CO₂ ship transport:
Benefits for early movers and aspects to consider

4th Report of the Thematic Working Group on:
CO₂ Transport, Storage, and Networks

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<th>Revision Date</th>
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About the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects under way across Europe in the field of carbon capture and storage (CCS) and carbon capture and utilisation (CCU). Our Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. By sharing knowledge and learning from each other, our project members will drive forward the delivery and deployment of CCS and CCU, enabling Europe’s member states to reduce emissions from industry, electricity, transport and heat.

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Executive summary

The aim of this report is to give an overview of the status, requirements, and issues for realising CO₂ ship transport within a CCS value chain. This report should aid emitters in early-stage project development, as well as policy makers and other stakeholders with understanding the role of CO₂ shipping for project development and its potential benefits.

Shipping is an attractive alternative for CO₂ transport, especially for early movers, because it is a flexible option that does not require fixed infrastructure. It is also scalable, and it is less sensitive to fluctuations in capture profile than piping.

Ship transport of CO₂ is mature and technically feasible. However, the optimal conditions for transporting CO₂ in a dedicated CCS value chain are still not defined, especially concerning transport pressure. While medium pressure (15 barg) has been traditionally used for commercial CO₂ shipping and will be used for pioneering projects such as the Longship project in Norway, research results as well as industry feedback signal that a lower pressure (7 barg) would be necessary for higher transport capacities. However, other transport conditions (e.g. 40 barg) may also be an alternative in some cases. This is further discussed in Section 3 of the report.

Further, some obstacles remain for large scale implementation of CO₂ ship transport. For example, there are some knowledge gaps regarding fiscal metering such as the ability of instruments to reach the accuracy required by the EU requirements for large flowrates. Therefore, a bottleneck for the verification of the performance of existing measurement principles for CCS is the lack of a primary reference and large-scale test facility for metering technologies. Informing the Commission about tailor-made monitoring plans for the CO₂ transported by ship is also critical.

Building a business case is key for the development of any CCS project, and transport is a core component of the CCS value chain. Contractual agreements, access to finance and coordinated timing of investment decisions along the CCS chain is essential.

This report presents input from the CCUS PN project members, namely, Northern Lights, Carbon Collectors and Storegga (Acorn), and CCUS Shipping, powered by Victrol.
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Table of Contents

1 Introduction ........................................................................................................................................... 8
  1.1 CO₂ capture and storage value chain ............................................................................................... 8
  1.2 Current status of CO₂ shipping ......................................................................................................... 9
2 Benefits of Shipping ............................................................................................................................... 10
  2.1 Technology readiness for short-term deployment .............................................................................. 10
  2.2 Flexibility of CO₂ shipping .............................................................................................................. 10
  2.3 Costs of CO₂ shipping ..................................................................................................................... 11
3 Technical requirements and constraints for shipping ........................................................................ 11
  3.1 Dimensions for inland and offshore ships ....................................................................................... 11
  3.2 Composition specifications .............................................................................................................. 12
  3.3 CO₂ transport pressure ................................................................................................................... 13
  3.4 Fiscal metering for loading and offloading ....................................................................................... 14
  3.5 Health, safety and environment ...................................................................................................... 14
    3.5.1 Identification and assessment of hazards and risks .................................................................. 15
    3.5.2 HSE regulation and standards ................................................................................................. 16
4 The London Protocol and transboundary CO₂ ship transport for storage .......................................... 17
5 Financing Shipping in Early Mover Projects ....................................................................................... 18
  5.1 Policy Support ................................................................................................................................ 18
    5.1.1 Projects of Common Interest under the TEN-E regulation ...................................................... 18
    5.1.2 The EU ETS and ship transport of CO₂ .................................................................................. 19
  5.2 Building a Business Case ................................................................................................................ 21
6 Conclusion ............................................................................................................................................ 22
7 Glossary and list of icons ...................................................................................................................... 24
8 Reference List ........................................................................................................................................ 27
Appendix: CO₂ specifications .................................................................................................................. 32
CO₂ ship transport: Benefits for early movers

1 Introduction

An aim of the CCUS Projects Network (CCUS PN) is to share knowledge and learnings, in order to drive forward the delivery of CCS and CCU and enable European countries to reduce CO₂ emissions from industry, electricity, transport and heat.

Documentation of learnings is important, both to spread a wider understanding of the current status of CO₂ capture projects and the lessons they have gathered, and to facilitate the implementation of these projects.

The present report aims to summarize the benefits and current status of CO₂ shipping as well as some issues that need to be considered by CCS projects that will incorporate shipping as a part of their value chain. Furthermore, the report presents input from the CCUS PN project members, namely, Northern Lights, Carbon Collectors and Storegga (Acorn), and CCUS Shipping, powered by Victrol.

1.1 CO₂ capture and storage value chain

Figure 1 shows examples of CCS value chains with ship transport. CO₂ is captured from industrial facilities which typically operate in a continuous manner. Then, CO₂ is conditioned for transport. Continuous transport of large CO₂ volumes is done via pipeline, with CO₂ as compressed gas, liquid or a liquid/dense-phase fluid. Modular transport of liquid CO₂ (LCO₂) is done by truck, train/railway, barges or ships. Ships and barges may carry CO₂ captured from one or several sources. This "milk round" approach may be used in scenarios where ships have sufficient storage capacity and emitter rates are low. In other scenarios, a large emitter may have a ship or multiple ships dedicated to servicing its needs.

CO₂ capture and conditioning is a continuous process. A solution to decouple modular transport with continuous processes is to have buffer storage at the industrial facility prior to transportation as well as between the modular means of transportation and permanent CO₂ storage, which is done via pipeline. Additional re-conditioning of the CO₂ may be required at some points of the value chains. The alternative at the bottom in Figure 1 depicts the situation with direct continuous ship loading and with the ship discharging its LCO₂ cargo straight into permanent storage, which can reduce the cost [1].
Figure 1 Simplified value chain alternatives for CCS. Note: Pumping not shown. A list of icons is in Table 2.

1.2 Current status of CO₂ shipping

CO₂ is used in beverage carbonization and in horticulture production (greenhouses). It is also used as working fluid for refrigeration and as chemical feedstock in chemical industries such as that of urea, polyurethane as well as acid and carbonate production processes [2].

