A REPORT TO STAKEHOLDERS FROM CONTAINER LINERS' PERSPECTIVE

CO_2 Abatement Potential from OCCS Application on Vessels of Five Container Liners on the North Europe-Asia Corridor

CMA CGM, Evergreen, Hapag-Lloyd, Maersk, MSC

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Objectives:

Demonstrate the CO_2 abatement potential from deploying Onboard Carbon Capture and Storage (OCCS) technology on vessels operated by the five container liners CMA CGM, Evergreen, Hapag-Lloyd, Maersk, and MSC on the North Europe-Asia corridor. Identify key prerequisites for implementation of OCCS as a decarbonization alternative for shipping, e.g. IMO and EU regulation. Provide stakeholders, such as investors and CO_2 value chain players, with input to enable CO_2 value chain implementation.

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1 EXECUTIVE SUMMARY

The group of the five container liners CMA CGM, Evergreen, Hapag-Lloyd, Maersk, and MSC, representing 60% [1] of global container shipping[1], support IMO's 2050 strategy and its associated net zero framework. The liners are keen to understand the potential of Onboard Carbon Capture and Storage (OCCS) as a practical, safe, compliant, and cost-efficient decarbonization pathway, complementary to other pathways such as sustainable fuels. Since 2021, several submissions have been made at IMO calling for a regulatory framework on OCCS, but progress has remained limited with other issues taking priority.

The purpose of this report is to outline key prerequisites for the physical end-to-end CO_2 value chain, using the busy North Europe-Asia (NEU-Asia) route for the five liners as a testbed for an OCCS corridor[2], and by quantifying CO_2 abatement potential of OCCS to eventually highlight the need for timely regulation.

A June 2025 workshop hosted by the Port of Rotterdam brought together the five liners as well as stakeholders along the CO_2 value chain including barge operators, providers of intermediate and permanent CO_2 storage, key North European ports, OCCS technology providers, regional legislative bodies and international industry associations. The workshop created awareness among the regional CO_2 value chain players of potential LCO_2 volumes offloaded by ships and confirmed their motivation to establish infrastructure to enable the reception and sequestration of ship-borne CO_2. The need for a first-of-a-kind OCCS corridor to demonstrate the feasibility of OCCS was widely acknowledged.

<u>The physical LCO_2 value chain</u>

This report considers a value chain where CO_2 is captured and liquefied onboard (LCO_2), e.g. with an amine-based system, offloaded to LCO_2 barges in ports which deliver it to intermediate storage terminals in the ports of Rotterdam and, e.g. Singapore. From there, CO_2 is either transported directly via pipeline for final sequestration (Rotterdam) or shipped by LCO_2 tankers to a second intermediate storage close to a suitable sequestration site and then pipelined to final sequestration (Singapore). While elements of the above LCO_2 value chain exist either in isolation or are missing today, the group of five liners and the authors believe that regulatory clarity is essential to incentivize investment towards integrating and developing the isolated and missing elements respectively:

- **OCCS technology:** Different options with varying degrees of technical maturity are being offered by over 10 different suppliers. To date >60 installations exist or are planned [1], most of which are amine-based systems on container vessels. Pilots on container vessels and a full-scale installation on a gas carrier report onboard feasibility, with no major barriers in terms of capture systems' onboard integration and operational safety, while full-scale application on a container vessel is yet pending. It should be noted that OCCS technology is applicable to all carbon-containing fuels, i.e. fossil, bio- and electro-fuels

- **Cornerstones of the LCO_2 offloading value chain:** While dedicated LCO_2 offloading barges for shipping do not exist today, LCO_2 tankers for long-distance transport, terminals for LCO_2 reception and intermediate storage as well as permanent storage facilities are developing: In Northern Europe, projects like CO2next (liquid CO_2 terminal) and ARAMIS (CO_2 transport) in Rotterdam are already planned, expecting final investment decisions (FID) in 2026/2027 and operations starting in 2030. While CCS infrastructure will be driven by land-based CO_2 emitters, participants of Port of Rotterdam's June 2025 workshop from across the CO_2 value chain indicated strong motivation of the regional CO_2 cluster to establish infrastructure to enable reception and permanent storage of ship-borne CO_2

<u>CO_2 abatement potential</u>

An analysis of the GHG intensity of fuels, considering parasitic loss and emissions along the Ship-to-Storage value chain, indicates that the net removal of CO_2 from vessels' exhaust gas by means of OCCS could reduce fuels' GHG intensity significantly. OCCS could reduce the emissions intensity by more half when used with conventional fossil fuels and enable net-negative emissions when used with high shares of carbon-containing low-GHG fuels such as B100, Bio-LNG and Bio-methanol as illustrated in Figure 1.

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[1] In terms of TEU capacity installed

[2] None of the terms "OCCS corridor", "North Europe-Asia corridor" and "NEU-Asia corridor" used in this report refer to the Rotterdam-Singapore Green and Digital Shipping Corridor (GDSC)

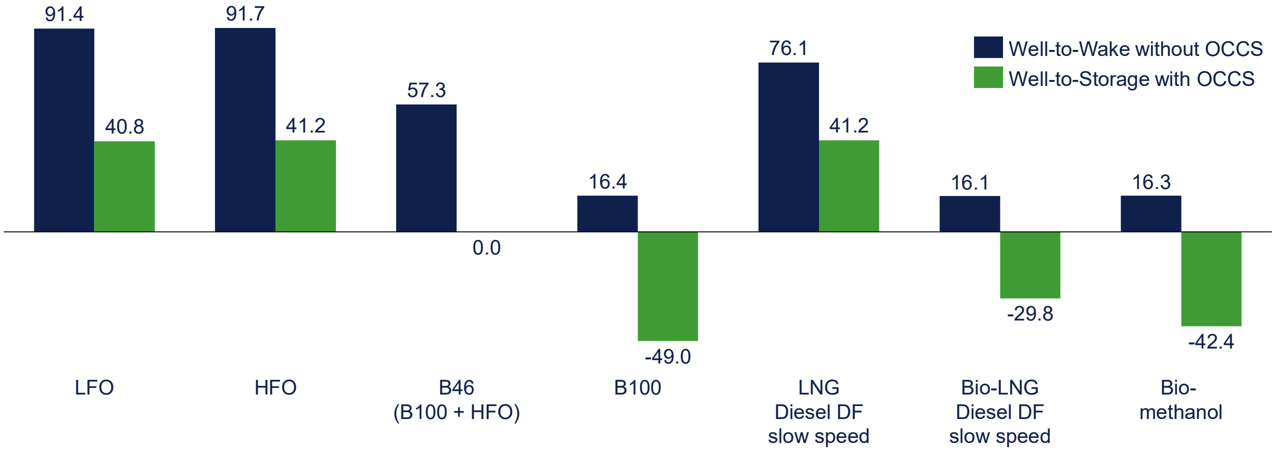

Figure 1: GHG intensity of selected fuels with OCCS offloaded in Rotterdam (gCO_2e/MJ) [2, 3, 4][3]

The uptake and CO_2 abatement potential of OCCS on the fleet operated by the five liners on the NEU-Asia corridor has been forecasted using DNV's comprehensive GHG Pathway Model [5]. Key factors considered include global seaborne trade and fleet growth, IMO and EU regulations, ship operational profiles, risk willingness and investment horizons, Well-to-Wake/Well-to-Storage emissions, as well as total cost (fuel cost, CAPEX, CO_2-related cost) for various fuels/technologies including OCCS.

Since LCO_2 offloading cost is a major driver of OCCS's economic viability relative to alternative solutions (consequently of OCCS adoption in the fleet) and the key factor, besides CO_2 volumes offloaded, towards influencing investment decisions across the value chain, this report evaluates the uptake of OCCS within the fleet in scope across three offloading cost scenarios resulting in high, medium and low uptake of OCCS.

In the scenarios modelled, annual total CO_2e abated, CO_2e abated with OCCS, CO_2 offloaded and CO_2 offloading cost/revenue pool (Mn USD available to CCS value chain from CO_2 offloading) from ships operated by the five liners ranges as follows:

Year	Total abated* (Mtpa CO_2e)	Thereof, abated with OCCS (Mtpa CO_2e)	CO2 offloaded (Mtpa CO_2)	Cost/Revenue pool (Mn USD)
2030	3.2	0	0	0 – 3
2035	13.5 – 14.9	0.4 – 3.5	0.4 – 3.7	60 – 278
2040	13.6 – 14.2	1.5 – 6.0	1.9 – 7.2	279 – 503
2045	14.0 – 17.8	1.8 – 7.0	2.0 – 7.8	261 – 490
2050	15.6 – 17.5	2.4 – 6.6	2.5 – 6.9	299 – 423
2030-2050	**276 – 309 (Mt CO_2e)**	**25 – 99 (Mt CO_2e)**	**28 – 111 (Mt CO_2)**	**3,865 – 7,260**

* Abated with fuels and OCCS (excluding energy efficiency)

<u>Conclusion</u>

Results suggest that use of OCCS technology on container vessels operated by the five liners along the NEU-Asia corridor could offer a cost-competitive decarbonization option to complement the use of low-GHG fuels.

Under the High Uptake scenario in 2040, OCCS is projected to be used in conjunction with 60% of the total energy consumed by ships of the five liners on the corridor, resulting in 6.0 Mtpa of CO_2 abated and 7.2 Mtpa of CO_2 offloaded in ports representing more than 1% of forecasted global CCS volumes [6]. These figures indicate that OCCS could bear a significant

[3] The GHG intensity analysis follows IMO LCA Guidelines (MEPC.391(81)), assuming a 75% gross capture rate and 20% energy penalty. Carbon factors are taken from FuelEU Maritime (Regulation (EU) 2023/1805, amending Directive 2009/16/EC). Exemplary emission factors for biodiesel (B100) from used cooking oil (UCO), for bio-methanol from waste wood, and for bio-LNG from 60% manure and 40% maize in combination with close digestate, off-gas combustion technology follow default values from Directive (EU) 2018/2001. These emission factors and biomass types were selected as examples of representative production pathways. The FuelEU Maritime carbon factors were chosen for this comparison since they offer more detailed values for different biofuel types compared to the broader default factors in IMO guidelines. Pilot fuels are not considered.

share of the GHG abatement needed as it scales up rapidly and remains a key decarbonization solution over time. However, the analysis also shows that OCCS uptake is highly sensitive to LCO_2 offloading cost, which yet remains uncertain.

From a LCO_2 offloading value chain perspective, the capture and offloading of LCO_2 from ships presents a significant opportunity, as in the High Uptake scenario, total offloading cost of 7.3 bn USD is expected to be borne by the five liners in the 2030-50 period, creating substantial revenue potential for the offloading value chain, enabling coverage of investment, operations and associated costs.

As upfront investment requirements needed to implement OCCS are high both on board as well along the offloading value chain, stakeholders involved will only invest in case of fundamental belief in scale and economic sustainability of the solution. As mentioned, analysis indicates that scale can be achieved if offloading cost remain reasonable. Conversely, higher offloading cost would erode the relative attractiveness of OCCS from a liners' perspective and may prevent the LCO_2 offloading value chain from reaching critical mass.

The group of five liners and the authors point out that for OCCS to contribute towards maritime decarbonization, the investment decisions needed onboard vessels and along the LCO_2 offloading value chain will only materialize if a supportive regulatory framework is in place in a timely manner. Timely implementation of IMO's ongoing workplan to develop a regulatory framework for OCCS, scheduled for 2028, is essential for OCCS to be implemented at scale starting in 2030, including guidance on LCA, data collection, and certification of sequestered CO_2. At the EU level, formal recognition of OCCS under FuelEU Maritime remains critical and should be prioritized. Additionally, conclusive IMO guidance on the applicability of the London Convention and London Protocol, and national legal carve-outs defining CO_2 destined for sequestration, resolving hurdles from its classification as waste or commodity, should be enacted promptly by CO_2 host countries to enable investment and operational certainty.

<u>Recommendations</u>

Regulatory bodies should prioritize the development of OCCS as a credible decarbonization measure and address long-standing regulatory barriers in a timely manner to instil shipowner and CCS value chain investor confidence and unlock necessary investments. Beyond ongoing efforts on OCCS such as the MEPC 83-approved work plan and reconsideration under FuelEU Maritime, given the technical complexity of OCCS, harmonization across regulatory regimes is essential to provide clarity and consistency. With no precedents from other industries and the novel nature of OCCS regulation, it is incumbent on regulatory authorities to demonstrate leadership and proactively remove obstacles hindering OCCS from realizing its full decarbonization potential.

Furthermore, it is critical that the CO_2 value chain ensures consistently low offloading costs across all major hubs to enable OCCS to scale effectively to shipping routes and ship types beyond those considered in this report.

Finally, it is recommended that the shipping industry and CO_2 value chain stakeholders intensify their information exchange, through formalized fast-moving groups, addressing agenda points such as status and outlook of FID, LCO_2 specification requirements, maritime regulation, LCO_2 volume projections, etc.

2 THE DECARBONIZATION CHALLENGE FROM CONTAINER LINERS' PERSPECTIVE

Container shipping operates 5,076 vessels today [7], consuming about 57 Mtoe or 28% of the reported 208 Mtoe annual fuel-oil consumption by ships in international trade above 5,000 GT [7].

