CCSA

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# Achieving a European market for $CO_2$ transport by ship

January 2024

**Disclaimer**

The report aims to provide an indicative description of the future European market for $CO_2$ transport by ship and recommendations to ensure the full development of this market. This report does not preclude or make assumptions on any future commercial development or decision.

**Recognition**

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# Executive summary

## Regulatory and policy

- Policymakers across Europe should support the development of $CO_2$ transport by ship as a credible and necessary component of carbon capture and storage and industrial decarbonisation.
- The future European market of $CO_2$ transport by ship should develop on a commercial basis. Regulated tariffs are not recommended.
- The cross-border transport of $CO_2$ requires the recognition of storage by other countries and the proof that the captured $CO_2$ is safely stored. The EU and the UK should enter into an agreement to ensure that emitters located either in the EU/EEA or the UK do not have to surrender ETS allowances when storing $CO_2$ in the other ETS system. Such an agreement is key to support cross-border $CO_2$ transport in Europe.
- To support the cross-border transport of $CO_2$, European countries that are parties to the London Protocol should deposit a notice to provisionally apply the Article 6 amendment to the London Protocol with the International Maritime Organization and sign bilateral agreements where needed.
- National and EU public authorities should ensure that subsidy mechanisms do not prejudice against those emitters reliant on shipping to access $CO_2$ stores.
- Regulatory frameworks should include compensation mechanisms for the losses of ETS credits linked to the $CO_2$ buffer storage volumes required to stabilise transport and storage systems.
- National authorities should incentivise investments to pre-invest in the expansion of key $CO_2$ shipping infrastructure components.
- The revision of the Monitoring and Reporting Regulation should address regulatory gaps regarding $CO_2$ transport by ship.

## Funding

- The development of sufficient geological storage capacity should be supported via adequate incentives.
- Public authorities should create mechanisms to make investments in $CO_2$ shipping at least as attractive as investments in conventional shipping businesses.
- Legislative frameworks should recognise $CO_2$ shipping as an enabler of bioenergy with carbon capture and storage (BECCS) and Direct Air Capture with Carbon Storage (DACCS) to allow funding through the voluntary market.
- Early projects should have sufficient funding support to demonstrate that $CO_2$ shipping is a viable alternative to pipeline transportation.
- Port authorities should incentivise port/harbour fees for $CO_2$ shipping and/or vessel prioritisation protocols for $CO_2$ shipping.

## Standardisation

- Recognising the different shipping conditions of $CO_2$ specifications for shipping, liquefaction, and onshore storage is recommended to ensure compatibility and consistency between CCS projects. A European $CO_2$ transport system covering all modalities (pipelines, road, rail, inland waterway, and ship) requires universal rules for allowable/acceptable $CO_2$ impurities. This transport grid should have the possibility to distinguish between transport modes. Shipping companies that take $CO_2$ out of a pipeline system will need to consider end-of-pipeline solutions to get the $CO_2$ to their required conditions.
- For the proposed transport conditions (low pressure, medium pressure, and high pressure, see definitions below) the Society of International Gas Tanker and Terminal Operators (SIGTTO) is encouraged to standardise ship-shore interface to enable compatibility, destination optionality, and increase market competition.
- International standard methodologies for $CO_2$ metering and calibration for mass-balance quantification should be developed.

## Research and development

- Public authorities should support research into the functioning of a multimodal $CO_2$ transportation system, where $CO_2$ is transported via trucks, train, barges, and ships.
- More research work should be undertaken on $CO_2$ specifications for ship transport to gather additional data and map the $CO_2$ stream compositions from all possible emitters.

## Operations

- Shipping companies should conduct structured classroom training to teach the specific hazards of $CO_2$ operations to ship crews.
- Competent authorities should develop effective safety and environmental footprint performance in early phases of $CO_2$ shipping as a pre-condition to vessel owner License to Operate.

## Main findings

- A 20,000-tonne cargo liquified $CO_2$ ship with a one-week round trip time can transport approximately one million tonnes of $CO_2$ per annum, assuming there are no logistical nor weather delays.
- As of today, in Europe, one project with a contracted $CO_2$ shipping capacity of 2 million tonnes per annum has taken a Final Investment Decision. Based on a review of projects currently under development, it is estimated that up to 39.5 million tonnes of $CO_2$ could be transported per year by 2030. The corresponding fleet of dedicated $CO_2$ carriers is evaluated between 6 (3 ordered and 3 anticipated, all related to Northern Lights) and 40 vessels. An educated estimate for the number of vessels required by 2030 is in the range 10 to 20 vessels. However, should every project come to fruition in the short term, which is unlikely, the total number of vessels could exceed 50. This estimation is purely indicative and aims to provide a view of the potential future market. The capacity of future European storage sites compatible with ship transport could exceed 50 million tonnes per year by 2030.
- Vessels are expected to be contracted for specific point-to-point $CO_2$ transport and will not be available for spot-market transport by 2030.

# Definitions

These are the pressure and temperature ranges of the three conditions considered for $CO_2$ transport. Density ranges have been rounded[1].

| | Low pressure | Medium pressure | High pressure |
|---|---|---|---|
| **Temperature (°C)** | -55 to -40 | -30 to -20 | 0 - 15 |
| **Pressure (barg)** | 5 – 10 | 15 – 20 | 35 - 50 |
| **Density (kg/m3)** | 1170 - 1120 | 1080 - 1030 | 930 - 820 |

1. Orchard et al., The status and challenges of CO2 shipping infrastructures, 2021, Greenhouse Gas Control Technologies Conference 15, MegaWatSoft, Carbon dioxide properties.

## The European Commission aims to store at least 50 million tonnes of $CO_2$ by 2030.

## Shipping will play a crucial role in Europe for the development of carbon capture and storage.

**1 million tonnes of $CO_2$ can be transported per year**

by a 20,000-tonne cargo liquified ship with a one-week round trip

Current projects under development could transport up to

**39.5 million tonnes of $CO_2$ per year by 2030**

Future European storage sites compatible with ship transport could exceed

**50 million tonnes of $CO_2$ storage**

**26 storage projects identified**

could use shipping to transport $CO_2$

European policymakers should support the development of $CO_2$ transport by ship for

**industrial decarbonisation**

## Key recommendations for European countries

- Incentivise funding and remove barriers to cross-border $CO_2$ transport by ship in EU and UK ETS systems.
- Provisionally apply Article 6 amendment of London Protocol with the International Maritime Organisation and sign bilateral agreements where needed.
- Support more research into a multimodal $CO_2$ transportation model to include ships, barges, trains and trucks.

# 1. Introduction

Year after year the consequences of climate change are becoming more and more perceptible for citizens across the world. Urgent and effective climate action is required by policymakers in Europe and across the world. The deployment of carbon capture and storage (CCS) at scale is indispensable to stay in line with global climate ambitions as repeatedly stated by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA). CCS development requires the effective deployment of the capture, transport, and storage parts of the value chain. Ship transport is essential to guarantee full-scale $CO_2$ transport across Europe. Among other reasons ship transport is crucial for smaller volumes of $CO_2$, transportation over longer distances and $CO_2$ from isolated sites as well as early and smaller projects. $CO_2$ transport by ship must therefore be an integral part of CCS policies developed across Europe.

CCS is currently experiencing a positive momentum across Europe. Recent positive developments include the awarding of 21 storage licenses by the North Sea Transition Authority (NSTA) in the UK and a wide-ranging political agreement on CCS in Denmark. Dedicated CCS strategies for France, Germany, and the EU are expected between 2023 and 2024. Crucial project announcements, including final investment decisions, are expected in the coming months. This positive policy and commercial momentum must be preserved and strengthened to ensure the success of CCS projects across Europe. This report aims to provide a description of the future European market for $CO_2$ transport by ship, identify the main barriers and enablers, and provide clear policy and technical recommendations to policymakers. These recommendations seek to guarantee the emergence of a European market for $CO_2$ transport by ship that is critical for Europe's industrial decarbonisation.

# 2.
# Mapping the European market for $CO_2$ transport by ship in 2030

## 1. Captured $CO_2$ that will be transported by ship

To identify the likely requirement for $CO_2$ shipping by 2030, we have examined those projects most likely to reach final investment decision (FID) in the period 2023-2028. The projects listed below have the potential to go ahead in this timeframe as they are either part of the 1st Union list of Projects of Common Interest (PCIs) and Projects of Mutual Interest (PMIs)[2] under the Trans-European Networks for Energy (TEN-E) policy or the UK CCS Cluster Sequencing process. The 14 projects selected in November 2023 under the 1st Union list are highlighted and used for the total estimated volumes. CCS is experiencing a strong momentum across Europe and new projects are announced regularly. As an example, the Porthos project in the Netherlands took a final investment decision in October 2023[3]. The description below is indicative and expected to evolve as new projects are announced.

| Emitter / Project | Timetable | Shipping volumes by 2030 |
|---|---|---|
| **EU TEN-E PCI/PMI Projects (based on the 1st list)** | | |
| **$CO_2$TransPorts**<br><br>**Rotterdam / Antwerp / North Sea Port link up to use Netherlands storage via pipeline to P18**<br><br>**Porthos (final investment decision taken)** | Phase 1 (2023) – Rotterdam pipeline network focus – no shipping<br>Phase 2 – Antwerp/ North Sea Port pipeline network focus – no shipping<br>Phase 3 (2030) – pipeline Antwerp/Rotterdam | No shipping likely unless a Rotterdam-Antwerp pipeline does not materialise. If no pipeline is built, Antwerp shipping volumes will be ~10 million tonnes per annum (mtpa) |

2. Annex on the first Union list of Projects of Common and Mutual Interest, DG ENER, European Commission, 28 November 2023.
3. First CO2 storage project in the Netherlands is launched, Porthos, 18 October 2023.

| Emitter / Project | Timetable | Shipping volumes by 2030 |
|---|---|---|
| **Northern Lights** | Phase 1 (1.5 mtpa capacity): Operational in 2024<br><br>Customers: (i) Heidelberg Materials (previously Norcem) cement factory in Brevik (Oslo Fjord), (ii) Waste-to-energy plant Hafslund Oslo (Oslo Fjord), (iii) Ørsted (Denmark)<br><br>Phase 2: (5 mtpa, including phase 1): Expansion of phase 1 facilities with additional wells, ships and onshore tanks | 5 mtpa |
| **Aramis** | Second Rotterdam-centered project using separate offshore pipeline | Shipping unlikely before 2030 |
| **Nautilus** | Link clusters in Le Havre, Dunkirk, and Duisburg, to a new storage site in the Norwegian North Sea | 2.5 mtpa (2027-2030) |
| **EU2NSEA** | Capture facilities on industrial plants in 8 EU member states,<br>including Belgium, Germany, and the Netherlands, plus the necessary pipeline infrastructure to transport $CO_2$ to the North Sea | Shipping unlikely before 2030 |
| **Norne** | Emitters in Denmark, Sweden, and Belgium – build out storage network using $CO_2$<br>pipeline infrastructure that enables $LCO_2$ ships to transport third-party CO2 | 18.7 mtpa by 2030 |
| **WH2V** | Wilhelmshaven, Shipping hub to export German $CO_2$ | 10 mtpa |
| **Noordkaap** | Project led by CapeOmega<br>Stage 1 – shipping from the Netherlands to Norway<br>Stage 2 – Additions in the Netherlands, Belgium, Germany, Sweden | 20 mtpa |
| **Bifrost** | Danish capture project with pipeline to offshore Danish chalk reservoirs<br>Work examines a fleet of low-temperature ships and a reception port<br>No timetable published | None<br><br>Injection capacity of 3 mtpa<br><br>No shipping likely by 2030, expected initial focus on onshore capture |
| **ECO2CEE** | $CO_2$ shipping terminal in Gdansk to ship Polish / Lithuanian emissions | 2.7 mtpa (2025-2030)<br>8.7 mtpa (2030-2035) |
| **CCS Baltic Consortium** | Baltic States CCS study | 1 mtpa by 2030<br>~20 mtpa over 20 years[4] |
| **Pycasso** | Onshore south-west France / north-west Spain project | None |
| **Callisto** | Italian $CO_2$ storage based on the Ravenna Hub | 3.6 mtpa (2027-2032) |

4. CCS Baltic, Project Benefits, as of 8 December 2023.

| Emitter / Project | Timetable | Shipping volumes by 2030 |
|---|---|---|
| **Augusta C2,<br>Prinos CO2 storage** | Italian / Greek project focused on the Prinos field store | 1 mtpa by 2025 |
| **Potential UK Clusters** | | |
| **Net Zero Teesside** | Pipeline only project | None |
| **Hynet** | Pipeline only project. Shipping discussed for a future phase | None |
| **Scottish Cluster** | Planned port infrastructure to receive shipped $CO_2$ | 1-2 mtpa |
| **Viking CCS** | Planned port infrastructure to receive shipped $CO_2$ | 1-3 mtpa |
| **Zero Carbon Humber** | Pipeline only project | None |

An analysis of the above information suggests a range of likely shipped volumes:

| Emitter / Project | Timetable | Shipping volumes by 2030 |
|---|---|---|
| **Projects seen as certain** | | |
| **Northern Lights (approved for PCI/ PMI status)** | Phase 1 (1.5 mtpa capacity)<br><br>Operationally ready in 2024 Customers: Heidelberg Materials cement factory in Brevik (Oslo Fjord), waste-to-energy plant Hafslund Oslo (Oslo Fjord), and Ørsted (Denmark)<br><br>Phase 2: (5 mtpa, including phase 1): expansion of phase 1 facilities with additional wells, ships, and onshore tanks | 5 mtpa<br>3 ships under construction[5] + 3 ships anticipated |
| **Projects seen as likely** | | |
| **CCS Baltic Consortium (approved for PCI/PMI status)** | Cross-border $CO_2$ transport via rail between Latvia and Lithuania with a multi-modal $LCO_2$ terminal in Klaipeda | 1 mtpa |
| **Nautilus (approved for PCI/PMI status)** | Link clusters in Le Havre, Dunkirk, and Duisburg, to a new storage site in the Norwegian North Sea | 2.5 mtpa |
| **Norne (approved for PCI/PMI status)** | Emitters from Denmark, Sweden, Belgium, and the UK<br>Storage network using a pipeline infrastructure that enables LCO2 ships to transport third-party $CO_2$ | 18.7 mtpa |
| **WH2V (not approved for PCI/PMI status)** | Wilhelmshaven, Germany Shipping hub to export $CO_2$ from Germany | 10 mtpa |

5. Northern Lights awards third ship building contract, Northern Lights, 1 September 2023.

| Emitter / Project | Timetable | Shipping volumes by 2030 |
|---|---|---|
| **Noordkaap (not approved for PCI/ PMI status)** | CapeOmega-led project, aims for direct injection<br>Stage 1: shipping from the Netherlands to Norway<br>Stage 2: added capacity in the Nether-lands, Belgium, Germany, and Sweden | 20 mtpa |
| **ECO2CEE (approved for PCI/PMI status)** | $CO_2$ shipping terminal in Gdansk (Poland) to ship emissions from Poland/Lithuania | 2.7 mtpa |
| **Callisto (approved for PCI/PMI status)** | Italian $CO_2$ storage based on the Ravenna Hub | 3.6 mtpa |
| **Prinos (approved for PCI/PMI status)** | Italian/Greek project focused on the Prinos storage site | 1 mtpa |
| | **Potential UK Clusters** | |
| **Scottish Cluster** | Planned port infrastructure to receive shipped $CO_2$ | 1-2 mtpa<br>NB: This is an import-only facility that is assumed to proceed once emitters are contracted. |
| **Viking CCS** | Planned port infrastructure to receive shipped $CO_2$ | 1-3 mtpa<br>NB: This is an import-only facility that is assumed to proceed once emitters are contracted. |
| | **Total volumes** | |
| **All above projects** | | 5 – 39.5 mtpa |

To put the above figures into context, a single 20,000 $m^3$ ship could transport approximately 1 million tonnes per annum based on typical shipping distances within the EU. A more detailed analysis is provided below, under subsection 2.3.

This would suggest a requirement for 6 to 40 vessels by 2030, with uncertainty associated with voyage length, duration, port capacity (dredged depth), and project completion. The lower range is based on the three vessels under construction for the Northern Lights project and the three additional vessels expected for this project. It is worth noting that projects were identified under the Union projects list and the UK Cluster Sequencing Process and that some may not materialise by 2030. The total size of the fleet depends on the cumulated success of several $CO_2$ transport by ship projects. In terms of pure probability, the upper range figure of 40 vessels is therefore less likely than the lower range figure of 6 vessels. An educated estimate for the number of vessels required by 2030 is in the range 10-20 vessels.

