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Carbon Hub

Assessing technical requirements, regulations and risks related to

- Transportation of CO_2
- Interim storage of CO_2

April 2024

Executive Summary

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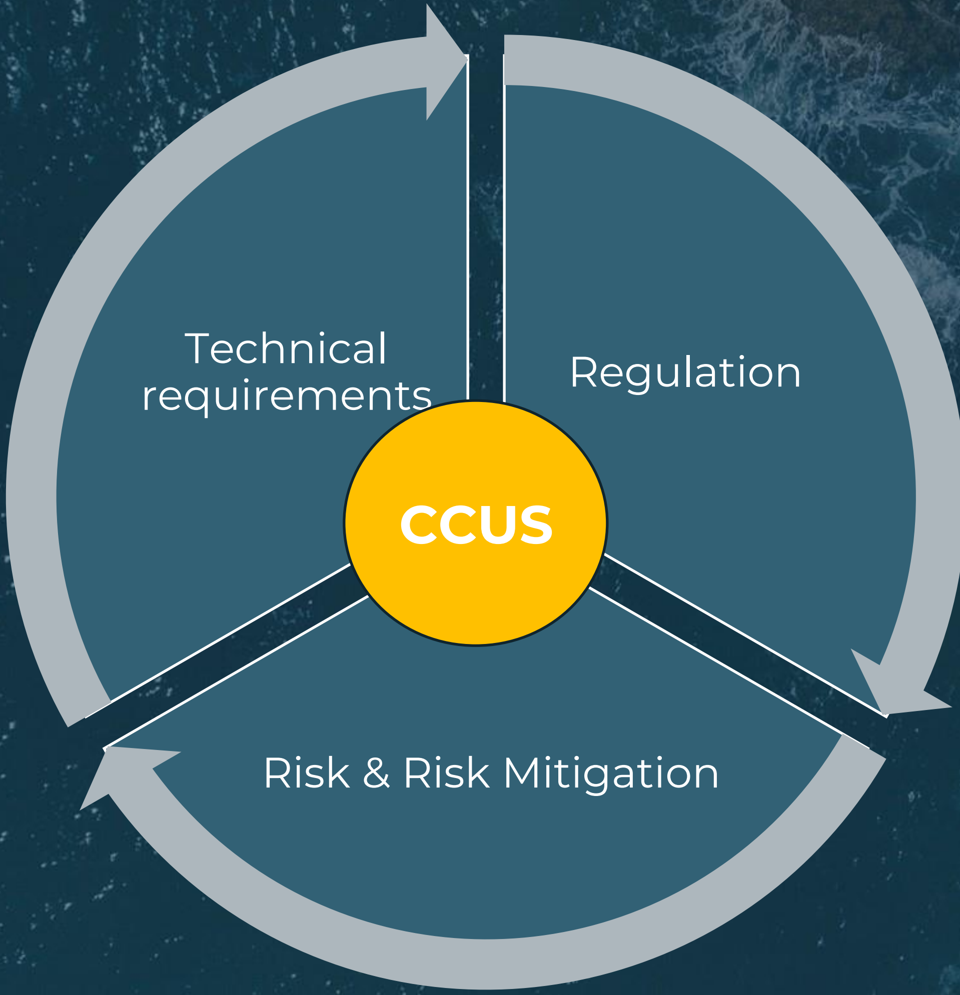
The successful implementation of Carbon Capture, Utilization, and Storage (CCUS) technologies holds immense potential in mitigating carbon emissions and facilitating the transition towards sustainable energy systems. Transportation of CO2 is needed to connect the various CCUS parts; capture, utilization and storage. However, dependent on volume, distance, current infrastructure and frequency, transportation of CO2 may occur by many different means and methods.

This work package (#2) under Ocean Valley's Carbon Hub project focuses on assessing the various CO2 transportation methods and storage options. The purpose is to showcase the different transportation methods and storage options related to the CO2 value chain on a general level.

Each transportation and storage option is assessed within a technical, regulative and risk related framework to illustrate both constraints and opportunities related to each transportation component.

Work package 3 underscores the importance of implementing transparent and clear regulatory frameworks on both national and international scale. This would ensure a simple deployment process simultaneously providing stakeholders with clear instructions on how to develop, expand and manage CO2 transportation.

The wheel influencing CCUS deployment



Key Findings

CCUS deployment is influenced by technical requirements, regulations, and risks associated with different transportation and storage methods.

- **Technical requirements:** The value chain involves new technical solutions and extensive CO2 handling, not previously subject to approval requirements under national laws.
- **Regulation**: The lack of knowledge regarding environmental permits and legal processes is a key challenge. CO2 is subject to different transportation methods and storage options; however, each element needs to be assessed to the given geographical and political context.
- **Risks & Risk Mitigation:** The CO2 value chain embeds various risks which need to be mitigated before implementation. Some risks can be mitigated by simply choosing different transportation or interim storage methods.