The global carbon dioxide market size was valued at USD 7.80 billion in 2020 [3] and the food and beverage industry is the largest end user of CO₂ [4]. Commercial food-grade CO₂ is currently transported by truck, train or ship, and typically as refrigerated liquid. This is generally high purity CO₂, typically captured from hydrogen production facilities¹ or other fermentation or chemical processes with a high CO₂ concentration by-product [5].

For the food and beverage industry, CO₂ is usually transported in ships with capacities lower than 2 kt CO₂. For example, CO₂ is today captured from fertilizer producer Yara, and routinely shipped for commercial use (e.g. food and beverage) by Larvik Shipping for Praxair [6]. These ships have a capacity of up to 1.8-2. kt per shipment [6], [7]. This CO₂ is transported in liquid form at 15-18 barg and

¹ Steam reforming of hydrocarbons with CO₂ capture

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approximately -22 to -28°C [6]. This is a smaller scale than it would be necessary for CCS [8]. For example, with the current Northern Lights specifications, each shipment will carry more than 8.2 kt².

2 Benefits of Shipping

The technology for CO₂ shipping is ready and there are ongoing projects for building the ships that will transport the CO₂ for the early mover CCS projects. Some of these are described in Section 2.1. Some potential benefits of shipping which are attractive for early movers are summarized in Section 2.2, and the costs of shipping, with focus on aspects also relevant to early movers are discussed in Section 2.3.

2.1 Technology readiness for short-term deployment

As mentioned above, LCO₂ shipping is done commercially, but at a smaller scale compared to what would be required for CCS. However, the shipping part of the CCS value chain is on time and advanced for the ongoing CCS projects.

Northern Lights in Norway adapted ship designs used for transporting liquefied petroleum gas (LPG), adding a liquefied CO₂ carriage system and insulation to maintain a temperature that keeps the CO₂ in a liquid state [9]. Northern Lights Joint Venture announced on 11 October 2021 [10] that they have ordered two dedicated LCO₂ carriers that will be ready for delivery by mid-2024. LCO₂ will be transported at cryogenic conditions (15 barg and equilibrium temperature). The ships will be built by Dalian Shipbuilding Industry and have a cargo size of 7500m³ (~7.5 kt) and a length of 130 m. The primary fuel in this design is LNG.

Carbon Collectors in The Netherlands have received Approval In Principle for the design of their tug-barge combination and the offshore mooring system. LCO₂ will be transported at temperatures above 0 °C, pressures above 40 barg. The nominal capacity for each barge is 5500m³ (~4.7 kt) and a length overall (LOA) of 130 m (barge only) and 150 m (tug-barge combination).

In addition, specialized companies for CO₂ seaborne transport are emerging. An example is Dan-Unity CO₂, collaborating with Carbfix (storage) [11], which recently announced they are able to build purpose-built CO₂ vessels with a capacity of 12500m³ and 22000m³ [12].

2.2 Flexibility of CO₂ shipping

Compared to pipelines, shipping of LCO₂ has some benefits in terms of flexibility which are especially attractive to emerging projects. For example,

- Scalable, for projects developed in more than one phase it will be possible to expand the ship fleet according to the project’s needs.
- Ability to transport to different storage sites (if/when available), depending on costs and availability.

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² The density of LCO₂ is 1101 kg/m³ and the Northern Lights specification require a ship capacity of 7500 m³ as can be seen in Table 1.

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• Flexible with respect to fluctuations in capture profile (utilization rate), which have less effect on shipping costs compared to pipeline [13].

• Water bound inland industry can be flexibly connected to seaports, giving access to several permanent storage sites.

• Barges can be "built to purpose", optimizing design and volumes, considering waterway restrictions. Ideally, ship size should be customized for each specific CCUS chain, also considering cost [14].

• Fast development cycle. Ships have in general shorter construction times than pipelines [15], [16]. As reference, the Northern Lights ships were ordered in October 2021 and are expected to be ready by mid-2024 [10] (~32 months). Barges have an average construction time of 26 months. In comparison, the construction time of pipelines usually lies between 1 and 4 years, depending on the length and complexity [17].

### 2.3 Costs of CO₂ shipping

Regarding costs, shipping has some advantages for emerging CCS projects. Shipping costs are dominated by OPEX, while costs for pipelines are dominated by CAPEX. In other words, shipping is less capital intensive [16]. In general, high transport capacity leads to a significant economy of scale for pipelines, which is less important for shipping [13]. In general shipping is more economically favourable than pipelines with lower CO₂ flowrates (less than ~5 Mtpa [8]), shorter project durations (less than ~20 years [8]) and longer transport distances [7], [8], [13].

The discount rates used for project evaluation and calculating impacts the CAPEX annuity depend on the type of project investors. National authorities use a lower discount rate than average companies, while oil and gas companies and companies dealing with risks use a higher discount rate and risk premium. This will lead to different net present values for the same project costs and revenues. At higher discount rates, the CAPEX annuity increases and marine transport becomes more cost-effective than pipeline [13].

### 3 Technical requirements and constraints for shipping

As the scale and logistics of CO₂ shipping for permanent storage, transport conditions, ship design and specifications do not necessarily need to be the same as current conditions for transport. Trade-offs between cost and operational complexity must be considered in choosing the most appropriate transport condition [7].

#### 3.1 Dimensions for inland and offshore ships

Inland ships and barges are constrained in height (bridge clearance), breadth (canal and lock width limitations), length (lock limitations), and draught (highly variable, dependent on the waterways). Therefore, the waterways may limit inland ship capacity. Energy efficiency of inland and offshore transportation is influenced by the chosen transport conditions and the need to convert between different conditions for different sections of the transportation chain.

*Table 1 Current requirements for CO₂ ship transportation and transfer to Northern Lights [18], [19]*

*This project is financed by the European Commission under service contract No ENER/C2/2017-65/SI2.793333.*

11
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<tr>
<td>Ship capacity</td>
<td>Maximum 7500 m³</td>
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<tr>
<td>Transfer pressure</td>
<td>15 barg (within 13-18 barg)</td>
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<tr>
<td>Transfer temperature</td>
<td>Equilibrium</td>
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<tr>
<td>Loading and offloading rate</td>
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Regarding offshore ships, the current concept is to use ships that resemble LPG ships [19]. Table 1 shows the current requirements for ship transportation and transfer to the Northern Lights infrastructure. The Northern Lights Project currently specifies that cargo ships, with a maximum capacity of 7500 m³ should be used for the transport of CO₂ to Kollsnes (Øygarden) [19], which is larger than the capacities currently used in the transport of CO₂ in the food industry. However, the size of the ship in future value chains may still be different [8].