These vessels are likely to be built on a project-by-project basis with vessels dedicated to transporting $CO_2$ from specific emitters to a specific storage location. It is possible that some vessels will be contracted to provide a 'milk run' service, collecting $CO_2$ from multiple collection points before heading to a destination port. However, the emergence of a spot market for $CO_2$ transport is not expected in this timeframe.

Container-size tanks are also envisaged for rail, road, and inland barge transport. This type of transport could be useful for small emitters, capture projects in their initial phase, and for the mitigation of low river levels and unforeseen events.

# 2. Storage sites for $CO_2$ transport by ship

A total of 26 $CO_2$ storage projects at varying stage of maturity have been identified. Many of the projects are still in the early stages of project concept selection and, as a result, are rather vague about $CO_2$ transportation plans, annual injection capacities, and overall storage capacities. Of these:

- 6 projects totalling a maximum of 15 mtpa injection are explicitly planning to use shipping to transport $CO_2$ to a reception port by 2030 – likely then transporting by pipeline to the offshore location.
- 1 project with a capacity of a further 3 mtpa injection is explicitly planning to use shipping to transport $CO_2$ to Project Coda in Iceland. This project is listed separately as it is a longer voyage and there is additional storage technology uncertainty, which may delay the project (the storage depends on $CO_2$ mineralisation).
- 2 additional projects totalling 14 mtpa injection are explicitly planning to ship CO2 directly to the offshore store for direct injection by 2030. Such schemes involve shipping at ~50barg – significantly higher than the more ‘conventional’ shipping conditions (low pressure at 7bar/-50˚C; medium pressure at 18bar/-30˚C).
- Of the UK projects, Acorn and Viking CCS have explicit plans for the shipping of $CO_2$ by 2030 – although all have deepwater ports near to their pipeline terminals and could take shipped $CO_2$ in the future. Acorn could take 1-3 mtpa of shipped $CO_2$ depending on contractual arrangements. Viking CCS could take 1-3 mtpa of shipped $CO_2$, subject to contractual arrangements[6][7][8][9].

6. Transforming the Humber into a net zero SuperPlace, Viking CCS.
7. Viking CCS and Associated British Ports embark on major step towards a future CO2 shipping industry in the UK, Associated British Ports, October 2022.
8. Viking CCS and Associated British Ports embark on major step towards a future CO2 shipping industry in the UK, Harbour Energy, Viking CCS, and Associated British Ports, October 2022.
9. Immingham Green Energy Terminal, 2023.

| Storage Site Name | Country | Name | Store type | Offloading port in plans | Injection capacity mtpa |
|---|---|---|---|---|---|
| **Onshore northern Croatia** | Croatia | Geothermal CCS Croatia | Depleted gas field | No – onshore | 1.04 |
| **Onshore Denmark** | Denmark | Norne | | Not yet defined, port identified | 20 |
| **Harald Field, Offshore Denmark** | Denmark | Bifrost | | Yes | 0,5 |
| **Offshore Denmark** | Denmark | Project Greensand | Depleted oil field | Yes | 1.5 |
| **Stenille** | Denmark | Stenlille | Aquifer | Not yet defined | Unknown |
| **Pycasso (Onshore storage)** | France | Lacq region | | Possibly | Unknown |
| **Prinos Field (offshore Greece)** | Greece | Prinos $CO_2$ Storage | | Pipeline or ship | 2 |
| **Carbfix mineralisation process** | Iceland | Carbfix Project Coda | | Ship | 3 |
| **Callisto** | Italy | Callisto Mediterranean $CO_2$ Network | Depleted gas field | Yes | 5.6 |
| **Offshore Netherlands** | Netherlands | Noordkaap | | Yes | 1 |
| **P18 Gas Field, Nether-lands** | Netherlands | Porthos | | Pipeline | 2.5 |
| **Offshore Netherlands** | Netherlands | $CO_2$TransPorts | Depleted gas field | Pipeline / Direct Injection from ship | 10 |
| **L10 Area, offshore Netherlands** | Netherlands | Neptune Energy | | Pipeline / Direct Injection from ship | 4 |
| **Aramis store, offshore Netherlands** | Netherlands | Aramis | Depleted gas field | Inland barge to pipeline | 5 |
| **Offshore Norway** | Norway | Luna | | Pipeline / Direct Injection from ship | Unknown |
| **Luna and Smeaheia** | Norway | Equinor store linked to EU2NSEA project | Aquifer | Pipeline / Direct Injection from ship | Unknown |
| **Offshore Norway** | Norway | Havstjerne Storage Project and Errai[10] | Aquifer | Pipeline / Direct Injection from ship | 7 |
| **Offshore Norway** | Norway | Poseidon Storage Project | Aquifer | Pipeline / Direct Injection from ship | Unknown |
| **Offshore Norway** | Norway | Northern Lights | Aquifer | Yes | 1.5 |
| **Acorn** | UK | UK Scottish Cluster | Depleted gas plus aquifer | Yes | 5 |
| **Liverpool Bay** | UK | UK Hynet | Depleted gas | Future possibility – port nearby | 4.5 |
| **Northern Endurance** | UK | Net Zero Teesside Cluster | Aquifer | Future possibility – port nearby | 4 |
| **Viking** | UK | Viking CCS | Depleted gas field | Yes | 10 |
| **Morcambe Bay** | UK | Spirit Energy CCUS Hub | Depleted gas field | Future possibility – port nearby | 10 |
| **Hewett** | UK | ENI Consortium – Hewett Storage Site | Depleted gas field | Future possibility – port nearby | 10 |
| **Unknown** | Italy and Greece | Augusta C2 | Unknown | Unknown | Unknown |

10. Wintershall Dea awarded second storage licence for CO2 in Norway, Wintershall Dea, 31 March 2023.

Pictured here: the first Northern Lights ships, 60% completed in production.
The sister ships have a cargo capacity of 7,500 m³ and will set sail in 2024.

Credits: Northern Lights JV; Dalian Shipbuilding Offshore Co.Ltd

# 3. Shipping routes and potential market

With five projects under construction, more than twenty under development and many more under discussion, Europe has been one of the leaders in the CCS infrastructure growth over the last years, leading the trend that has expanded globally, and especially in the US and China.

Due to geographical characteristics $CO_2$ shipping is expected to play a crucial role in Europe for the development of CCS. This contrasts with the United States and China where announced projects rely mainly on onshore pipeline infrastructure. That is why leading European projects are progressing the construction of $CO_2$ carriers (three under construction and more under consideration/discussion with the shipyards). These projects are also progressing construction of $CO_2$ terminals, either for loading or unloading $CO_2$ at the emitting source or emitters' hub side or at the storage side respectively. Plans for $CO_2$ transhipment terminals have also been revealed, but these are expected to materialise at a later stage depending on how the carbon capture projects develop and on the availability of storage sites.

The $CO_2$ value chain for storage purposes depends on funding incentives or market-based measures put forward by the EU and national governments to reduce industrial $CO_2$ emissions. Reusing $CO_2$ via CCU could generate revenue streams and support the development of transhipment terminals and the expansion of the $CO_2$ transportation market. Incentives provided by the EU and UK ETS will be crucial since emission allowances costs associated with $CO_2$ transport by ship and permanently stored can be avoided. Carbon credits for negative emissions associated with bioenergy with carbon capture and storage (BECCS) and direct air capture with carbon storage (DACCS) represent another potentially significant funding tool.

The Clean Air Taskforce map below illustrates CCS projects, both storage and industrial hub and terminal type, that are either under construction or under development in Europe. Areas in dark grey represent the geological formations with $CO_2$ storage capabilities.

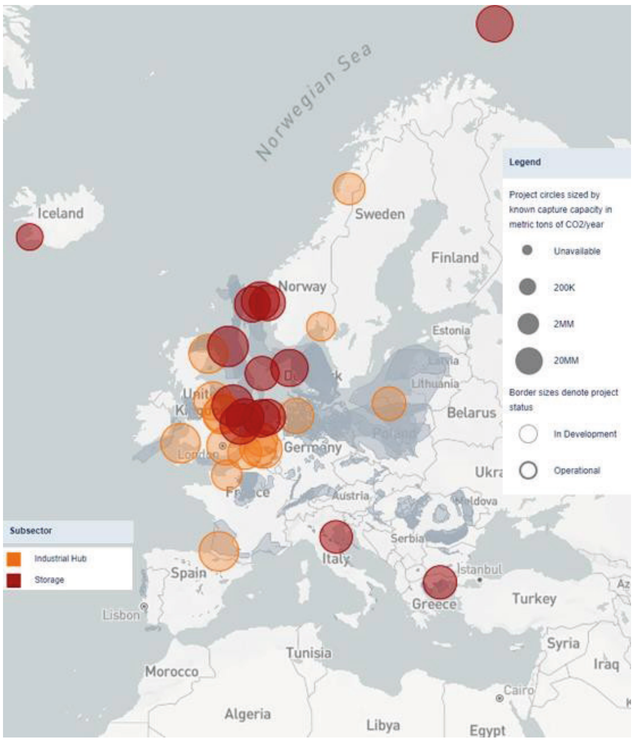



Figure 1: Europe Carbon Capture Project Map – Clean Air Task Force

Based on this map Europe can be divided in three main areas:

a) the north-western area, where there is an abundance of available $CO_2$ storage sites (due to the concentrated oil and gas activities and the numerous offshore sites developed in the North Sea over the last fifty years);

b) the central area, where there are potentially available geological formations with $CO_2$ storage capabilities, but with limited CCS project initiatives; and

c) the southern area, where there is limited availability of $CO_2$ storage sites but where CCS projects are already under development.

$CO_2$ transport by ship is currently developing on a regional basis, where relatively large emitters (e.g., large cement plants with carbon capture rates of approximatively 1mtpa or more) get into long-time charter agreements with specific storage site locations within short distances in the same region. The ship transportation cost strongly depends on the volumes transported and the distance. Large emitters located relatively close to storage sites can benefit from low ship transportation costs. On the other hand, this model requires the construction of a dedicated liquefied $CO_2$ loading terminal at the emitters site, which is a highly CAPEX-intensive investment for emitters. This model may also entail critical limitations to the ship's design or operation due to the geographical location of the emitter and any draught restrictions or operational disturbances due to passage through congested areas. With respect to the conditions under which the $CO_2$ is liquefied and transported (low pressure between 6-8 barg, medium pressure 16-19 barg or high pressure 35-45 barg) this depends on:

a) the volumes to be transported – larger ship sizes are easier and more efficiently designed and constructed at low design pressures; and

b) whether CO2 will be liquefied and stored at both the loading (emitter's site) and unloading (storage site terminal), which drives capital investment requirements for the storage tank and the equipment needed, and also drives the operational expenses and procedures required for maintaining an efficient supply chain.

$CO_2$ well injection rates are expected to be much lower than the normal discharging rate for liquefied $CO_2$ ships, so buffer storage tanks will be required at the unloading terminal close to the sequestration site. If the site is expected to receive liquid $CO_2$ from various sources, then the required buffer storage capacities will be high (3-5 ship cargoes – potentially as much as 100,000 tonnes of storage).

Whilst $CO_2$ transportation can be undertaken in gaseous, liquid, or solid phase, the liquid phase provides both the high density and ease of handling required for meaningful bulk transportation. Given the temperature and pressure of its triple point (5.4 bar, -56 °C), $CO_2$ needs to be pressurised to be in a stable liquid state. This is a defining feature of its transportation.

The transport of other gases can use pressure as an alternative to lower temperatures; pressure is essential for $CO_2$.

The mass that can be transported in a $CO_2$ tank increases with the difference in density between the liquid and gaseous phase. Counter-intuitively the mass of $CO_2$ that can be transported in a given tank is lower at higher pressure/higher temperature than it is for a lower pressure/low temperature condition.

Transport at higher pressure and ambient temperature requires less energy in the $CO_2$ liquefaction process (being more compression and less cryogenic) but requires a larger tank volume for the same mass due to reduced density. Higher pressure transportation also allows greater tolerance of $CO_2$ impurities, simplified loading systems due to the higher temperature envelope and facilitates potential direct-to-store applications, further simplifying the value chain and potential speed of deployment.

Conventional wisdom was that medium pressure (MP) would be preferred up to 10,000 tonnes (being the maximum size of very similar 'Fully Pressurised' LPG Carriers) and low pressure (LP) for larger cargos. However higher pressure (HP) solutions, particularly for 'direct-to-store' applications are also being developed and there is a credible prospect of both HP and MP carriers with up to 40,000 tonne capacity.

The $CO_2$ transport model described above has been adopted by early movers in northern Europe and by developers in south-eastern Europe, mainly due to the small size of the market, its geography, and the density of the emitters in these areas.

In the north-west of Europe, several governments have decided to incentivise the creation of clusters (e.g., the UK, the Netherlands or Denmark). This approach has stimulated the development of projects for the construction of $CO_2$ hubs and terminals, with $CO_2$ collected and conditioned in large quantities and either transported to nearby sequestration sites via pipelines or liquefied and transported via ships to longer distances. This cluster model can support the development of carbon capture projects for small emitters close to the loading terminal hubs. These hubs could move their $CO_2$ either via pipelines or containers (virtual pipeline concept), so the terminals will have to be capable to handle these multi-modal transportation means. This concept is particularly likely to be adopted in north-west of Europe due to the abundance of storage sites, as illustrated in Figure 1 above, but also due to the density and distribution of emitters in the area, as described in the two figures hereafter.

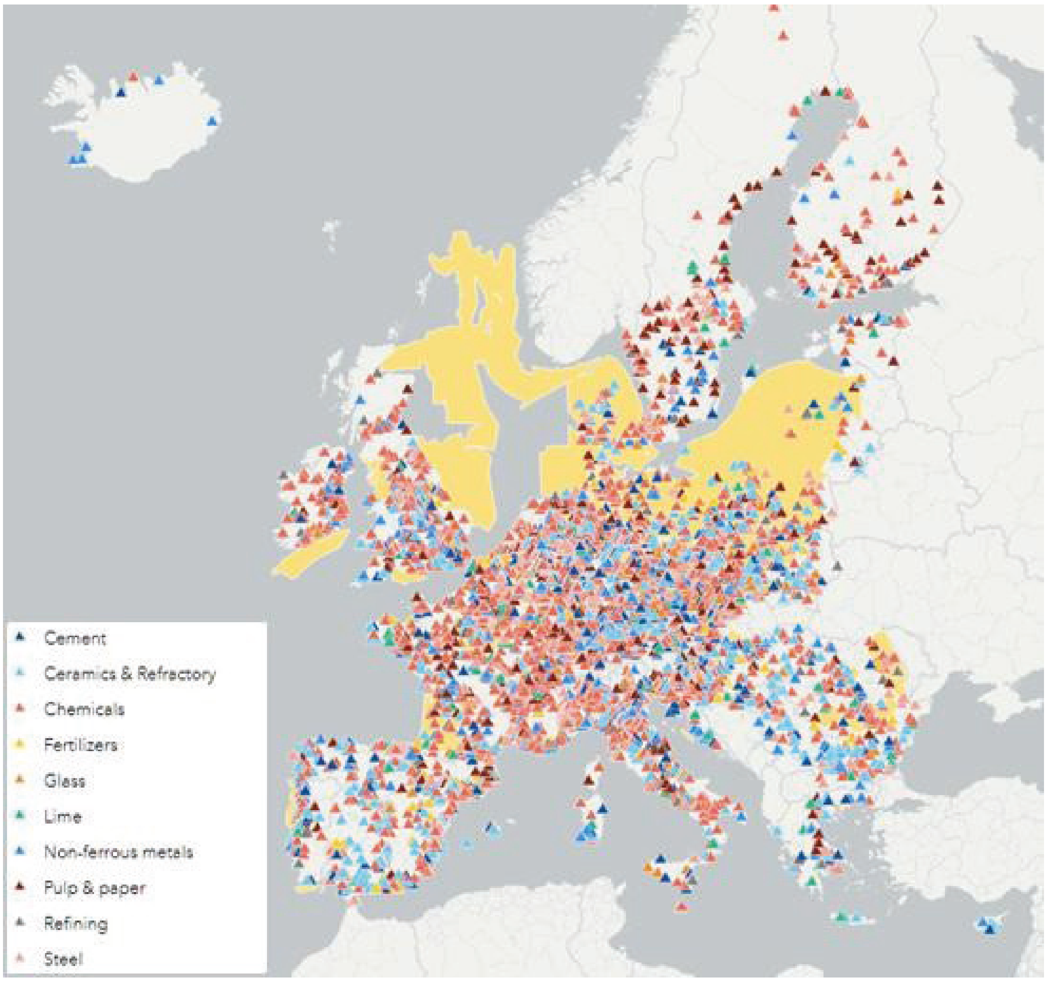



Figure 2: Emitters registered in E-PRTR system – Energy and Industry Geography Lab