For container shipping to reach intermediate decarbonization goals and decarbonize by 2050[4], sustainable fuels need to become available in the quantities needed while also being price competitive. Other aspects of the onboard implementation of sustainable fuels, such as safety, technology, operations, etc., will require further work but are generally considered feasible.

<u>Availability of sustainable fuels</u>

To meet IMO's 2030 target of a 20% emissions reduction (from 2008 levels), DNV estimates that shipping requires access to 25 Mtoe of low-GHG fuels annually [8]. This is a steep increase from shipping's 1 Mtoe biofuel equivalent use in 2024 and represents approximately 25-35% of the total projected low-GHG fuel supply for all sectors globally by 2030 (70-100 Mtoe) as shown in Figure 2. Considering that shipping represents 11% of global transport energy demand and 3% of global energy demand today, it will face intense competition for these fuels from other sectors such as aviation, road transport, and industry, each with their own commitments to decarbonize and potentially higher ability/willingness to pay (by passing costs to end consumers) than shipping.

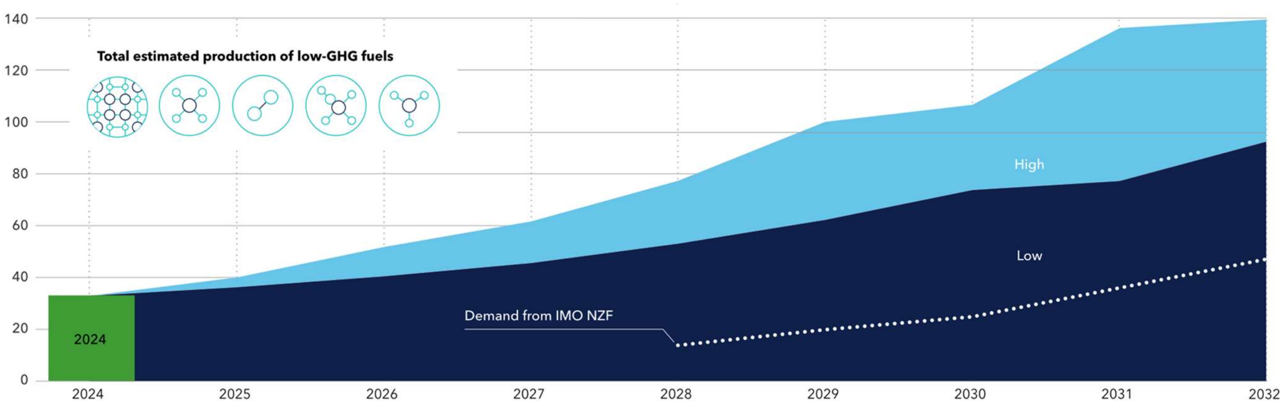

Figure 2: Estimated global production of low-GHG fuels across all sectors (Mtoe) [8]

Also, the development of low-GHG fuel production, especially hydrogen and its derivatives, will need support on different levels to reach full potential. Accordingly, both the group of the five liners as well as the authors believe in the potential of OCCS to act as a complementary decarbonization solution alongside sustainable fuels especially over the coming decade.

<u>Cost of sustainable fuels[5]</u>

Most sustainable fuels come at higher cost per unit energy than fossil fuels, today and in the future. According to DNV's analysis, bio- and blue fuels (if available) are more expensive than fossil fuels today and in the future. Until 2030, cost and price improvements are foreseen across all sustainable fuel families, except for Bio-MGO – the most available sustainable fuel today – facing demand due to its drop-in capabilities, which is expected to increase in price due to increasing demand and limited supply. Further price reductions are expected until 2050, however, sustainable fuels will remain more expensive than fossil fuels, as fossil fuels are forecasted to further reduce in price.

[4] Supporting IMO's Revised GHG Strategy, adopted at MEPC 80 [36].

[5] Fuel cost in this paragraph relates to the cost per energy unit [31].

3 SCOPE, BOUNDARY CONDITIONS AND REPORT ASSUMPTIONS

In June 2025, the five liners as well as stakeholders along the CO_2 value chain including barge operators, providers of intermediate and permanent CO_2 storage, key North European ports, OCCS technology providers, regional legislative bodies and international industry associations participated in a 2-day OCCS/CO_2 workshop initiated by the Port of Rotterdam. The workshop created awareness among the regional CO_2 value chain players of potential LCO_2 volumes offloaded by ships and confirmed their motivation to establish infrastructure to enable the reception and sequestration of ship-borne CO_2. The need for a first-of-a-kind OCCS corridor to demonstrate the feasibility of OCCS was widely acknowledged.

This report aims to:

- Describe required cornerstones of the physical end-to-end CO_2 value chain for OCCS
- Demonstrate the CO_2 abatement potential of OCCS, quantify the infrastructure implications and resulting economic opportunity on a major shipping lane
- Highlight main items pending towards implementation

Scope of this report:

Container vessels on the NEU-Asia corridor which provide an ideal starting point for OCCS deployment. Their predictable calling patterns, sizeable fuel consumption, and significant CO_2 emissions – combined with the corridor's high traffic density and proximity to existing and planned CO2 storage hubs – create favourable conditions for implementation.

For this reason, the report focuses on vessels operated by CMA CGM, Evergreen, Hapag-Lloyd, Maersk, and MSC along this route, with Rotterdam and Singapore assumed as primary LCO_2 offloading ports. Both ports are established bunkering hubs, and Rotterdam is actively positioning itself as a future CO_2 hub, integral to the emerging cross-border CCS shipping ecosystem in Northwestern Europe [9]. The five container liners, together with the authors, view this OCCS corridor concept as a blueprint for future scaling to additional routes, ship types, and ports.

Boundary conditions and assumptions:

- CO_2 is captured and liquefied onboard (LCO_2), e.g. with amine-based OCCS technology
- Vessels offload LCO_2. The offloaded LCO_2 meets the purity standards required by the downstream physical CO_2 value chains in Rotterdam and Singapore regions. (Note: Other existing OCCS technologies and other CO_2 offloading pathways such as, e.g., CO_2-rich amine or mineralized CO_2 are not considered[6])
- OCCS is considered as a valid carbon abatement technology with respective LCA, MRV and chain of custody under IMO Net Zero Framework, FuelEU Maritime and EU ETS (see chapter 6)
- Legal and administrative hurdles arising from London Convention and London Protocol as well as from classification of CO_2 as waste are addressed. (see chapter 6)
- Vessels can offload LCO_2 in ports of Rotterdam and Singapore. A physical CO_2 value chain is present in both port regions (see chapter 4)
    - LCO_2 barges (and, only in Singapore, LCO_2 carriers)
    - LCO_2 intermediate storage facilities (receiving terminals)
    - Permanent storage facilities (Rotterdam and Southeast Asia)

It should be noted that focus of the report is on permanent storage of CO_2; pathways of CO_2 usage and a circular CO_2 economy are more complex, on a later schedule and require further investigation.

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[6] Not scalable or expected to face challenges in terms of regulatory compliance

4 THE PHYSICAL LCO_2 VALUE CHAIN

4.1 Envisaged LCO_2 value chains in the ports of Rotterdam and Singapore

For OCCS to contribute to maritime decarbonization, key elements along the physical LCO_2 value chain need to be in place: OCCS installations on ships, LCO_2 offloading barges, potentially LCO_2 carriers, intermediate storage terminals, and pipelines to permanent storage facilities. Elements of the envisaged value chains would differ in the ports of Rotterdam and Singapore to a certain degree, as shown in the figures below.

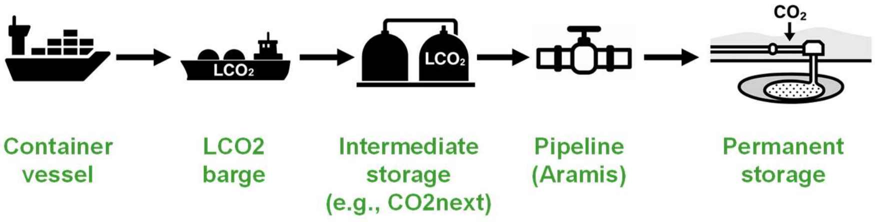


Figure 3: Physical LCO_2 value chain in Rotterdam

LCO_2 captured onboard container vessels is expected to be offloaded in the ports of Singapore and Rotterdam to dedicated LCO_2 barges, which transport the captured CO_2 to intermediate storage facilities as part of the downstream value chain.

In Rotterdam, intermediate storage could be provided by CO2next, feeding into Porthos' compressor station. From there, the ARAMIS offshore pipeline transports the LCO_2 to a permanent storage site. The final storage site is a depleted gas field in the North Sea, located about 3-4 km beneath the seabed.

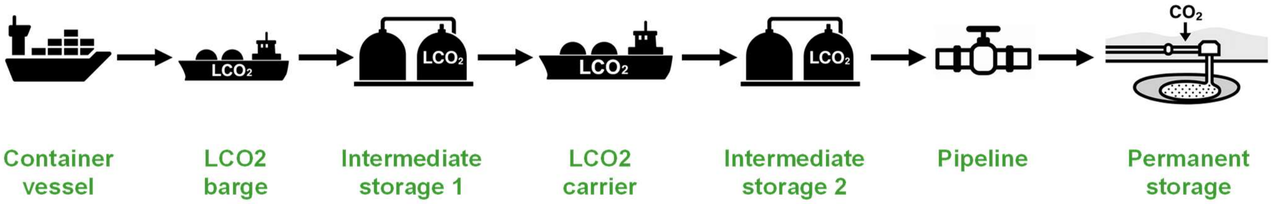


Figure 4: Physical LCO_2 value chain in Singapore

In Singapore, the downstream value chain could follow a similar initial setup, with LCO_2 transferred to a barge and delivered to a first intermediate storage facility. As there are no permanent storage options in the immediate vicinity of Singapore, the LCO_2 would need to be transported over longer distances. Based on currently planned projects, DNV estimates an average transport distance of 725 km from Singapore to a second intermediate storage site in Malaysia or Indonesia, using LCO_2 carriers. From there, pipeline delivery of the LCO_2 to permanent offshore storage beneath the seabed is assumed.

It should be noted that the physical CO_2 value chain from OCCS via CO_2 barges/carriers, terminals, and pipelines down to permanent storage is yet to be developed. End-to-end cost implications of developing and operating the physical LCO_2 value chain are considered when analysing OCCS' relative competitiveness to alternative solutions in chapter 5. Basic requirements and status of the value chain elements, including the requirement of CO_2 purification, are described in the following sections.

4.2 OCCS on container vessels

OCCS technology

While carbon capture technology has been applied in land-based industries since more than 50 years [10], OCCS has only been installed onboard ships since the early 2020s, even though it has been explored as a viable maritime decarbonization measure since at least as far back as 2013 when DNV and PSE published a press release on an investigative study on OCCS [11].

A broad range of OCCS technologies exist today and can be classified into pre- and post-combustion depending on the stage when the carbon is captured. Post-combustion OCCS technologies are more mature, with the main types shown in Figure 5 below.

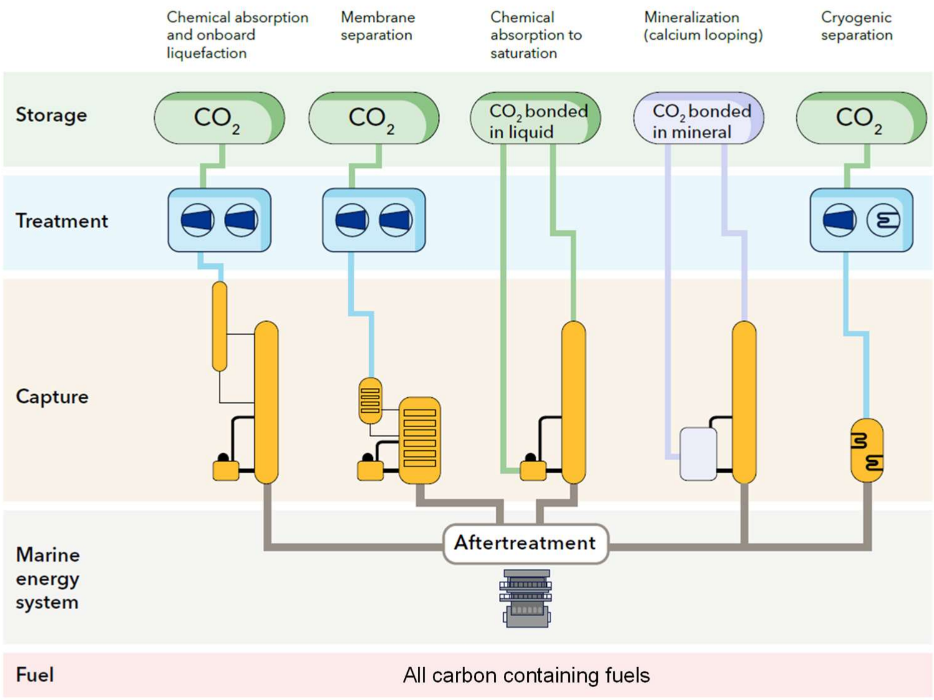


Figure 5: Main post-combustion OCCS technologies [12]

The main post-combustion OCCS technologies can be distinguished in terms of CO_2-separation approach and chemical compound offloaded:

- **Chemical absorption and onboard liquefaction:** Exhaust gases are scrubbed with a chemical solution (e.g., amines) that absorbs CO_2, which is later released through a regeneration process. The captured CO_2 is then liquefied for onboard storage before offloading
- **Membrane separation:** CO_2 is separated from exhaust gases by passing through selective membranes, producing a clean gas stream and a CO_2-rich stream for further treatment and storage. Hybrid systems combining membranes with liquid absorption can improve efficiency and reduce space and energy needs
- **Chemical absorption to saturation:** Exhaust gases are scrubbed with a chemical solution (e.g., amines) that absorbs CO_2. The saturated solution is offloaded, and the CO_2 is extracted ashore. The system requires storage for both fresh and saturated amine (2-2.5 t or 2-2.5 m^3 saturated amine needed to capture 1 t or 1 m^3 of LCO_2). Due to significant storage space requirements onboard, this technology necessitates more frequent offloading and an amine value chain that is connected to the LCO_2 value chain
- **Mineralization (calcium looping) and caustic soda absorption:** Exhaust gases react with minerals/solution in a reactor, binding CO_2 into solid compounds that form sludge/liquid for port offloading. These systems require storage for both fresh minerals/caustic soda and the CO_2-saturated product/sodium (bi)carbonate

- **Cryogenic separation:** The exhaust gas is cooled until CO_2 condenses into liquid or solid form, achieving high-purity CO_2 separation

63 OCCS systems have been installed by 2025, see Figure 6. However, it should be noted that a (potentially large) share of the installations are pilots, such as the retrofit installation on the 14,110 TEU vessel EVER TOP owned and operated by Evergreen. In fact, the OCCS retrofit installation on the CLIPPER ERIS, an 18,100 DWT Ethylene carrier owned and operated by Solvang ASA, is the only full-scale installation known today.

