooring lines and fenders are decided from case to case.[389]

[388] Mamoun, N., Waals, O., & de Wilde, J. (2007). Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering. San Diego: ASME.
[389] Wang, H.-C., & Wang, L. (2013). Ocean Systems Engineering Vol 3 (pp. 275-294).

Figure 10-26 Side-by-side offloading[390]

10.7 Onshore infrastructure

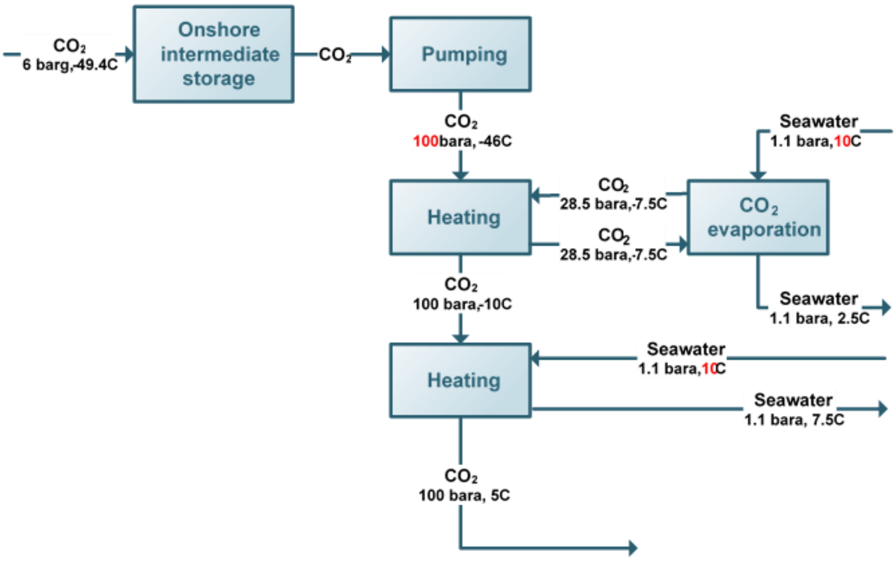

Figure 10-27 Example process for heating and pumping Low P CO_2 to conditions suitable for pipeline transport or injection to a reservoir

[390] Zhao, W. et al. (2018) Ocean Engineering, 99-110

10.8 Cost modelling assumptions and parameters

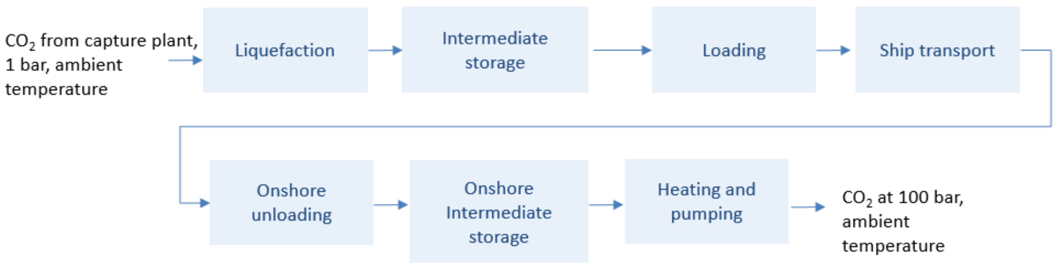

Figure 10-28 Battery limit for Scenarios 1 and 2 (Low P and Medium P onshore unloading, respectively)

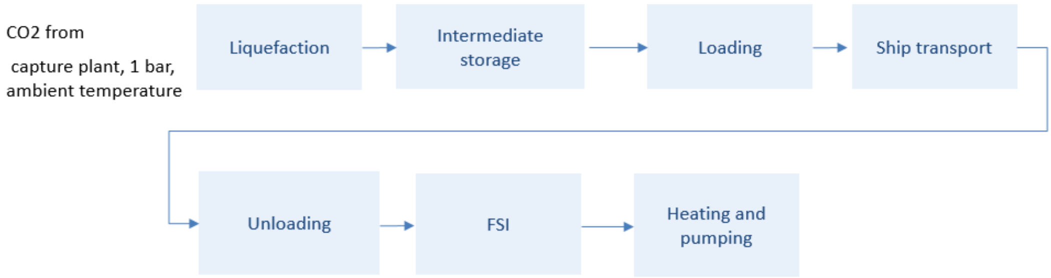

Figure 10-29 Battery limit for Scenario 3A (offshore unloading to an FSI)

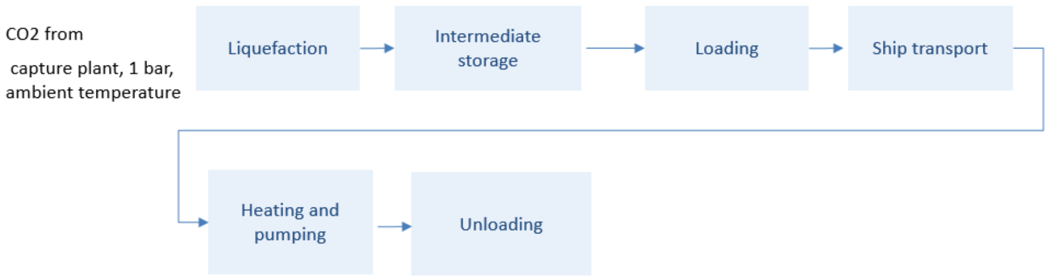

Figure 10-30 Battery limit for Scenario 3B (direct injection)

10.8.1 Shipping costs

Fully pressurized LPG gas carriers are a well-established concept with a number of ships in operation. CO_2 carriers will be based on the same principle but with different specification regarding tank design. When estimating ship CAPEX we assume we are in a technical/commercial situation beyond first of a kind stage benefitting from experience of design and construction of LPG carriers. Technical estimates are based on MTO from a preliminary tank design and scaling from similar size ships.