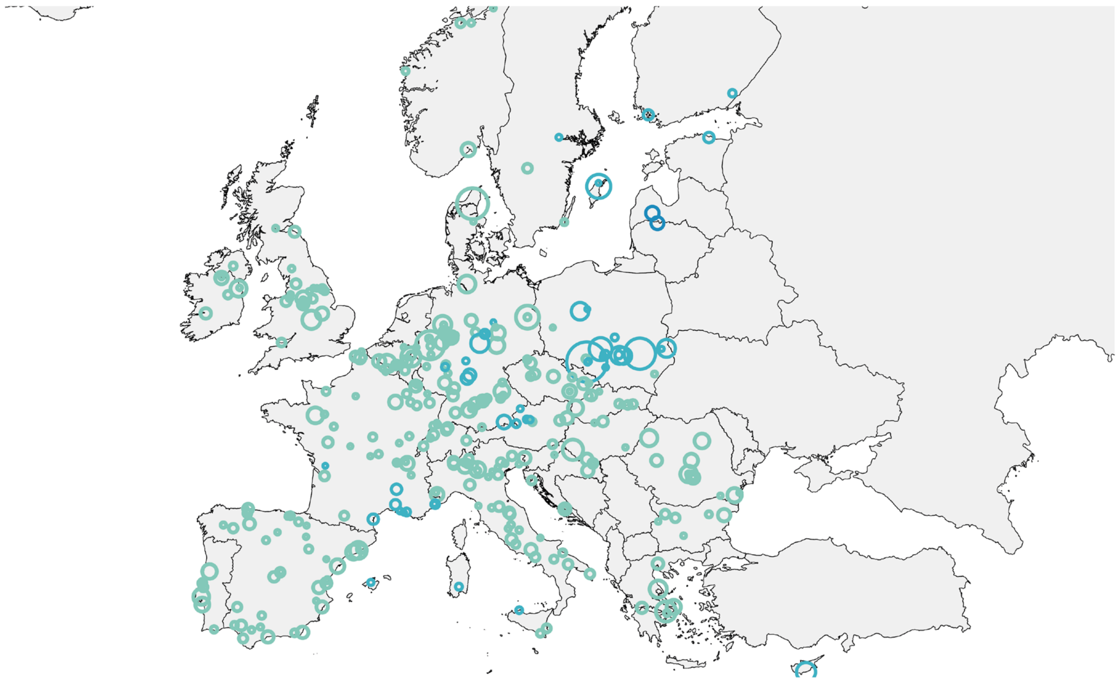


Figure 3: The total 343 facilities for cement, lime, and other non-metallic minerals in Europe – Mapping the cost of carbon capture and storage in Europe – Clean Air Task Force

The same model could be developed at a later stage in southern Europe to collect $CO_2$ in large quantities and ship them to northern Europe since, according to Figure 1, southern Europe lacks storage capacities in existing geological formations with $CO_2$ storage capabilities. Such a concept would require significant governmental support to incentivise the development of the required infrastructure and to overcome regulatory and social barriers like the London Protocol and/or local community acceptance.

In central Europe where there is no direct access to either onshore/offshore sequestration sites or to any of the $CO_2$ collection hubs, inland waterways could provide a possible transport solution, especially for emitters along the main rivers like the Rhine, the Danube, and the Elbe.

There may be significant limitations to the large-scale deployment of this transportation mode – with issues such as the maximum allowable tonnage, draught restrictions, speed limits, and the stops expected at locks in some specific segments presenting significant challenges and, as a result, the transportation cost per tonne of $CO_2$ is expected to be higher than in the open sea.

Another concept where inland waterways transport could potentially play a role is a multimodal transportation model with $CO_2$ containers transported via trucks, train, and ships/barges, which could find application for small emitters. Further research is required in this field.


Figure 4: Map of the European inland waterway network

Figure 5 below describes the potential $CO_2$ shipping routes as described in the various project proposals announced over the last few years. In the North Sea a complex network of loading, unloading and/or transshipments terminals has been proposed and the aggregate $CO_2$ shipping transportation volumes in this region could reach 25-30 mtpa for the 2030-2035 period (see section 2.1), and expand above 50 mtpa from 2040 onwards.

In southern Europe these volumes are not expected to exceed 10 mtpa by 2035. It is not clear how this capacity could expand towards 2040 since the storage capacity is limited and there is currently no clear plan for large emitter hubs development and long transportation to other regions.

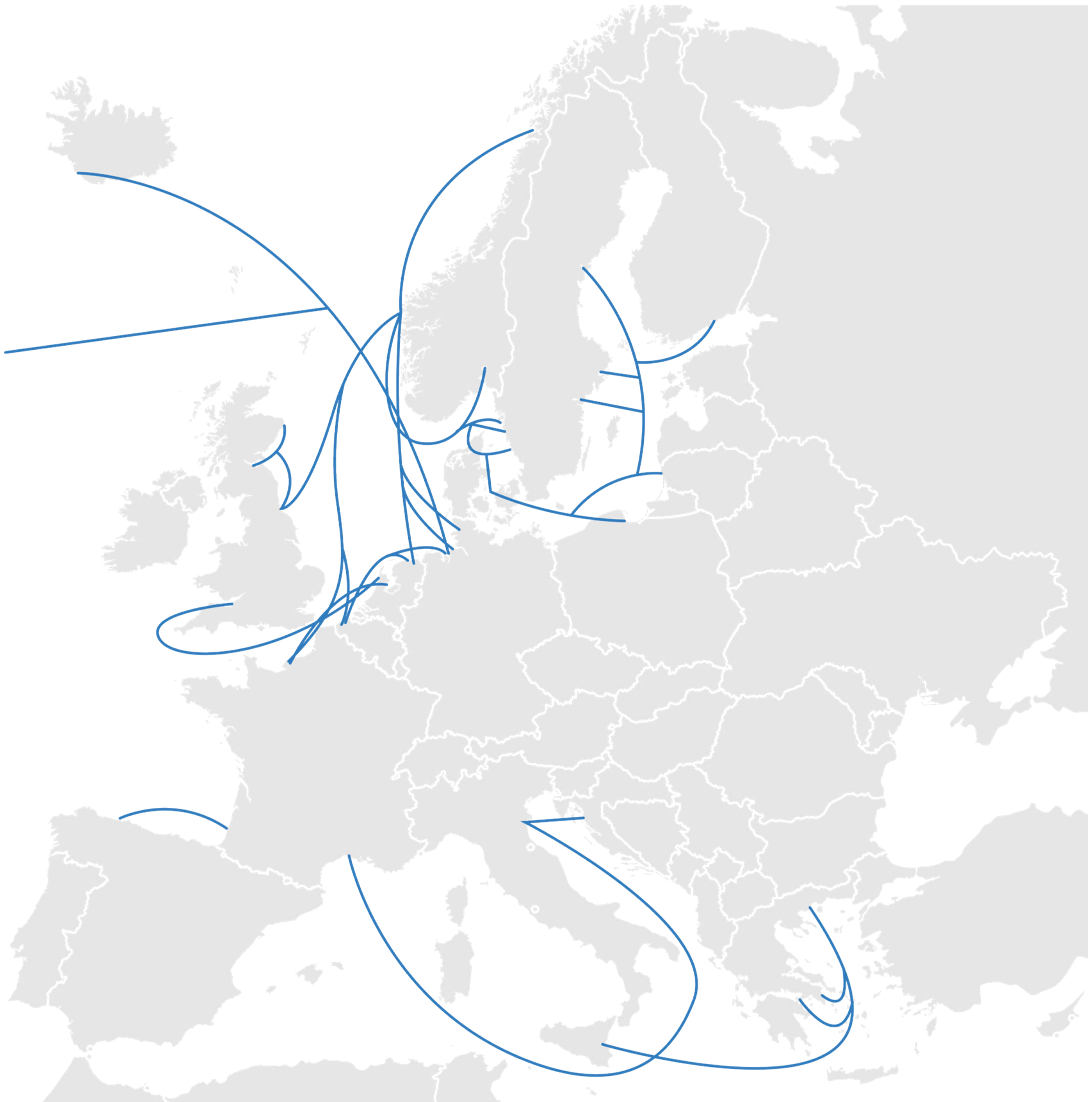


Figure 5: Potential $CO_2$ shipping routes.

## Determinants of shipping capacity

The purpose of this section is to set out the influences on $CO_2$ shipping requirements and provide a basic indicator of the numbers and capacity of carriers required for a range of transportation distances applicable for CCS in northwestern Europe.

The main determinants of shipping capacity for a particular operation are identified hereafter:

- **Cargo**
  - » Volume – rate per year and regularity (consistency throughout year)
  - » Distance by navigable route between loading and discharge ports
  - » Transport condition – if liquid, whether it be Low Pressure (LP), Medium Pressure (MP) or High Pressure (HP)

- **Gas carriers**
  - » Cargo capacity – specifically mass of $CO_2$ that can be loaded and discharged in the normal operating cycle.
  - » Transit speed – in both loaded and unloaded conditions.
  - » Operating constraints – restricted waters and weather conditions.

- **Loading and discharge ports**
  - » Distance from open water – the time required at reduced speed and for manoeuvring to and from the designated berth.
  - » Port and berth access constraints – tide, weather, congestion, pilotage and towing.
  - » Cargo transfer at the berth – pumping rate and pressure at loading port / receiving rate and back pressure at discharge port.
  - » Reliability of delivering / receiving the nominated cargo parcel at the specified time.
  - » Port availability – susceptibility to weather and availability of required port services.
  - » Prevailing weather conditions.

- **Other factors include**
  - » Requirement to transit any restricted waterway, such as a river or a canal.
  - » Bunkering constraints – availability of the required bunker fuel at either the loading
  - » or discharge port and any additional ‘offline’ time required to undertake bunkering.
  - » Number of carriers in the fleet – spare capacity to accommodate outages.

- Shore tank buffer capacity.
- Injection rate.
- Degree of ship transport resilience.

Most of these parameters are straightforward. The more complex ones are discussed in the next section.

### Transport condition – gas carriers

The capacity is determined by the total useable volume of the tanks and the shipping condition, as explained above. Typically, the usable/pumpable volume is around 92-96% of actual volume for Type C tank vessel, which allows for a cargo heal.

As explained previously $CO_2$ can be transported in gaseous, liquid, or solid phase. However, the liquid phase provides both the high density and ease of handling required for meaningful bulk transportation. Given the temperature and pressure of its triple point (5.4 bar, -56 °C), $CO_2$ needs to be pressurised to be in a stable liquid state. This is a unique feature of $CO_2$. Transportation of other gases use pressure as an alternative to lower temperatures; pressure is essential for $CO_2$ to be a liquid. Counter-intuitively the mass of liquid $CO_2$ that can be transported in a given tank is lower at higher pressure/higher temperature than it is for a lower pressure/low temperature condition.

Transport at higher pressure and ambient temperature requires less energy in the $CO_2$ liquefaction process but requires a larger tank volume for the same mass due to reduced differential in densities. Higher pressure transportation also allows greater tolerance of $CO_2$ impurities, simplified loading systems due to the higher temperature envelope and facilitates potential direct-to-store applications, further simplifying the value chain and potential speed of deployment. High pressure (HP) vessel solutions are also being developed that would be capable of facilitating shipping for direct to store injection of $CO_2$ without the need for energy-intensive cooling and liquefaction processes.

Conventional wisdom was that medium pressure (MP) would be preferred up to 10,000 tonnes (being the maximum size of very similar ‘Fully Pressurised’ LPG Carriers) and LP above that. That boundary is increasing, with the credible prospect of MP carriers with 20,000 tonne capacity.

The transit speeds for both the loaded and unloaded leg of the round trip have a direct impact on the total cycle time as does time spent in port, at reduced speed, and any seen or unforeseen delays. Whilst increased transit speed enables transportation of more cargo, it requires greater power with increased emissions/larger energy storage.

## Loading and discharge ports

The key factor is the time taken to either load or discharge the carrier taken from the moment of reducing speed prior to entry and until regaining transit speed on leaving the port. This includes the time required to enter the port, manoeuvre to, and moor up at the berth, connect transfer hoses, undertake the cargo transfer, complete the loading and associated documentation, disconnect, un- moor, leave the berth and exit the port. This will involve tug assistance and probably a pilot (depending on familiarity). Additional time may be required due to port congestion, waiting for the designated berth, bunkering if not able to be undertaken simultaneously and any scheduled or unscheduled maintenance.

A further factor is the ability to receive the cargo parcel at the time of arrival. This will be largely dictated by the regularity of $CO_2$ arriving at the loading/onward transmission from the port and the interim storage of the terminal itself. Based on offshore shuttle tanker operations, it is typical to nominate a 3-day loading window for the cargoes scheduled for a calendar month at the beginning of the previous month. For efficient terminal operations it is necessary to have enough interim storage to receive a full cargo, facilitate the loading windows plus having a tolerance for un-scheduled occurrences. It is debatable how much interim storage capacity will be required over and above the designated parcel size but having at least 140% of the carry capacity is a good starting point. Having unreliable $CO_2$ inflow (or outflow for a discharge port), ports with significant non availability, and only a small number of carriers in the system would be good reasons to have additional interim storage capacity.

There is a clear benefit in having compatibility of carriers that are operating in the area with a cooperation/backup arrangement to reduce the need for contingent capacity. Availability of the desired bunker fuels at either the loading or discharge port is also important as is the ability to undertake bunkering simultaneously with a loading or discharge operation.

## Liquid $CO_2$ carrier capacity and fleet requirements

The following provides an indication of carrier fleet requirements for a range of throughput, distances between ports and carrier sizes. This is based on the following base assumptions.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Carrier** | Speed | Liquid/'loaded' | 13 | knots | Gaseous /'unloaded' | 13 | knots |
| | Utilisation factor | | 90 | % | | | |
| **Loading Terminal** | | hours | | | **Offload Terminal** | | |
| | Hold time | 6 | | | Hold time | 2 | |
| | Passage in | 4 | | | Passage in | 4 | |
| | At berth | 24 | | | At berth | 24 | |
| | Passage out | 2 | | | Passage out | 2 | |
| | Total Time | 36 | | | Total Time | 32 | |