Furthermore, the operational status of today's installations is unknown; scarcity of offloading facilities for LCO_2 and treatment plants for saturated amine suggest that many installations are not fully operational today. However, both installations on the CLIPPER ERIS and EVER TOP are reportedly operational, with LCO_2 offloading demonstrated by the EVER TOP, see chapter 4.3.

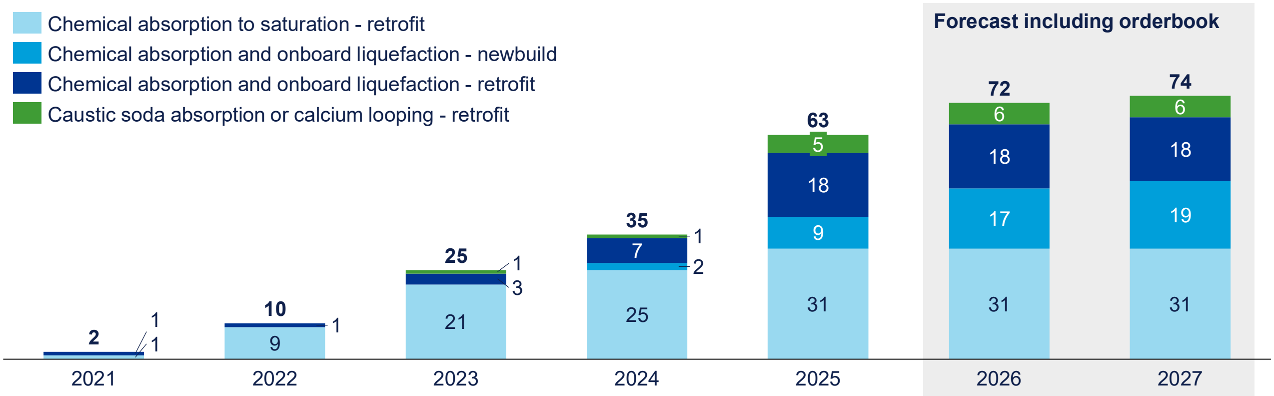
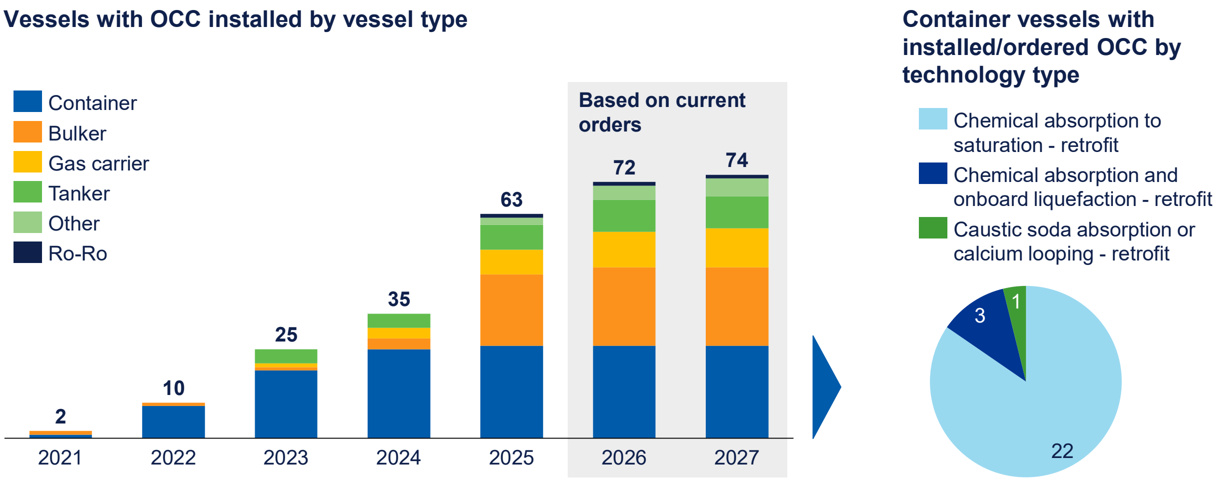


Figure 6: Uptake of OCCS by technology over time [1]

As shown in the figure above, the majority of the installations use chemical absorption, e.g. an amine-based solution. From 2021 to 2024, "Chemical absorption to saturation" with CO_2-rich amine being offloaded has been the favoured option, but recent growth rates of "Chemical absorption and onboard liquefaction" indicate that offloading of LCO_2 is the preferred future solution, especially for ships with longer typical voyages. Other technology options such as caustic soda absorption or calcium looping, membrane and cryogenic separation show very low or no market penetration in the fleet and orderbook. Overall, it is fair to state that at this early stage the OCCS market remains nascent and is gradually evolving.

Figure 7 below indicates that until 2024 the largest share of OCCS installations has been on container vessels, with installations on bulkers, gas carriers, tankers and other segments recently increasing. The vast majority of OCCS installations on container vessels are retrofits with "Chemical absorption to saturation"-technology, only recently have newbuildings been equipped with the "Chemical absorption and onboard liquefaction" option.



Source: Clarksons database, last accessed 30 Oct 2025, DNV analysis

Figure 7: Uptake of OCCS by ship segment over time, OCCS technology split in container segment [1]

As “Chemical absorption and onboard liquefaction” technology is scalable to the majority of ship types, is largely proven, applicable as retrofit and newbuild, and supports integration with existing (and growing) CCS infrastructure, it is the chosen base assumption for the scope of this report. Furthermore, evidence from full-scale onboard installations has demonstrated its feasibility to enable safe and controllable operations.

This report considers a gross CO_2 capture rate of 75% and a parasitic loss of 20%. The gross capture rate represents the share of CO_2 removed from the ship’s exhaust, whereas parasitic loss refers to the extra fuel required to operate the OCCS system, causing extra emissions. Higher capture rates generally require more energy, increasing parasitic loss.

A recent GCMD study, based on installed equipment and assumptions about future technology, reports a capture rate of 40% with a 5.8% parasitic loss, while indicating that 70-80% capture is possible at ~23-30% loss [2]. An earlier MMMCZCS study, focusing on the current state of technology, finds capture rates between 30-82% with a parasitic loss of ~7-43% [13]. OGCI and Stena Bulk assess land-based OCCS and translate these findings to shipping, concluding that combinations such as 50% capture rate with 22% parasitic loss or 90% capture rate with 53% loss are feasible [14]. Studies modelling technical feasibility also identify more favourable trade-offs. Visonà et al. (2024) report capture rates of 65-83% with a parasitic loss of 7-22% [15]. A full-scale example on a retrofit non-container vessel shows a 75% capture rate at below 25% parasitic loss today, targeting losses below 20%. Further, based on input from OCCS manufacturers, significant technological development is to be expected in the coming years. Therefore, a combination of **a 75% capture rate and 20% parasitic loss is regarded as a realistic assumption** for the 2030-2050 period under future technological development.

<u>LCO_2 tanks</u>

Medium-pressure technology is well-established, a proven standard on LCO_2 carriers today, and the likely pressure level for receiving terminals such as CO2next in Rotterdam. Furthermore, as the medium-pressure regime is embedded in the CO_2 transport value chain due to high operational maturity, it is likely to remain so due to long lifetimes for storage and transport assets.

To enable medium-pressure LCO_2 storage for 75% of gross capture of emissions on a Rotterdam-Singapore voyage (or vice versa) at 20% parasitic loss, IGC[7] Type C tanks with aggregate volumes up to 4,750 m^3 for the largest container vessels would be required. Similar space trade-offs also apply to all non-drop-in alternative fuels, including LNG. While the relative cargo loss from OCCS and alternative fuels has not been specifically modelled as part of this study, shipowners will evaluate reduced carrying capacity and stowage flexibility on a case-by-case basis when selecting technologies. For both OCCS and alternative fuels, developing offloading and bunkering infrastructure at strategic points along key routes (e.g. Suez for the NEU-Asia corridor) will be key towards enabling smaller tank sizes and reducing the impact on cargo capacity.

[7] International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

CO$_2$ concentration

Concentration is the proportion of CO_2 in a mixture. Initial OCCS installations, such as EVER TOP, have achieved CO_2 purities above 99.95%, exceeding Northern Lights' specification of 99.81%. Hence, technical barriers to achieving high CO_2 concentration (though not purity) have already been overcome. Nevertheless, concentration remains a critical parameter, the precise measurement of which is expected to become a core requirement across regulatory frameworks, including IMO and EU regimes.

CO$_2$ purity

Purity refers to the absence of impurities within the CO_2 stream. Currently operational and pre-FID sequestration projects such as Northern Lights and ARAMIS respectively have laid out stringent purity requirements for CO_2. This arises from the high sensitivity of sequestration infrastructure to even trace impurities which can compromise structural integrity, environmental safety and physical manageability of the CO_2. So far, OCCS has yet to achieve these purity specs, with results from the EVER TOP CO_2 offloading showing need for improvement in the purity of CO_2 captured onboard.

CO_2 purity requirements will be determined by the cost trade-off between purification and impurity tolerant infrastructure (besides integrity and safety needs). However, it is important to note that shipping is not driving CCS infrastructure development; rather, it will often rely on infrastructure built for large land-based industrial emitters. Requirements are therefore set also considering the purity achievable by these main users, making it unlikely that providers will relax them only for shipping. And although post offloading CO_2 purification is technically feasible, it does add cost, value chain complexity, and risk to the long-term integrity of both ship and CO_2 offloading barge tanks.

Based on the above, current dynamics indicate that, in the event of a mismatch on purity, it will be the shipping sector that must adapt and further enhance its CO_2 purification capabilities to meet stringent requirements of the CCS value chain. This could be achieved either onboard via advances in OCCS technology or via purification during/post offloading at barge/land-based purification facilities respectively.

4.3 CO$_2$ offloading

LCO$_2$ offloading

Offloading of LCO_2 from container ships is feasible and has been demonstrated successfully in pilots such as from the EVER TOP to the barge DEJIN 26 in the port of Shanghai in June 2025, as well as via an ISO tank container in the port of Rotterdam in January 2025. Although local regulations for the safe transfer of LCO_2 are not yet fully established in all relevant ports, the success of initial pilot projects and the applicability of proven practices from mature ship-to-ship (STS) operations with gases such as LNG/LPG suggest that these frameworks will develop without any foreseeably insurmountable obstacles.

LCO$_2$ barges

It is envisaged that LCO_2 captured onboard ships will be collected by LCO_2 barges in ports. With few exceptions, such dedicated barges do not exist today. However, from a design, construction and operation perspective, these are considered technically feasible and – provided sufficient LCO_2 quantities – also economically viable. Barge operators in Rotterdam have indicated initial business interest in making such barges available. The minimum size of such barges will be determined by the quantities offloaded from ships on the one hand and by the minimum batch size required by berthing/offloading infrastructure available at the intermediate storage facility on the other. A large container ship could discharge up to 5,000 m³ of CO_2, while terminals such as CO2next reportedly prefer batch sizes of at least 6,000–8,000 m³, in which case the latter would mark the lower limit for the size of LCO_2 barges in the port of Rotterdam, potentially serving as a proxy for other ports once the CO2 value chain is fully developed.

4.4 CO$_2$ terminals and transport

As for the envisaged value chain, LCO_2 offloading is required in the ports of Rotterdam and Singapore, focus is put on these two. However, further ports in North Europe, the Far East and even Middle East regions may add additional LCO_2 offloading points in future, reducing required tank sizes on board, enabling OCCS on more routes and vessel segments, and increasing offloading price competition.

Rotterdam

CO2next is developing an open-access terminal for liquid CO_2 at the Maasvlakte in the port of Rotterdam. It will enable industries that are not connected to CO_2 pipelines, to transport captured and liquefied CO_2 for Carbon Capture and Storage

(CCS). CO_2next will operate as a non-discriminatory, multi-customer terminal, open to all companies. Using the Porthos compressor station, the terminal will link to the ARAMIS transport infrastructure.