Ship OPEX is based on cost of operating equivalent ships with state-of-the-art technology. Crew costs are based on Norwegian tariffs. Fuel consumption is based on data from comparable tank ships but with shore power and batteries for port entries and departure.

Assumptions:

- The ship is not first of a kind, effect of learning curve will enable construction at cost effective shipyards.
- Cost of steel-structure 3 USD/kg.
- Relatively high crew costs based on Norwegian tariffs.
- Cost of energy 400 EUR/ton diesel, 0.08 EUR/kWh shore power. No carbon credits are included.
- For offshore unloading station keeping by a mooring system, no DP.

Technical configuration:

- 15 barg ship has a 4 tank lay-out
- 7 barg ship has 2 tank lay-out
- Hybrid diesel/electric propulsion with shore power supply.
- Pilot charges are 300 kEuro and port fees are 300 kEuro per year, these may be significantly higher.

Uncertainty of cost estimate

- CAPEX cost estimate is based on a 3 level SFI (standard methodology for ship calculation) break down. Technical uncertainty is relatively low. Commercial uncertainty is dominant. Financial costs are not included.
- OPEX is based on a bottom up calculation including cost of: energy, crew, maintenance, shore support/admin, pilot and port fees.

10.8.2 FSI costs

We have assumed the FSI will be a turret moored ship shape concept. This is a concept well known from oil and gas FPSO and FSOs. The technology used in the FSI will be based on technology transfer from similar oil and gas facilities. Although the shape of the facility is well known size difference is a challenge with respect to technical scaling inaccuracy. When doing the cost estimate the technical accuracy sizing of tanks, cargo system, pre-treatment unit and turret is relatively good, while the technical uncertainty of the hull, marine systems and LQ is substantial. The cost estimates may be considered on the conservative side taking into account that the facility will be a first of kind. The cost estimate is not a classified estimate. The estimate is comparable to estimates used in an early concept screening process. A $\pm$ 25% allowance should be used as a minimum for the CAPEX.

OPEX of the FSI is based on typical crew set up for an oil and gas floating storage unit in the Norwegian sector. Crew related cost will be the dominant for such facilities. Salaries and shift system are serious cost drivers. OPEX in other shelf states may therefore be significantly lower. The cost of the FSI is done as a bottom up m^3.

10.8.3 Onshore infrastructure costs

The cost of the land facilities is estimated based on a factor method approach. The Equipment cost is calculated in AspenTech In plant cost estimator. The cost is estimated in EUR 2017, and then escalated to 2018 by using Eurostat statistic to gain the equipment cost for each equipment. The Equipment cost is then multiplied with an installation factor to get the final installation cost for each equipment. 20 % contingency is included in CAPEX. OPEX is calculated based on consumption of electricity, manning, cooling water, and maintenance. 4 % maintenance is included in OPEX. Other OPEX items are not included. The OPEX is very dependent on the input values for electricity and cooling water, which is very site specific. The report assumptions are based on the Rotterdam area.

Table 10-6 Cost calculation assumptions for onshore infrastructure

Cost calculations assumptions	Value
Reference year for cost level	2018
Currency	EUR (€)
Escalation for changes in year	CPI in Eurostat
Electric Power [kWh]	0.08 EUR/KWh
Cooling Water [m^3]	0.02 EUR/m^3
If not specified, Nth of a kind is assumed	
Design lifetime for land-based installations: 2 years for construction and 20 years operation	
The liquefaction and intermediate storage will be treated as an extension to the existing capture plant	
No additional cost for quay, offices, canteen or other secondary buildings are foreseen	
The cost estimate is +/- 40 % within a 80 % confidence interval	

10.8.4 Learning curve and cost reduction for NOAK

The first plant or technology is called First of a kind (FOAK). As the number of installations and operating experience increases, the cost is normally reduced for new technology. When all the cost reduction for learning is included, the installation is called Nth of a kind (NOAK). As some of the technologies used in the transport chain are proven technology, the cost may not be reduced as much as for new technology.

The cost from building the first plant is generally higher compared to building a plant when you have a lot of experience of building the same plant. All engineering, equipment, construction, testing, tooling, project management, and other costs that are repetitive in nature would be reduced if a plant identical to a FOAK plant were built. For ships, there is a lot of experience. FOAK is first of a kind installation, i.e. developed and used for a specific purpose. A FOAK equipment and/or process usually has excess handling capacity, excess control systems, duplicate of equipment unit, all to ensure that the system works according to design. As the number of operating hours and installations increases, the need for extra margins is reduced, and thereby also costs will be reduced.