Ships can be built specifically for LCO₂ transport, but there is also the possibility of repurposing LPG tankers. It should be noted that due to differences in fluid density, only 50%-60% of a tank capacity designed for LPG can be used for LCO₂ [14].

3.2 Composition specifications

The maximum acceptable concentration of a single impurity will depend on the concentration of the other impurities, the pressure and the temperature, it is not possible to give universal recommendations for the safe CO₂ compositions. Considering ship transport in which LCO₂ is transported in carbon steel tanks, composition requirements should prevent the formation of corrosive phases for the steel, for example in the presence of water, hydrogen sulphide (H₂S), sulphur dioxide (SO₂), nitrogen dioxide (NO₂) and oxygen (O₂). Also hydrates may form in the presence of water and hydrogen sulphide [20].

Satisfying higher purity requirements may require additional investment and/or operational costs. It may also imply a higher energy intensity of the overall process. When different potential impurity scenarios are considered, impurities that are soluble in the liquefied CO₂ stream may need to be purged. As a consequence, the conditioning cost also increases [21]. If the purge is vented, it may carry some CO₂ and to compensate this and maintain the desired overall CO₂ capture rate, the capture rate in the CO₂ capture process may need to increase, with the associated cost. To remove some impurities, specific separation steps, with an associated investment and energy consumption, are required (e.g. dehydration).

Reference composition limits for CCS are included in the Appendix and in [20]. The 1st Report of the CCUS PN Thematic Group on CO₂ transport, storage and networks [5] presents the requirements specifications for transport and some end-uses.

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3.3 CO\textsubscript{2} transport pressure

In Figure 2 it can be observed that at atmospheric pressure, CO\textsubscript{2} only exists either on solid or gaseous state and it needs to be pressurized to be in liquid state. The theoretical limitation on minimum pressure for pure CO\textsubscript{2} is represented by its triple point of 5.1 absolute bar and -56.6°C [22], which in practice results in a transport pressure around 7 barg and -50°C to be considered a low-pressure condition for ship transport of CO\textsubscript{2}. This limitation, as well as liquefaction and transport costs are affected by impurities [18], [23]. This can be identified in Figure 2, which shows the phase diagram for CO\textsubscript{2}.

The overall cost is a trade-off between the cost of conditioning and the CO\textsubscript{2} storage in the ship. With conditioning, CO\textsubscript{2} is brought from the conditions of the CO\textsubscript{2} capture process to the conditions required for transportation. For amine-based post-combustion CO\textsubscript{2} capture, this means compressing CO\textsubscript{2} from a low pressure and then refrigerating it, as shown in Figure 2. Power requirement for liquefaction, and thus conditioning cost, decreases with increasing pressure because the liquefaction temperature increases. On the other hand, at higher pressure, the cost of storage tanks, and thus ships, increases [8].

![Figure 2 Phase diagram of pure CO\textsubscript{2} with ranges for CO\textsubscript{2} capture and shipping transport indicated. Figure modified from [24].](image)

The Northern Lights specifications do not deviate from current standard CO\textsubscript{2} ship technology for small-scale food industry, which considers a transfer pressure of 15 barg [18], which is considered "medium pressure" for transportation. This has advantages such as accumulated experience, and existing standardization, and thus a lower risk. However, a lower transport pressure may be required for larger ship capacities [18], [19], for which cargo tank wall thicknesses would be uneconomic at 15 barg and -30°C.

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Recent work has shown that transporting CO$_2$ at lower pressure could result in significant reductions in investment, operating cost, and overall cost [1], [21], [23], [25]. However, other studies [26] have found the optimal pressure to be 15 barg. With this, the optimal pressure would be determined considering the entire CCS value chain for each project.

It is possible that in the future, there could be two types of LCO$_2$ ships, those with capacities lower than 10000 m$^3$ and transport pressures of 15 barg, such as the current Northern Lights case, and ships with larger capacities and transport conditions of 7 barg and -50°C.

3.4 Fiscal metering for loading and offloading

Accurate measurement is essential along the CCS value chain for environmental monitoring and reporting on greenhouse gas emissions, as well as process control and leak detection. Technical performance of fiscal meters is, hence, key for the CCS business to provide fair financial transactions and traceable environmental compliance. However, this is an area where large knowledge gaps remain. Transport conditions for CCS shipping occur at close to liquid-vapour equilibrium at low temperatures, expectedly down to -50 °C. This poses a challenge for fiscal metering technologies, where no capacities to provide traceable fiscal metering exist worldwide [27]. Some of the most promising benchmarked technologies for CCS fiscal metering are Coriolis, Ultrasonic, and differential pressure – DP – devices ([28], [29]). The induced pressure drop, characteristics of Coriolis or DP's would require pressure boosting upstream the metering unit to avoid gasification of the fluid within the unit, and with it rapid changes in density and viscosity that preclude accurate measurement, and compromise the unit integrity. The only technology with published studies claiming accuracies below the EU requirements is Coriolis ([30]–[32]), but only for pure CO$_2$ at temperatures above 15 °C and flow rates (3600 kg/h) far below what will be required ahead (see Table 1). Early results of ultrasonic measurements for static CO$_2$ ([33]) show promise for conditions similar to ship transport, but dynamic effects that are known to influence the performance and accuracy, nor traceability are yet available.