The project features two jetties where barges and carriers can deliver LCO_2. It is planned to provide a buffer storage capacity of 48,000 m^3, and an initial handling capacity of 5.4 Mtpa, with growth potential of up to 10 Mtpa in a first growth phase and later up to 15 Mtpa, depending on demand.

CO2next is developed by Gasunie, Vopak, TotalEnergies, and Shell; it entered Front-End Engineering Design (FEED) in June 2024 [16]. Final Investment Decision (FID) is targeted for 2026/2027, and according to planning the terminal will be ready to start operations in 2030[8].

ARAMIS is developing an open-access CO_2 transport infrastructure in the port of Rotterdam. It will enable hard-to-abate industries in the Netherlands and neighbouring countries to transport captured CO_2 for permanent storage in depleted gas fields 3-4 km under the seabed of the Dutch North Sea. The system is designed with an "open access" philosophy, allowing multiple customers and storage operators to connect over time.

The project will provide an onshore collection hub at Maasvlakte, integrating the CO2next terminal for liquid CO_2 and Porthos' compressor station for gaseous CO_2. ARAMIS will transport the CO_2 with a new 200 km long offshore trunkline to a distribution platform in the North Sea, with spur lines to various storage fields. The initial capacity of at least 7.5 Mtpa is scalable in phases up to 22 Mtpa, with total storage potential exceeding 400 Mt of CO_2.

ARAMIS is developed by a consortium of TotalEnergies, Shell, EBN, and Gasunie. It entered FEED in November 2024 [17], and FID is targeted for 2026/2027. According to planning, the operations will start in 2030[9].

As a fallback position, i.e. in case FID for CO2next and/or ARAMIS is not reached in time, LCO_2 collected in Rotterdam could be exported (at an additional cost) to projects which have passed FID, such as Northern Lights.

<u>Singapore</u>

The government works with S-Hub, a consortium comprising Shell and ExxonMobil, to study the viability of developing a cross-border CCS project from Singapore[10] to decarbonize local hard-to-abate industries.

Due to Singapore's lack of domestic storage capacity, the project focuses on cross-border partnerships, including agreements with Indonesia and Malaysia for offshore storage sites. CO_2 aggregated in respective facilities in Singapore will be transported via shipping and pipelines to regional storage sites.

S-Hub aims at a capacity of 2.5 Mtpa by 2030 and is designed for scalability, with funding provided by Singaporean government. A Memorandum of Understanding was signed in December 2023 and feasibility studies are ongoing. The Final Investment Decision (FID) is outstanding, with operations targeted to start in 2030 [18] [19].

<u>LCO_2 carriers</u>

In locations where the receiving LCO_2 terminal in the port has no direct pipeline connection to a permanent storage site, longer distance transport of the LCO_2 by means of seagoing LCO_2 carriers is required. Currently, seven LCO_2 carriers with capacities from 1,000 to 7,500 m^3 and one barge are in operation, and seven further vessels ranging from 5,000 to 21,500 m^3 are on order [1] [20].

Existing and planned vessels carry LCO_2 at medium pressure (15-20 barg, -30 °C). Low pressure vessels (7-10 barg, -50 °C) for scale and high pressure vessels (40-50 barg, >0 °C) for operational flexibility have been launched [21] and are being investigated respectively [22].

In July 2025, a milestone was reached when the NORTHERN PIONEER successfully offloaded LCO_2 at Norway's Northern Lights Øygarden facility – the first industry-scale CO_2 transport for permanent storage. In the coming years, global LCO_2 transport capacity is expected to grow rapidly to meet growing storage demand and although LCO_2 carriers are not purpose-built for transporting CO_2 from OCCS, they will play a key role in transporting aggregated CO_2 volumes from shipping hubs to final storage sites where needed.

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[8] Source: Information provided by Port of Rotterdam, 28 Oct 2025

[9] Source: Information provided by Port of Rotterdam, 28 Oct 2025

[10] Source: https://www.edb.gov.sg/en/about-edb/media-releases-publications/appointment-of-s-hub-to-develop-cross-border-carbon-capture-and-storage.html

4.5 Permanent storage

In this report, permanent subsurface storage of CO_2 in deep geological formations, i.e. in depleted oil and gas fields or deep saline aquifers, is considered as the preferred means of CO_2 removal from the atmosphere.

Global perspective

Globally, the pipeline of carbon capture and storage (CCS) projects continues to grow robustly since 2017 driven by policy support, commercial interest, and the growing recognition of CCS as a critical climate solution [23], see figure below.

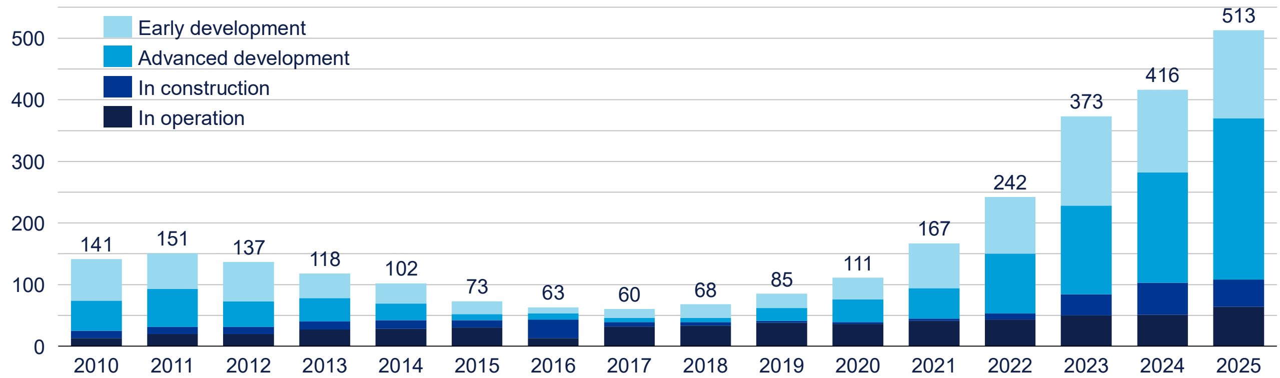

Figure 8: CO_2 capture capacity of commercial CCS facility pipeline since 2010 (Mtpa) [23]

DNV forecasts an increase in CO_2 captured and stored from 41 Mtpa in 2024, to 210 Mtpa in 2030, 640 Mtpa in 2040 and 1,300 Mtpa in 2050, with North America and Europe leading the uptake. Today, most CO_2 is captured from natural gas processing and used for enhanced oil recovery, but only permanent storage and utilization pathways can deliver net GHG reductions. Towards 2040, hydrogen as an energy carrier, electricity from biomass, and cement production will be the next sectors driving uptake, while towards 2050, global deployment is expected to increase steadily as CCS becomes more attractive for other industrial and transport sectors. [6]

Regional perspective [6] [24]

In addition to the home regions of Rotterdam and Singapore, Europe and Southeast Asia respectively, China (main trade partner on NEU-Asia corridor) and the Middle East (en-route Europe-Asia) are discussed due to their relevance for potentially providing further offloading opportunities of LCO_2 captured on ships.

- **Europe**
  A leading region for CCS deployment, also because of strong policy support: The EU has established a legally binding target to be climate neutral by 2050 and sees the deployment of CCS, particularly in hard-to-decarbonize sectors, as a key tool to achieve this. The EU's industrial carbon management strategy, adopted in February 2024, established targets to capture 450 $MtCO_2$/yr by 2050. Moreover, the Net Zero Industry Act mandates oil and gas producers to collectively invest in, and provide, storage capacity of 50 $MtCO_2$/yr by 2030.

  CCS development in Europe to date is largely driven by the financial incentive to reduce EU ETS obligations and the provision of subsidies. The cost of meeting obligations by purchasing allowances on the EU ETS is the main incentive for emitters to capture CO_2. At the EU level, the Innovation Fund, the Connecting Europe Facility for Energy and Horizon Europe have been three key support mechanisms enabling CCS deployment while additional support is available at the country level in many cases.

  Europe's commitment to CCS has strong momentum; with a few operational CO_2 storage projects (e.g., Northern Lights/Norway and ENI Ravenna Phase 1) [23], more than 100 commercial-scale CCS projects are currently in development, see Figure 9. As demonstrated by Porthos, CO2next and ARAMIS in the Netherlands and Northern Lights in Norway, regional development is characterized by CCS clusters, where CO_2 transport and storage ("T&S") is managed and offered as a service to emitters. Developers from the oil and gas industry are the main drivers of large-scale storage projects. This approach leverages economies of scale, with shared infrastructure consolidating larger volumes and emitters paying a tariff for CO_2 transport and storage.

Various bilateral and multilateral agreements are in place to enable cross-border transport and storage of CO_2 in proximate countries such as Denmark, the Netherlands, and Norway. DNV expects such agreements to become increasingly important as emitters in countries that currently lack local storage, such as Germany, begin to use CCS to decarbonize.

The North Sea is currently the dominant location for CO_2 storage sites in Europe, where injection and permanent storage will be provided by storage providers like Shell, TotalEnergies, etc., but storage projects are emerging elsewhere, including in Greece, Italy, and Poland. Denmark is the first country in Europe that has awarded multiple exploration licenses for CO_2 storage onshore. This development could be important for future CCS deployment in Europe, as it offers the potential for cost reductions compared to offshore storage.

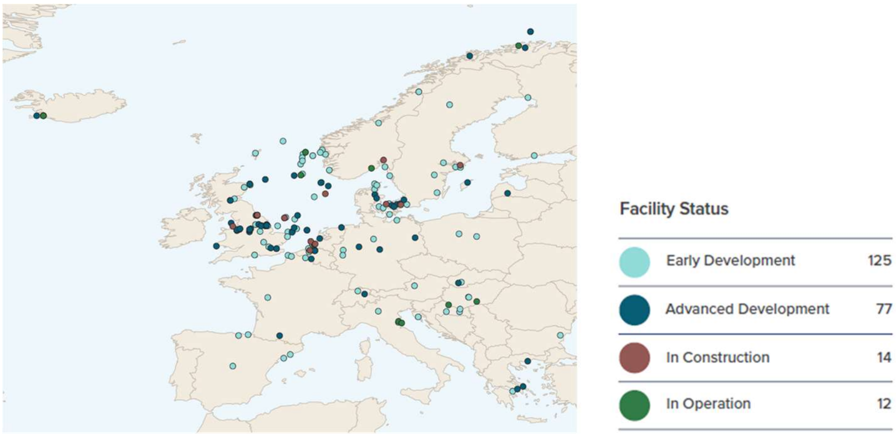

Figure 9: CCS project pipeline in Europe [23]

- **Southeast Asia**
  Several countries in Southeast Asia view CCS as key for sustainable development, as it provides opportunities for economic growth while reducing net greenhouse gas emissions. With various bilateral and multilateral agreements established, cross-border collaboration characterizes CCS deployment in the region. Malaysia and Indonesia are currently developing regional hubs to enable storage of CO2 from both domestic sources and nearby countries such as Singapore, Japan, and Korea. Policy and regulatory frameworks are being implemented to enable CCS. In Malaysia, the Carbon Capture, Utilization, and Storage Act (2025) and the Land (Carbon Storage) Rules (2022) in Sarawak have been introduced to regulate capture, transportation, and storage. The Malaysia Carbon Capture, Utilization, and Storage Agency oversees these activities, providing a detailed regulatory environment for cross-border CO2 transport. Indonesia's Government Regulation No. 71 of 2019 and various specific CCS regulations establish a framework for cross-border CO2 transportation, outlining the rights, obligations, and liabilities of parties involved.

  A key hub in the region, Singapore, aims for net zero by 2050 and is progressing at pace with CCS strategy as it targets to capture 2 MtCO2/yr by 2030 and over 6 MtCO2/yr by 2050. Singapore is evaluating cross-border CO2 transport with storage options being examined in Australia, Indonesia, and Malaysia. Indonesia and Malaysia aim to be storage hubs for the region's emissions and are at an advanced stage of developing regulation driven by industry emissions from Japan and South Korea as well. Within this picture, numerous companies are forming partnerships and joint ventures to prepare for emissions capture, transport, and storage. [6]

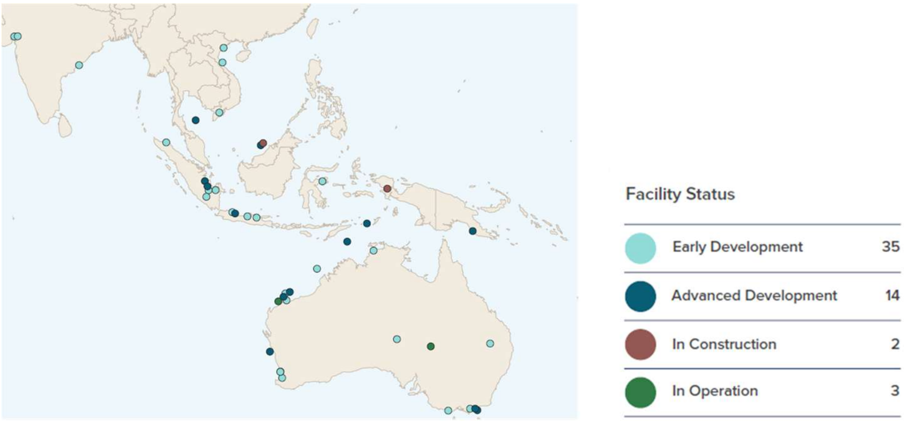

Figure 10: CCS project pipeline in Southeast Asia [6]

- **China**
  Targets to achieve peak emissions by 2030 and carbon neutrality by 2060 have been established by China. CCS is seen as critical to achieving these targets and its deployment will continue to be supported as part of the 15th Five-Year Plan. Financial mechanisms such as the People's Bank of China's Carbon Reduction Facility and Clean Coal Refinancing Loan have supported CCS deployment. With the expansion of China's national ETS to cover 60% of total emissions, DNV expects carbon pricing to become a driving factor for CCS activity in future. There are a few operational CCS facilities in China, and several other CCS facilities are currently under construction.