Figure 6 – Carrier fleet requirements

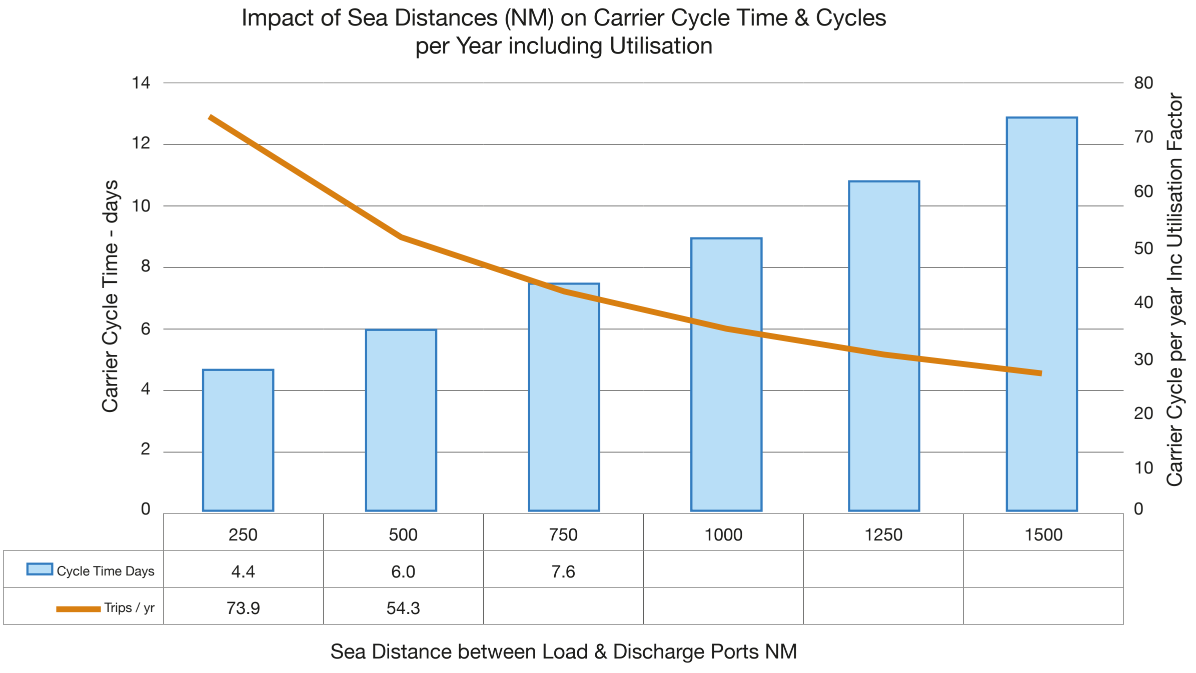
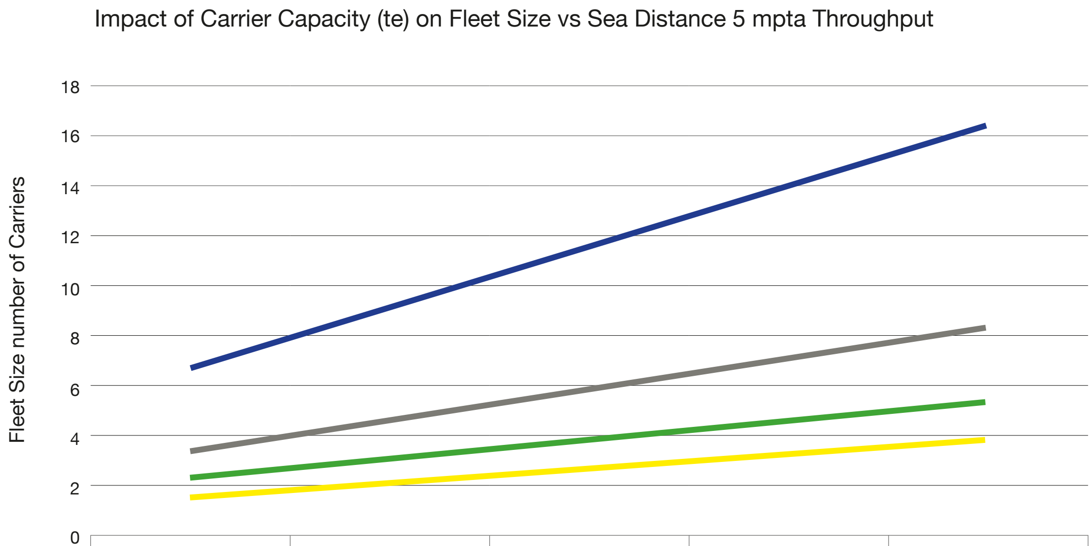



Figure 7: Impact of sea distances




| | 250 | 500 | 750 | 1000 | 1250 |
|---|---|---|---|---|---|
| 10,000 | 6.8 | 9.2 | 11.7 | 14.1 | 16.6 |
| 20,000 | 3.4 | 4.6 | 5.8 | 7.1 | 8.3 |
| 30,000 | 2.3 | 3.1 | 3.9 | 4.7 | 5.5 |
| 40,000 | 1.7 | 2.3 | 2.9 | 3.5 | 4.1 |

Sea Distance between Load & Discharge Ports NM

Figure 8: Impact of carrier capacity

The fleet size is shown to one decimal place. Whilst the number of carriers required will always be rounded up, the decimal provides an indication of the margin. For example, 5 mtpa transported over 1,000 nautical miles in carriers of 20,000 tonne capacity requires 7.1 carriers. However, if this can be optimised by saving 4 hours in the cycle time, the requirement would drop to below 7. Whilst the modelling of fleet and carrier requirements is relatively straightforward, the graphs above provide a useful initial indication.

As an approximation, a 20,000-tonne cargo liquified $CO_2$ ship with a one-week round trip time can transport approximately one million tonnes of $CO_2$ per annum, assuming there are no logistical nor weather delays. There is a potential requirement of 6 to 40 dedicated vessels to serve the 2030 European market described in the previous section. These are likely to be related to separate emitter-ship-store project contracts, with individual stores being involved in several different emitter projects. In such an early and emerging market, it is likely that the vessels will be contracted for specific point-to-point $CO_2$ transportation work and will not be available for spot-market transportation of $CO_2$ by 2030.

It is the subjective view of the authors group that the number of vessels operational by 2030 will be in the range 10-20 ships.

# 3. Interoperability of $CO_2$ transport by ship

## 1. $CO_2$ specifications in the report 'Guidance for $CO_2$ transport by ship'

The Carbon Capture & Storage Association (CCSA) and the Zero Emissions Platform (ZEP) published a report called 'Guidance for CO2 transport by ship' in 2022[11]. The key findings of this report are the following:

- The CCS value chain is complex, and decisions taken at one point in the value chain can have significant technical and economic impact elsewhere along the value chain. A decision to ship $CO_2$ liquefied at -50˚C requires the emitter to purify the $CO_2$ to a more rigorous standard than might otherwise be required. At this early stage of the development of the liquified CO2 shipping market, it appears likely that two or more "standards" of temperature and pressure and composition will be appropriate – most likely at a "low pressure" of 5.5- 7barg and -50 ˚C or at a "medium pressure" of 15-18barg and -30˚C. The report notes that some projects are considering transport at closer to ambient temperatures linked to direct ship-to-offshore offloading.
- Some elements of $CO_2$ phase behaviour are similar to liquified petroleum gas (LPG) which is already widely transported by ship, although it is noted LPG does not solidify close to the transport conditions. Existing standards for the transport of LPG and other liquified gases are largely fit- for-purpose for the transport of liquified $CO_2$ – indeed many standards specific to the transport of liquefied $CO_2$ already exist. It is recommended that the relevant standards and guidelines issuing organisations be requested to review their specific standards and guidelines with a view to adapting them for the high-volume transportation of liquified $CO_2$ associated with CCS.

11. Guidance for CO2 transport by ship, CCSA and ZEP, 2022.

## 2. Additional considerations

From the perspective of ship transport, low pressure (with a corresponding low temperature) is considered as optimal due to the high liquid density and low gas density[12]. Few studies have included the impact of $CO_2$ stream composition on ship transport. Engel and Kather (2018) considered the liquefaction of a pipeline $CO_2$ stream[13]. They found that an increased impurity concentration leads to an increased energy demand of the liquefaction process, and to a shift from electrical to thermal energy demand for the injection. The relative merits of the three transport condition categories, in the context of the full value chain are presented in the table below.

| | Advantages | Disadvantages |
|---|---|---|
| **Low Pressure / Low Temperature** | • Highest density of $CO_2$ implies higher amount of $CO_2$ per volume of tank<br>• Wall thickness of tanks can be lower than for Medium Pressure and High Pressure reducing weight and cost<br>• Tanks can be larger than in Medium Pressure and High Pressure cases as structural guidelines imply maximum tank sizes decreasing with increasing pressure. This implies a lower number of tanks being required for the same volume of shipped $CO_2$ | • Closeness to triple point of $CO_2$ implies operational risks, in particular dry ice formation<br>• Higher quality material of tanks required to withstand low temperatures<br>• Insulation of tanks required to maintain low temperature<br>• Low Pressure $CO_2$ transport case may limit the cargo transfer velocity, which in turn take longer for loading/discharge operation. This is yet to be fully verified<br>• Preconditioning (heating and boosting pressure) of low pressure $LCO_2$ is required before injection process |
| **Medium Pressure / Low Temperature** | • Mature concept with many years of experience in the food and drinks sector<br>• Higher density than High Pressure while lower operational complexity than Low Pressure due to sufficient distance from triple point<br>• Lower energy requirement for liquefaction than Low Pressure[14] | • Higher amount of steel in tank system required to withstand higher pressure implying higher CAPEX and fuel cost of ship than for Low Pressure<br>• Structural challenges due to the maximum size of tanks imply a maximum ship size of around 10,000 tonnes in this condition |

12. Aspelund et al., Ship Transport of CO2: Technical Solutions and Analysis of Costs, Energy Utilization, Exergy Efficiency and CO2 Emissions, Chemical Engineering Research and Design, 2006.
13. Engel and Kather, Improvements on the liquefaction of a pipeline CO2 stream for ship transport, International Journal of Greenhouse Gas Control, 2018.
14. Comparison of CO2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain, Youngkyun Seo et al., International Journal of Greenhouse Gas Control, 2016.

| | | |
|---|---|---|
| **High Pressure / Ambient Temperature** | • Lowest energy requirement for liquefaction<br>• No/less insulation of tanks and loading/unloading facilities required as $CO_2$ is transported at ambient temperature<br>• Scalable tank capacity as tanks are small and can be arranged vertically to fit within a given ship hull<br>• Lowest energy demand for conditioning as transport condition is close to storage injection conditions<br>• Potentially higher impurity tolerance due to lower impact of impurities on the phase envelope at higher pressure | • Lowest CO2 density reducing the amount of CO2 per volume of tank<br>• Tank/pressure containment system is heavier due to required increase wall thickness. For the same carrying capacity (cbm) an LP/MP vessel will be smaller due to the higher density of $CO_2$ at LP and MP |

Table 3: Transport categories – Advantages and disadvantages – NB: For all different transport conditions, appropriate mitigation measures should be taken to ensure that the risk is as low as practically possible.

## Composition - General considerations

The primary objective of $CO_2$ shipping is to transport $CO_2$ from an emitter to a storage site. As a result, the cargo will be predominantly $CO_2$. Lower limits must be defined for certain impurities, in particular for water, but also for amines and glycols. Depending on the feedstock and the $CO_2$ generating and capture processes, $CO_2$ streams captured from industrial sources or power generation contain various impurities (that is, stream components other than $CO_2$). The impurities differ in their concentrations but also in their physical and chemical properties, which create several areas of concern:

- **Health**
  - » Impurities at low concentrations in the $CO_2$ cargo may be toxic (*e.g.,* hydrogen sulphide or carbon monoxide) and could have an impact on release. Impurities should be assessed on a case-by-case basis.

- **Safety/Integrity**
  - » Minor components may be corrosive. For instance, components such as $SO_x$, $NO_x$, $O_2$ and $H_2S$, can react together in the absence of free water to produce corrosive components[15]. $CO_2$ with free water creates carbonic acid, which is highly corrosive.
  - » Hydrogen can cause an embrittlement of steels.

15. Dugstad, Morland, and Clausen (2011), Corrosion of transport pipelines for CO2 – effect of water ingress, Energy Procedia.

- **Phase behaviour**
  - » Some impurities materially change the phase envelope of $CO_2$, potentially creating issues with keeping the $CO_2$ in a liquid phase where the deviation of the phase envelope from pure $CO_2$ increases with decreasing temperature. This is illustrated in the figure below.

Impurities can have a significant effect on the phase behaviour of $CO_2$ streams in relation to their concentration. Additional purification of the $CO_2$ stream increases capture costs. Chemical effects also include metal corrosion. The composition of the $CO_2$ stream can also influence the injectivity and the storage capacity, due to physical effects (such as density or viscosity changes) and geochemical reactions in the reservoir. In case of a leakage, toxic and ecotoxic effects of impurities contained in the leaking $CO_2$ stream could also impact the environment surrounding the storage complex (see ISO TR 27921).

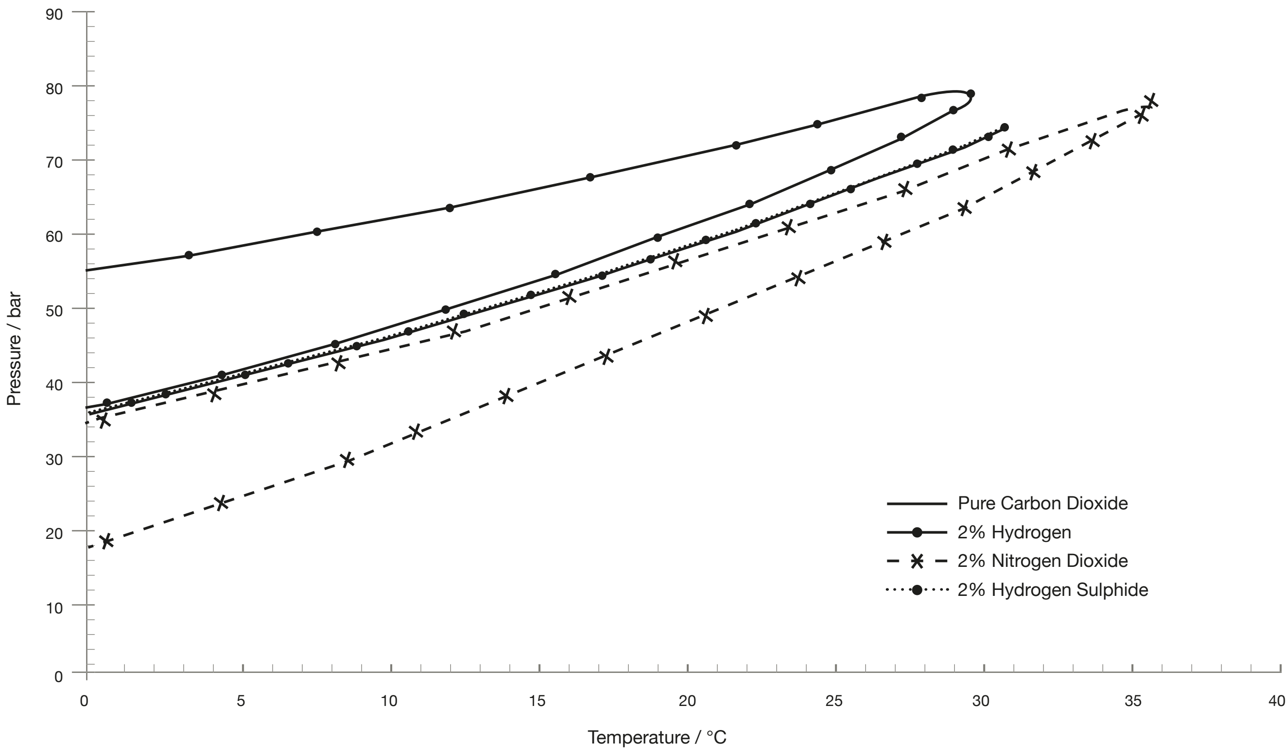



Figure 9 - Phase diagram for binary combinations of CO2 and 2mol% $H_2$, $H_2S$, and $NO_2$ calculated using the Peng Robinson equation of state.

## Published specifications for $CO_2$ shipping

The following table shows two published $CO_2$ compositions for shipping taken from the ZEP/CCSA report published in 2022[16].

| Component | Northern Lights[17] Concentration (ppm mol) | EU CCUS Projects Network recommendations [18][19] |
|---|---|---|
| **Carbon Dioxide (CO2)** | Not defined | >99.7% by volume |
| **Acetaldehyde** | ≤20 | Not defined |
| **Amine** | ≤10 | Not defined |
| **Ammonia (NH3)** | ≤10 | Not defined |
| **Argon (Ar)** | Not defined | <0.3% by volume |
| **Cadmium (Cd) / Titanium (Ti)** | ≤0.03 (sum) | Not defined |
| **Carbon monoxide (CO)** | ≤100 | <2000ppm |
| **Hydrogen (H2)** | ≤50 | <0.3% by volume (considered too high and impractical for ship operations by at least one operator) |
| **Hydrogen sulphide (H2S)** | ≤9 | <200ppm |
| **Formaldehyde** | ≤20 | Not defined |
| **Mercury (Hg)** | ≤0.03 | Not defined |
| **Methane** | Not defined | <0.3% by volume |
| **Nitric oxide / nitrogen dioxide (NOx)** | ≤10 | Not defined |
| **Oxygen (O2)** | ≤10 | Not specified as literature is inconsistent |
| **Sulphur oxides (SOx)** | ≤10 | Not defined |
| **Water (H2O)** | ≤30 | <50ppm |

Table 5 - Two published $CO_2$ compositions for shipping

16. Guidance for CO2 transport by ship, CCSA and Zero Emissions Platform, 2023.
17. Quality specification for liquified CO2, Northern Lights, 2021.
18. Briefing on carbon dioxide specifications for transport, CCUS Projects Network, 2019.
19. This recommendation should be taken with caution. Hydrogen concentration only just below 0.3% by volume is considered impractical for ship operations by at least one operator since the pressure/temperature regime is outside of ship operations parameters.

### Inter-related compositions and impacts

For streams that could be/are going to be mixed, limits must be defined in such a way that any possible combination of streams cannot result in potentially dangerous mixtures when it comes to health and safety, system integrity in general and corrosion specifically, potential storage impairment, and operational procedures.