Ship transport of CO_2 at 15 barg and -28°C is proven technology from shore to shore, although at relatively small scale. This includes the necessary process steps before and after transport. The major uncertainty lies in the CO_2 stream quality to be transported/stored. Transporting food-grade CO_2 is done today and achieving a high-quality CO_2 stream is technically feasible but could be costly if the allowed amount of impurities is very low. Large-scale ship of other gases (e.g. LNG, LPG) is proven technology, including offshore to shore transport.

The Norwegian CCS project FEED study costs for transport are high likely due to a FOAK approach and that there are considerable safety margins in place to make sure that it operates as intended. The cost estimates in this study have been developed based on cost factors without additional safety margins (oversize of equipment, redundancy requirement) that is likely to be installed in a FOAK CCS chain.

FOAK costs can be calculated from NOAK costs by increasing the capacity to meet the first performance requirements and redundancy. Increased capacity and redundancy will be reduced due to the learning effect when several CCS chains are in operation.

10.8.5 Ship logistics inputs

	7 barg transport and offloading to shore	15 barg transport and offloading to shore	7 barg transport and offshore offloading to FSI	7 barg transport and offshore offloading by direct injection to well	
Scenario	**1**	**2**	**3A**	**3B**	**unit**
Number of wells	2	2	2	2	-
Max injection rate per well	114	114	114	114	t/h
Ship Cargo Capacity (100%)	10000	10000	10000	10000	t
Tank filling	98%	98%	98%	98%	-
Tank sump	1%	1%	1%	1%	-
Sailing distance (roundtrip)	1080	1080	1080	1080	nm
Operational transit speed	12	12	12	12	knots
Speed at approach	10	10	10	10	knots
Approach/departure	60	60	60	60	minutes
Mooring/unmooring	15	15	15	15	minutes
Weather margin	0.95	0.95	0.95	0.95	-
Operational margin	0.98	0.98	0.98	0.98	-
Roundtrip sailing time	98	98	98	98	hours
Loading rate	600	600	600	600	t/h
Time for loading connect/disconnect	120	120	120	120	minutes
Time for loading	20.2	20.2	20.2	20.2	hours
Unloading rate	600	600	600	228	t/h
Time for unloading connect/disconnect	120	120	180	180	minutes
Time for unloading	20.2	20.2	22.2	48.5	hours
Unloading availability factor	1.00	1.00	0.92	0.92	-
Unloading unavailability	0.0	0.0	11.3	13.4	hours
Mean time for roundtrip	139	139	153	182	hours
Trips per year	63	63	57	48	-
Number of ships	3	3	3	3	-
Vapour return	2.0%	4.0%	2.0%	2.0%	-
CO_2 available for injection	1.80	1.76	1.63	1.37	Mt/y

Figure 10-31 Operational profiles for the logistics scenarios

10.8.6 Pipeline cost estimate

- Pipeline costs were calculated as a function of pipeline length and diameter.
- The distance from the onshore port to the offshore storage site is calculated from the latitude and longitude of each site using the spherical law of cosines.
- A routing factor of 1.2 was applied to convert straight-line distances to pipeline lengths.
- Transmission diameter size is calculated assuming pressure drop should not exceed 15 MPa.
- It is assumed that the CO_2 is delivered at 10 MPa at the required purity to the shoreline boosting hubs for offshore pipeline transport and geological storage and compressed to 25 MPa.
- Capital cost of transmission pipeline = pipeline length x routing factor x cost per km.inch x inner diameter
- The capital costs were consistent with those used in previous models.[6,61,391]

10.9 Techno-economic modelling methodology

Liquefaction

Table 10-7 shows the liquefaction cost estimates as calculated in Section 4.

The main model updates are the following:

- The model calculates CAPEX based on flow rate by applying a scaling factor (0.8 below 1 Mtpa, 1 above 1 Mtpa). Previously, costs were modelled as scaling linearly with the annual flow rate at all flow rate ranges (i.e. below as well as above 1 Mtpa).
- Fixed OPEX of 6% of CAPEX is applied in the model, based on the average of the range identified in the new data.
- An electricity price of €0.08/kWh is assumed.
- Costs of cooling water have been added to the model as a separate cost item, assuming a water cost of €0.02/m^3 (SINTEF input).

Table 10-7: Liquefaction cost and performance data as estimated in Section 4

Transport pressure	Inlet pressure	Capex (€/(t CO_2/y))	Fixed Opex (% of Capex)	Energy (kWh/t CO_2)	Labour opex (€/(tCO_2/y))	Cooling water (m^3/(tCO_2)
Low	Pressurised	16.3	4%	39.00	0.49	3.65
Low	Non-press.	38.9	4%	134.0	0.49	7.44
Medium	Pressurised	12.7	4%	16.0	0.50	4.11
Medium	Non-press.	36.4	4%	114.0	0.50	20.65

Storage

Apart from the updates of the used values of specific costs, the following updates have been made:

391 The technoeconomic model used in reference 6 is available to download from https://www.gov.uk/government/publications/shipping-carbon-dioxide-co2-uk-cost-estimation-study