- **Middle East**
  The region has significant CCS ambition, with three operational CCS projects (Al Reyadah steel plant in the UAE, Qatar's Ras Laffan LNG Facility, and Saudi Arabia's Uthmaniyah gas processing plant) and six under construction. Initially driven by enhanced oil recovery (EOR), the regional CCS focus is increasingly changing to decarbonizing energy and the production of low-carbon fuels. The UAE's Long Term Strategy highlights CCS as crucial for industrial sector decarbonization, targeting 43.5 Mtpa of CO_2 capacity by 2050. ADNOC plans a 23 bn USD budget for decarbonization, aiming for 10 Mtpa of CO_2 captured by 2030 and net-zero operations by 2045. Saudi Arabia aims to capture and store 44 Mtpa of CO_2 by 2035 and launched a domestic carbon crediting scheme in 2024. By 2027 the Jubail CCS hub in Saudi Arabia will store 9 $MtCO_2$/yr from natural gas processing and industrial sources in an onshore saline aquifer. Oman aims to utilize its pipeline infrastructure for hydrogen and CO_2 transport in new CCS and EOR projects.

In more mature CCS ecosystems, e.g. in Europe or North America, Shipping may benefit from CCS developments, which are driven by land-based hard-to-abate industries. In less mature CCS ecosystems, such as Asia, shipping could create early demand for CCS projects – subject to adoption of IMO’s global Net Zero Framework – helping projects in development reach FID.

A reliable and safe CO_2 sink in the form of geological storage has been assumed. A safety evaluation of permanent storage facilities is not part of this report. Storage safety will be addressed by the CCS industry and is reflected in the cost assumptions made.

5 CO_2 ABATEMENT POTENTIAL FROM OCCS FOR THE FIVE LINERS ON THE NORTH EUROPE-ASIA CORRIDOR

5.1 Emissions baseline

Around 230 Mtpa TtW (Tank-to-Wake) CO_2 [25] emitted from container shipping accounts for just over a quarter of global shipping's annual GHG emissions of 911 Mtpa CO_2e [26]. The NEU-Asia container shipping corridor, as shown in Figure 11 below, is one of the most traffic-dense routes in global shipping and a significant contributor to emissions, accounting for 18.9 Mtpa CO_2[11]. However, the proximity of the nodes of the route to CO_2 storage sites creates strong implementation conditions for OCCS on this corridor.

Figure 11: Definition of NEU-Asia corridor [27]

An analysis based on publicly available AIS provides baseline fuel consumption and emissions on the NEU-Asia corridor from vessels operated by the five liners. The analysis includes all voyages between the two regions bound by outermost ports served directly on this route (including parts of voyage within a region) as illustrated in Figure 11. To reflect long-term operating conditions, rerouting via the Cape of Good Hope has been excluded, hence the analysis covers a 12-month period from 19 Oct 2022 to 18 Oct 2023.

The analysed fuel consumption and TtW CO_2 emissions from all container ships operating on this corridor amounted to 6.0 Mtoe and 18.9 Mtpa, respectively. Ships operated by the five liners represent two-thirds or 3.9 Mtoe/12.3 Mtpa CO_2 of the estimated fuel consumption and TtW CO_2 emissions respectively (Figure 12 below).

In the evaluation period, approximately 70% of TtW CO_2 emissions of ships operated by the five liners on the NEU-Asia corridor originated from vessels larger than 15,000 TEU. In contrast, vessels below 8,000 TEU accounted for less than 10% of total emissions as they are typically deployed on one-off voyages or during changes in operating regions.

A similar pattern as for larger vessels is reflected in vessel age on the NEU-Asia corridor. About 70% of total fuel use and emissions originated from vessels under 10 years old, with 24% younger than 5 years and 46% from ships aged 5–9 years. By contrast, vessels over 20 years old account for less than 5% of the emissions.

[11] DNV analysis of AIS data for 19 Oct 2022 to 18 Oct 2023 period

The 'new/large' age/size profile trend of ships on this route reflects the significant growth of larger, newer vessel segments over the past decade, purpose-built for the high-volume NEU-Asia trade.

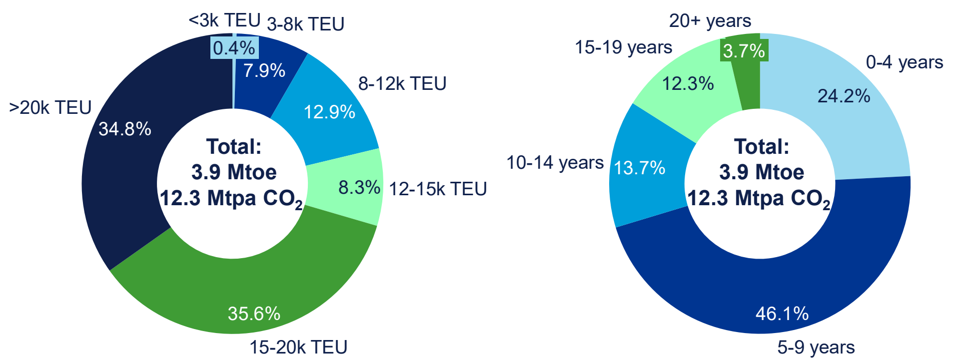

Figure 12: Annual fuel consumption + Tank-to-Wake CO_2 emissions share by vessel size + age on NEU-Asia corridor[12]

With containerized trade projected to grow by up to 150% by 2050 [28] compared to 2020 levels, without decisive decarbonization action, emissions along this corridor will also rise. Other hard-to-abate sectors such as, but not limited to, power generation and road transport are accelerating their transitions to renewables and electrification respectively. Without decarbonization action, shipping's GHG emissions could draw heightened scrutiny as a disproportionate source of global warming.

As industries globally, but also across Europe and Asia, advance toward net-zero, driven by regulatory mandates and customer expectations, the NEU-Asia container shipping corridor, one of the most emission-intensive trade routes globally, faces distinct challenges in decarbonization. Yet, these very challenges also create a unique opportunity for transformative change. The predictable operating pattern of liner shipping, strong or growing regulatory momentum to decarbonize in the two respective regions on the ends of the corridor, and the accelerating build-out of carbon capture and storage (CCS) infrastructure, which is largely driven by adjacent sectors, create the ideal conditions for piloting and scaling OCCS. If successfully demonstrated, this could deliver a substantial and replicable contribution to the decarbonization of global shipping, turning a high-emission route into a model for transition.

The following sections assess the potential of OCCS to decarbonize shipping through the lens of the vessels operated by the five liners on this corridor. Starting with providing an analysis of OCCS to understand its GHG reduction potential, followed by an assessment of its possible uptake, CO_2 abatement potential, infrastructure implications, and the cost/revenue pool it could create under different scenarios.

5.2 Analysis of Well-to-Storage GHG emissions

Assessing the emissions intensity of OCCS requires a Well-to-Storage (WtS) approach, covering all emissions from fuel production to permanent CO_2 storage. Under such an approach, the starting point is the familiar Well-to-Wake (WtW) emissions intensity from fuel (upstream and combustion) itself. The operation of onboard capture, liquefaction and temporary storage of LCO_2 on board requires additional energy, which is referred to as parasitic energy loss. This parasitic energy loss results in emissions that proportionately uplift the initial WtW emissions intensity, resulting in a WtW emissions intensity of all energy used onboard (including parasitic loss and before capture). Then, CO_2 emissions captured are deducted, resulting in a WtW emissions intensity of OCCS. The amount of CO_2 emissions captured is relative to the gross capture rate of 75%. Finally, emissions resulting from the energy use of downstream transport and sequestration are added to give the WtS intensity of OCCS use. The downstream transport of LCO_2 refers to emissions from the energy used for transportation. This includes moving CO_2 from the capturing vessel via barge to an onshore terminal, shipment by LCO_2 carrier from intermediate storage to the sequestration site (for Singapore), and pipeline transport to the final storage location. Emissions for intermediate and final storage refer to the energy required to operate the intermediate storage facilities, operate the final storage site, and inject

[12] DNV analysis of AIS data for 19 Oct 2022 to 18 Oct 2023 period

CO_2 into the final storage location. This approach of calculating the WtS emissions intensity follows IMO's 2024 LCA Guidelines [29]. Fugitive emissions resulting from CO_2 slip are not included.

For HFO as an example fuel, Figure 13 below illustrates the Well-to-Storage emissions intensity for OCCS, resulting in net emissions intensity reductions (net capture rate) of 55.1% for a Rotterdam-type value chain (see chapter 4 Figure 3). For a Singapore-type value chain (see chapter 4 Figure 4), Wake-to-Storage emissions increase to 0.8 gCO_2e/MJ, which results in a net capture rate of 54.5%. Figure 13 highlights that while OCCS can significantly reduce net emissions, its overall impact is moderated by and will depend on the capture rate vs parasitic loss (mainly) and Wake-to-Storage emissions (less so) when used with fossil fuels.

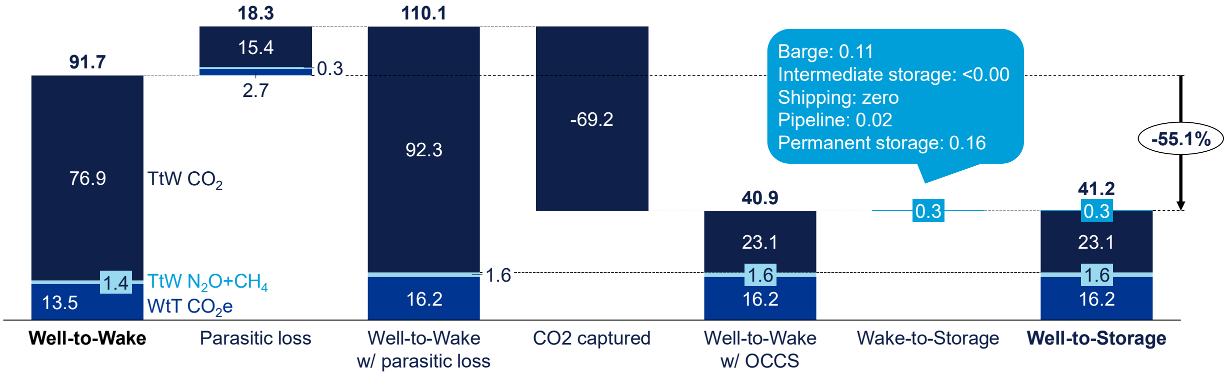

Figure 13: HFO + OCCS GHG intensity @ 20% parasitic loss, 75% capture rate, offloaded in Rotterdam (gCO_2e/MJ) [2, 3, 4]

While using OCCS with 100% HFO as calculated above can sustain compliance with the proposed IMO GFI Base Target [30] only through 2038[13], its potential as a decarbonization technology extends well beyond: OCCS can match net-zero emissions achievable with sustainable fuels, when blending low-GHG carbon-based fuels, and can potentially go beyond net-zero, achieving negative emissions intensity. Low-GHG fuels like biofuels in combination with OCCS can achieve negative emissions since OCCS removes CO_2 from the carbon cycle, which is in line with IMO's LCA Guidelines [2, 29]. Nevertheless, it is not yet defined how negative emissions would be treated for compliance purposes.