### Material integrity

With various combinations and concentrations of potentially reactive impurities ($H_2O$, $NO_2$, $SO_2$, H2S, $O_2$), it was clearly shown that many impurity combinations were basically inert, while other resulted in chemical reactions and some combinations even resulted in the formation of a separate aqueous phase that contained high concentrations of sulfuric and nitric acid as well as elemental sulphur. This aqueous phase was corrosive to carbon steel. The concentration limits for reactions and corrosion to occur vary strongly with the type and number of impurities that are present.

Such testing is often performed at high pressures, reflecting the need for elevated pressures for injection. For the investigated conditions, 100 bar and 25°C, the concentration limit for each impurity should be below 20 parts per million by volume (ppmv) if $NO_2$, $SO_2$, $H_2S$, and $O_2$ are present together. This is to provide a margin to the result that in the presence of 35 ppmv of $SO_2$, $O_2$, $H_2S$, and $NO_2$ resulted in formation of a separate aqueous phase that contained sulfuric and nitric acid, acids that are highly corrosive. If either $H_2S$ or particularly $NO_2$ was removed, these reactions did not occur, and will allow the limit on other impurity concentrations to be increased. Limits must be defined in such a way that any possible combination of streams cannot result in potentially dangerous mixtures (when it comes to health and safety, corrosion, and operational procedures). Materials must be selected in such a way that they are suitable for $CO_2$ within the defined limits for impurities.

### Phase envelope

The presence of "non-condensable substances", $N_2$, Ar, $H_2$ and $CH_4$ belong to this category (ISO/TR 27921), impacts the phase envelope in a cumulative way. This means that their maximum allowable concentration by individual component cannot be uniquely defined as it is possible to allow different quantities of different non-condensables and still be within an acceptable phase envelope impact. Assessing the cumulative "functional impact" is a preferable approach towards minimising the overall cost than selecting arbitrary values for components that have different impacts and should not be defined singularly. An example of such approach is to define the limit as a minimum temperature on the saturated liquid line considering the cumulative effect of all non-condensable components, although this may need to be referenced to a specific transport condition (LP, MP, or HP).

### Optimisation of $CO_2$ stream composition based on techno-economic assessments

The impacts of various impurities and combinations of impurities on the individual steps of the CCS chain have been outlined in the previous sections. If impacts of impurities in individual components of the CCS chain are known, $CO_2$ stream composition could be adjusted to avoid undesirable impacts. Optimisation of $CO_2$ stream composition along the CCS chain could ensure safety of transport, injection and storage while reducing energy consumption and costs of the CCS chain operation. This optimisation could be realised by way of various options for the technical design of the CCS chain.

To assess various transport network design options, techno-economic assessments have proven to be a valuable tool. In general, pipeline specification of $CO_2$ will be less onerous than for shipping. Few studies exist that assess impacts of impurities along the whole CCS chain. For projects that require both pipeline and ship transport of CO2, a project-specific study will be required to optimise $CO_2$ stream composition.

The cost challenges associated with CCS are well documented and will be covered further in this report. Some of the CCS costs are associated with the "purification" of the $CO_2$ stream to meet some of the published specifications. A Joint Industry Project (JIP) led by DNV recognises this fact and, as part of its objective, states "*it is desirable to limit the need for cleaning $CO_2$ from the various industry emitters of harmful impurity elements by keeping its composition as wide as possible without jeopardizing the risk of corrosion and material degradation".* Whilst this JIP is pipeline specific, the statement is equally relevant for transport by ship[20].

### Conclusions on composition specification and infrastructure reuse impact

A European transport grid requires universal rules for allowable concentrations. The CCUS Forum report on $CO_2$ specifications recommends to "develop as rapidly as possible a network code and standards for a multimodal $CO_2$ transport network in the EU/EEA"[21]. The authors recognise that the $CO_2$ from some projects will be transported via pipeline before being transported by ship. This may require additional processing of the $CO_2$ at the port prior to loading on a ship.

20. Design and Operation of CO2 pipelines – CO2SafePipe, DNV.
21. 'An Interoperable CO2 Transport Network – Towards Specifications for the Transport of Impure CO2', CCUS Forum, 2023.

For a pure shipping project (point source-to-point sink project), concentration thresholds are case-specific and subject to optimisation for the entire CCS process with respect to safety and environmental protection, costs, and energy demand (see ISO TR 27921).

## Selecting the optimum transport conditions and composition for an individual project – key aspects to be considered by each project

The following table seeks to identify the key factors that must be considered:

| Factor | Impact |
|---|---|
| **$CO_2$ production rate by a cluster and the phasing of growth** | What are the production rates in the initial phase and how can shipping support this and the longer-term projected growth |
| **Reservoir** | Different reservoir characteristics may become a challenge for a European solution – this aspect requires further investigation |
| **Optimal ship parcel size versus onshore storage requirements** | Optimum vessel size for a particular project will determine the onshore buffer storage requirement. Using smaller or larger vessels will result in inefficiencies but development of standard sizes will allow use of vessels across different routes. Such flexibility will provide additional redundancy and support open-market development over time. |
| **Shipping pressure and temperature that determines the liquefaction process required** | Conditions of the $CO_2$ gathering network impact on the amount of processing required for liquefaction<br>Availability of a suitable, preferably green, energy source for the liquefaction process<br>Liquified $CO_2$ storage design, including pumping system<br>CAPEX and OPEX of the liquefaction process |
| **Shipping travel times from the emitter / cluster to a $CO_2$ storage provider** | The travel time will impact the size and number of vessels which in turn determines the amount of storage at the loading and unloading terminals. This will be optimised for each project. |
| **Dense phase** | Energy-efficient regasification for injection is an important point (using heat from seawater is a possibility that should be investigated). Regasification that relies on the direct use of<br>electrical power would be costly. |
| **Standard specification and impurity limitations** | Physical testing needs to be carried out to test impurities and their impact on phase behaviour. The aim is to have an industry standard (which could include component-by-component limits and/or cumulative impact limits) for composition for carriage conditions for HP, MP and LP. |

Table 6: Key shipping aspects to be considered

# 3. IMO, SIGTTO, and CEN work on standards for $CO_2$ transport by ship

The European Committee for Standardization (CEN) created a new Technical Committee on $CO_2$ capture, transportation, utilization, storage (CCUS) and carbon accounting in November 2023. CEN stated that “international standardization activities on CCUS are developed in ISO/TC 265. The proposed new CEN/TC aims to build on existing ISO/TC 265 standards, supplementing them with homegrown documents tailored to the needs of European stakeholders. Through establishing liaisons with the relevant CEN and ISO Technical Committees, the standardization activities will be coordinated, and collaboration will be encouraged to avoid duplication of work or conflicting requirements”[22].

The Society of International Gas Tanker and Terminal Operators (SIGTTO) submitted paper CCC 8/10/1 to the IMO Sub-Committee on Carriage of Cargoes and Containers (CCC) about the triple point and the toxicity of liquified $CO_2$ transportation. Furthermore, SIGTTO submitted paper CCC 9/4/3 to clarify the understanding about how regulations in IGC Code shall apply to exclusive CO2 carriage.

Flag state delegates agreed about the proposal of liquid $CO_2$ triple point. Most major flag states and industry bodies agreed that the significant issue with $CO_2$ is toxicity, but also worry about the deletion of asphyxiation. An additional discussion about waivers of IGC Code requirement especially Ch.11 was carried out. Not all toxic cargo requirements should be applied to $CO_2$, and the retroactivity should also be considered. Considering the limited time and the process of CCC meeting, these details will be discussed in correspondence group and settled down in CCC 10 (2024).

22. A new CEN/TC will develop standards for carbon capture, utilization and storage, CEN-CENELEC, 2023.

| IGC Code Chapter | Application for $CO_2$ | Remarks |
|---|---|---|
| **1 – General** | Applicable | - |
| **2 – Ship survival capability and location of tanks** | Applicable | - |
| **3 – Ship arrangements** | Applicable | 3.1.2 and 3.1.3 – A single gastight bulkhead A-0 class may be sufficient<br>3.2.5 – A-60 Class may not be required<br>3.2.6 – Air inlet and outlet capable of being operated from inside the space<br>3.3.1 – May not require explosion prevention. Consider SOLAS II-2/9.2.3 for fire protection<br>3.8.2 – Bow cargo transfer may be allowed<br>3.3.4 – Bulkhead may not be required<br>3.6 – Airlocks may not be required |
| **4 – Cargo containment** | Applicable | - |
| **5 – Process pressure vessels and liquids, vapour and pressure piping systems** | Applicable | 5.7.4 may not be required |
| **6 – Materials of construction and quality control** | Applicable | - |
| **7 – Cargo pressure/temperature control** | Applicable | If a flammable or more toxic refrigerant is used then this should be highlighted in the risk assessment |
| **8 – Vent systems for cargo containment** | Applicable | - |
| **9 – Cargo containment system atmosphere control** | Significant Exclusions | 9 – May not require inert gas. Dry air may be required to prevent condensation in cargo tanks and piping<br>9.3 – Dry air to prevent condensation in space |
| **10 – Electrical installations** | Significant Exclusions | 10 – May not require any measures for fire prevention from cargo<br>10.2.6 – should be applied |
| **11 – Fire protection and extinction** | Significant Exclusions | 11 – May not require fire protection and extinction from cargo. May be able to use SOLAS requirements for general cargo vessels |
| **12 – Artificial ventilation in cargo area** | Applicable | 12.1.1– Required<br>12.1.7– May not require explosion prevention.<br>12.1.9 – May not apply |
| **13 – Instrumentation and automation systems** | Applicable | 13.6.5; 13.6.6 should be applied |
| **14 – Personnel protection** | Applicable | 14.3.2.4; 14.4.3 may not apply<br>14.4.2; 14.4.4 should be applied |

| | | |
|---|---|---|
| **15 – Filling limits for cargo tanks** | Applicable | |
| **16 – Use of cargo as a fuel** | Not applicable | 16 – Cargo cannot be used as fuel. Other type of fuel used will require additional measures and may require reinstating requirements for other Chapters |
| **17 – Special requirements** | Applicable | - |
| **18 – Operating requirements** | Applicable | 18.10.3.2 – may not required |
| **19 – Summary of minimum requirements** | Applicable | Recommended changes are given in Table 7. Reclaimed quality does not require a separate column and can be captured in the text of the IGC Code |

Table 7: Suggestions for the application and improvement of the IGC Code

| a | b | c | d | e | F | g | h | i |
|---|---|---|---|---|---|---|---|---|
| **Product name** | | Ship type | Independent tank type C required | Control of vapour space within cargo tanks | Vapour detection | Gauging | | Special requirements |
| **Carbon dioxide (high purity and reclaimed quality)** | | 3G | - | - | ~~A~~ T | ~~R~~ C | | 14.4.2, 14.4.4 17.21,17.22 |
| ~~**Carbon dioxide (Reclaimed quality)**~~ | | ~~3G~~ | - | - | ~~A~~ | ~~R~~ | | ~~17.22~~ |

Table 8: Suggested changes to IGC Code summary of minimum requirements[23]

The International Convention for the Safety of Life at Sea (SOLAS) Chapter III 31.1.6 should also be updated.

23. Based on the summary of minimum requirements in Chapter 19 of the IGC Code.

## Industry guidance

Very little industry guidance is written specifically for $CO_2$ and what is written for other gas carriers cannot simply be applied to $CO_2$ without review. The documents in this section are valuable and can provide general guidance.

## Manifolds

Recommendations for Liquefied Gas Carrier Manifolds specify the size and arrangement of cargo and bunker manifolds. This is used by loading arm manufacturers and terminal designers to design terminals.

## Marine loading arms

Manufacturers design loading arms to ensure that they do not exceed the loads specified in Design and Construction Specification for Marine Loading Arms. Designs should consider the density of $CO_2$ as it is heavier than other liquefied gases typically used in the industry.

The guidance in the Oil Companies International Marine Forum (OCIMF) document can be useful for $CO_2$, along with the following considerations:

- The material should be suitable for possible impurities and the minimum temperature that can be reached in an emergency, i.e., stainless steel is recommended for dry ice.
- Credible scenarios should be considered to determine if emergency release is necessary.
- If an emergency release system (ERS) is fitted, then it should be designed to release under pressure.
- The swivel joint should be designed to prevent damage from dry ice if there is a leak.
- Pressure loss in the system derived from cargo transfer velocity, piping diameter, $CO_2$ density and $CO_2$ viscosity should be considered.

### Emergency shutdown systems

The purpose of SIGTTO's recommendations in ESD Systems is to reduce risk in process systems. This will help to minimise the consequences of an incident. $CO_2$ carriers should follow the recommendations in ESD Systems, except for sections on gas burning in the engine room, liquid sensor in vent mast and firefighting triggers.

### Mooring

Mooring Equipment Guidelines provides a standardised approach for gas carriers and terminal moorings and should be suitable for $CO_2$ carriers, and terminals.

### Alarm management, human-machine interface, and cargo control room

SIGTTO recommendations for alarm management, human-machine interface (HMI) and cargo control rooms (CCRs) provide good design practice for gas carrier CCRs and alarm systems. The guidance in these documents is recommended for $CO_2$ carriers.

### Training and experience

Structured classroom training should be carried out to educate the crew on the specific hazards of $CO_2$ operations. Training should cover safety, contingency planning, and all routine operations. The training programme should be similar to LPG Shipping Suggested Competency Standards.

# 4. CCNR work on $CO_2$ transport

A second edition of the International Safety Guide for Inland Navigation Tank-barges and Terminals (ISGINTT) was published in 2023[6]. The Central Commission for the Navigation of the Rhine (CCNR) published a roadmap on reducing emissions in inland navigation in 2022[24][25][26].

The transport of $CO_2$ as a dangerous substance is regulated by the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN) agreement, for which the CCNR acts as co-secretariat[27]. The ADN is a European agreement regarding the transport of dangerous goods on inland waterways. There is no CCNR working group on the issue of the geological sequestration of $CO_2$. The CCNR's work is aimed at reducing emissions from the current fleet ($CO_2$ and other pollutants). The CCNR have applied for $LCO_2$ shipping by inland barges to be included as a dangerous good in the ADN list. Member countries apply with the governing body in Geneva to have the listing amended. This process can take more than two years.

24. International Safety Guide for Inland Navigation Tank-barges and Terminals (ISGINTT), 2023.
25. CCNR roadmap for reducing inland navigation emissions, Central Commission for the Navigation of the Rhine, 2022.
26. Key points of the CCNR roadmap for reducing inland navigation emissions, Central Commission for the Navigation of the Rhine, 2022.
27. European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways, United Nations Economic Commission for Europe, 2023.

# 5. Potential gaps on $CO_2$ specifications for ship transport

As mentioned above the deployment of a European transport grid will require universal rules for allowable concentrations. It is possible to distinguish between transport modes. This implies accepting hubs with further $CO_2$ treatment at points where transport modes change. This will be a more effective solution than fulfilling all constraints resulting from all transport modes at any point in the network.

It is recommended that the early technical focus is on impurities that are the most likely to be found and which are likely to influence the corrosion regime. These impurities would be associated with industries for which long-term $CO_2$ capture remains the most likely option, including hard-to-abate sectors such as cement, steel, waste-to-energy, chemicals, blue hydrogen and dispatchable power options. These should be carried out in multi-impurity tests, $NH_3$, CO and HCN are examples of impurities that could be expected at relevant concentrations. Sulphur containing species could in principle react and contribute to the total $SO_2$ level and should be particularly focused on (e.g., mercaptans, thiols, carbon disulphide or carbonyl sulphide).

Using impurities within these streams, defining how they exit the expected capture processes, plus any further potential contamination of the $CO_2$ from the capture process itself, may help constrain the concentration range and number of impurities that need to be further studied. More research work should be undertaken to gather additional data and map the $CO_2$ stream compositions from all possible emitters[28]. Direct air capture has been excluded from this list because of the relatively early stage of development and the relative flexibility of its location.

Furthermore, the current guidelines are only provided at “typical” pipeline conditions, the evaluation of the corrosion impact of the potential impurities needs to be extended to the full value chain, in particular to the transport conditions of low and ambient temperature transport and the conditions likely to be encountered within the well, during both during injection operations and shut down.

The work done to date (see Figure 3 from the earlier CCSA/ZEP report) shows that acids are less soluble at lower temperatures and less soluble at pressures below 100 bar. The current ‘guidelines’ may therefore not be conservative enough for some shipping temperature conditions. Only one paper, studying the corrosive effects of one combination of impurities at low temperature, confirmed that the reaction mechanisms observed in the pipeline were also valid for this lower temperature condition[29]. Further work includes an assessment of corrosion implications against the grade of steel used for low temperature transport since this grade is likely to be different from the grade

28. Such work includes, for instance, the Wood Joint Industry Project “Industry Guidelines for Setting the CO2 Specification for CCS Chains”. This work is ongoing and not published at this time.
29. Tjelta, Morland, Dugstad, and Svenningsen, Corrosion reactions in simulated CO2 ship transport conditions, CORROSION 2020, 14 June 2020.

used at warmer transport temperatures. Similarly, the grades of steel that are expected to be used in the well injection tubing will need to be defined and included in the test work.