As discussed above, the major bottleneck for the verification of the performance of exiting measurement principles for CCS is the lack of a primary reference and large-scale test facility for metering technologies ([27], [55]). Several early initiatives, which combine public and private investments, are ongoing to, at least partially, abate some of the pending obstacles with regards to measurement traceability and accuracy, e.g., (i) progress the development CO$_2$ liquid primary standard (Green deal - CCUSMet [56]), (ii) development of a primary reference for liquid CO$_2$ (Infrastruktur [57] ECCSEL V-lab proposal), (iii) development of a large scale fiscal metering test/verification facility FMet (NCCS [58], ECCSEL). However, the complexity of the market and the level of investment required would most likely entitle international cooperation and mixed public and private funding. Steps have been made at NCCS, via a Business Case for FMet, to identify stakeholders and possible investors for the life-cycle investments and the OPEX; where European funding streams like Horizon and Innovation Fund are attractive and necessary to help develop a large-scale facility.

3.5 Health, safety and environment

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This section will provide a concise overview of potential threats of CO$_2$ shipping to health, safety and environment (Section 3.5.1) and existing regulation on the safety of CO$_2$ shipping in Section 3.5.2.

3.5.1 Identification and assessment of hazards and risks

The work done by Ter Mors (2011) [34] resulted in the identification and description of a number of threats for safe transport of CO$_2$ by ship. For the purpose of this report DNV executed a Quantitative Risk Assessment (QRA) of CO$_2$ shipping infrastructure in the Rotterdam harbour area. The QRA results for CO$_2$ shipping showed that risk stays within acceptance levels according to criteria in the Netherlands. The main findings of Ter Mors (2011) [34] are represented below, which in some instances have been expanded with information from Baroudi et al. (2021) [35] and Equinor (2019) [19].

**Overall chain reliability and need for maintenance and repair**

Venting will be necessary during maintenance and repair activities, which will lower the efficiency of the activity and will pose a risk to people and the environment near the CO$_2$ vent. A robust ship design with appropriate preventative measures will reduce the downtime of the ship.

**Boil-off gas generation** [35]

During loading, transport and unloading of LCO$_2$ vapour is released in variable amounts. In particular during loading and unloading gas generation is enhanced. Also the sloshing of liquid CO$_2$ in the vessels and the penetration of ambient heat may lead to an increase in gas generation. Re-liquefaction might be considered as a mitigating measure.

**Degradation of metallic and polymer chain components**

In the presence of free water, carbon steel will be subjected to corrosion. For the use of carbon steel CO$_2$ should be dry. For wet CO$_2$ conditions austenitic steel, 13% Cr steel or duplex stainless steels can be used. H$_2$S impurities can react with carbon steel [35] and enhance corrosion. Equipment on Seagoing ships may be protected by a coating and cathodic protection.

Polymers need to be resistant to CO$_2$ to avoid diffusion of CO$_2$ into the polymer, expansion or cracking [35].

**Cool down and heat up effects**

High or low temperatures may result in material failure. At temperatures down to -60 °C (near triple point temperature) one may use fine-grained steels to prevent brittle failure. At even lower temperatures of about -78.5 °C (near sublimation point at atmospheric pressure) 3.5% Ni steel might be used. Equipment must be designed such that it can absorb contraction or expansion as a consequence of temperature changes.

**Waterhammer and slugging**

As a consequence of fluid flow velocity changes a pressure wave may be generated, which could damage the equipment (water hammer). The design of flow velocities and opening or closing of the valves can help minimizing this effect. In addition safety valves can be installed.

Particular attention is required for the occurrence of two-phase flow and the creation of slugs in the fluid (see also hydrate and dry ice formation).
Hydrate and dry ice formation

Formation of hydrates or dry ice is of particular relevance for shipping of low pressure CO\(_2\) near the triple point. These solid substances may lead to clogging and pressurization of pipes, valves and vessels [19].

Careful management of operating pressure reduces the occurrence of hydrates or dry ice [35]. An appropriate safety margin with respect to the triple point and hydrate stability envelope is to be considered. Impurities influence the position of the hydrate stability zone.

Ship wave interaction

Sloshing of liquid CO\(_2\) in partly filled tanks may be triggered by ship wave interaction. Devices to mitigate sloshing could be installed. Stabilisation of the ship is possible with the help of a Dynamic Positioning System when connecting the ship to loading/unloading infrastructure.

Accidental loss of containment

When an inland barge or seagoing ship collides with another ship or with a harbour or offshore terminal, this may lead to accidental loss of CO\(_2\). This may also happen by accidents on the ship itself. The terminal area in the harbour is considered to be a zone of relatively high risk. For that reason an Emergency Shutdown System could be installed [35]. Furthermore, terminal areas should be at a suitable distance from vulnerable objects.

The accidental loss of CO\(_2\) may result in the presence of a CO\(_2\) fluid on the water surface and the creation of dry ice and hydrates. Personnel can get wounded because of freezing or by the impact of dry-ice projectiles. The presence of CO\(_2\) may lead to breathing problems or even asphyxiation; combustion engines may stop [35]. Due to the formation of dry ice and condensing water, visibility decreases [19]. High evaporation rate and expansion of fluids from a ruptured pipe or vessel could cause a Boiling Liquid Expanding Vapour Explosion or BLEVE [35].

3.5.2 HSE regulation and standards

Seagoing ships

The international SOLAS Convention [36] defines the rules for safety of seagoing ships in addition to requirements for the design, construction and operation of the ship. Part C of Chapter 7 deals with ships for bulk transport including CO\(_2\). This subtheme or code is referred to with the IGC code or in full “International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk” [37]. The code describes that a certificate must be required entitled “International Certificate of Fitness for the Carriage of Liquefied Gases in Bulk”. Requirements depend on the class of hazardousness of the transported substance. CO\(_2\) falls in the lowest class 3G (from Element Energy, 2018) [38]. Chapter 17 sets special requirements for reclaimed quality CO\(_2\). In addition to the rules for pure CO\(_2\), CO\(_2\) must be kept at a pressure of 0.05 MPa (about 0.5 barg) above the triple point, comply with specific monitoring requirements and measures to control corrosion.

Liability for loss of containment has been dealt with in the HNS Convention [39] but this treaty has not yet been enforced [40]. Liability is organized in two tiers, one compensation by the ship owner as an insurance and the second one as financial compensation from a HNS fund.
Additional guidance for safety can be found in the International Safety Guide for Oil Tankers and Terminals (ISGOTT)” [41] and “Liquefied Gas Handling Principles on Ships and in Terminals [42].