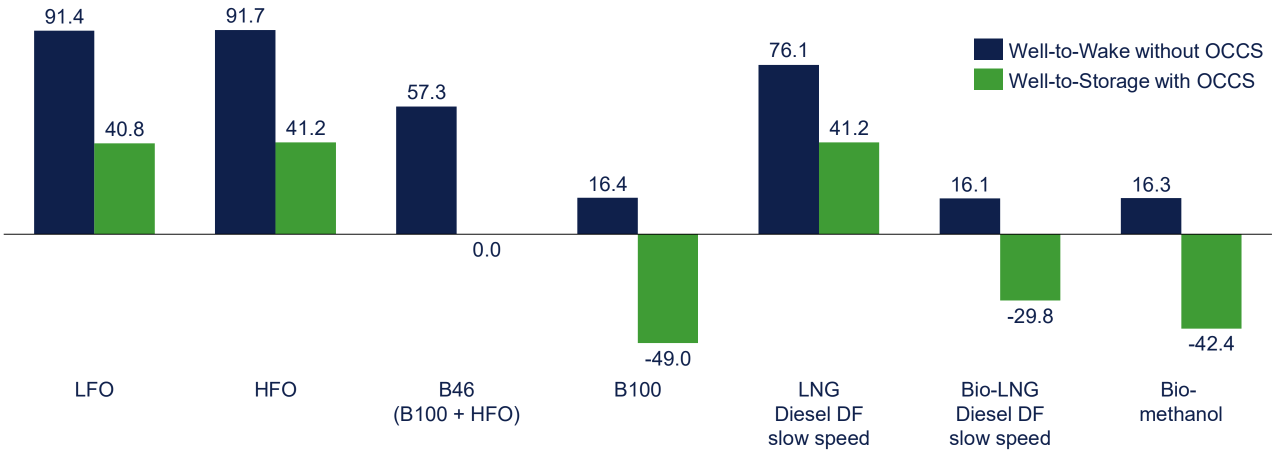

Figure 14: GHG intensity of selected fuels with OCCS offloaded in Rotterdam (gCO_2e/MJ) [2, 3, 4][14]

[13] DNV analysis based on IMO GFI Base Target [37]

[14] The GHG intensity analysis follows IMO LCA Guidelines (MEPC.391(81)), assuming a 75% gross capture rate and 20% energy penalty. Carbon factors are taken from FuelEU Maritime (Regulation (EU) 2023/1805, amending Directive 2009/16/EC). Exemplary emission factors for biodiesel (B100) from used cooking oil (UCO), for bio-methanol

As illustrated in Figure 14 (Rotterdam example), a B46 blend when used with OCCS results in net-zero emissions, while a B100 fuel achieves a negative emissions intensity that is equivalent to eliminating all onboard emissions and additionally reducing over half the WtW GHG emissions intensity from another identical but exclusively HFO-powered ship. Values for offloading in Singapore differ slightly.

As OCCS addresses only TtW CO_2 and not the WtT or non-CO_2 (N_2O and CH_4 slip) TtW emissions, the absolute impact of OCCS in gCO_2e/MJ differs among fuels – lower for LNG and higher for liquid fuels. Additionally, among biofuels, the fuel emissions intensity depends on the biomass, with the above values chosen to portray the impact of OCCS on biofuels from representative production pathways[15].

5.3 Forecast of OCCS uptake and CO_2 abatement potential

5.3.1 Modelling and scenario definition

To evaluate the potential contribution of OCCS to decarbonize shipping on the NEU-Asia corridor for ships operated by the five liners, an assessment has been performed along the following three dimensions:

I. Environmental impact – Mtpa CO_2e (WtW) abated relative to baseline
II. Infrastructure implications – Mtpa CO_2 offloaded along the corridor to illustrate the scale of supporting logistics/infrastructure required and provide an indication of the potential CO_2 volumes to be handled; and
III. Cost/revenue implications – Costs paid by the five liners for CO2 offloading i.e. the revenue pool in USD for Ship-to-Storage value chain

The assessment uses DNV's GHG Pathway Model [5], a comprehensive, global fleet-level simulation tool which has been used for various assessments such as for MEPC 82/INF.8/Add.1. The model projects the adoption of decarbonization technologies (including OCCS) and fuels until 2050 on a ship level, based on relative costs of competing technology and fuel combinations shown in Figure 15 below, regulatory trajectories (proposed IMO GFI, FuelEU Maritime, EU ETS) and technology maturity. The model dynamically integrates year-by-year feedback loops capturing the current orderbook, future fleet renewal, technology learning effects, regional fuel and infrastructure availability, and evolving compliance costs including compliance surplus and deficits, providing projections of the uptake various technologies and fuels under a net-zero by 2050 scenario.

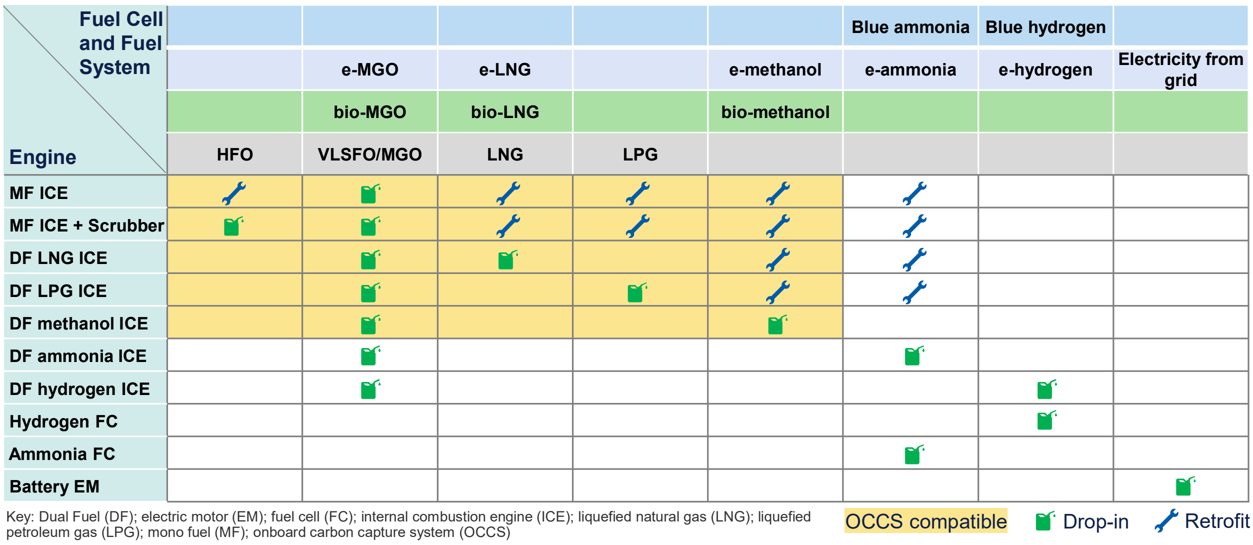

Figure 15: Competing decarbonization technology and fuel configurations in the GHG Pathway Model

For each ship in the world fleet and for each year up till 2050, the GHG Pathway Model determines the most cost-effective combination of decarbonization measures, such as the use of alternative fuels, onboard carbon capture, energy efficiency

15 From waste wood, and for bio-LNG from 60% manure and 40% maize in combination with close digestate, off-gas combustion technology follow default values from Directive (EU) 2018/2001. These emission factors and biomass types were selected as examples of representative production pathways. The FuelEU Maritime carbon factors were chosen for this comparison since they offer more detailed values for different biofuel types compared to the broader default factors in IMO guidelines. Pilot fuels are not considered.

improvements, speed reduction, and the potential sale or purchase of surplus emissions allowances to meet regulatory requirements over time. The model simulates the decision-making process of ship owners based on a Net Present Value (NPV) criterion for total cost. Cost elements considered as part of total cost include CAPEX for newbuilds or retrofits of converter and other technologies (as outlined in Figure 15) and energy efficiency packages, annual costs for the fuels (listed in Figure 15) or viable combinations thereof (based on DNV's Marine Fuel Price Mapper [31]), as well as CO_2 offloading costs and applicable CO_2 fees, taxes, and potential rewards, depending on the trading pattern of a vessel. By assessing all feasible options annually for each vessel, the model projects the fleet-wide adoption of technologies and fuels under specific conditions, helping to determine the most efficient and economically viable decarbonization pathway for the entire fleet under a given set of inputs.

OCCS adoption and its potential to decarbonize shipping, both in the model and in practice, will primarily be shaped by its economic attractiveness compared to competing solutions such as sustainable fuels/technologies, paying CO_2-related costs or any combination of these, which is driven by three key factors:

i) OCCS CAPEX
ii) OCCS performance (capture rate and parasitic loss)
iii) CO_2 offloading costs

For this assessment, present-day CAPEX input in terms of per-MW costs for the capture and liquefaction unit and per-m³ costs for liquid CO_2 storage tanks has been sourced from current technology providers. Potential cost advantages for OCCS retrofit for ships already fitted with scrubbers have not been considered in the modelling. For OCCS performance, a capture rate of 75% with a corresponding energy penalty of 20% has been used, see chapter 4.2, "OCCS technology".

While the first two factors (OCCS CAPEX and OCCS performance) are relatively well established, CO_2 offloading cost – which represents the cost to ship operator or revenue to the Ship-to-Storage CCS value chain for offloading and permanently sequestering CO_2 – is both the most uncertain and an influential factor towards OCCS uptake. The uncertainty in CO_2 offloading costs stems from the nascency of the CO_2 offloading and sequestration value chain and limited transparency on the price per ton of CO_2 offloaded at port. Offloading cost for OCCS covers the following components:

- **Barge offloading**: Includes handling and operational charges incurred for the transfer of CO_2 from ship to barge and onward facilities
- **Transport**: Cost for onward CO_2 transport to the final sequestration site, influenced mainly by distance, volume, transport mode, and fluid phase (gaseous/liquid/supercritical)
- **Storage**: Covers site characterization (subsurface evaluation and testing), well drilling, sequestration operations, and post injection monitoring
- **Tariffs**: Cost paid by emitters to third-party transport and storage operators, includes direct costs plus margins for profit, risk, contingencies, and phase-in inefficiencies

Figure 16 below presents the breakdown of offloading costs with barge offloading cost based on a 50 km round-trip assessment and the transport, storage, and tariffs figures [6], reflecting cost assumptions aligned with European market conditions which are on the conservative side.

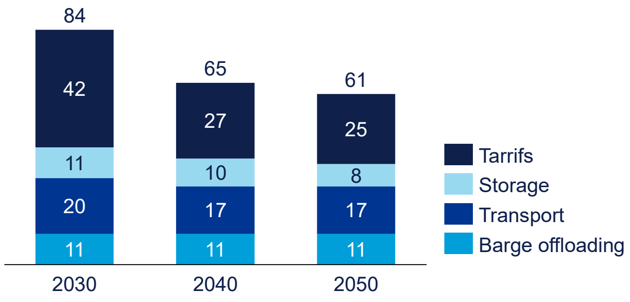

Figure 16: Base offloading costs (USD/tCO_2) [6]

Given the sensitivity of OCCS adoption to offloading costs – and the inherent uncertainty surrounding these – three distinct scenarios have been developed. Each scenario reflects a different CO_2 offloading cost assumption: The first applies the base costs shown in Figure 16 while the second and third scenario increase these costs by 50% and 100%, respectively as summarized in Table 1 below. The base-cost scenario represents conditions conducive to **High OCCS Uptake**. By scaling costs upward in the other two scenarios, the analysis evaluates how higher offloading expenses influence OCCS adoption and the resulting cost/revenue pool under a **Medium Uptake (50% higher offloading costs)** and **Low Uptake (100% higher offloading costs)** scenario.

Scenario name	Offloading cost 2030-2050 (Variation from base case)
High Uptake	84 – 61 USD/tCO_2 (base case)
Medium Uptake	126 – 92 USD/tCO_2 (+50% on base case)
Low Uptake	168 – 121 USD/tCO_2 (+100% on base case)

Table 1: Scenario differentiation used in modelling

This approach appraises the trade-off between higher per-ton revenue and lower CO_2 volumes offloaded and is complemented by insights into shipowners' economic preferences for high- (e.g., OCCS) versus low- (e.g., drop-in fuel) CAPEX solutions as well as the relevance of offloaded CO_2 volumes to scaling the nascent Ship-to-Storage infrastructure.

It should be noted that 2030 has been assumed as a start date for OCCS in the modelling, mirroring industry consensus, reflecting current status of OCCS and the potential lag between regulation and infrastructure readiness. Therefore, to enable OCCS deployment by 2030, it is important that regulatory frameworks are established by 2028. This lead time is crucial, as not only OCCS installations but also investments for infrastructure development in the CCS value chain, for reception, transport and storage of CO_2 from OCCS, require significant outlay of capital and development periods.

5.3.2 Modelling results

This section outlines the evolution of the energy-mix and OCCS penetration across three scenarios to highlight OCCS's role in and contribution towards maritime decarbonization and economic upside for the CCS value chain arising from it.

Share of energy used with OCCS

Figure 17 below shows the modelling results for the three scenarios in terms of projected energy demand, effect of energy efficiency (net of parasitic loss) and energy used with OCCS.

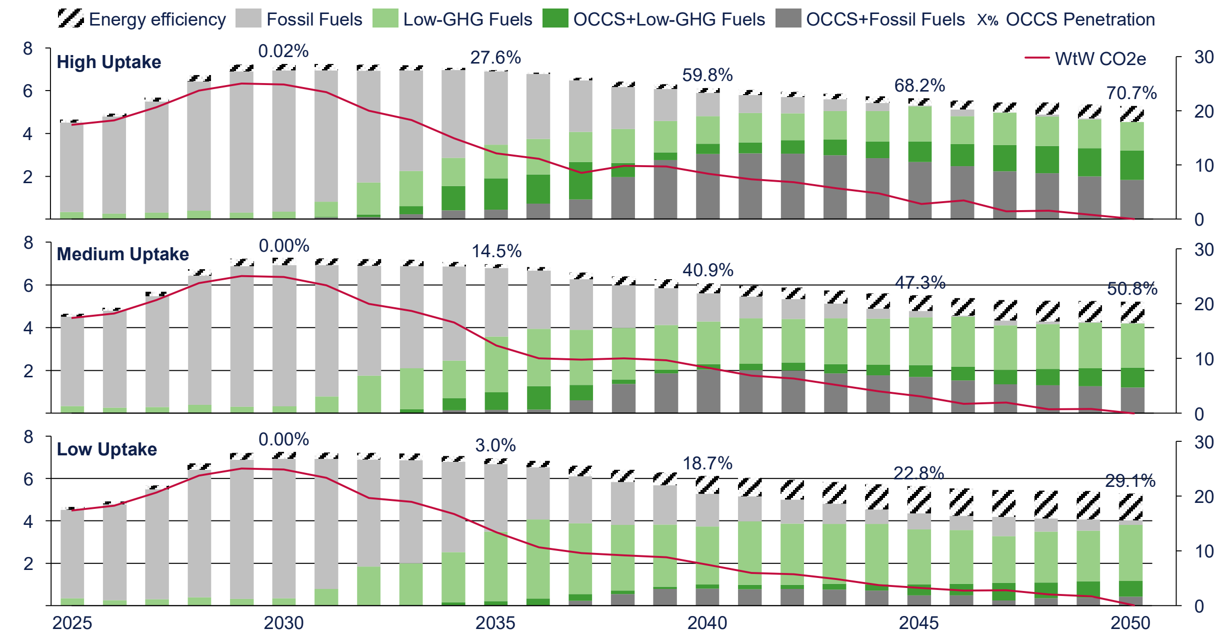

Figure 17: Energy used (Mtoe; left axis), WtW CO2e emissions (Mtpa, right axis) by the five liners on NEU-Asia corridor

The baseline energy consumption of 3.9 Mtoe in 2023 (see 5.1), subsequently 4.6 Mtoe in 2025, shows a steep initial increase towards 2029, followed by a gradual tapering towards 2050 reflecting the dynamic balance between projected transport work demand and the modelled supply of container shipping capacity.