Recommendations

Three recommendations are deducted from the work completed in work package 2.

To advance current CO2 transportation methods and storage opportunities it is recommended to:

See slide 32 for further details

1) Simplify environmental permits and legal processes

2) Ensure 3rd party access to pipelines and interim storage

3) Implement standardized CO2 specifications across EU

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Insights to technology and regulation improves understanding of CO_2 transportation

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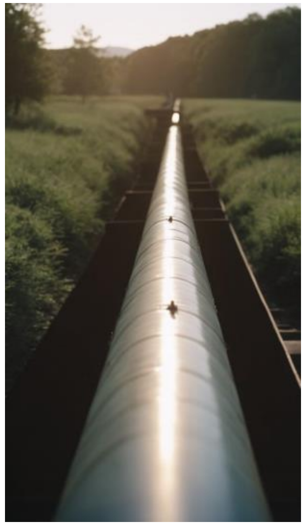
It is imperative to ensure safety and efficacy when addressing obstacles in all steps of the CO_2 value chain. Consequently, all stakeholders in the CO_2 value chain must understand and comply to comprehensive regulatory and technical requirements while understanding and mitigating associated risks.

This presentation will examine regulatory and technical requirements related to transportation and storage of CO_2 to improve the general understanding of opportunities and constraints related to CCUS.



> CnetSS: “*A challenge in the development of CCUS value chain is the lack of laws and regulation*”

> C4: “*Regulation and frameworks need to be in place now. There is a need for a swift clarification of the frameworks for the development of CO_2 infrastructure.*”

The focus of the analysis is transportation and interim storage

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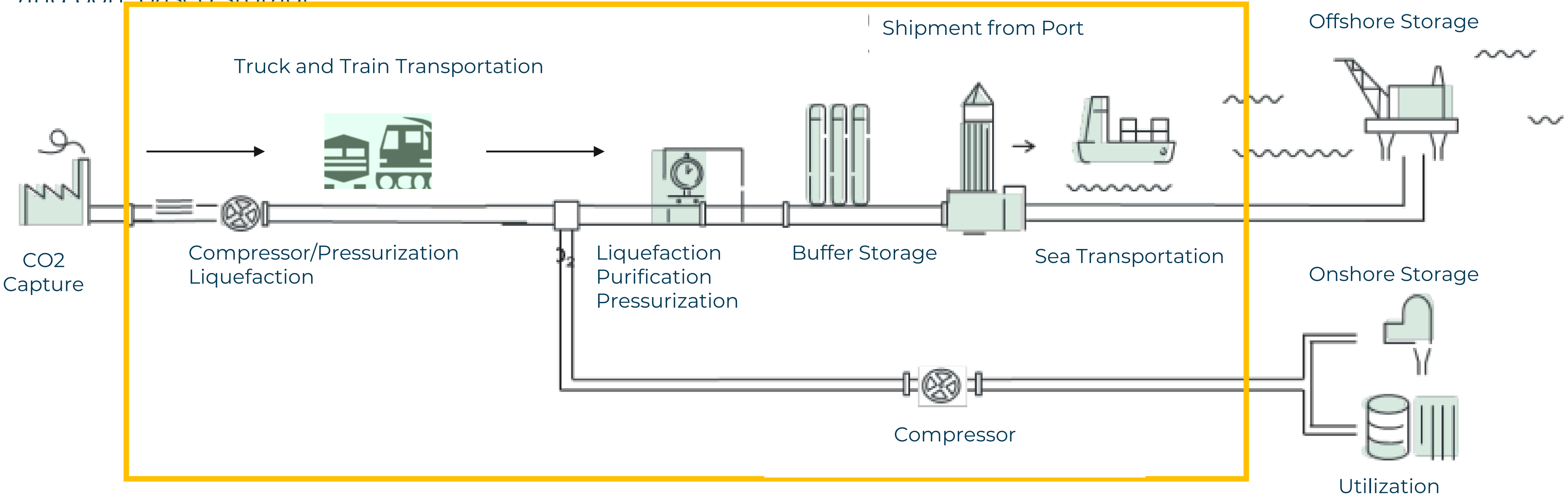
The CO2 value chain is complex and wide. Hence, we need to narrow down the focus of the analysis to the most critical phases of the CO2 value chain to delve deeper into the analysis and understanding of the technical and regulatory requirements related to CO2 storage; transportation and port-based storage



The content of the CO2 value chain varies according to geographical, geological, and political context, making it rather difficult to depict a one-size-fits-all concept. This report will take its point of departure in the Oresund region and add additional context where relevant.