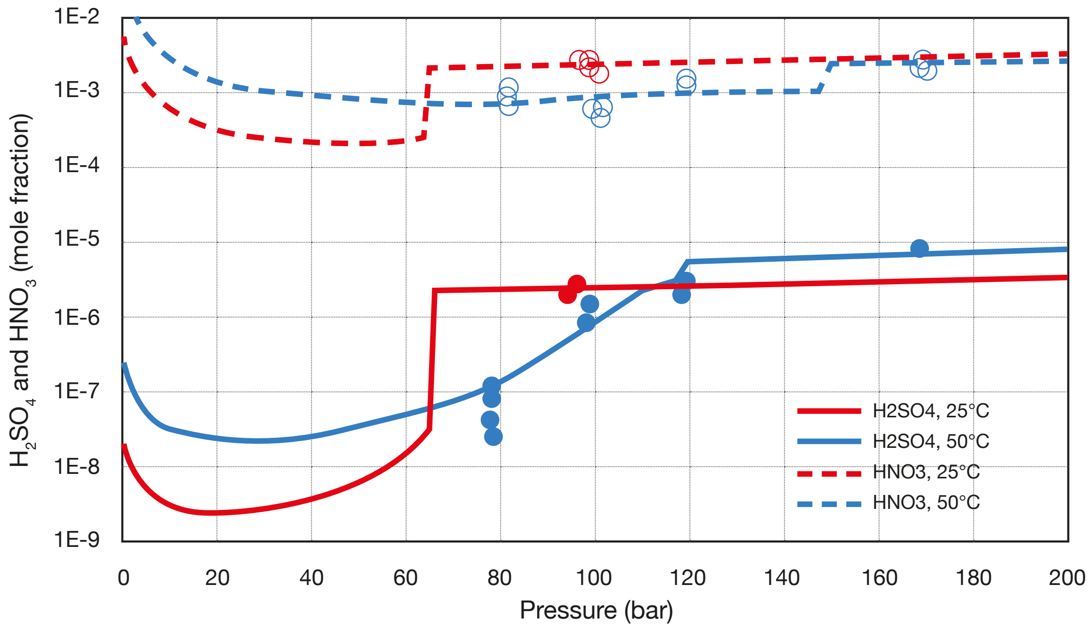



Figure 3. Comparison of calculated and experimental solubilities of sulfuric acid (solid lines symbols) and nitric acid (dashed lines, hollow symbols) in $CO_2$. The lines show the OLI MSE calculations whereas the symbols denote the experimental data.

In summary, the following measures can be recommended for future research work:

1. Evaluate the likely impurities (substance and concentration) in $CO_2$ emitted and captured from the flowing industries, cement, steel, waste-to-energy, chemicals, blue hydrogen and likely dispatchable power options, including impurities from the prominent capture processes.

2. Use the output from point 1 and the learning from the evaluation of the interaction between the impurities $H_2O$, $NO_2$, $SO_2$, $H_2S$, $O_2$, to evaluate the impact of other impurities at different concentration whose interactions could generate new corrosion risks or contribute to the acid generating interactions already identified. Provide guidelines on limits of respective combinations and "relaxation options" as per the original work.

3. Repeat the original corrosion risk evaluation and any additional corrosion risk identified in point 2 at the conditions (temperature and pressure) of the potential transport conditions (low and ambient temperature) as well as conditions likely to be encounter in the well during in-

jection operations and whilst shut down. Highlight any differences/amendments, particularly more restrictive compositional limitations, necessary to the guidelines on limits of respective combinations and "relaxation options" in point 2 associated with the different transport or well conditions.

4. Evaluate the corrosive impact of impurities, which have been studied on the basic grade of carbon steel and consider the impact of other steel grades or alloys that are likely to be selected, either because they are required for low temperature transport conditions or are used in the wells for either temperature or used as mitigation measures, where the well could be exposed to higher water content originating from the reservoir rather than the injected $CO_2$.

5. The following anti-corrosion measures should be considered to safeguard containment integrity:
    1) Material upgrading (stainless steel of certain composition that is suitable for small tanks);
    2) Additional thickness of the plate and extra thickness will depend on points 2 and 3 of the analysis above;
    3) Suitable coating of the areas internally more prone to corrosion (e.g., bottom, cargo well, others);
    4) Cathodic protection in way of areas more prone to corrosion (see above); and
    5) Optical or other principal continuous monitoring of pH, aqueous phase formation; set point value will depend on 2&3 analysis above.

## Safety risk

The current approaches available to assessing the risk of a $CO_2$ release to individuals is covered in the UK Health and Safety Executive document 'Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment'. This document offers two methods of assessing risk, using the 'Probit Functions', or using the data for specified level of toxicity (SLOT) and significant likelihood of death (SLOD). Both of these methods evaluate the risks of the components on an individual basis. However, it is known that carbon dioxide induces increased respiration rate at above 2% concentration (50% respiration increase) and the respiration rate doubles at 3% concentration. In addition, the increased concentration of $CO_2$ produces oxygen depletion, and this can increase the uptake of other toxic components present in the atmosphere.

To date there is no known publication or specific guidance on the impact of the impurity when combined with the presence of 'bulk' CO2. It may be that, for shipping, the relatively high purity of $CO_2$ required negates this risk as the allowable concentration of other impurities is relatively low and may be more relevant for pipeline projects that can tolerate high impurity concentration, but this could still be valid for port facilities that receive inputs from both pipeline and shipping.

### Conditional recommendation

If data is not available and the risk is confirmed, the recommendation would be to establish concentrations of other toxic components individually but in the presence of bulk $CO_2$ (and the impact that bulk $CO_2$ has on the individual component).

# 4. Barriers and enablers for the commercialisation of $CO_2$ transport by ship

## 1. Regulatory barriers to a European market for $CO_2$ transport by ship

Several interlocking international legal instruments regulate the transboundary shipment of $CO_2$. While recent international and European law developments support CCS and CCU, three elements of the applicable legal frameworks require further attention to incentivise transboundary transport and sub-seabed storage activities within Europe, as well as between European and non-European countries. The present chapter focuses on, firstly, regulatory barriers emanating from the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 1972 (the "London Convention"), and the 1996 Protocol to the London Convention (the 'London Protocol')[30][31]. Secondly, the chapter identifies barriers to $CO_2$ transport emanating from the 1996 International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea and its 2010 Protocol ('HNS Convention'). Finally, it considers how the EU Emissions Trading System (EU ETS) applies to certain shipping related CCS/CCU activities.

### Prevention of Marine Pollution by Dumping of Wastes

International rules on marine pollution regulate transboundary shipping and maritime geological storage of $CO_2$. For example, the 1982 United Nations Convention on the Law of the Sea obliges its parties to "prevent, reduce and control pollution of the marine environment by dumping"[32].

30. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (opened for signature on 29 November 1972, entered into force on 30 August 1975) 36 ILM 7.
31. 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (opened for signature on 7 November 1996, entered into force 24 March 2006) 36 ILM 7.
32. Article 194(1), United Nations Convention on the Law of the Sea, opened for signature on 10 December 1982 (entered into force on 16 November 1994).

The London Convention and the London Protocol are additional treaties restricting maritime dumping. Moreover, regional agreements—including the 1992 Convention for the Protection of the Marine Environment of the North-East Atlantic ("OSPAR Convention")—regulate marine polluting activities[33].

## The 1972 London Convention and 1996 London Protocol

In 2019 the countries of the London Protocol took steps to enable the transboundary movement of $CO_2$ for CCS activities. This has removed a key barrier to the development of CCS projects which are seeking to use ships to move $CO_2$ between countries.

The London Convention was one of the first international treaties on protecting the marine environment. It sought to place limitations on the uncontrolled dumping of waste at sea. Generally, under the London Convention, disposal of certain types of wastes was prohibited outright, whilst other wastes were subject to prior permitting.

Despite its innovative legal framework, some observers criticised the London Convention for its perceived lack of ambition and regulatory stringency in controlling marine pollution. Following this, states agreed the London Protocol in 1996 (it entered into force in 2006) to modernise and eventually replace the London Convention. Most EU member states and European Economic Area (EEA) countries are contracting parties to the London Protocol. Although the USA is a party to the London Convention, it has not yet ratified the London Protocol. Compared to the London Convention, the London Protocol's dumping regime raises environmental ambition by operating on a "positive listing" basis[34]. This approach means that the Protocol prohibits any dumping of any wastes or other material at sea, unless the type of material falls within an exception listed in Annex 1. Any permitted disposal is subject to adequate regulation and the issuance of permits by its parties.

Significantly, the London Protocol also widens the definition of "dumping" to include "any storage of wastes or other matter in the seabed and the subsoil thereof". The parties have resolved that offshore CCS activities constitute a prohibited form of dumping under the London Protocol. The London Convention's and London Protocol's scope covers all marine waters, other than the internal waters of states and "sub-seabed repositories accessed only from land"[35]. Notably, Article 6 also prohibits the export of waste for the purposes of dumping at sea. Its rationale is that prohibiting dumping alone is not effective if waste can be exported for dumping by another state.

33. Convention for the Protection of the Marine Environment of the North-East Atlantic (opened for signature on 22 September 1992, entered into force on 25 March 1998).
34. Article 4, London Protocol.
35. Annex 1, paragraphs 1.8 and 4, London Protocol, as amended by IMO Resolution LP.1(1) (Adopted on 2 November 2006).

## The 2006 and 2009 Amendments

An amendment to Annex 1 of the London Protocol in 2006, proposed by Australia, the UK, Norway, France and Spain, added captured $CO_2$ streams—which “consist overwhelmingly” of $CO_2$ (and “no other waste or matter”) disposed into sub-seabed geological formations—as a category of waste to the list of exceptions permitted for disposal at sea. This exception is subject to adequate permitting, monitoring, and risk assessment outlined in Annex 2. The amendment entered into force for all contracting parties in 2007, making offshore carbon storage permissible under international law.

Subsequently, the International Maritime Organization (IMO) examined the feasibility of cross-border exports of $CO_2$ for CCUS purposes. Its secretariat concluded that Article 6 of the London Protocol had initially intended to prevent contracting parties from exporting waste to non-parties (in attempts to circumvent the London Protocol’s controls). However, it noted that the article could pose a significant barrier to deploying CCUS projects. The export prohibition enshrined in Article 6 would capture all exports of $CO_2$ designated for storage at sea – including to the London Protocol’s contracting parties – rather than merely exports to non-parties. In 2009, the contracting parties adopted an amendment, adding a new paragraph to Article 6 allowing countries to export and receive CO2 for offshore geological storage (the “2009 Amendment”).

The 2009 amendment applies two main conditions to such exports:

1. Firstly, there must be an agreement or arrangement between the countries concerned, allocating permitting responsibilities between the parties[36].[18] For exports to non-contracting countries, such an arrangement must include provisions consistent with the London Protocol (including the minimum regulatory requirements prescribed in Annex 2)[37].
2. Secondly, parties to such an agreement or arrangement must notify the IMO[38].

36. The IMO parties clarified the responsibilities of parties and requirements of the agreements and arrangements which must be entered into by Parties and non-Parties wishing to undertake export of CO2 in its 2013 Guidance on the Implementation of Article 6.2 on Export of CO2 Streams for Disposal in Sub-seabed Geological Formations for the Purpose of Sequestration, LC 35/15, Annex 6 (2013). In particular, a contracting party is responsible for issuing permits where a CO2 stream is loaded onto a vessel in its territory, and also where a vessel flying its flag loads a CO2 stream in the territory of a non-Party for export to another country. In the case of exports to non-parties, it is the full responsibility of the contracting party to ensure “that the provisions of the agreement or arrangement would need to reflect the appropriate permitting responsibilities of each”. This requirement ensures the same level of environmental protection when a non-party stores a party’s $CO_2$.

37. It is also understood that the bilateral agreement is only required for storage and that a ship carrying CO2 can pass through territorial waters of a third country without such country being required to either deposit a declaration, or enter into a bilateral agreement.

38. IMO Resolution LP.3(4) (Adopted on 30 October 2009).

The 2009 Amendment allows countries wishing to participate in CCS and CCU activities—but which do not have access to offshore storage sites within their national boundaries—to do so under international law. However, the 2009 Amendment's entry into force requires ratification by two-thirds of the London Protocol's contracting parties (or 36 countries), which has not yet happened. Ten parties have ratified the 2009 Amendment: Norway, the UK, the Netherlands, Iran, Finland, Estonia, Sweden, Denmark, Belgium, and the Republic of Korea.

In the interim, the parties adopted a resolution in October 2019 allowing provisional application of the CO2 export amendment to Article 6[39]. Provisional application means that any party may implement the Article 6 amendment before the article's formal entry into force. The IMO reports that Belgium, Norway, the Netherlands, Denmark, Sweden, the Republic of Korea, and the United Kingdom have commenced provisional application of this amendment. Nevertheless, some commentators have suggested that this is not the most appropriate solution, and that the contracting parties should have instead issued an interpretative resolution stating that Article 6 does not apply to cross-border transfer of CO2. In the latter case, no formal amendment would be needed[40]. In any case, the 2019 resolution removed the last significant international legal barrier to the export and receipt of CO2 for offshore storage. The first bilateral agreement under Article 6 of the London Protocol (as amended by the 2009 Amendment) was signed between Belgium and Denmark on 26 September 2022. Other countries have also declared plans to formalise bilateral arrangements (including Belgium and Norway, Norway and Sweden, as well as the UK and Norway)[41].

Other types of international law arrangements can satisfy the requirements of Article 6.2 (as amended by the 2009 Amendment). For instance, in September 2022, the European Commission published a paper on the compatibility of EU law and the London Protocol requirements[42]. The conclusion stated by the European Commission in the paper is that EU law, and the EEA legal regime incorporating relevant EU law, are sufficient to constitute "an arrangement" under the amended Article 6 of the London Protocol. The European Commission's view is that any bilateral arrangements should be limited to residual matters falling outside EU law. On this interpretation, arrangements between EU/EEA member states that are contracting parties to the London Protocol would only require limited bilateral agreements. The bilateral agreement between Belgium and Denmark is one example of such an agreement. This position was held by the European Commission in a report published in 2023, stating that "any operator of $CO_2$ transport networks and/or $CO_2$ storage sites enjoys the full benefit of the EU legal framework to import or export captured $CO_2$. The implemented EU legal framework acts as the relevant "arrangement" between the Parties in the meaning of Art. 6(2) of the London Protocol, given the substantive alignment with the requirements of the London Protocol"[43].

39. IMO Resolution LP.5(14) (Adopted on 11 October 2019).
40. Viktor Weber, Are we ready for the ship transport of CO2 for CCS? Crude solutions from international and European law, 2021, RECIEL 387.
41. Naida Hakirevic Prevljak, How can Europe and Norway cooperate to scale up the CCS market?, 3 October 2022, Offshore Energy.
42. European Commission, EU – London Protocol Analysis paper final 0930, 30 September 2022.
43. Report on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide, 24 October 2023, European Commission.

Consequently, we might consider that any regulatory barriers emanating from the London Protocol flow from a lack of political will by contract parties, as opposed to any inherent regulatory issues. Put alternatively, it is not so much the London Protocol regime that precludes the shipping of $CO_2$ for storage. Instead, the lack of coordinated efforts by contracting parties to ratify, provisionally apply, or enter into bilateral agreements impedes the implementation of the 2009 Amendment. However, as governments increasingly recognise the importance of CCUS as part of their energy strategies and decarbonisation efforts—and major cross-border CCUS projects are under development—we only envisage more arrangements facilitating cross-border movement of $CO_2$ for storage soon.

Nevertheless, countries' insufficient domestic regulatory and bilateral efforts pose challenges to deploying international CCUS projects. Many countries have not yet ratified the London Protocol, including the USA, India, Indonesia (and most of South-East Asia), Russia, Brazil (and most of South America), as well as most African states. Their ratification status does not preclude those countries from exporting $CO_2$ streams to London Protocol contracting parties. However, it may complicate $CO_2$ exports to non-contracting parties, as the bilateral agreements underpinning those exports must likely include detailed provisions incorporating safeguards consistent with the London Protocol.

ZEP recommends that European countries that are parties to the London Protocol deposit a notice of provisional application of the $CO_2$ export amendment with the IMO to enable the development of cross-border $CO_2$ transport in Europe.