- Previously, the same costs were assumed for the onshore as well as offshore temporary storage. Now a different cost is assumed for the offshore storage on the FSI than for onshore storage. This is in line with the more detailed estimation of components included in each cost.
- The storage cost on the offshore platform, is based on the estimate by Brevik of €35m for 45,000t storage.
- The following storage factors are applied:
    - For the storage in the **exporting port,**
        - a **storage factor of 1** is assumed in the case of **onshore unloading**
        - a **storage factor of 1.5** is assumed in the case of **offshore unloading**
        - and for the storage in the importing port (in the case of onshore unloading), a storage factor of 1 is assumed;
    - In the case of the unloading to a platform with storage, a minimum storage size of 30,000t and a storage factor of 1 is assumed. This is in line with the more detailed assessment of operational requirements in Section 4. The storage size is determined by the ship size as well as expected unavailability of the platform due to weather conditions and the minimum injection rate required by the storage site.

Table 10-8: Updated storage cost assumptions used in the shipping model

Location	Transport pressure	Capex (€/(t CO_2 stored in tankers)	Opex (% of Capex)
Onshore	Low	1,300	5%
Onshore	Medium	2,770	5%
FSI	Low	778	5%

Loading costs

Loading costs were previously assumed to scale with the annual flow rate (i.e. the total transported CO_2 per year) but costs are now assumed to scale with the hourly loading rate. Both approaches are to some extent equivalent as the annual loading rate will need to be increased to enable high annual flow rates.

Table 10-9: Updated cost assumptions for loading infrastructure used in the shipping model

Capex (€/(t CO2/y))	Capex (€/(tCO_2/h))	Opex (% of Capex)
	600	6%

It is assumed that equivalent infrastructure as for loading the CO_2 (loading arms or flexible hoses) onto the ship is required for unloading and the cost for these are included in the unloading costs in the model. While these costs are the only unloading costs in the case of onshore unloading, they are additional to other costs in the case of offshore unloading (e.g. the cost of the platform).

Shipping costs

Ship CAPEX estimates from Section 4 for case 1, 2, 3A and 3B have been added to an existing database of ship costs and new fitting curves for low pressure and medium pressure transport ships have been calculated[392]. Figure 10-32 shows the updated data and corresponding fitting curves.

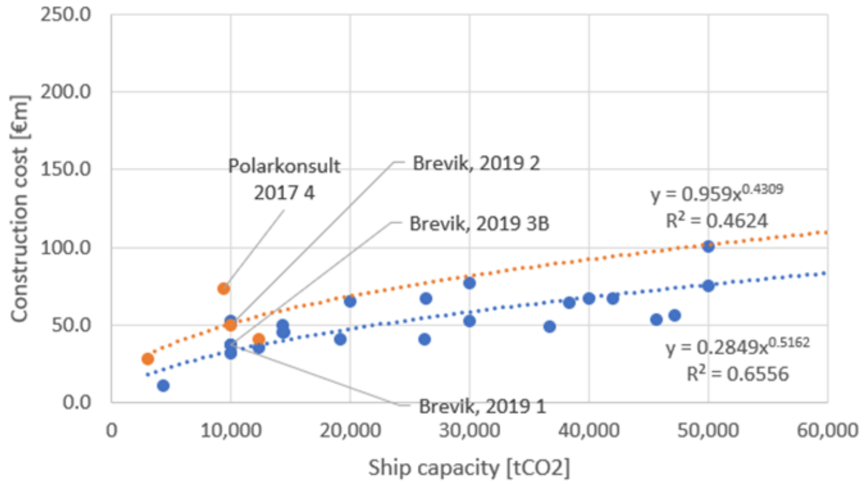

Figure 10-32: Updated ship cost data and corresponding fitting curves

Table 10-10 shows the cost model parameters used. Capex constant and exponent describe the fitting curves, displayed in **Figure 10-32**, which are used to estimate the cost the cost of a ship for a given ship size (in tCO_2 transport capacity) in the model.

It should be noted that the coefficient of determination of the fitting curves is relatively low (66% for the low pressure ships and 46% for the medium pressure ships). This reflects the fact that there is a significant degree of uncertainty involved in the estimation of the costs. The collected data points show a high level of variation due to varying assumptions and approaches and the fitting curve can only be seen as a high level approximation.

Table 10-10: Updated ship cost parameters used in the shipping model

Transport CO_2 pressure	Capex constant (€/t CO_2)	Capex exponent	Opex (% of Capex)	CAPEX of 10,000t ship (€m)
Low	284,900	0.5162	5%	33
Medium	959,000	0.4309	5%	51

Apart from the ship CAPEX and fixed OPEX, the model also captures **harbour fees** and **fuel cost** as separate components which add to the shipping cost. The assumptions on these costs have not been changed.

Fuel consumption is assumed to increase linearly with the cargo weight. The estimation of the fuel consumption is based on literature review. A 10,000t ship is assumed to have a fuel consumption of 263MWh/day, corresponding to 23 tonnes of marine diesel oil (MDO) per day (1tMDO = 11.63MWh).

392 All data has been converted to 2018€.

Harbour fees are assumed to increase linearly with the cargo weight and the corresponding linear function is based on data collected from literature review. The calculated harbour fees are similar to those identified in Section 4.