Specifying the Key Value Chain Elements subject to further analysis

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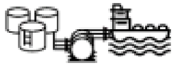
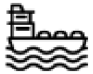
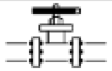
The table below specifies the elements of the CO_2 value chain that this reports focus on. They each serve distinct functions which are described on a high level in the table.

	**Liquefaction**. Liquefaction is necessary for the transportation of CO2 by ships, trains, or trucks, typically involving specific conditions such as a medium pressure range of 15/20 bar and temperatures between -20°C to -30°C. This involves a crucial step in which CO2 is cooled and pressurized.
	**Buffer storage**. Buffer storages are essential for preparing CO2 for transportation via ships, trains, or trucks. These storage tanks vary in size but are generally crafted to hold CO2 quantities equivalent 1-1.5 times the ship size.
	**Loading facilities**. Loading facilities encompass pumps, piping, and other necessary infrastructure that facilitates the transfer of CO2 from buffer storage to the actual transport means such as ships, trains, or trucks.
	**Ship**. Ships used for transporting CO2 can be purpose-built or adapted for this role. They come in three pressure types: low pressure, medium pressure, and high pressure. Currently, medium pressure technology is the most developed. Although their size is relatively small today (<10,000 m^3), the industry is actively working to expand these ships to a capacity of up to 50,000 m^3.
	**Pipeline**. In the CCS context, pipelines may operate both with gas and dense phase, and they consist of interconnected pipes, valves, and monitoring systems, ensuring the safe and efficient transfer of CO2.
	**Train**. The transportation of CO2 by train utilizes specialized railcar tankers, typically with a capacity of approximately 80 tons. These tankers are typically designed with insulation to maintain temperature control but do not require refrigeration. This insulation helps ensure the stable and safe transport of CO2 by rail.
	**Truck**. CO2 can be transported via tank trucks, with the tanker's capacity subject to local regulations but generally falling within the range of 20 to 40 tons. Much like trains, these trucks are typically equipped with insulation to regulate temperature but do not necessitate refrigeration for CO2 transportation.
	**Unloading facilities**. Unloading facilities encompass a set of essential components, including pumps, piping, and other infrastructure, that facilitate the transfer of CO2 from the transport mode (such as ships, trains, or trucks) to the next item in the value chain, typically a buffer storage system.
	**Compressor**. Compressors play a crucial role in the transportation of CO2 by pipeline, whether for gas or dense-phase CO2. Typically, CO2 at atmospheric conditions undergoes a sequence of intercooled compression stages, often numbering between 3 to 5, to achieve the necessary conditions for pipeline transport.

(Source: DNV, 2024)

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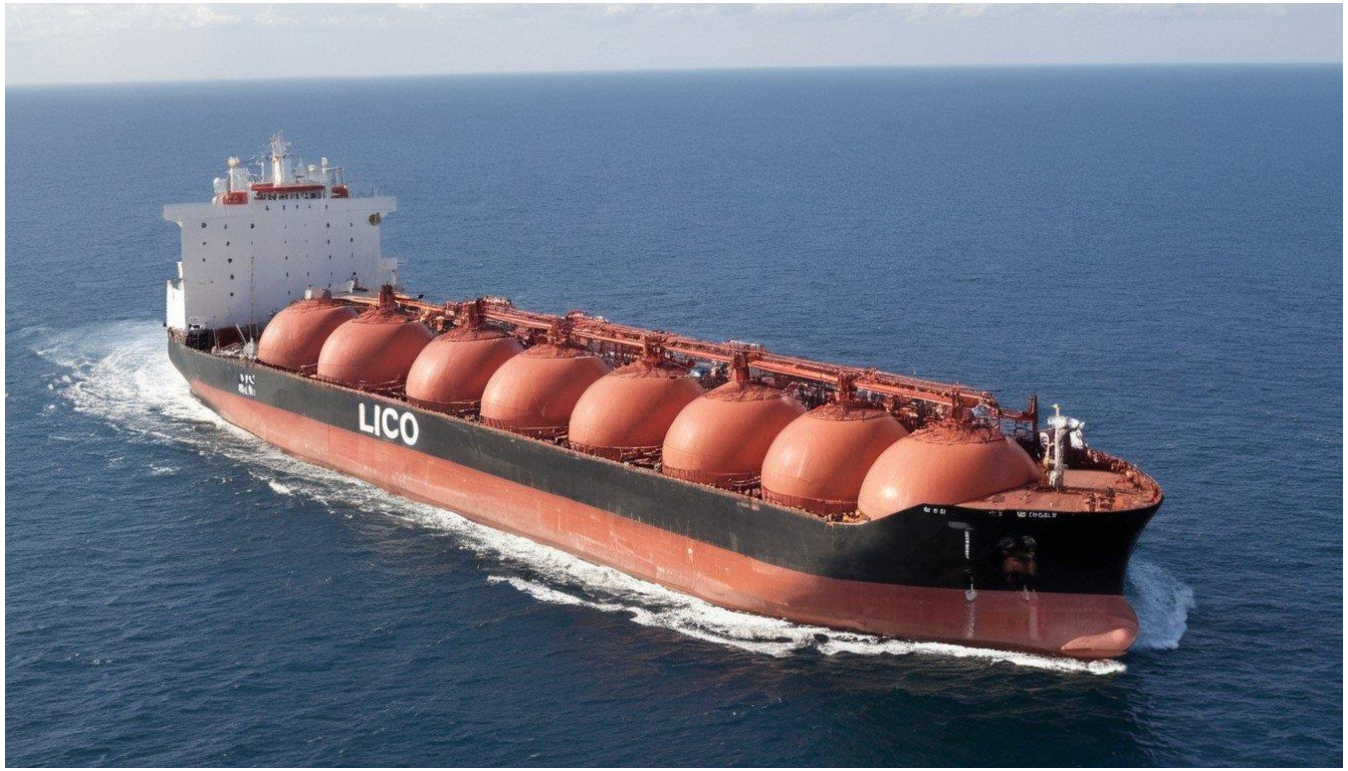