While underlying global transport work projections show a steady rise in containerized trade through 2050 [28], in the near term, the vessels in shipping's current orderbook drive up total fleet energy consumption even further (into the late 2020s). Thereafter, as scrapping outpaces newbuilding, the model achieves an endogenous balance aligning supply with demand and stabilizing overall energy requirements.

Another factor that reinforces the interplay between fleet utilization, fleet size, and total energy use is vessel speed management. As ships reduce operating speed to optimize fuel use or meet regulatory constraints, this lowers the transport work contribution per vessel. To compensate, more ships are needed to meet the same transport work demand.

Results show that under the High Uptake (low offloading cost) scenario, OCCS is significantly attractive in comparison to other decarbonization options as its penetration of the energy-mix reaches 71% by 2050. However, as offloading costs rise, penetration declines sharply under the Medium Uptake (50% higher offloading cost) and Low Uptake (100% higher offloading cost) scenarios to 51% and 29% in 2050, respectively. In all cases, OCCS uptake accelerates sharply toward 2040, driven by cost competitiveness of OCCS in achieving the desired emissions reduction compared to competing solutions (sustainable fuels/technologies, paying CO_2-related cost or a combination of these). However, as the economic advantage from pairing OCCS exclusively with fossil fuels to meet regulatory requirements diminishes, this leads to a stabilization in OCCS penetration throughout the 2040s.

Furthermore, even though the additional energy demand from OCCS partly offsets energy efficiency gains under the higher uptake scenarios, similar WtW CO2e emission levels across all three scenarios demonstrate that OCCS delivers the necessary emission reductions, making the technology's overall impact favourable towards abatement and instrumental in achieving net-zero.

OCCS' role across the three scenarios highlights the following:

- **Complementarity to low-GHG fuels**: Across all scenarios, OCCS complements fuel-based decarbonization by acting both alongside and in conjunction with low-GHG fuels to deliver the necessary emissions reductions through the years, especially as progressively stricter GHG reduction requirements render fossil-only OCCS use insufficient in the 2040s
- **Role as a potential bridging technology:** In addition to complementing low-GHG fuels, OCCS can help smoothen the price volatility and transition from drop-in biofuels (amid foreseen tightening supply/increasing costs) to more sustainable and lower-GHG fuels (initially expensive but expected to reduce in costs as production scales), by providing shipping with a reliable pathway for continued decarbonization
- **Enabler for net-zero**: Most low-GHG fuels have a well-to-wake footprint. By capturing emissions from low-GHG fuels, OCCS can provide a practical pathway to net-zero

CO_2e abatement potential (WtW)

The CO_2e abatement potential represents the GHG emissions avoided compared to a defined baseline under a given scenario. For this analysis, the baseline is derived from the scenario-specific energy consumption (excluding energy efficiency) of ships operated by five liners on the NEU-Asia corridor and the average Well-to-Wake (WtW) emissions intensity of shipping in the reference year. Parasitic loss (which leads to higher overall energy consumption and emissions) has been accounted for and any inherent reductions from low-GHG fuels used in conjunction with OCCS are attributed to the fuel, not the capture system – i.e. only emissions savings directly attributable to OCCS are considered.

Modelling results indicate a substantial CO_2e abatement potential (WtW) from ships operated by the five liners on the NEU-Asia corridor. Depending on the scenario, OCCS could deliver abatement in the ranges of:

- 0.00 to 0.01 Mtpa CO_2e (WtW) in 2030
- 1.5 to 6.0 Mtpa CO_2e (WtW) in 2040
- 2.4 to 6.6 Mtpa CO_2e (WtW) in 2050

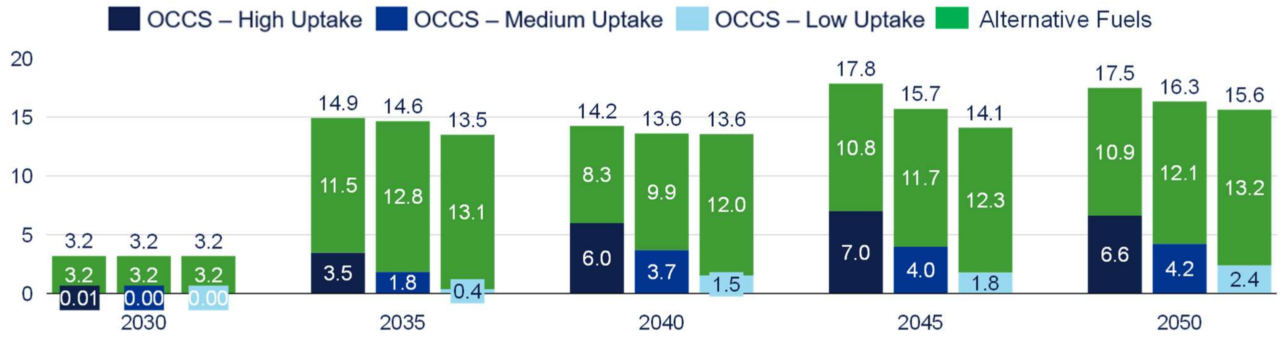

Figure 18: WtW emissions abated (excluding energy efficiency) by five liners on NEU-Asia corridor (Mtpa CO_2e)

Through 2030-2050, depending on the scenario, OCCS could account for approximately one-third, one-fifth, or less than one-tenth of the total CO_2e abatement from ships operated by the five liners operating on this corridor. In absolute terms, this corresponds to 99 mn, 57 mn, and 25 mn tons of CO_2e abated over the 2030-2050 period.

While the CO_2e abatement potential specified above and in Figure 18, represents sizeable WtW emissions savings, it does so for a limited subset representing only vessels operated by the five liners on this corridor. If other container vessel operators on this route, representing an additional 50% of current emissions on this route, were to be included, the abatement potential would increase proportionally.

Abatement cost covering CAPEX of the capture and liquefaction unit and LCO_2 storage tanks, parasitic fuel costs and LCO_2 offloading can provide an estimate of the comparative cost of OCCS to other decarbonization solutions. It must be noted that this cost can vary significantly from variability in container ship size (TEU) and year of construction/remaining operational lifetime among other factors such as OCCS unit CAPEX and OPEX and offloading costs.

CO_2 offloaded in ports

Assessing CO_2 volumes offloaded at the ports of Rotterdam and Singapore is vital for understanding the scale of CO_2 value chain logistics and infrastructure required. This can provide investors and stakeholders a picture of the CO_2 handling capacity needed and will ultimately shape how the infrastructure necessary to integrate shipping into the wider CCS network develops.

Results indicate the CO_2 quantities offloaded by the five liners operating on the NEU-Asia corridor to be in the ranges of:

- 0.00 to 0.04 Mtpa CO_2 in 2030
- 1.9 to 7.2 Mtpa CO_2 in 2040
- 2.5 to 6.9 Mtpa CO_2 in 2050

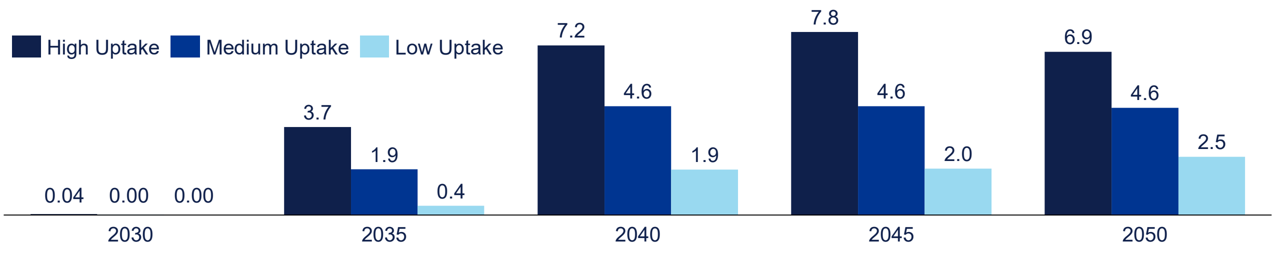

Figure 19: CO_2 offloaded from ships operated by five liners on NEU-Asia corridor (Mtpa CO_2)

Assuming a one-third/two-thirds split between Rotterdam and Singapore based on their locations closer to and away from the nodes of the corridor respectively, in 2040 Rotterdam would require handling 0.6 to 2.4 Mtpa CO_2 from just the five liners. For context, this represents roughly 3% to 11% of the 22 Mtpa CO_2 capacity of the ARAMIS project in Rotterdam [32].

By 2035, under the High Uptake scenario, vessels operated by the five liners on the NEU-Asia corridor alone are expected to offload an average of one batch of liquefied LCO_2 per day per port with batch sizes ranging from 2,750 to 4,750 m³. From

2040 onwards, this would increase to just over two batches. It can be expected that given the economic attractiveness of OCCS, shipowners would consider leveraging full-scale installations, especially considering mechanisms such as pooling which can help offset emissions from other ships.

Furthermore, considering (a) other international and regional container shipping routes using the two ports as hubs, (b) additional container vessel operators besides the five and (c) other ship segments capturing and offloading CO_2 would result in significantly higher number of batches and volumes of CO_2 offloaded.

CO_2 offloading cost/revenue pool

One key driver for engaging the CCS ecosystem and attracting investment into OCCS/shipping-related infrastructure will be the total costs paid by shipping for offloading and permanently storing CO_2. From the point of view of the CCS value chain, this represents the available revenue pool, i.e. the opportunity in terms of the monetary value available to the CCS value chain for offloading, transporting and finally sequestering CO_2 from shipping.

Results show the CO_2 offloading cost/revenue pool generated by the five liners operating on the NEU-Asia corridor to be in the ranges of:

- 0 to 3 mn USD in 2030
- 279 to 503 mn USD in 2040
- 299 to 423 mn USD in 2050

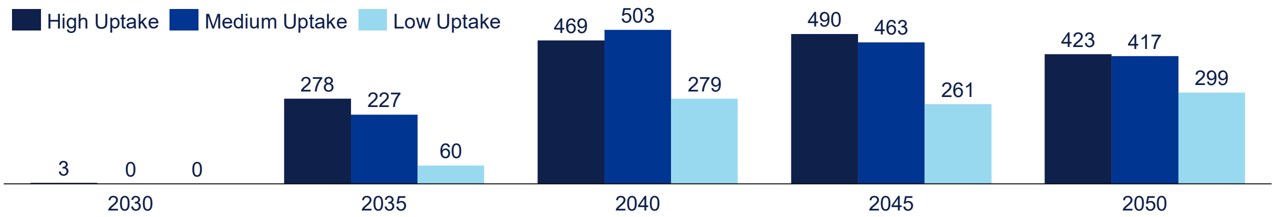

Figure 20: CO_2 offloading cost/revenue pool from ships operated by the five liners on NEU-Asia corridor (mn USD)

The High Uptake (low offloading cost) scenario results in the strongest overall revenue pool of 7.3 bn USD for the period 2030-50. From CO_2 offloaded by the five liners, the offloading value chains in Rotterdam and Singapore could generate total revenue of about 278 mn USD/year by 2035, stabilizing well above 400 mn USD/year for the 2040-50 period.

In the Medium Uptake (50% higher offloading cost) scenario, by 2035, CO2 offloaded on the corridor by the five liners could yield 227 mn USD/year and remain above 400 mn USD/year for the 2040-50 period. The higher per ton offloading cost largely counteracts the effect of lower CO2 volumes, with the cost/revenue pool for the 2030-50 period only 6% lower than the High Uptake scenario. However, this does come with a high risk of losing revenue to alternative decarbonization options as higher offloading costs make OCCS economically less competitive.

The Low Uptake (100% higher offloading cost) scenario severely constrains OCCS adoption. By 2035, just 0.4 Mtpa are offloaded on the corridor, generating 60 mn USD/year. In the 2040s, as offloaded CO2 volumes increase to 2.5 Mtpa, revenues remain limited at less than 300 mn/year. Besides cutting the revenue pool by nearly half over 2030–2050 compared to the High Uptake scenario, this scenario carries the highest risk of diversion of the revenue pool toward competing solutions and inability of the required infrastructure to scale due to low CO_2 volumes.