Inland ships

For inland shipping in Europe, the ADN [43] is ruling. ADN stands for “European Agreement for Transportation of dangerous goods by inland waterways”. The Agreement and associated regulations entered into force in 2008 and strives for a high level of safety and environmental protection, and facilitation of international transport and trade.

The CCNR & OCIMF (2010) [44] developed guidelines for safe inland barge transport but with little attention for CO\textsubscript{2} transport. The International Safety Guide for Inland Navigation Tank-barges and Terminals (ISGINTT) is an industrial best practice with additional recommendations for the safe transport of hazardous substances by inland ships and safe handling at terminals.

4 The London Protocol and transboundary CO\textsubscript{2} ship transport for storage

This section presents the legal framework for transboundary transport of CO\textsubscript{2} for geological storage under the seabed, that is provided by the London Protocol.

The London Protocol [45] was designed in order to protect the marine environment from dumping of wastes. This however turned out to provide a barrier to transboundary CO\textsubscript{2} transport for storage, since Article 6 of the protocol bans transport of wastes to other countries for dumping at sea. In 2006 an amendment was made to the London Protocol allowing storage of CO\textsubscript{2} under the seabed and in 2009 an amendment was made to Article 6 allowing for transborder movement of CO\textsubscript{2} for the purpose of offshore storage [46]. However, for the amended Article 6 to enter into force it must be adopted by 2/3 of the 53 parties of the protocol, which has not happened so far.

In October 2019, based on a suggestion from Norway and the Netherlands, the International Maritime Organization (IMO) decided to allow for provisional application of the 2009 amendment to Article 6 of the London Protocol. Therewith, countries who wish to use the amendment to Article 6 have the right to do so, while it has no legal bearing for the parties who do not wish to export or import CO\textsubscript{2} for permanent geological storage.

In practice, countries who wish to allow for export or import of CO\textsubscript{2} for injection and permanent storage under the seabed must deposit a Unilateral Declaration on the provisional application of the 2009 amendment to the London Protocol Article 6 to the Depositary (Secretary-General of the IMO). Thereafter, a bilateral agreement must be established between the CO\textsubscript{2} exporting and importing countries, which shall include confirmation and allocation of permitting responsibilities between the two countries, consistent with the provisions of the London Protocol and other applicable international law, to define a stable framework for the transboundary CO\textsubscript{2} transport. This agreement should be expected to cover items such as cost sharing, monitoring of the transport, reporting and liability in addition to the mentioned permitting regimes. This bilateral agreement shall also be notified to the Secretary-General of the IMO.

It is the authors' current understanding that the unilateral declaration of the provisional application of the amended Article 6 is only necessary for the two countries exporting and receiving CO\textsubscript{2}, and for
the purpose of offshore CO₂ storage, i.e. that a ship carrying CO₂ can pass through the territorial waters of a third country, without this third country having to deposit a unilateral declaration to the IMO or enter into an agreement with the countries exporting and receiving.

The London protocol does not regulate transport of CO₂ for other purposes, such as, for CCU. As mentioned in section 1.2, CO₂ captured from ammonia production is today being transported by ship for commercial use.

5 Financing Shipping in Early Mover Projects

5.1 Policy Support

5.1.1 Projects of Common Interest under the TEN-E regulation

The Trans-European Networks for Energy (TEN-E) is a policy that is focused on linking the energy infrastructure of EU countries. The EU helps countries in priority corridors and thematic areas to work together to develop better connected energy networks and provides funding for new energy infrastructure. Cross-border carbon dioxide network is one of the three priority themes in the TEN-E regulation.

Projects of common interest (PCIs) are key cross border infrastructure projects that link the energy systems of EU countries. The PCIs are intended to help the EU achieve its energy policy and climate objectives: affordable, secure and sustainable energy for all citizens, and the long-term decarbonization of the economy in accordance with the Paris Agreement. Every two years since 2013, the European Commission draws up a new list of project of common interest [47]. The fifth list, adopted in November 2021 [48], includes six CO₂ projects:

- **CO2 TransPorts**: aims to establish infrastructure to facilitate large-scale capture, transport and storage of CO₂ from Rotterdam, Antwerp and the North Sea Port
- **Northern lights project**: commercial CO₂ cross-border transport connection project between several European capture initiatives (United Kingdom, Ireland, Belgium, the Netherlands, France, Sweden) and transport the captured CO₂ by ship to a storage site on the Norwegian continental shelf
- **Athos project**: proposes an infrastructure to transport CO₂ from industrial areas in the Netherlands and is open to receiving additional CO₂ from others, such as Ireland and Germany. Developing an open-access cross-border interoperable high-volume transportation structure is the idea. However, this project was cancelled after Tata Steel, which was the main source of CO₂ for the project, decided to use an alternative technology (direct reduced iron, DRI) to produce steel [49], [50].
- **Aramis**: cross-border CO₂ transport and storage project (intake from emitters in the hinterland of Rotterdam harbour area and storage to location on the Dutch continental shelf)
- **Dartagnan**: CO₂ export Multimodal HUB from Dunkirk, France, and its hinterland (emitters from the industrial cluster in the area of Dunkirk with storage where available in the North Sea country territories)
- **Poland – EU CCS Interconnector**: emitters from the industrial cluster in the area around Gdansk, Poland, with storage where available in the North Sea country territories.
Projects of common interest are eligible for funding from the Connecting Europe Facility (CEF). The new CEF Programme for 2021-2027 [51] allocates a total budget of €5.8 billion to the energy sector. The first CEF Energy PCI call for proposal under this new CEF programme was open for submissions from 7 Sept – 19 Oct 2021.

5.1.2 The EU ETS and ship transport of CO₂

Each year industrial installations that are included in the EU Emission Trading System (EU ETS) must surrender a number of allowances that are equal to the total amount of fossil CO₂ emissions from that installation during the preceding calendar year. The EU ETS allows subtracting emissions that are captured and thereafter transferred to a transport network with the purpose of long-term geological storage or directly to a storage site. Therewith the emission allowances need not be surrendered but can be traded and generate an income, and therewith contribute to building a CCS business case. However, transport network is in the CCS directive (Directive 2009/31/EC) defined as a network of pipelines for the transport of CO₂ to the storage site.