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Transporting CO2 via Pipelines

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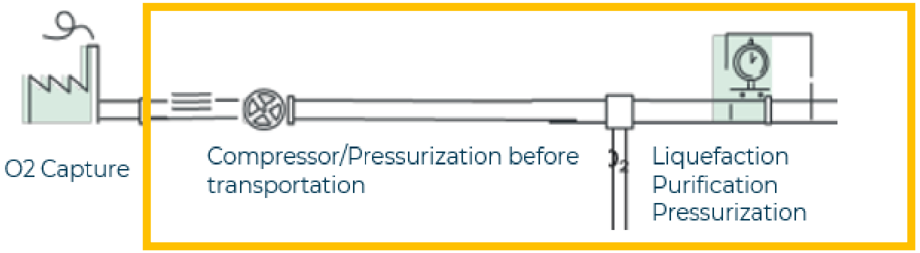
Transporting CO2 via pipelines are cost-efficient but not widely deployed in Europe

Pipelines are expected to be the most cost-efficient transportation method compared to trucks, trains and ships, however future infrastructure setups of pipelines are yet to develop in Europe, despite transporting CO2 through pipelines has been a well-known practice for decades, especially in the American oil and gas industry.



Following capture, CO2 undergoes conditioning for transportation, which includes processes aimed at adhering to the necessary specifications including temperature, pressure and cleanliness for safe transport and storage. Subsequently, the CO2 is compressed and introduced into the pipeline system.

There are four central components in the CO2 pipeline infrastructure:

- CO_2 compressor/pump stations
- Measurement stations for CO_2 purchase/sale
- CO_2 conditioning (heat exchangers, filters, drying units)
- Pipes and valves

Disclaimer
The slides does not showcase an exhaustive list of technical requirements, regulatory compliances and risks related to pipeline infrastructure. They are merely intended to give a short introduction to a complex reality with many legislative and technical gaps to be further examined.

CO_2 may be transported in a liquid state or gaseous state

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Gaseous state transport is the most cost-efficient method as it only requires compression

- Similar to natural gas
- CO_2 is conveyed in its gaseous phase (pressure below 40-50 bar- subject to project-specific considerations)
- For extended pipeline routes, the inclusion of boosting stations may become necessary

Liquid phase transport requires more processing which is necessary when the CO_2 is subsequently transported by other means*

- Prevailing method for CO_2 transportation
- Pressure raised to 80-120 bar
- Requires multi-stage compressors before injection into the pipeline system

Compressors play a crucial role in the transportation of CO_2 by pipeline, whether for gas or dense-phase CO_2. Typically, CO_2 at atmospheric conditions undergoes a sequence of intercooled compression stages, often numbering between 3 to 5, to achieve the necessary conditions for pipeline transport.