### OSPAR Convention

Regional instruments, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic ("OSPAR")—which include the EU countries, Iceland, Norway, Switzerland, and the UK as signatories—are also relevant. In particular, OSPAR regulates the storage of $CO_2$ in geological formations under the seabed[44]. The OSPAR Parties have set out minimum standards on $CO_2$ marine disposal activities and published guidelines on risk assessment and management. Importantly, there is no export prohibition on wastes under OSPAR.

44. Article 5, OSPAR Convention (1992).

## $CO_2$ Transport under the Convention on Hazardous and Noxious Substances

The Hazardous and Noxious Substances (HNS) Convention has 45 signatories. It intends to establish an international liability framework for hazardous and noxious substances. The HNS Convention's provisions were modelled on the international legal regime applicable to the carriage of oil and gas. While neither the Convention, nor its 2010 Protocol, has entered into force, six states (Canada, Denmark, Norway, South Africa, Turkey, and Estonia) have now ratified both agreements[45]. While fewer than the 12 states are needed for entry into force, the IMO anticipates several additional states may ratify the agreements immediately, enabling entry into force shortly[46]. Upon entering into force, the HNS Convention will apply to ships carrying $CO_2$, with the regulation of liquified bulk $CO_2$ falling within its regulatory scope[47].

However, the maritime transportation of $CO_2$ for CCS and CCU purposes was not envisioned during negotiations of the HNS Convention. As a result, $CO_2$ transport would fall under the HNS regime. This regime is arguably inappropriate for early-stage $CO_2$ transportation activities, particularly given the anticipated low environmental risk profile of $CO_2$ streams transported by sea[48].

The HNS Convention imposes liability on ship owners to compensate those suffering loss or damage from an HNS incident. This includes liability for accidents in which fault rests with third parties[49]. The HNS Convention limits ship owners' liabilities to a certain amount, beyond which the HNS Fund compensates those affected parties. Each limit depends on the ship's size and the cargo type[50], and is denominated in terms of Special Drawing Rights ("SDRs"). An SDR is a supplementary international reserve asset, created by the International Monetary Fund. The IMF defines the SDR as equivalent to the value of a basket of world currencies. IMF members can hold and exchange SDRs for currency, when required. The applicable limits apply only when cargo is on board, rather than awaiting transfer to the vessel from onshore storage tanks or following discharge to the storage site.

45. Under the agreement, the NHS Protocol will enter into force 18 months after the date on which it is ratified by at least 12 states, including four states with not less than 2 million units of gross tonnage, and having received during the preceding calendar year a total quantity of at least 40 million tonnes of cargo that would be contributing to the general account.
46. Status of the HNS Convention and 2010 Protocol.
47. More specifically, "[h]azardous and noxious substances" under Article 1(5)(a)(v) of the NHS Convention include "liquified gases as listed in chapter 19 of the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk", such as liquified bulk CO2.
48. Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos, and Leo Meyer (eds), Carbon Dioxide Capture and Storage (Cambridge: Cambridge University Press, 2006), Sections 4.3 and 4.4.4.
49. Articles 7(1), (5), and (6) of the HNS Convention.
50. Under Article 9 of the NHS Convention, the general formula limits liability for the first 2,000 units of tonnage to 10 million Special Drawing Rights. It adds 1,500 SDRs per tonne between 2,001 to 50,000 tonnes, and 360 SDRs per tonne above 50,000 tonnes, to the liability cap.

The HNS Fund is financed by contributions from cargo receivers to which the HNS Convention applies[51]. The regime creates a general account—for bulk solids and other hazardous or noxious substances—along with a separate oil account, an LNG account, and an LPG account. These different accounts emanate from the unwillingness of less hazardous sectors to cross-subsidise damages from other sectors. Upon the HNS Convention's entry into force, the HNS's general account will likely fund liabilities arising from CCUS incidents.

A legal question arises regarding whether $CO_2$ cargo shipped to storage sites should trigger the need for storage site operators to contribute funds to the general account, particularly given CCUS projects' nascent stage of maturity, commercial viability, and reliance on public subsidies. CCUS participants also do not import or trade in the same way as other entities covered under the HNS Convention. Specifically, those participants are, at present, unlikely to sell $CO_2$ on the market, or use $CO_2$ to produce other goods in material volumes. These factors may justify an exception or reduced contribution, particularly in promoting CCUS activities for accelerating global climate change mitigation.

Furthermore, $CO_2$ is not flammable, and many experts suggest its inadvertent release at sea is not anticipated to have the same long-term environmental effects as crude oil spills[52]. Marine transport of $CO_2$ is also likely to have a similarly strong safety record as other transportable gases. Therefore, if contributions for $CO_2$ are deemed necessary under the HNS Convention, it may be suitable to create a separate account, applicable specifically to $CO_2$.

51. Ibid, Articles 16-20 and Annex II.

52. Bert Metz, Ogunlade R Davidson, Heleen de Coninck, Manuela Loos, Leo Meyer, IPCC Special Report on Carbon Dioxide Capture and Storage (Cambridge: Cambridge University Press, 2005), pp. 188-189.

### The regime for shipped $CO_2$ under the EU ETS

The EU ETS applies in the EU and the European Economic Area (EEA)[53]. It requires operators of certain covered installations to purchase and surrender allowances—corresponding to the amount of $CO_2$ they produce—unless they capture and "permanently" store that $CO_2$ for CCS and CCU purposes[54]. Consequently, operators have incentives to partake in CCS and CCU activities, where the costs of capture, transport, and injection of $CO_2$ cost less than the price of emitting the $CO_2$ (as determined by EU allowance prices). However, the EU ETS's drafters initially focused on $CO_2$ transportation by pipeline, rather than envisioning the possibility that the instrument might also include maritime transport of CO2 to storage sites[55].

### The right to subtract captured and stored $CO_2$

Sectors covered under Annex I of the EU ETS directive include electricity and heat generation, oil refining, iron, steel and aluminium, paper, glass, organic chemical production, maritime transport, and aviation within the EEA. As part of its significant "Fit for 55" legislative reforms, passed on 20 April 2023, the EU amended this list of covered sectors to include maritime transport[56].

The EU Monitoring and Reporting Regulation requires that operators measure and report both emissions from these activities and fugitive emissions[57]. However, it allows operators to subtract from an installation's emissions any amount of $CO_2$ produced from covered activities that is not emitted into the atmosphere, but is transferred — to a capture installation, transport network, or storage site within the EU/EEA — for long-term geological storage purposes[58]. In this context, neither the Monitoring Regulation nor the CO2 storage directive expressly envisage transport of CO2 by ship (although they do include provisions relating to transport via pipelines). As a result, it is unclear whether subtraction of CO2 from the installation's emissions is permitted where the transfer from a covered installation is by ship. Insofar as EU ETS liabilities could still attach to CO2 shipped and injected into a storage site—the regime may lead to unduly restrictive outcomes.

53. What is the EU ETS?, European Commission website.
54. Parliament and Council Directive (EC) 87/2003 of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community [2003] OJ L275/32 ("ETS Directive"). Article 12(3a) of the EU ETS Directive stipulates that: "An 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 the CCUS Directive." Further evidence of permanent containment includes the "conformity of the actual behaviour of the injected CO2 with the modelled behaviour", the "absence of any detectable leakage", and that "the storage site is evolving toward a situation of long-term stability". See Article 18(2) of the Parliament and Council Directive (EC) 31/2009 of 23 April 2009 on the geological storage of carbon dioxide [2009] OJ L140/114 ("CCUS Directive"); European Commission (DG CLIMA), Implementation of the CCUS Directive: Guidance Document 3 (Criteria for Transfer of Responsibility to the Competent Authority), 2011.
55. Directive (EU) 2023/959 states that "As CO2 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".
56. Parliament and Council Directive (EC) of 20 April 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system.
57. Commission Regulation (EU) 2066/2018 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council [2018] OJ L334/1 ("Monitoring Regulation").
58. Ibid, Article 49(1).

No subtraction of $CO_2$ from the installation's emissions is permitted for any other type of transfer from a covered installation. Insofar as EU ETS liabilities could still attach to $CO_2$ shipped and injected into a storage site—because the $CO_2$ was not transferred exclusively through a pipeline network—the regime would lead to unduly restrictive outcomes. As a result, the European Commission recently clarified—in response to a request from the Norwegian Environment Agency—that transfer of captured $CO_2$ to a ship, and later transferred from the vessel to a pipeline transport network or directly to a storage site, does not alter the right of $CO_2$ producers to subtract that captured and stored $CO_2$ from their EU ETS liabilities. Upon transfer of the transported $CO_2$ to the storage site, the $CO_2$ producer can subtract that transferred $CO_2$ from their emissions. However, $CO_2$ leaked during transport cannot be subtracted from the $CO_2$ producer's emissions[59].

Therefore, in the Commission's view, the transport of $CO_2$ by ship within the EU/EEA is unimpeded by its lack of explicit inclusion in the EU ETS. Yet, at present, the inclusion of $CO_2$ transport by ship in the EU ETS relies on this specific legal interpretation, rather than being explicit on the face of the legislation. While highly persuasive, the Commission's view is merely an opinion, rather than binding legal authority.

In addition, absent further legal clarity, EU/EEA $CO_2$ emitters intending to export $CO_2$ for storage outside the EU/EEA are not eligible to deduct captured and stored $CO_2$ from their EU ETS liabilities. Similarly, despite ongoing negotiations between the EU and UK, the EU ETS is also not currently linked with the UK ETS. This impedes both EU/EEA and UK $CO_2$ producers—seeking to export $CO_2$ to storage sites located in the other jurisdiction—from subtracting the transferred $CO_2$ from their EU ETS and UK ETS liabilities, respectively. These are significant regulatory barriers to scaling up $CO_2$ export activities, both within Europe and worldwide. Legal arrangements addressing cross-border $CO_2$ shipments between EU/EEA and non-European governments could make $CO_2$ producers eligible for deductions to their ETS liabilities. Such arrangements could generate crucial financial incentives for scaling up CCS and CCU activities. It is worth noting that the EU ETS directive includes the following provision: "When reviewing this Directive […] the Commission shall analyse how linkages between the EU ETS and other carbon markets can be established without impeding the achievement of the climate-neutrality objective and the Union climate targets laid down in Regulation (EU) 2021/1119"[60]. This provision opens the door to a potential future linkage between the EU and UK ETS. The possibility of such linkage and collaboration on carbon pricing is also mentioned in the EU-UK Trade and Cooperation Agreement. In addition, ZEP has proposed that "the UK and the EU should agree on the definition of 'high-quality storage of $CO_2$' and the rules that underpin this definition" to enable the subtraction of $CO_2$ across both emissions trading systems[61].

59. See Letter from the Norwegian Ministry of Climate and Environment to the European Commission, DG CLIMA, "The Norwegian CCS Demonstration Project – Request for Legal Clarifications Related to the ETS Directive and the MR- Regulation' (7 July 2019). In response, see Letter from the European Commission, Directorate-General, Climate Action to the Ambassador of Norway to the European Union" (Ref. Ares(2020)3943156 –27/07/2020), cited in Weber (2021), p. 394. At the time of writing, the latter letter is not available online.

60. Directive amending Directive 2003/87/EC and Decision (EU) 2015/1814, 2023, EUR-Lex.

61. Need for similar rules on CO2 storage in the EU and UK ETS, 16 June 2022, Zero Emissions Platform.

The transport of $CO_2$ across ETS systems will require the recognition of storage by other countries and the proof that the captured $CO_2$ is safely stored.

## Monitoring plans and surrendering allowances: the distribution of responsibilities between operators

Assuming the Commission's view is accurate, potential issues associated with the distribution of responsibilities between operators under the EU ETS remain. Recent legislative amendments phase the shipping sector into the EU ETS from 2024. The Monitoring Regulation now includes provisions to measure and report shipping emissions. Nonetheless, there remains a question of how these amendments will operate alongside the Commission's position on $CO_2$ transport by ship.

For example, the amended legislation requires shipping companies to surrender EU allowances corresponding to greenhouse gases emitted from covered vessels on voyages and port calls within the EU/EEA, or into or out of the EU/EEA. Under this amended legislation, shipping companies transporting $CO_2$ to a storage site are likely liable for transport emissions. In contrast, $CO_2$ producers could bear liability for any fugitive emissions caused by $CO_2$ leakages occurring en route to the storage site.

Nevertheless, EU ETS coverage of shipping emissions will remain limited at the outset. For example, in-scope emissions will be progressively phased in from 2024 onward, and shipping companies will not initially be liable for emissions from smaller vessels[62]. Therefore, an issue arises regarding which counterparty will be liable for emissions from uncovered emissions or below-threshold shipping activities. For example, will $CO_2$ producers be held liable for those residual transport emissions under the EU ETS? While that is potentially a rational outcome, the position has not been confirmed in legislative instruments or by the Commission.

Similarly, the legislation offers limited guidance on methods to calculate and monitor operational or fugitive emissions occurring during specific maritime journeys to transport $CO_2$ to storage sites. The amended Monitoring Regulation requires shipping operators to report aggregate emissions data only at the company level, rather than for specific journeys. Furthermore, when and under what circumstances might title to the $CO_2$ stream—and liability for leakages—pass to a party other than the $CO_2$ producer? How should $CO_2$ leakages during transport be attributed to individual co-producers?

62. From the introduction of shipping into the EU ETS in 2024, the ETS will only cover ships above 5,000 gross tonnes, CO2 emissions, and 50% of emissions for voyages into and out of the EU/EEA.

Absent further legislation or regulatory guidance, these regulatory gaps may give rise to methodological ambiguities—and the possibility of multiple approaches to measurement and reporting—which could compromise the integrity of $CO_2$ accounting within CCUS supply chains. Ultimately, this may risk dissuading private investment in otherwise promising CCUS projects. The process for a revision of the Monitoring and Reporting Regulation has started in 2023 and provides an opportunity to address these issues.

ZEP proposed changes in the context of the public consultation on the revision of the Monitoring and Reporting Regulation to ensure an adequate inclusion of ship transport under the regulation[63].

63. ZEP feedback 'EU emissions trading system (ETS) – update of the rules for monitoring and reporting emissions, 2023, Zero Emissions Platform.

# 2. Commercial barriers and enablers to a European market for $CO_2$ transport by ship

### Developing a commercial setup for $CO_2$ transport by ship

The UK plans to use a regulated asset base model for the transport and storage of $CO_2$, in which users will pay fees to use the transport and storage (T&S) network. This model would include regulated tariffs for the use of onshore and offshore pipelines. While gas networks have monopolistic features ship transport is expected to become a competitive activity as several companies can compete to transport $CO_2$ from industrial emitters to storage sites[64]. Regulated tariffs are therefore not recommended for the future European market for $CO_2$ transport by ship.

### Existing financial incentives and gap in required funding

There is a gap between the cost of emitting $CO_2$ and the cost of implementing CCS. Policies are in development to close this through the EU ETS system and emitter subsidies and infrastructure funding mechanisms. A successful implementation of CCS to meet Europe's climate goals will rely on $CO_2$ transport to grow at a sufficient scale to match at least at the same rate as capture and storage capacity, for $CO_2$ shipping is a critical solution for industry emitters (hubs) without access to pipelines. It is important that $CO_2$ shipping as a solution is developed at a sufficient scale and speed to be able to meet the climate goals, and there is a risk that this scale is achieved too late.

The key complication for CCS solutions between emitters and stores that rely on $CO_2$ shipping to decarbonise is the challenge of higher costs at the emitter side compared to emitters that have access to (existing) pipelines, due to additional investments required (liquefaction, buffer tanks, jetty) and operational costs.  For the end-to-end value chain $CO_2$ shipping will be able to provide the advantage of accessing lower cost store options and by providing a capacity to stabilise CCS system due to the logistics and buffer storage optimisation. This raises the key question: what can be done to ensure the gap in financial incentives is closed for $CO_2$ shipping? The following levers are identified to bridge the gap in financial investment to unlock $CO_2$ shipping:

64. Kahn, A.E. The Economics of Regulation, The MIT Press, 1988.

### Fair competition for funding support available to industrial emitters that rely on $CO_2$ shipping

It is crucial to ensure that industrial emitters that rely on $CO_2$ shipping solutions can have a fair competition for sufficient subsidies to decarbonise. $CO_2$ shipping projects find it difficult to compete with pipeline emitters for subsidy funding. If there are not enough shipping customers that have enough incentive due to competition from pipeline emitters this will delay the forming of a $CO_2$ shipping market development at scale and would also result in a 'geographically skewed' transition, favouring sites that happen to be near pipelines. An example is the Dutch SDE++ subsidy scheme, where there is a separate 'Cryogenic' category with higher subsidy amounts to cover the extra costs for emitters that rely on $CO_2$ shipping. In case there is still uncertainty in the transport concept of the projects, flexibility for projects to switch/fall-back to the required subsidy category would be necessary to avoid a lock-in to unviable concepts (e.g., uncertainty as to whether pipeline options will be available or not). The Carbon Capture & Storage Association (CCSA) published a paper in September 2023 highlighting that ship and non-pipeline transport should be reflected in bid instructions for Track-1 and Track-2 expansion capture bidding process[65].