In order to get a clarification regarding whether CO₂ transported by ship for permanent storage can be covered by the EU ETS, Norway sent a request to the European Commission in April 2020 with an argumentation for this, that was summarized as follows: "When transfer of CO₂ from a ship or truck to the pipeline transport network or storage site is completed, Norway's understanding is that the capture installation can subtract the CO₂ from its emissions".

The Norwegian request was sent to EU with reference made to the Norwegian plans for full-scale CCS (the Longship project) where ship transport of CO₂ is part of the CCS chain. In a reply from DG CLIMA to Norway in July 2020 from the European Commission Directorate General Climate Action to the Norwegian Ambassador to the EU, the Commission agrees with the Norwegian view. "The capture installation should be allowed to deduct from its emissions any CO₂ intended for the offshore storage facility." Furthermore, the letter states that the Commission needs to be informed by the measures put in place, including tailor-made monitoring plans that are to be developed for each capture installation, accounting for any CO₂ lost in transport. The measurement of CO₂ losses during transport would be made at the point of delivery, to the transport network or the storage site.

Responsibility for CO₂ emissions during transport with ship: The consequence of the answer from DG CLIMA to Norway in July 2020 would be that the capture installation would be fully responsible for CO₂ emitted to the atmosphere during ship transport. However, the suggested amendment to the ETS Directive (2003/87/EC), dated 14 July 2021[52], recital 41, says that:

As carbon dioxide is also expected to be transported by means other than pipelines, such as by ship and by truck, the current coverage in Annex I to Directive 2003/87/EC for transport of greenhouse gases for the purpose of storage should be extended to all means of transport for reasons of equal treatment and irrespective of whether the means of transport are covered by the EU ETS. Where the emissions from the transport are also covered by another activity under Directive 2003/87/EC, the emissions should be accounted for under that other activity to prevent double counting.

The practical meaning of this amendment is that emissions of CO₂ during ship or truck transport will be the responsibility of the ship or truck owner/operator.

Summary: Provided that the suggested amendment of the ETS directive enters in force, the situation would be the following for ship transport of CO₂:
• The CO₂ capture installation can subtract emission allowances for captured fossil CO₂ when it is delivered from a ship to a pipeline transport network or directly to a storage site (provided that the storage site is permitted under Directive 2009/31/EC). I.e. there is a time delay between when the CO₂ is captured and when the emission allowances can be subtracted.
• The owner/operator of the ship that is transporting the captured CO₂ from the capture installation to the transport network will be responsible for the CO₂ emissions during this transport.
• The CO₂ capture installation will not be able to subtract emissions that occur during ship transport to the pipeline network, i.e. the amount of CO₂ emissions to be subtracted would during normal operations be slightly lower than the amount of CO₂ captured – contractual agreements will be needed between the capture installation and the ship owner/operator to cover this. This, in turn, will call for accurate fiscal metering during on- and offloading. Also, CO₂ emissions from the ship propulsion system could be relevant to include in the contractual discussions/agreements.

5.1.2.1 EU ETS and fiscal metering

In Section 3.4, it was discussed that the technical performance of fiscal meters for liquid CO₂ is an open question, and more research is needed to address the existing knowledge gaps in aid of a fair CCS business. That is, fair financial transactions along the CCS chain and accurate subtraction of emissions under the EU ETS will depend on accurate CO₂ measurements throughout the CCS value chain, including on- and offloading on ships, that enable accurate emission monitoring and reporting. Emissions monitoring and reporting within EU ETS is regulated by the ETS M&R Regulation 2018/2066 [53], [54]. Continuous measurement systems (i.e., fiscal metering) with uncertainties below 2.5% are required for reporting of captured CO₂ at the capture site (article 49). In addition to the uncertainty of the measurement instrument, the uncertainty of the associated instrument calibration and specific use of the instrument are included in the 2.5 % requirement. As a result, the uncertainty of the measurement instrument must be lower than 2.5 %, probably below 1.5 %, which is the uncertainty specified by the EU measurement instrument directive (MID), Annex VII.

On the other hand, there are cases where it is technologically or financially infeasible to meet the 2.5 % requirement, in which case the regulations open for a relaxation to 5 % uncertainty. This is the case if the financial benefit is lower than the cost of complying with the highest tier. With regards to the technical feasibility, the lack of traceable calibration of fiscal meters for liquid CO₂ at transport conditions, yields uncertainty on whether the meters meet the strictest EU ETS requirements during CCS operations. Furthermore, it is unclear if the regulations controlling the type of measurements at the capture site apply for the emission control during shipping, even if the uncertainty requirements are expected to be the same. Thus, using less costly measurement methods (e.g. radar level gauging) than fiscal metering may be an option in shipping. This is, however, provided that they at least meet the 5 % requirement, and that no other feasible measurement methods have uncertainty lower than 1.5 % at realistic operation conditions. In other words, fiscal metering is likely to yield the lowest uncertainty, and is superior to other measurement techniques, but further research and development is currently necessary to establish the uncertainty of the fiscal meters at realistic operating conditions.
5.2 Building a Business Case

CO₂ transport by ship is technically feasible, just as the other components along the CCS chain, and the two first vessels for transporting CO₂ intended for permanent geological storage have been ordered by Northern Lights. CCS needs to be deployed on a large scale to contribute to reaching EU climate goals and meeting the targets in the Paris Agreement. For early movers, initial small volumes or for long distances, CO₂ transport by ship provides flexibility, scalability and low initial capex.

In order for a commercial business for CO₂ shipping to actually evolve, there must be agreements on e.g. cost and risk sharing for CO₂ losses during ship transport, and agreements on the duration of the shipping contract. An important issue for contractual arrangements is the point of transfer of liability for CO₂ losses between the capture installation and the transport and storage operator (ref to the summary in section 5.1.2. Orchard et al. [7] identified metering as a cost driver, representing a conflict between legal obligation and cost-effective operation. Resolving this conflict through alternative contractual arrangements may be possible or necessary to consider in future [7].