Conditioning cost

Table 10-11 shows the updated assumptions on the costs for conditioning (heating and pumping) the CO_2 from the transport condition to the condition for either injection to the long term storage (in the case of offshore unloading) or pipeline transport (in the case of onshore unloading).

Direct injection: Cost were previously modelled as scaling with the annual flow rate but are now assumed to scale with the ship capacity (in tCO_2) and are based on a cost of €8m per ship for conditioning treatment on board a 10,000t ship (from Section 4). Conditioning equipment needs to be installed on each ship (i.e. three times for three ships).

Platform with storage: Costs were previously modelled as scaling with the annual flow rate but are now assumed to scale with the ship capacity and based on a cost of €8m for 10,000t ships (from Section 4). Conditioning equipment only needs to be installed on the platform (i.e. once for three ships).

Table 10-11: Updated cost assumptions for CO_2 conditioning used in the shipping model

Transport CO_2 pressure	Unloading option	Capex (€/(t CO2/y))	Capex per ship cap. (€/tCO_2)	Opex (% of Capex)	Opex (€/t CO2)	Energy (kWh/t)
Low	Onshore	4.21		11%		2.53
Medium	Onshore	4.1		11%		2.3
Low	Direct injection		800	5%		2.53
Low	Platform w/ storage		800	5%		2.3

Overall conditioning cost estimates are increased due to more detailed engineering analysis compared to previously used data, however conditioning cost still remain a small cost component of the overall cost.

Offshore unloading cost

The detailed engineering study in Section 4 allowed refinement of the estimation of the offshore unloading costs. Table 10-12 shows the updated cost assumptions for offshore unloading.

Unloading to an FSI:

- The FSI costs (without FSI related costs onboard the ships) are modelled as a linear function of the storage capacity on the FSI based on the cost estimates of an FSI of 30,000t and one of 45,000t storage. The storage capacity on the FSI is sized as described above.
- The updated FSI cost also include a cost per ship of €10m for the dynamic positioning system (DPS) and of €1.8m for the bow loading system (BLS).

Direct injection:

- The updated estimates include a cost of €2.7m per ship which has been identified in the engineering study in Section 4.

Table 10-12: Updated cost assumptions for offshore unloading used in the shipping model

Unloading	Fixed Capex (€m)	Capex (€/(t CO2/y))	Capex per ship (€m)	Opex (% of Capex)
Unloading to FSI	95	1,800	11.8	5%
Direct injection	16.5		2.7	5%

10.10 Legal and regulatory framework – detailed discussion

10.10.1 Public international law

UNCLOS – definitions and interpretation

Pollution of the marine environment: Article 1(4) defines *"pollution of the marine environment"* as *"the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities."*

Dumping: Dumping is defined under UNCLOS as, amongst other things, *"any deliberate disposal at sea of wastes or other matter from vessels, aircraft, platforms and other man-made structures",* cf. Article 1(5)(a). This wording does not include references to the subsea bed or subsoil, leaving some room for interpretation. Further, what is comprised by the wording "at sea" is not defined. However, some guidance regarding the interpretation of the term dumping may be found in Section 6 on enforcement. Subject to Article 216 *"[l]aws and regulations adopted in accordance with this Convention and applicable international rules and standards established through competent international organizations or diplomatic conference for the prevention, reduction and control of pollution of the marine environment by dumping shall be enforced (a) by the coastal State with regard to dumping within its territorial sea or its exclusive economic zone or onto its continental shelf;*[393] *[…]."* Although not directly including CO_2 storage, the intention and geographical scope of the instrument has to be taken into consideration.[394] Further supporting the inclusion of CO_2 offloading and storage is the sovereign rights under Article 56 for the costal State *"for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the waters superjacent to the seabed and of the seabed and its subsoil […]"*[395]. Further, Article 77 emphasizes the coastal State's right to exercise sovereign rights for the purpose of exploring and exploiting the natural resources of its own continental shelf, implying storage of CO_2 may be initiated without hindrance of UNCLOS. These provisions support an interpretation of including the subsea bed in scope of UNCLOS and thus "dumping" to comprise CO_2 storage in the subsea bed.

Application of UNCLOS to CCS activities: Regardless of a direct or indirect inclusion of storage, a reasonable interpretation would indicate that offshore offloading from vessels at a storage site could be subject to UNCLOS, c.f. the words "disposal" and "at sea", although

393 Our underlining.
394 As elaborated on in e.g. the UNCLOS Preamble
395 Our underlining.

being mindful the CO_2 is not intended to be released into the sea itself. Further, being mindful of the coastal State's sovereign rights to explore and exploit the continental shelf's natural resources as provided for in UNCLOS Article 77, and Article 76 including the seabed and subsoil in its definition of continental shelf. Finally, newer treaties and conventions developed subject to UNCLOS allows for offloading and storage of CO_2 offshore. It is therefore our understanding that UNCLOS regulates CO_2 offloading and storage in a similar manner as transport. This implies UNCLOS Part XII provisions for the protection and preservation of the marine environment are similarly relevant for offloading and storage and that these activities shall be undertaken subject to the general obligation to protect and preserve in Article 193, c.f. Article 192. The general obligation to *"protect and preserve"* the marine environment pursuant to Article 192 c.f. Article 193 consequently limits the right of States to freely *"exploit their natural resources"* in Article 77, c.f. Article 193. Further, as for transport, it is thus up to the states to individually and jointly to implement policies to meet this obligation, leaving the detailed and limiting framework to other instruments.