****Liquefaction*** *is necessary for the transportation of CO_2 by ships, trains, or trucks, typically involving specific conditions such as a medium pressure range of 15/20 bar and temperatures between -20°C to -30°C. This involves a crucial step in which CO_2 is cooled and pressurized.*

Technical requirements for pipeline transportation of CO_2

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In general, the use of pipelines is well understood from the natural gas industry and widely used in the US. As such, the pipeline technology is of a high technical maturity. Below follows a list of high-level technical requirements for CO_2 pipeline transportation:

- Higher CO_2 volumes requires larger pipeline diameters to accommodate the flow
- Increasing the density of the fluid requires greater pipeline wall thickness
- May be transported using existing gas pipelines
- When CO_2 is transported in gas form, the CO_2 needs to be pressurized, for example, to 30 bar at each capture facility
- The total costs of gas infrastructure are lowest, as additional compression/decompression is only carried out when necessary and can be managed collectively

Regulatory framework for pipeline transportation of CO2

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- Concessions need to be granted to draw and use pipelines longer than 20 km for CO2 transportation for geological storage. Concessions can be valid for maximally 40 years

- Considerations:

  - CO2 transporting companies must publish tariffs and conditions for the use of the CO2 transport network and CO2 storage site.

  - Ensure third-party access to all CO2 pipelines, so infrastructure owners cannot unfairly exploit a monopolistic position

  - There will be a need for a tariff structure that ensures that capture operators delivering the dirtiest CO_2 to the pipeline infrastructure also pay for the additional costs it incurs in the purification process

Risk assessment of CO2 transportation via pipelines

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- When transporting CO_2 in gas form, it is crucial to first dehydrate the CO_2 and remove hydrogen sulfide, as these elements can corrode the gas pipelines.
- The captured, gaseous CO2 contains moisture and impurities that are not tolerated by the pipeline infrastructure.
- Safety considerations when transporting CO2 in urban areas
- Public acceptance is needed to construct pipeline systems in people's “backyard”
- Common infrastructure setups comes with financing risks. Who would like to pay the initial investments when one can wait and let other stakeholders take the financial risks.

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Transporting CO_2 via Trucks and Trains

Comparing trucks and trains as CO_2 transportation means

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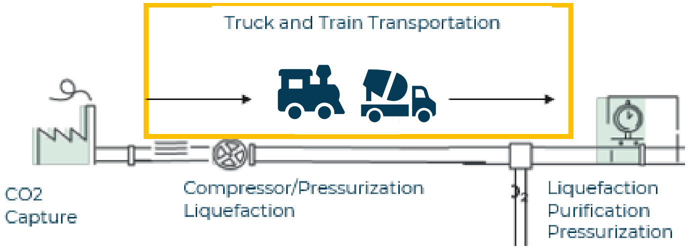
Transporting CO_2 via trucks and trains is fast, easy and flexible. It can utilize current infrastructure but the variable costs for the truck or the train scales as the volumes increase hence eliminating economics of scale. Truck and train transportation also comes with technical, regulatory, and risk-related challenges.

This section examines key considerations in CO_2 transportation, focusing on technical requirements, regulations, and associated risks for both truck and train methods.



Transportation by train

- Utilizes specialized railcar tankers, typically with a capacity of approximately 80 tons
- Typically designed with insulation to maintain temperature control but do not require refrigeration
- Insulation helps ensure the stable and safe transport of CO_2 by rail

Transportation by truck

- Truck's capacity subject to local regulations but generally falling within the range of 20 to 40 tons.
- Trucks are typically equipped with insulation to regulate temperature but do not necessitate refrigeration for CO_2 transportation.

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Assessment of technical requirements, regulatory constraints and risks

	Technical requirements	Regulation	Risks
Truck	• Operating temperature -27 °C to -30 °C • Unloading flowrate 75 m3/h • Operating pressure 15-18 bar • CO_2 must be compressed into a liquid, which is significantly more energy-intensive • Transporting 30 t/CO2 25 km will result in emission of less than 1% of the CO2 for a round trip • Capacity between 20-50 tons per truck	• CO2 semi-trailers are accepted for road transport of CO2 today	• Leaking CO2 will have relatively local effect. • In congested areas such as in tunnels or in narrow streets dangerous levels of CO2 is more likely to form in case of a large leakage. • Highest number of incidents in CO_2 transport occurred in highway trucking
Train	• Needs to be liquefied at low temperature. • Unloading flowrate 500 m3/h • Operating temperature -27 to -30 °C • Operating pressure 15-18 bar • Rail transport of CO_2 will be relevant for small to medium quantities, for example, from small point sources to CO_2 utilization facilities or export terminals • Capacity between 60-80 tons per truck	• For decades, the rail industry has safely transported liquified CO2 as hazardous material • CO2 must be transported in tankers, which are jacketed, insulated, and pressure-regulated with a full sill underframe • Liquid CO2 is transported via iso-containers in Europe	• Incidents include deliberate releases due to over pressurization as well as accidental, uncontrolled releases resulting from faulty components, human errors, and external damage • Rail transport has the lowest incident rate

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Interim storage of CO_2 at ports

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Once the captured CO_2 has been liquefied and purified, it can be stored in interim storage tanks.