### Allocate infrastructure funding to establish regional shipping terminal hubs

This allocation is required with sufficient pre-invested capacity of the shore/port facilities to facilitate further expansion and regional aggregation. How can we ensure that there is an incentive to invest and 'oversize' the capacity of key $CO_2$ shipping infrastructure components (terminal capacity, aggregation capacity) for the next waves of industrial emitters to benefit from, due to increased economies of scale and elimination of future bottlenecks?

65. Integrating CO2 transport by ship into the Track-2 and Track-1 expansion capture bidding process, 2023, CCSA.

### Mechanisms for long-term certainty to underpin value streams for $CO_2$ shipping

Long-term certainty can be supported via the following measures:

- Set high-quality carbon credit accounting standards to build integrity for $CO_2$ transport by ship as a trusted solution the CCS value chain.
- Consider mechanisms to provide additional support for investment in ships that are in line with environmental and climate objectives. This includes recognising $CO_2$ shipping as a trusted low-carbon solution for sustainable CCS under supporting policy schemes. Recognise $CO_2$ shipping as an enabler for BECCS and DACCS enabled as a carbon dioxide removal (CDR) technology, to fund investments through the voluntary market and enable revenue certainty for $CO_2$ shipping projects through long-term carbon purchase commitments.

### Support de-risking of $CO_2$ shipping for future access to low-cost capital

It is crucial to demonstrate the project delivery, availability, and stability for the $CO_2$ shipping solution in the initial projects to sufficiently de-risk future investments for eligibility for bankability with access to low-cost capital. It is recommended to have highly capable partnerships in initial phases to share risks and have sufficient funding support as an incentive to demonstrate that it works.

### Operational cost of $CO_2$ transport by ship

Typically, normal yearly ship operational costs fall into three categories: fixed, fuel, and port fees. Fixed costs are associated with the administration, insurance, crew, maintenance, and repair. The crew and maintenance depend on the equipment type and size of the vessel. The port or harbour fees vary between various regions of the world. The fee is based on the capacity of the ship. Finally, the third element is the fuel cost which is variable and based on the size of the vessel, engine type, the type of fuel used, the cost of the fuel and the voyage. The voyage is the function of the distance between two ports.

In addition to the normal ship operational costs, there are also significant supply chain operational costs associated with the $CO_2$ conditioning (purification, liquefaction), loading and temporary storage (buffer) costs. Especially in non-normal operating conditions, these components may cause significant operational cost overruns when not adequately controlled. The following recommendations can be made in that regard:

- Port authorities should consider incentivising port/harbour fees for $CO_2$ shipping and/or vessel prioritisation protocols for $CO_2$ shipping and not apply existing conventional practices.
- Standards should be developed for $CO_2$ carriage conditions for cost-saving potential and controlling mechanisms to avoid system disruptions: a standard (set of) $CO_2$ compositional specification on the control of impurities and Carriage conditions are expected to drive down operational costs for CCS projects by achieving standard designs for the $CO_2$ conditioning and storage. Moreover, it is vital to have the right controlling mechanisms to avoid $CO_2$ contamination in $CO_2$ ships and transport systems.
- Compensation mechanisms should be put in place for the impact of required liquid $CO_2$ buffer storage volumes to stabilise transport and storage systems: if there is a time-lag between transport storage there will likely be a 'dead-stock value', which could result in a gap or significant delay to be able to receive EU ETS credits.
- Fit-for-purpose onshore metering standards, including measurements. Establish standard methodologies for CO2 metering and calibration for mass-balance quantification, avoiding excessive requirements on ship instrumentation that will result in excessively high-costs and operational complexity by having metering onshore (i.e., at terminal loading/unloading facilities).
- Implement innovation at the right pace: non-standard, multi-purpose and bespoke designs are likely to increase operational costs if they are implemented too early in the operational phase of a CO2 shipping market. At the same time, these are critical for longer-term step-changes to innovate. It is recommended to first fully demonstrate these in the R&D phase before upscaling these for wider implementation in the value chain.

### European storage availability and need of backup system to drive down costs, national governments willingness to take over long-term storage liability costs

The International Energy Agency (IEA) stated that "with growing plans to equip facilities with $CO_2$ capture, spurred by strengthened climate goals, a gap is starting to emerge between anticipated demand for $CO_2$ storage and the pace of development of storage facilities"[66].

To enable a $CO_2$ shipping market at scale it will be critical that storage developments that have or are linked to receiving terminal scope pick up pace. In addition, $CO_2$ shipping can support CCS hubs with more flexibility in volume streams due to liquid $CO_2$ buffer storage capacities at either end of the shipping route increasing the overall stability and availability of the system. $CO_2$ shipping can also enable destination optionality between a set of stores in case of storage disruptions, outages, or deviations from projected injectivity (both downside and upside).

66. Website of the International Energy Agency; Energy system, Carbon Capture, Utilisation and Storage; CO2 Transport and Storage.

Sufficient $CO_2$ shipping volumes in the CCS ecosystem will provide terminal buffering capacity of liquid $CO_2$ volumes and can enable high availability in storage systems. Especially for depleted field injection, it is critical to keep the system stable in initial phases and prevent disruptions in the injection operations and in the transport part of the value chain. The following statements can be made in that regard:

- Hub setups with competent operators are key, incentivised to drive performance; and
- Liquid $CO_2$ buffering capacity as part of the receiving terminals for $CO_2$ shipping can play a critical role to stabilize CCS hub system fluctuations, through management of the tank levels. It is critical that sufficient $CO_2$ shipping volumes are part of the buffering capacity to enable higher availabilities.
- The development of excess storage capacity should be accelerated with a receiving terminal link by enhancing the risk/reward balance and upside potential for storage investors to accelerate timely storage investments.
- When investment returns are commensurate with the associated subsurface and operational project risks to the investors, this will result in increased levels and speed of storage investments.
- Lack of upside for investors in the system, causes stringent agreements on send-or-pay for investors to manage risk. If more upside sharing is allowed, risk/reward considering increasing $CO_2$ prices can be further shared across different players in the value chain providing an incentive to accelerated storage and transport development investments. It is unlikely that there will be investment in excess storage capacity, e.g., for backup capacity or to facilitate flexibility combined with $CO_2$ shipping – if there is no clear upside unless supply/demand can be priced (e.g., ETS $CO_2$ price linkage in tariff).

### A competitive $CO_2$ market via open access

A competitive $CO_2$ market will need to accommodate several different shipping business models, for instance:

- A ‘pick-up’ service by the storage provider;
- A ‘drop-off’ model where the emitters provide its own shipping, and
- An independent shipper model, where the shipper acts as an intermediary between emitter and the store.

A market that encourages competition and incentivises the aggregation of additional (international) users is expected to lower the overall cost of $CO_2$ shipping. Such a market would require the possibility to ship $CO_2$ from various emitter sources through aggregation hubs. In the establishment of a competitive open-access $CO_2$ market, barriers are likely to emerge in the form of compatibility issues between multiple sources and destinations and the high levels of operational and commercial complexity due to operations and agreements between emitters, shippers, terminals/transport networks, and storage providers. The following recommendations are offered to be considered to allow formation of a successful open- access $CO_2$ shipping market:

- Standardisation of ship-shore interface (e.g., loading arms, interfacing connections) by the appropriate shipping organisation (SIGTTO), to enable compatibility, destination optionality and ultimately increase market competition;

- Standardisation of $CO_2$ specifications for shipping, liquefaction, and onshore storage to ensure compatibility and consistency between CCS projects to be achieved through Joint Industry Projects dedicated to the subject followed by establishing a working group and publications by ISO;

- Acceleration of a cross-border $CO_2$ shipping transportation regulatory framework that covers the UK, the EU, and the EEA. This can be achieved via ratification/acceptance of the Article 6 amendment to the London Protocol, country-to-country agreements, and by mutual recognition and mechanisms for credits and liability transfer between the EU and UK ETS systems;

- An adequate business environment enabling multiple international $CO_2$ shipping providers to invest and offer services on a competitive basis. This will give CO2 shipping providers the incentive to carry the risk they are best place to manage, improve operational performance, and perform portfolio optimisation activities, resulting in a reduction of overall costs;

- Port constraints and prioritisation – $LCO_2$ shipping results in increase frequency whereby port authorities may give preference to other business (e.g., hydrogen or ammonia); and

- Extremely good safety and environmental footprint performance in early phases of CCS and $CO_2$ shipping to deserve License to Operate. Lower risk / more proven concepts should potentially be prioritised over higher risks/novel concepts, unless there is a high degree of assurance. The environmental footprint of shipping itself (NOx, $CO_2$ emissions, etc.) should also be minimised.

A commercial framework should be considered to manage the operational complexity introduced by parallel business models, especially where the emitter is in charge of its own shipping or it is provided through an independent/intermediary shipper. The following recommendations can be made in that regard:

- Frameworks for the different models on how open access is ensured and where responsibilities lie throughout the shipping and transport and storage value chain for liabilities, title and risks, and how due diligence and 'duty of care' assessments are carried out.

- Standard terms and conditions for operational planning and disputes on how to use a network and how to deal with deviations, including multiple measurement/transfer points and allocation standards. For instance, when there are logistics issues at the receiving terminal, sending terminal, during shipping, or a combination – who compensates whom in case of unavailability of the end-to-end system? How to address the impact on other shippers and how to resolve disputes in case of unclear circumstances? What happens if there is a loss/mismanagement?

### Public funding

Whilst the UK CCS target for 2030 remains within reach, the inclusion in $CO_2$ transport via road, rail and ship for currently operating plants is essential to achieve the goal. The recent announcements under the UK cluster sequencing competition, for example, the East Coast Cluster in the Teesside, UK, demonstrates the UK government ambition to fund large scale new build blue hydrogen (i.e. with carbon capture) and zero emission power plants (with carbon capture), and in parallel fund the development carbon capture networks within industrial clusters, but does not demonstrate a significant investment or interest in the reduction of $CO_2$ emissions from existing operating emitters.

The funding competitions and business models do not provide the clarity needed for existing emitters to continue the efforts and costs of designing a carbon capture project, without the opportunity to connect to the developing $CO_2$ gathering networks. The funding competitions for carbon capture networks in the UK do not provide an opportunity to 'aggregate' $CO_2$ and co-mingle with various sources of $CO_2$ to improve the condition (pressure, temperature and impurity) and/or the technical/commercial attraction of the project. The lack of ability to continue a design or concept based on aggregating $CO_2$ to achieve scale and reduce unit cost of sequestration will pause the development of multiple carbon capture projects.

The carbon capture networks and clusters illustrate a significant increase in yearly storage capacity after 2030, but the delay from now until 2030 will no doubt result in the closure of facilities that could have continued to operate with the benefit of a carbon capture project in development. As the European market continues to reposition the energy infrastructure assets, including refineries, gas plants and import and export terminals, judgements will be made on the future of the assets linked to the viability of a connection to a $CO_2$ storage location, or the ability to transport the $CO_2$ to a terminal for onwards shipping. The ability of an existing energy infrastructure asset to connect to a carbon capture store, either directly or indirectly, ensures the future interest to invest and operate the facilities long into the 2030s.

### Timeline

The scale of the currently anticipated CCS projects presents a potential for delay during design, planning, and construction, with the cost of materials and labour playing a significant role in capital projects delay and cost overrun in recent times, coupled with the cost of energy and raw materials feeding into the production costs of construction materials.

### Opportunity for existing/inland emitters

A review of existing operating emitting sites, and a detailed analysis of the 'deliverability' of carbon capture and transport will result in an opportunity list, detailed by market segment that will show the potential volume of $CO_2$ that can be captured and stored before the end of the decade. The deliverability criteria should assess the distance from the store or $CO_2$ shipping terminal, the volume of $CO_2$, the impurity level, and transport mode i.e., inland waterway, rail, road, or pipeline. Part of the challenge in assessing the opportunity for carbon capture across the sectors, for example energy-from-waste or the construction materials industries, is the lack of knowledge or funding available to provide an investment case and business model for carbon capture. In many cases, the cost of the concept study is prohibitive, and the operating company will not have the speculative funding available to assess the opportunity for carbon capture.

## Regulation

The local planning and permitting environment is essential for the success of large scale $CO_2$ terminal infrastructure to enable the shipping of $CO_2$. Existing import and export locations are likely to be fully occupied, given the long-term nature of the supply chains for chemicals and fuels, along with the lack of physical space to develop additional storage, even for existing customers. Future terminal development will consist of years of planning and permitting, before construction, which will include seasonal environment and wildlife assessments.

The local and national planning regime must ensure the national infrastructure regulations and support mechanism can be flexible to assist in the planning consents for large scale $CO_2$ terminal development, to prevent a lengthy delay and objections. The proactive planning approach will also need to consider the potential impact to the safety permitting for large scale storage of $CO_2$, which is not currently included in normal terminal operations. This could add complexity and add delay to the planning process.

## Commercial arrangements

The traditional import and export terminal business would usually recover design and construction costs within a long term (15 to 20 years) commercial arrangements, where estimates for yearly volumes and additional throughput charges are included in the agreements. For the existing chemicals and fuels storage and handling, the supporting infrastructure i.e., rail and road transport assets, pipelines, pumps, and storage vessels are already well established and, in many cases, transferable between materials, reducing the risk and cost to enable new customers and markets to develop.

The $CO_2$ market requires new build storage and handling infrastructure and the supporting network infrastructure i.e., vessels or train carriages, particularly at scale, to enable the transport and storage of $CO_2$, resulting in a need for the funding framework to have flexibility in the model to compensate for emitters with a range of investments cases, i.e. some emitters will have relatively low-cost liquefaction and transport costs versus some emitters who will need enhance carbon capture technology for impurities, and the need to transport $CO_2$ a greater distance. For example, the current model for the cluster sequencing competition suggests a connection to the broader carbon capture and storage network at the physical boundary of the emitter i.e., the fence line, this is not a practical if the emitter is at a prohibitive distance from the cluster.

### Managing cross-chain risks (liquefaction, shipping, storage)

Many companies are now operating in a rapidly evolving new market, and in many cases with new technology, and new green field development locations, compounding the projects back-to-back risk. The addition of ‘buffer’ storage and handling at the sending and receiving locations in the system requires designing and including in the end-to-end system design, from emitter to store, via a CO2 shipping terminal. In many cases, the ‘buffer’ storage is expected to be 7-10 days of production or loading/transfer rates of CO2 between storage and transport mode, to provide flexibility to producing emitter plant and the shipping sending or receiving terminal.

In some sectors, there is a co-location benefit, for example, in proximity clusters, the ability to scale and source CO2 from a range of emitters can result in a scale benefit as smaller emitters can transport CO2. The requirement to gather CO2 in a central location, at a technical and economically way is an opportunity to extend the reach of the first phase of carbon capture clusters, by enabling the economical capture and transport of CO2 from inland emitters such as energy from waste plants, cement, and steel industries.

The gathering of CO2 from inland locations and transporting to a coast via road, rail or vessel for reinjection is not currently clearly supported in the funding opportunities. The complexity with each case i.e., the distance between the emitter and the store, the volume of CO2 per year to be transported, and the technology required for each sector of the market create funding requirements to remove the back-to-back risk of developing a project linked to a cluster development and prevent a domino effect of one project delaying the multi model – multi-directional transport of CO2. The current funding mechanism only considers one directional CO2 storage from the emitter, directly to the permanent store.

The potential to develop a merchant CO2 shipping business is present but requires flexibility in the funding and policy to allow European (UK to Europe and vice versa) movement of CO2 for sequestration and use.

### Stranded asset risk for first generation ship and terminal designs and finite contract duration of first projects/customers

There is significant stranded asset risk. An opportunity to lower the risk is to allow aggregation in the form of a CO2 transport and storage hub, ideally co-located with access to a developing large-scale store, reducing the project risk and financial investment risk. The scale also needs to be large enough to reduce the cost of carbon and the cost of developing the storage and jetty infrastructure. Co-locating in an existing terminal location or European shipping hub would allow for de-risking by using the jetty and terminal infrastructure for other products, and de risking the permitting process.

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