London Protocol

Definitions and applicability to CCS activities:

While the London Convention uses the wording *"any deliberate disposal at sea"* of either wastes or vessels to define dumping in Article III(1)(i) and (1)(ii) respectively, the London Protocol contains both more paragraphs (1-4) and more precise wording, e.g. both specifically mentions storage and defines storage as something that takes place in the seabed and subsoil thereof.

Although it is unclear from the definition of dumping, it is our understanding that offloading activities are regulated by the London Protocol as a consequence of the wording in Article 10 on application and enforcement. Subject to Article 10, Contracting Parties, meaning contracting States, are obligated to implement the requirements of the London Protocol to *"vessels […] loading in its territory the wastes […] which are to be dumped […] at sea"*[396] and *"vessels, […] and platforms or other man-made structures believed to be engaged in dumping […] at sea […].*[397]

CO_2 offloading and storage are both exempt from direct prohibition if the CO_2 is injected into a sub-seabed geological formation, consists overwhelmingly of carbon dioxide and contains no other matter for the purpose of disposing of those wastes.[398] Storage of CO_2 further requires compliance with requirements of auditing and monitoring[399] to ensure that the permit conditions are met.[400]

Overcoming the export prohibition:

Options to overcome the export prohibition are outlined Ithe International Energy Agency (the IEA) in the 2011 study *"Options for Enabling Transboundary CO_2 Transfer"*[401]*;* the options are listed below:

- an interpretative resolution based on the general rule of interpretation;
- resolving to provisionally apply the 2009 amendment;
- subsequent agreement through an additional treaty (bilateral or multilateral);

[396] Article 19.1.2
[397] Article 19.1.3
[398] Annex 1 paragraph 4.
[399] As set out in Annex II
[400] See Annex II nr. 1 and 16-17.
[401] *Carbon Capture and Storage and the London Protocol: Options for Enabling Transboundary CO_2 Transfer* (2011) International Energy Agency.

- modification of the operation of relevant aspects of the London Protocol as between two or more Contracting Parties;
- suspension of the operation of relevant aspects of the London Protocol as between two or more Contracting Parties;
- and conducting CCS through non-Contracting Parties.

The options were further analysed by Arntzen de Besche Law Firm in 2017[402] and finally by IOM Law in the 2018 article *"Cross-border CCS infrastructure in Norway, the UK and the Netherlands".* The first option involves interpreting a treaty in direct conflict with the wording and established intention and was deemed unfortunate.[403] Further the alternative of the parties entering into a subsequent agreement to directly replace Article 6, was considered a risk to diplomatic relations and thus an ineffective solution.[404] While the modification through negotiation by two or more parties is allowed and only requires notification to the other contracting parties, this option would only provide a solution for the parties involved and otherwise lead to a dis-incentive for the ratification of the original amendment for other parties to the London Protocol. Thus, this option was not recommended by the authors either. Similarly, the possibility to temporarily suspend the prohibition between two or more parties, was considered not only to be ineffective but also go against principles of sovereignty and the obligation to honour agreements.[405] The final option was not addressed in the 2018 paper but in the 2017 paper, it was observed that the London Protocol does not prevent import from non-members.

As stated in Section 7.3.3, provisional application of the amendment is the recommended course of action, and is the one that has been taken. It is worth noting is that the above-mentioned analysis is limited to cross-border collaboration between three named countries, all having ratified the 2009 amendment. For infrastructure reaching other countries, the options would have to be revisited and reconsidered.

OSPAR

General provisions for transport, offloading and storage of CO_2: Pollution control and prevention are regulated by Article 5, which sets out the obligation to *"[…] take, individually and jointly, all possible steps to prevent and eliminate pollution from offshore sources […]"*. "Offshore sources" are defined in Article 1(k) and comprise *"offshore installations and offshore pipelines".* Although the wording only specifically includes pipelines as known means of transportation, and thus may give the impression of leaving ships out of the equation, "offshore installations" are further defined as *"any man-made structure, plant or vessel or parts thereof, whether floating or fixed to the seabed, placed within the maritime area for the purpose of offshore activities"*[406] Pursuant to Article 1(n), the wording "vessels or aircraft"[407] comprises *"waterborne or airborne craft of any type whatsoever",* cf. Article 1(n).

MARPOL

Definitions and interpretation:
Harmful substances: Pursuant to Article 2(2), a harmful substance is *"any substance which, if introduced into the sea, is liable to create hazards to human health, to harm living*

[402] D. E. Henriksen and I. Ombudstvedt (2017) Energy Procedia vol. 114, p.7443-7458
[403] M. Gran, I.Ombudstvedt (2018) 14th International Conference on Greenhouse Gas Control Technologies. p. 3.
[404] M. Gran, I.Ombudstvedt (2018) 14th International Conference on Greenhouse Gas Control Technologies p. 6.
[405] M. Gran, I.Ombudstvedt (2018) 14th International Conference on Greenhouse Gas Control Technologies p. 7.
[406] Article 1(l).
[407] See Article 1 of Annex II and II

resources and marine life, to damage amenities or to interfere with other legitimate uses of the sea, and includes any substance subject to control by the present Convention".