Interim storage may be useful prior to CO_2 reutilization or accumulation for final storage transportation.

The interim stored CO_2 may be reused in various applications, such as production of e-methanol, sustainable aviation fuels, e-methane (refer to Carbon hub's Work Package 1 report for further details).

Ports offer a theoretical ideal location for carbon hub (interim storage) whether land-based or on a barge because of the interconnection between emitters and off-takers.

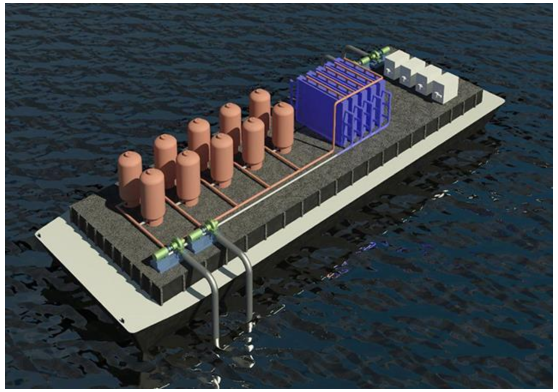
However, port-based locations presents other concerns that must be addressed such as risks of leakages close to the sea and urban population as well the general population's acceptance of proximity to interim CO_2 storage

Two types of interim CO2 storage at a port

Storage tanks for interim storage at ports vary in size depending on expected future CO2 supply and the size (1-1,5x) of the vessel(s) chartered for final storage transport. Due to uncertainties of future supply of CO2 and vessel capacity, combination of the following two types of interim storage methods may come into play:

Interim storage in ports or on land

- If CO2 is to be transported by ship to the final storage, it must be stored in interim storage when there is no vessel available to receive it
- The size of the intermediate storage is determined by the size of the ship (at least 120% of the ships total capacity)
- There are significant economies of scale associated with interim storage, as the storage becomes relatively smaller with faster turnover of the stored CO2
- The interim storage is highly scalable and can be expanded based on demand, but space must be allocated for the interim storage in advance
- Should operate in the same pressure and temperature as anticipated in maritime transport



Floating Barge or Storage Vessels

- A floating barge or interim storage vessel for CO2 is a specialized maritime infrastructure designed to temporarily hold CO2 before it is transported to its final storage or reutilization site
- These vessels are typically equipped with storage tanks or containers capable of safely storing CO2 under specific pressure and temperature conditions
- Barges are pivotal in situations where there may be fluctuations in demand or when there are delays in vessel availability for direct transportation to the final storage site

Comparing the two interim storage methods

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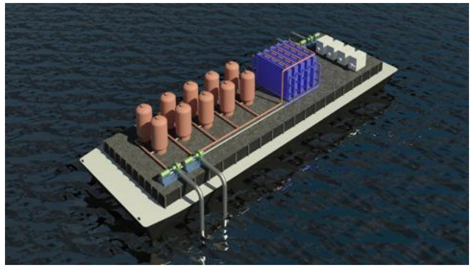
Floating Barge

- Flexible capacity; **can be scaled up or down** based on demand without significant land constraints.
- **High mobility** allows for strategic positioning closer to emission sources or end-users; can serve multiple ports or offshore facilities.
- Subject to **maritime regulations** and **environmental permits**; may require adherence to international maritime laws
- May **require coordination** with vessels for loading and unloading



Interim Storage at a port

- **Limited by available land space;** expansion may require additional permits and construction.
- Requires **safety distance** to urban environments
- Subject to **port regulations** and **environmental permits**.
- **Easily accessible** for loading and unloading operations.
- **Relatively secure** due to stationary infrastructure and port security measures
- **Limited mobility**; dependent on port infrastructure and transportation logistics

*The choice between these interim storage methods depends on factors such as **proximity to emission sources, mobility requirements, regulatory considerations, and cost-effectiveness**.*

Assessing risks and regulation related to carbon hub(s)