CEF funding may be a means to fund the realisation of trans-boundary ship transport of CO₂, but there must also be funding for realising capture and storage at scale. However, the realisation of ship transport must be aligned with funding for capture and storage. Sale of emission allowances under the EU-ETS can contribute to realising such business cases in certain industrial sectors, and the Innovation Fund can support up to 60% of the cost for a capture project, but there are currently not sufficient long-term predictable financial/regulatory mechanisms that support CCS deployment on the scale that it is being deployed. In sum, contractual agreements, access to finance and coordinated timing of investment decisions along the CCS chain is essential.
6 Conclusion

CO₂ transport is a key component of the CCS value chain. Experience from other industries (e.g., food and beverages) is at a smaller scale compared to the foreseen scale for CCS. However, this experience, combined with experience transporting other substances (e.g., LPG) is being used to define technical issues related to CO₂ ship transport. However, with more experience gathered and optimization of the whole CCS value chain, CO₂ specifications for shipping such as impurities, ship capacities, and especially transport pressure may change in the future compared to specifications for current projects.

Shipping offers a flexible solution for CO₂ transport, which is scalable and with lower investment costs compared to pipelines, especially with long transport distances and relatively smaller volumes. This can be especially attractive for early-movers and CO₂ shipping can thus enable early CCUS projects by reducing the cost and financial risk.

An aspect not discussed in this report is the means of propulsion for CO₂ ship transportation. For the Northern Lights project, the primary fuel will be LNG [9], which has a low environmental footprint compared to other fuels [59]. However, other alternatives such as batteries [60], carbon-free maritime fuels such as ammonia [61], [62] and hydrogen [63], or on-board CCS [64] are being developed for minimizing the environmental footprint of shipping. These alternatives will contribute to further increase the CO₂ avoided of the full CCS value chain.

Legally, it is since October 2019 possible to export and import CO₂ for the purpose of permanent geological storage under the seabed: countries who wish to allow for this must deposit a Unilateral Declaration on the provisional application of the 2009 amendment to the London Protocol Article 6 to the Secretary-General of the IMO. Thereafter, a bilateral agreement must be established between the CO₂ exporting and importing countries, which shall include confirmation and allocation of permitting responsibilities between the two countries, consistent with the provisions of the London Protocol and other applicable international law, to define a stable framework for the transboundary CO₂ transport. The amended Article 6 would enter in force when ratified by 2/3 of the London Protocol members. The unilateral declarations and bilateral agreements would then no longer be necessary.

With the suggested amendment of the ETS directive from 14 July 2021 in force, the situation will be the following for ship transport of CO₂ under the EU-ETS:

- The CO₂ capture installation can subtract emission allowances for captured fossil CO₂ when it is delivered from a ship to a pipeline transport network or directly to a storage site (provided that the storage site is permitted under Directive 2009/31/EC). I.e., there is a time delay between when the CO₂ is captured and when the emission allowances can be subtracted.
- The owner/operator of the ship that is transporting the captured CO₂ from the capture installation to the transport network will be responsible for the CO₂ emissions during this transport.

The CO₂ capture installation will not be able to subtract emissions that occur during ship transport to the pipeline network, i.e. the amount of CO₂ emissions to be subtracted would during normal operations be slightly lower than the amount of CO₂ captured – contractual agreements will be needed between the capture installation and the ship owner/operator to cover this. This, in turn, will

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call for accurate fiscal metering during on- and offloading. Also, CO$_2$ emissions from the ship propulsion system could be relevant to include in the contractual discussions/agreements.

Fiscal metering is crucial for transactions and monitoring emissions, and accurate measurements are necessary to achieve this goal. An important step to verify the performance of exiting measurement principles for CCS is the establishment of a primary reference and large-scale test facility for metering technologies.

It should also be stressed that contractual risk sharing is important. Contractual agreements should consider regulations, cost drivers, and ETS should be put in place. “Cluster-agreements”, with back-to-back long-term contracts can be a tool to avoid stranded assets.
### Glossary and list of icons

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>ADN</td>
<td>European Agreement for Transportation of dangerous goods by inland waterways</td>
</tr>
<tr>
<td>atm</td>
<td>Standard atmosphere. Unit of pressure defined as 101,325 Pa</td>
</tr>
<tr>
<td>bar</td>
<td>Unit of pressure corresponding to 100 000 Pa or approximately 0.9869 atm</td>
</tr>
<tr>
<td>barg</td>
<td>Unit of gauge pressure, which is zero-referenced against ambient air pressure</td>
</tr>
<tr>
<td>BLEVE</td>
<td>Boiling Liquid Expanding Vapour Explosion</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital expenditures</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon capture and storage</td>
</tr>
<tr>
<td>CCU</td>
<td>Carbon capture and utilization</td>
</tr>
<tr>
<td>CCUS</td>
<td>Carbon capture, utilization and storage</td>
</tr>
<tr>
<td>CCUS PN</td>
<td>CCUS Projects Network</td>
</tr>
<tr>
<td>CEF</td>
<td>Connecting Europe Facility</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DRI</td>
<td>Direct reduced iron</td>
</tr>
<tr>
<td>ETS</td>
<td>(EU) Emissions Trading System</td>
</tr>
<tr>
<td>H₂S</td>
<td>Hydrogen sulphide</td>
</tr>
<tr>
<td>HNS</td>
<td>Hazardous and noxious substances</td>
</tr>
<tr>
<td>HSE</td>
<td>Health, safety and environment</td>
</tr>
<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>ISGINTT</td>
<td>International Safety Guide for Inland Navigation Tank-barges and Terminals</td>
</tr>
<tr>
<td>kt</td>
<td>kilo ton</td>
</tr>
<tr>
<td>LCO₂</td>
<td>Liquefied CO₂</td>
</tr>
<tr>
<td>LOA</td>
<td>Length overall</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied petroleum gas</td>
</tr>
<tr>
<td>m³</td>
<td>Cubic meter</td>
</tr>
<tr>
<td>MID</td>
<td>Measurement Instrument Directive</td>
</tr>
<tr>
<td>MPA</td>
<td>Mega Pascal. Unit of pressure corresponding to 1 000 000 Pa</td>
</tr>
<tr>
<td>Mtpa</td>
<td>Mega ton per year (annum)</td>
</tr>
<tr>
<td>NO₂</td>
<td>Nitrogen oxide</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(O_2)</td>
<td>Oxygen</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operating expenditures</td>
</tr>
<tr>
<td>Pa</td>
<td>SI derived unit of pressure, defined as one newton per square meter.</td>
</tr>
<tr>
<td>PCI</td>
<td>Projects of Common Interest</td>
</tr>
<tr>
<td>QRA</td>
<td>Quantitative Risk Assessment</td>
</tr>
<tr>
<td>SI</td>
<td>International System of Units</td>
</tr>
<tr>
<td>(SO_2)</td>
<td>Sulphur dioxide</td>
</tr>
<tr>
<td>t/h</td>
<td>ton/hour</td>
</tr>
<tr>
<td>TEN-E</td>
<td>Trans-European Networks for Energy</td>
</tr>
<tr>
<td>USD</td>
<td>US Dollars</td>
</tr>
</tbody>
</table>
Table 2 List of icons used in this report