Discharge: What is meant by discharge is defined both positively and negatively in Article 2, which states:

> *"a). "Discharge", in relation to harmful substances or effluents containing such substances, means any release howsoever caused from a ship and includes any escape, disposal, spilling, leaking, pumping, emitting or emptying;*
>
> *"b). "Discharge" does not include:*
>
> *(i). dumping within the meaning of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, done at London on 13 November 1972; or*
>
> *(ii). release of harmful substances directly arising from the exploration, exploitation and associated offshore processing of sea-bed mineral resources; or*
>
> *(iii). release of harmful substances for purposes of legitimate scientific research into pollution abatement or control.*

The definition above has resulted in some authors interpreting the application of MARPOL to be limited to CCS activities that fall outside the scope of application of the London Convention and that MARPOL as such could not apply to offshore CCS projects or CCS projects classified as land-based sources of pollution.[408] In our opinion, this interpretation is incorrect. The negative limitation of the meaning of the word "discharge" related to the London Convention should not be seen as limiting the scope of MARPOL in relation to offshore CCS projects. Rather, the definition of discharge limiting the scope of MARPOL in relation to the London Protocol should be seen as drawing a line between deliberate disposal, i.e. dumping, and unplanned, accidental or operational disposal, i.e. discharge. Our interpretation finds support in a report prepared by IMO, stating in relation to the definition of dumping under the London Convention that *"in its second part the definition expresses what is not meant by dumping, namely the disposal of wastes and other matter derived from normal operation of vessels, […] (operational discharges)."*[409] Thus, the London Convention and MARPOL is needed in combination to regulate the full value chain transporting CO_2 by ships to a storage site for offloading and storage.

Applicability:
The MARPOL Convention covers six special areas and its specific technical rules are provided for in the separate Annexes. All parties are bound by the first two Annexes, something which has earned the principles and regulations in these Annexes gain the status of "generally accepted international rules and standards", implying that the provisions are enforceable against all states, not only those which have ratified MARPOL.[410] The other Annexes are optional so that each State at the time of ratification may accept one, several or all, cf. Article 14 nr.1. Of the contracting parties to the convention, not all have adopted all remaining four Annexes,[411] although the number of ratifications is so high also for these Annexes, which has resulted in argumentation for treating all of MARPOL's Annexes as "generally accepted international rules and standards".[412]

[408] F. M. Lehmann (2011) *Offshore Carbon Dioxide Capture and Storage. An International Environmental Law Perspective* pp. 121-122
[409] *London Dumping Convention: The First Decade and Beyond* (1990) IMO Secretariat p. 17
[410] P. Birnie et al. (2009) International Law & the Environment. Third edition. p. 404
[411] http://www.imo.org/en/About/Conventions/StatusOfConventions/Pages/Default.aspx
[412] P. Birnie et al. (2009) International Law & the Environment. Third edition. p. 404

MARPOL comprises provisions regarding to ships entitled to fly the flag of, or which operates under the authority of a Party to the Convention, cf. Article 3 nr. 1 (a)(b). However, in combination with UNCLOS, MARPOL has addressed problems related to ships' owners and flag states not operating under sufficiently stringent regulation or taking enough care of e.g. maintenance, training and safety by strengthening the rights and jurisdiction of the costal and port states by relying on these states' fully recognised right to regulate conditions of entry to or passage through their internal waters,[413] c.f. Chapter 5.3.1 above on UNCLOS. MARPOL is emphasizing the costal and port States' right to control through Article 5, allowing for any ships required to hold a certificate subject to the technical standards of MARPOL to be inspected in the port State. Held up to what was said in the previous paragraph relating to generally accepted international rules and standards, one could interpret this to imply a right for the port state to inspect any ship entering its port, regardless of origin, and thus not limited to ships flying the flag of a contracting State to MARPOL.

SOLAS

Transport of CO_2

The provisions of SOLAS Chapter VII have potential implications on transport of CO_2 by ship as it is dedicated to the carriage of dangerous goods. Included in the definition of dangerous goods is liquid gases and chemicals. These are defined in the IMO International Code for the Construction and Equipment of Ships Carrying Liquified Gases in Bulk (IGC Code). Ships carrying such substances must meet the requirements of the IGC Code, e.g. provisions in chapter 19 regarding the safety and construction of the ships. Chapter 17 also provides special requirements for ships carrying such substances. As the IMO IGC code is only available upon purchase, neither its list of substances nor the specific requirements in its chapters have been assessed. However, in 2006, the IMO Maritime Safety Committee added CO_2 to the list of products in the table of chapter 19, cf. Resolution MSC.220(82), paragraph 11.[414] This has been accessed and supported by literature.[415] We have however observed opposing views by e.g. Weber (2017). Should CO_2 not be included in the IGC Code by explicit listing, CO2 may still be subject to the rules by decision of State Administrations, c.f. Article 1.6.6 of the Code.[416].