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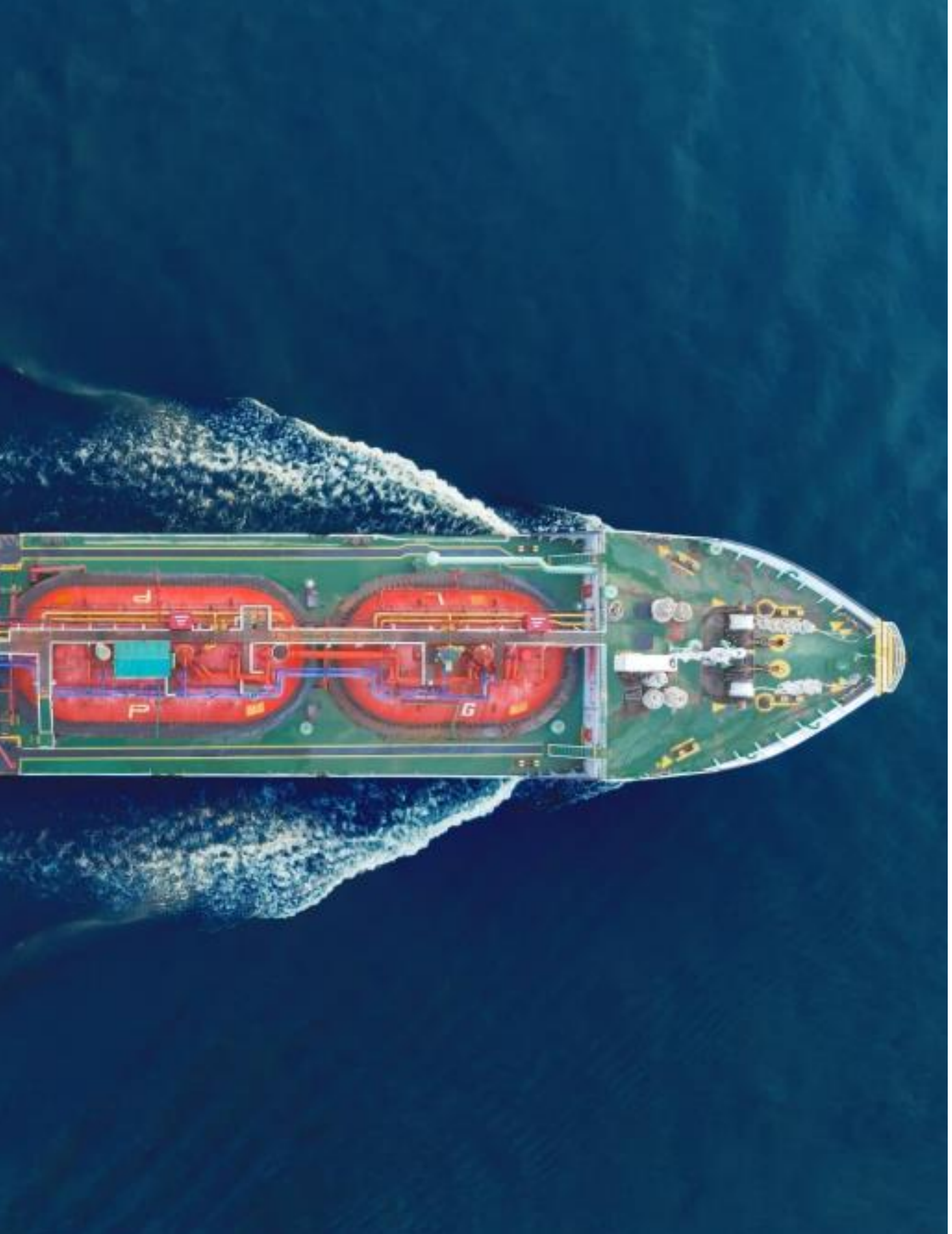
Risks associated with deployment of carbon hubs

- Risk of heightened demands for temporary storage due to authorities and county boards lacking experience from similar projects.
- Community acceptance challenges arise when hubs are situated near residential areas.
- Maintaining safety distances becomes crucial in case of leaks from the storage site
- Many ports have limited space making it difficult to reserve the needed space required by carbon hub(s)

Regulatory understanding

- Interim storage of CO_2 is seen as storage of non-harmful waste requiring a permit if the quantity stored exceed 10,000 tons in Sweden.
- A detailed procedure must be developed to secure safe filling of CO_2 to the CO_2 tankers. Special care must be taken to make sure the pipeline is emptied for liquid CO_2, before disconnecting the pipelines.

Maritime transport of CO2



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Maritime transportation of CO_2 offers strong value proposition for transporting captured CO_2 over long distances and in big volumes. Therefore, it plays a significant role in the global carbon capture and storage (CCS) infrastructure

CO_2 transporting vessels serve as vital conduits for the efficient distribution of CO_2 to various utilization sites or permanent storage facilities, contributing to the mitigation of greenhouse gas emissions on a significant scale.

Tankers optimized for transport of liquefied CO_2 tankers are already in the order book at multiple shipyards and the first “liquefied CO_2” ships are expected to be delivered in 2024 according to the Northern Lights Project (Link)

Transporting CO_2 by vessel is a niche focusing on specific point sources, distances and volumes

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Ship transport of CO_2 is most relevant for transport of medium to large volumes of CO_2 over medium to long distances e.g. from large point source emitters to offshore storage destination or land-based terminals. Ships do however also have the flexibility to operate in a route network picking up CO_2 from multiple locations. Ships used for transporting CO_2 can be purpose-built or adapted for this role.