<table>
<thead>
<tr>
<th>Icon</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="CO₂ emitter icon" /></td>
<td>CO₂ emitter (e.g. industrial plant, refinery)</td>
</tr>
<tr>
<td><img src="image2" alt="CO₂ capture icon" /></td>
<td>CO₂ capture</td>
</tr>
<tr>
<td><img src="image3" alt="CO₂ conditioning icon" /></td>
<td>CO₂ conditioning (compression, liquefaction)</td>
</tr>
<tr>
<td><img src="image4" alt="CO₂ buffer storage icon" /></td>
<td>CO₂ buffer storage</td>
</tr>
<tr>
<td><img src="image5" alt="Railroad for CO₂ transport icon" /></td>
<td>Railroad for CO₂ transport</td>
</tr>
<tr>
<td><img src="image6" alt="Truck for CO₂ transport icon" /></td>
<td>Truck for CO₂ transport</td>
</tr>
<tr>
<td><img src="image7" alt="Pipeline for CO₂ transport icon" /></td>
<td>Pipeline for CO₂ transport</td>
</tr>
<tr>
<td><img src="image8" alt="Ship for CO₂ transport icon" /></td>
<td>Ship for CO₂ transport</td>
</tr>
<tr>
<td><img src="image9" alt="Barge for CO₂ transport icon" /></td>
<td>Barge for CO₂ transport</td>
</tr>
<tr>
<td><img src="image10" alt="CO₂ permanent storage icon" /></td>
<td>CO₂ permanent storage</td>
</tr>
<tr>
<td><img src="image11" alt="Ocean icon" /></td>
<td>Ocean</td>
</tr>
<tr>
<td><img src="image12" alt="River icon" /></td>
<td>River</td>
</tr>
</tbody>
</table>

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8 Reference List


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Appendix: CO₂ specifications

The 1st Report of the CCUS PN Thematic Group on CO₂ transport, storage and networks [5] presents the requirements specifications for transport and some end-uses. Here we present a summary for reference.

As CO₂ has a variety of uses in industry, there is also a variety of grades or purity specifications for commercial CO₂ [5].

Table 3 shows the maximum allowable concentration of contaminants in the CO₂ delivered to the Northern Lights infrastructure and the recommendations by Aspelund [65], based on the DYNAMIS project [66]. Aspelund [65] recommends a concentration of >99.7%v for CO₂. Therefore, the >0.3%v recommendation for non-condensable gases is for the sum of all non-condensables, including CO. It should also be mentioned that Northern Lights will entertain discussions with capture plants with other CO₂ compositions [66].

<table>
<thead>
<tr>
<th>Component</th>
<th>Northern Lights specification, ppm (mol basis)</th>
<th>Recommendation by Aspelund, Limitation</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water, H₂O</td>
<td>≤ 30</td>
<td>50 ppm</td>
<td>Design and operational considerations Freeze-out in heat exchangers</td>
</tr>
<tr>
<td>Oxygen, O₂</td>
<td>≤ 10</td>
<td>-</td>
<td>Design and operational considerations Challenges in the reservoir</td>
</tr>
<tr>
<td>Sulfur oxides, SOx</td>
<td>≤ 10</td>
<td>-</td>
<td>Health and safety considerations -</td>
</tr>
<tr>
<td>Nitric oxide/Nitrogen dioxide, NOx</td>
<td>≤ 10</td>
<td>-</td>
<td>Health and safety considerations -</td>
</tr>
<tr>
<td>Hydrogen sulfide, H₂S</td>
<td>≤ 9</td>
<td>200 ppm</td>
<td>Health and safety considerations Short-term exposure limit</td>
</tr>
</tbody>
</table>

Table 3 CO₂ specifications for delivery to the Northern Lights infrastructure [18] and recommendations for ship transport by Aspelund [65] (adapted from [5])
<table>
<thead>
<tr>
<th>Component</th>
<th>Northern Lights specification, ppm (mol basis)</th>
<th>Recommendation by Apelund, ppm</th>
<th>Limitation</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon monoxide, CO</td>
<td>≤ 10</td>
<td>2000 ppm</td>
<td>Health and safety considerations</td>
<td>Short-term exposure limit</td>
</tr>
<tr>
<td>Methane, CH₄</td>
<td>-</td>
<td>&lt;0.3% v (all non-condensable gases)</td>
<td>Design and operational considerations</td>
<td>Dry ice formation, costs of liquefaction</td>
</tr>
<tr>
<td>Amine</td>
<td>≤ 10</td>
<td></td>
<td>Design and operational considerations</td>
<td></td>
</tr>
<tr>
<td>Ammonia, NH₃</td>
<td>≤ 10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen, H₂</td>
<td>≤ 50</td>
<td>&lt;0.3% v (all non-condensable gases)</td>
<td>Design and operational considerations</td>
<td>Dry ice formation, costs of liquefaction</td>
</tr>
<tr>
<td>Nitrogen, N₂</td>
<td>-</td>
<td>&lt;0.3% v (all non-condensable gases)</td>
<td>Design and operational considerations</td>
<td>Dry ice formation, costs of liquefaction</td>
</tr>
<tr>
<td>Argon, Ar</td>
<td>-</td>
<td>&lt;0.3% v (all non-condensable gases)</td>
<td>Design and operational considerations</td>
<td>Dry ice formation, costs of liquefaction</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>≤ 20</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>≤ 20</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mercury, Hg</td>
<td>≤ 0.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cadmium, Cd (sum)</td>
<td>≤ 0.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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