LLMC

Limitation of scope of application:

LLMC negatively limits its scope of application in Article 3 by e.g. excluding claims arising under other named or categories of conventions as well as nuclear damage. Finally, the limitation of liability is barred subject to Article 4 in the case of wilful misconduct or negligence. The term "shipowner" means the *"owner, charterer, manager and operator of a seagoing ship*", cf. Article 1 paragraph 2.[417]

The limitation of liability applies to claims such as "loss of life or personal injury" of "damage to property", provided that they occur *"either on board or in direct connection with the operation of the ship"*, cf. Article 2(1)(a) Further, pursuant to Article 2(1)(b), claims related to losses resulting from delays may be subject to limitations, as well as claims related to loss

413 P. Birnie et al. (2009) International Law & the Environment. Third edition.p. 405
414 http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Maritime-Safety-Committee-(MSC)/Documents/MSC.220(82).pdf
415 I. Havercroft et al. (2018) *Carbon Capture and Storage Emerging Legal and Regulatory Issues*. Second Edition p. 258 and *Shipping CO_2 – UK Cost Estimation Study* (2018) Element Energy for BEIS p. 54.
416 Weber (2017) p. 161
417 https://www.jus.uio.no/english/services/library/treaties/06/6-07/liability-maritime-claims-consolidated.xml#treaty-header1-1

resulting from infringement of rights (c), claims related *to "raising, removal, destruction or the rendering harmless of s ship which is sunk, wrecked, stranded or abandoned"* (d), claims related to *"removal, destruction or the rendering harmless of the cargo"* (e), and finally claims related to third party claims related to *"measures taken in order to avert or minimize loss"* (f). Article 2 does not address liability for e.g. environmental damages such as water damages, i.e. the release of CO_2 at sea and the consequences of such release, being such as mass death of fish, the death of coral reefs or other damage to the surrounding environment. Thus, liability for environmental damage may not be limited pursuant to the provisions of LLMC.

HNS Convention

Limitation of scope of application:

The limits of liability are prescribed in article 9, paragraph 1, to cover liability for damage under the HNS Convention. Where damage has been caused by bulk HNS, as for ships transporting CO_2, the limits set out in a (a) are:

(i) *"10 million units of account for a ship not exceeding 2,000 units of tonnage; and*

(ii) *for a ship with a tonnage in excess thereof, the following amount in addition to that mentioned in (i): for each unit of tonnage from 2,001 to 50,000 units of tonnage, 1,500 units of account; for each unit of tonnage in excess of 50,000 units of tonnage, 360 units of account; provided, however, that this aggregate amount shall not in any event exceed 100 million units of account."*

10.10.2 EU Law

There are a wide range of instruments in EU law that regulate the full life cycle of shipping. Examples of relevant instruments are given below (underlined instruments are those explored in detail in the main text; list is non-exhaustive):

Regulations covering operation:

- Regulation (EC) No 725/2004 of the European Parliament and of the Council of 31 March 2004 on enhancing ship and port facility security;
- Directive (EU) 2019/883 of the European Parliament and of the Council of 17 April 2019 on port reception facilities for the delivery of waste from ships, amending Directive 2010/65/EU and repealing Directive 2000/59/EC;
- Regulation (EC) No 1891/2006 of the European Parliament and of the Council of 18 December 2006 on multiannual funding for the action of the European Maritime Safety Agency in the field of response to pollution caused by ships and amending Regulation (EC) No 1406/2002;
- Regulation (EU) No 911/2014 of the European Parliament and of the Council of 23 July 2014 on multiannual funding for the action of the European Maritime Safety Agency in the field of response to marine pollution caused by ships and oil and gas installations;
- Regulation (EC) No 336/2006 of the European Parliament and of the Council of 15 February 2006 on the implementation of the International Safety Management Code within the Community and repealing Council Regulation (EC) No 3051/95;
- Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste;

- Regulation (EU) No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU.

Regulations covering liability and insurance:

- Regulation (EC) No 392/2009 of the European Parliament and of the Council of 23 April 2009 on the liability of carriers of passengers by sea in the event of accidents;
- Directive 2009/20/EC of the European Parliament and of the Council of 23 April 2009 on the insurance of shipowners for maritime claims;

Regulations covering decommissioning and recycling of ships and mobile installations

- Regulation (EU) No 1257/2013 on ship recycling and amending Regulation (EC) 1013/2006 and Directive2009/16/EC) (Ship Recycling Regulation);
- Decision (EU) 2016/2324, Decision (EU) 2016/2322.

10.10.3 Norwegian Law

1981 Pollution Control Act and Regulations

The Pollution Control Act defines as "*any seagoing vessel, irrespective of whether the vessel has propulsion machinery of its own"*. This does not cover offshore units."[418] An offshore unit is defined as "*an installation or other facility used in the petroleum activity, irrespective of whether the construction is fixed or mobile. An offshore unit also includes pipelines and cables used in the petroleum activity*." Offshore installations are carved out of Part 6, as they are regulated by the Petroleum Act and Regulations, as well as the Storage Regulations and the separate part 7A of the Pollution Control Regulation.

[418] The official translation of Section 21-1(1). Similar definitions apply for the other chapters of Part 6

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