They come in three pressure types:

- Low pressure: few bar above the triple point (5.2 bar, -56°C) and approx. -50°C. These conditions will result in the highest CO_2 density and lowest thickness of pressure tanks.
- Medium pressure: 15-18 bar and -25 to -30°C. This is the most common conditions for transport of liquid CO_2 today.
- High pressure: : 40-50 bar and +5 to +15°C. This alternative will require pressure vessels with higher design pressure, but less insulation is needed.

Currently, medium pressure technology is the most developed. Although their size is relatively small today.

Assessment of technical requirements, regulatory constraints and risks

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	Technical requirements	Regulation	Risks
Ship	• Medium-pressure CO_2 transport, operating at approximately -25/-30°C and 13-16 bar • CO_2 must be compressed into a liquid • Already known technology designed for transporting CO_2 in liquid phase, like the characteristics of liquefied petroleum gas (LPG) carriers • The capacity range considered for ships in a CCS value chain are from 2,000 to 100,000 t CO_2 capacity • Northern Lights Project have ordered two ships with a capacity of 7,500 m3 (le ngth / draught of 130 / 8.5 meters). They a re currently evaluating a larger ship capa city of 12,000 m3 (length / draught of 150 / 9.5 meters) • Greensand is considering 4 different ship sizes: 7,500 / 12,500 / 22,000 / 50,000 m3	• Pressure tanks on ships are normally designed according to the international maritime organization's regulation. The code specifies higher safety factors and margins compared to land-based pressure tank. • In terms of shipping, lack of permits for cross-border CO_2 transport is another significant barrier. Currently, CO_2 is classified as a waste product under the London Protocol, effectively restricting its cross-border transportation. • It is worth noting that if a more fluid spot market for maritime CO_2 transport is to be developed in the long term, it would be highly relevant to establish a common standard for the pressure and temperature regimes required during transportation. This would enable multiple operators to utilize the same port facilities.	• Impurities can shift the actual triple point, thereby risking the formation of dry ice, for example, during expansion in pumps and pipes used to move CO_2 in and out of the tank systems • Because of the large volumes of CO_2 onboard ships or at land-based terminals, accidental release of large volumes of CO_2 is the main safety concern. • Special vessels such as LCO_2 vessels require long term contracts with CO_2 suppliers. No shipowner build a ship with special purpose without any long commitment from supply side.

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Introduction

Assessing technical requirements and regulations related to

- Pipelines
- Trucks and trains
- Interim storage
- Maritime transport

General risks and risk mitigation

Recommendations and next steps

General risks associated with deployment of CCUS in value chain perspective

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Financial – Risks affecting the project's business case directly.

Geographic location / logistics - Risks associated with logistic solutions and the location of the CCUS facility.

Environment/health – Risks affecting the immediate environment and risks that may directly impact human health.

Consortium collaboration – Risks associated with collaboration among project participants collectively.

Technology – Risks associated with CCUS technology.

Time – Risks directly impacting the project schedule.

Permits – Risks related to permits from authorities and county boards

Mitigating general risks

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- Infrastructure design is conducted according to standards that account for annual variations from group of emitters
- Risk-based maintenance programs are developed for completed facilities as well as alarm systems, including gas detectors.
- Declarations of intent are signed between project participants and any third parties to ensure roles and responsibilities.
- Continuously monitor any legal requirements and practices regarding CO2 infrastructure.

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Recommendations summarized

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By implementing below listed recommendations, governments, industry stakeholders, and policymakers can accelerate the development and deployment of CO_2 infrastructure, facilitate the transition to a low-carbon economy, and mitigate the impacts of climate change.

- **Enhance Third-Party Access**: Ensure that CO_2 infrastructure, including pipelines and storage facilities, allows for third-party access. This promotes competition, fosters innovation, and reduces costs by encouraging multiple users to share infrastructure resources and operational expenses.

- **Establish Clear Regulatory Frameworks**: Develop clear and consistent regulatory frameworks at national and international levels to provide certainty for stakeholders in the CCUS value chain. Standardized CO_2 specifications must be established between respective emitters, CO_2 transport operators, and interim storage hubs.

- **Facilitate Collaboration**: Foster collaboration among industry partners, research institutions, and government agencies to facilitate knowledge sharing, technology transfer, and cost-sharing opportunities. Collaborative efforts can accelerate innovation, reduce duplication of efforts, and address common challenges more effectively.

For further information

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