This highlights an important aspect: While the modelling evaluates ship-level economics, it does not explicitly account for the potentially varying CO_2 offloading infrastructure availability in a year, which would depend on aggregated CO_2 volumes delivered from shipping. Meaning that higher CO_2 offloading costs not only erode OCCS's cost advantage on a ship level but also risk preventing the LCO_2 offloading value chain from reaching critical mass – an essential threshold for sustaining the infrastructure needed for CO_2 handling and storage. Therefore, in practice two perspectives will be essential to consider:

- Shipowner's perspective: For shipowners to allocate significant upfront CAPEX to a less mature and operationally somewhat complex solution, the economic case must be compelling – anchored by low and predictable CO_2 offloading costs. Even moderate increases in these costs can erode OCCS's competitiveness, making alternative decarbonization options – particularly drop-in fuels with minimal retrofit requirements – more attractive. Besides, other sizeable target ship segments such as tankers and bulk carriers, (whose non-liner type voyage patterns are less attractive for OCCS adoption) have lower fuel consumption and subsequently lower per-vessel offloaded CO_2 volumes, meaning that their OCCS viability is highly reliant on low offloading costs to offset the high CAPEX

- LCO_2 value chain's perspective: Realizing OCCS's substantial potential in shipping requires initial scaling and is hence fundamentally a volume-driven challenge more than a margin-driven one. Rapid development of currently immature elements within the Ship-to-Storage value chain depends on achieving high and reliable throughput, which in turn requires consistently low offloading costs to stimulate adoption and unlock economies of scale

And finally, as with offloaded CO_2 volumes, the cost/revenue pools assessed above represent a sizeable but narrow segment of the overall opportunity – limited to five operators on a single trade lane. While its assessment is not within the scope of this study, the overall opportunity when considering other ship types, routes etc. would be substantially larger, especially when driven by low offloading costs and the economic appeal of OCCS for more cost-sensitive ship segments.

6 NEED FOR REGULATION

To unlock the potential of OCCS in enabling maritime decarbonization, a timely and supportive regulatory framework harmonized on IMO and EU levels needs to be established. Furthermore, the legal status of CO2 with regards to its treatment under London Convention and London Protocol as well as its treatment as waste or commodity needs to be clarified. These are critical since deploying OCCS requires substantial capital investment, both for onboard systems and for the wider CO_2 offloading and storage infrastructure. Without regulatory certainty, these investment decisions remain stalled, creating a bottleneck for progress. Moreover, given the long lead times required to develop and scale such infrastructure, any delay in regulatory alignment risks pushing implementation beyond the milestones set by IMO and EU decarbonization strategies. This section highlights the key regulatory uncertainties, offering suggestions where possible, to help clear these hurdles and enable progress.

6.1 IMO

At IMO, starting with South Korea's April 2021 submission to MEPC 76/7/44, several submissions have been made calling for a regulatory framework on OCCS, but progress has remained limited with other issues taking priority.

However, at MEPC 83 in April 2025, the IMO agreed on a work plan to develop a regulatory framework for the use of OCCS. This ongoing work aims to ensure environmentally safe and traceable CO_2 handling, address legal and logistical barriers to its transfer and storage, secure access to certified reception facilities while enabling transparent data reporting and recording. This framework, expected to be finalized by 2028, would pave the way for OCCS to be integrated into the proposed IMO Net-Zero Framework and possibly other GHG related regulations such as the CII and EEDI. The following section outlines three key aspects vital for OCCS integration with the proposed IMO NZF: Life cycle assessment (LCA), data collection, and certified CO_2 sequestration schemes.

<u>LCA</u>

Enabling effective evaluation and implementation of any decarbonization measure, whether fuel-based or technological, requires a credible and auditable emissions-based accounting framework applicable on a ship level. It must, among other things:

- Allow for meaningful and fair comparison of emissions intensity reduction resulting from fuels and technologies, such as OCCS
- Align with relevant regulatory mechanisms such as the IMO GFI under the NZF

IMO's LCA Guidelines (MEPC.391(81)) have been developed with this in mind, based on a Well-to-Wake (Well-to-Storage where relevant) approach. The current version of the guidelines focuses on the method for fuels, while the evaluation of OCCS is still pending further methodological developments.

When calculating the GHG intensity of OCCS, it is important to consider the parasitic energy use and emissions onboard the ship, as well as emissions and CO_2 leakage from the ship to the storage site. A tentative method to calculate the net emission credit, which includes emissions from capturing, compression, cooling, transport and final storage, is included in the IMO LCA Guidelines, as outlined by the formula below [29].

$$
\begin{aligned}
&Eoccs = csc - ecc - et - est - ex \\
&Eoccs: Net\ emissions\ credit\ from\ OCCS \\
&csc: CO_2\ captured\ and\ stored\ (offloaded) \\
&ecc: Emissions\ from\ parasitic\ loss\ (capturing, compression\ and\ cooling) \\
&et: Emissions\ from\ CO_2\ transport\ to\ final\ storage\ site \\
&est: Emissions\ from\ CO_2\ storage \\
&ex: Any\ other\ emissions\ related\ to\ OCCS
\end{aligned}
$$

To credibly include OCCS under LCA, there is a need to effectively address two concerns regarding parasitic loss emissions ecc :

I. Concerns about the possible double counting due to the term ecc in the LCA formula
II. Concerns on measuring/quantifying ecc

The first concern can be addressed by simplifying the current LCA formula to show that it correctly accounts for $ecc: Emissions\ from\ parasitic\ loss\ (capturing, compression\ and\ cooling)$ as shown in appendix 8.1.

The second concern however – quantifying ecc, particularly the parasitic loss (pen) term within it – remains. Since there is no discrete 'parasitic exhaust' to measure and OCCS emissions are embedded within the ship's overall exhaust flow, direct metering is not feasible. Instead, measuring/quantifying parasitic energy (either via live onboard measurement or at commissioning) offer practical alternatives for future LCA methodological developments.

Data collection

A robust standardized mechanism for annual reporting and verification of CO_2 transferred from ships for sequestration will be essential to ensure transparency and regulatory compliance. Currently, no IMO guidance exists on verifying offloaded CO_2 quantities, which is critical to determine the volumes eligible for deduction under GFI, CII, and other frameworks. Once established, these guidelines would need to allow for data collection and verification of the following aspects related to CO_2 offloaded for sequestration:

- Requirements for reporting and verifying CO_2 quantity offloaded for sequestration (csc) under IMO DCS
- Quantification of Ship-to-Storage emissions (et), long-term storage related emissions (est), and any other emissions (ex) either via default factors under LCA or verified values reported to IMO DCS
- Requirements for quantifying/measuring, reporting, and verifying either Parasitic Emissions (ecc) or Parasitic Energy (pen)

Although OCCS has significant potential to decarbonize shipping, enabling verifiable and standardized CO_2 sequestration globally – despite the absence of regulatory precedents from other industries – will require the IMO to demonstrate regulatory leadership and prioritize closing data collection gaps in a comprehensive yet implementable way.

Certified CO_2 sequestration schemes

To ensure the credibility of CO_2 sequestration, global CO_2 sequestration schemes would need to develop and be recognized by IMO and other regulators. Currently, there is no IMO guidance on recognized sequestration certification schemes.

Guidelines similar to Regulation 34 (Sustainable Fuels Certification Scheme) under the proposed NZF regulation under MARPOL Annex VI will be needed. These will define requirements for certified CO_2 sequestration schemes and specify approved verification schemes that meet IMO standard.

6.2 EU

Europe's mature EU ETS and MRV systems, advancing CCS regulation, large sequestration capacity and networks uniquely position it to lead OCCS enablement. With FuelEU Maritime's 2026 revision, OCCS could become a potential compliance option, but unlocking OCCS's full decarbonization potential will require regulatory clarity and coordinated alignment across regulations such as EU MRV, FuelEU Maritime, EU ETS, and the CCS Directive.

EU ETS

Under current EU ETS rules, ships can reduce their emissions liability by capturing CO_2 onboard and delivering it to a geological storage site (certified under Directive 2009/31/EC). DG Clima has issued guidance [33] covering detailed rules for OCCS under ETS but there are no well-documented cases of CO_2 offloaded from ships to get credit under ETS yet.

While receiving credit for CO_2 captured onboard and sequestered is technically possible under ETS now, given OCCS's strong decarbonization potential, EU regulators should also consider issuing guidance to ensure clarity for ship operators and investors especially on open issues such as those related to viability of offloading CO_2 bound to amine for ETS deduction.

Furthermore, on an EU level, since international shipping emissions fall outside national carbon budgets, this may limit access to nationally funded or subsidized CCS budgets and schemes. To support shipping's access to the CCS market, the EU Industrial Carbon Management Strategy [34], which aims to establish a single market for CO_2 transport and storage by 2030, should be expanded to explicitly include onboard carbon capture.

FuelEU Maritime

Currently, FuelEU Maritime (Regulation (EU) 2023/1805) does not consider OCCS as a compliance option for reducing a vessel's GHG intensity. However, the European Commission has indicated that this position may be reconsidered in the 2026 review cycle.

Allowing OCCS would mean that Annex I of the regulation integrates CO_2 captured for sequestration into the GHG intensity formula, shifting from a Well-to-Wake to a Well-to-Storage approach while also accounting for parasitic loss. More importantly, this would necessitate the development of a robust and verifiable MRV framework to account for CO_2 captured and transferred for storage (currently addressed under EU 2018/2066 Annex X), parasitic emissions/parasitic energy (EU 2018/2066 Annex IV), and additional Ship-to-Storage emissions (currently addressed under EU 2018/2066 Annex X). It is recommended to align EU MRV Regulation (2015/757) with FuelEU Maritime (as then amended), EU ETS, and the CCS Directive (2009/31/EC). Given the complexity and time-consuming nature of such alignment, prioritizing it is essential, especially since it has the potential to deliver the regulatory certainty and investment signals needed to unlock OCCS-driven decarbonization in line with the EU's CCS targets.

6.3 Legal status of ship-borne CO_2

Cross-border transport of CO_2: London Convention and London Protocol

The 1972 London Convention (LC) prohibited dumping of wastes at sea, while the 1996 London Protocol (LP) introduced stricter controls via a reverse list. In 2006, an amendment to LP allowed CO_2 storage in sub-seabed formations under defined conditions within national boundaries. But since Article 6 of LP bans export of wastes for dumping this hinders cross-border CO_2 transport. The 2009 amendment to LP (LP.3(4)) permitted such exports under bilateral agreements but remains unenforced due to limited ratifications. A 2019 resolution to LP (LP.5(14)) allowed provisional bilateral application allowing cross-border CO_2 transport, which has been adopted by a small group of countries including Belgium, Denmark, the Netherlands, Norway, Korea, Sweden, Switzerland, the UK, and Australia.

It is worth noting that the legal framework for LC/LP was designed for land-based CO_2 sources where ownership is tied to a country, which may not suit CO_2 captured on ships. Also, as per LC article III, paragraph 1(b), "dumping" does not include "the disposal at sea of wastes or other matter incidental to, or derived from the normal operations of vessels (…) and their equipment".

Given the above, the applicability of LC and LP to OCCS remains unresolved. Two possible outcomes in terms of interpretation could be:

I. LC article lll, paragraph 1(b) applies and CO_2 captured on a ship does not fall under the purview of LC/LP, or
II. Since each ship is registered under a Flag State, the applicability of the London Convention (LC) and the London Protocol (LP) to CO_2 transport from a ship (territory of Flag State) to a Receiving State depends on the relative status on LC and LP of both the Flag State and the Receiving State

Legal certainty on CO_2 transport is essential and requires IMO to seek urgent clarification from the appropriate body under LC and LP. If possible, IMO should be recognized as the primary regulator of shipping-related CO_2 to ensure a uniform and robust global criterion.

Waste vs commodity

Classifying CO_2 captured onboard for sequestration as either a waste or a commodity presents distinct challenges. As waste, it triggers legal complexities under the LC/LP and also adds administrative, regulatory, and perception barriers to CO_2 infrastructure development. As a commodity, it risks adding taxes and tariffs on an otherwise valueless stream, potentially undermining the business case for sequestration.

Given the prohibitive and varied national implications from treating CO_2 as waste, a viable solution is for jurisdictions to adopt CCS-specific legal carve-outs that exempt CO_2 captured and destined for permanent geological storage from ordinary waste legislation – conditional on compliance with defined shipment and storage rules. This can help streamline CO_2 sequestration value chains by removing the administrative and legal complexities arising from classification of CO_2 as waste.

6.4 Other aspects

Aspects such as classification society rules, safety and toxicity, and crew training – although not explored in great depth in this report – are important enablers for OCCS adoption. All major class societies have now published OCCS guidelines or notations, addressing hazard analysis, containment, integration, and emergency systems, with iterative updates anticipated as OCCS adoption grows and new technologies mature. The IMO has decided to develop interim guidelines for the safety of ships using OCCS systems by 2028. Ensuring safe operations, both onboard and during offloading, is a critical element to be addressed. Evidence from initial studies shows that safety risks can be managed, especially by building on existing LNG/LPG best practices. Additionally, safety management systems must adapt to integrate OCCS procedures under the ISM Code, ensuring compliance and risk mitigation, especially for crew onboard who will require special training. The EVER TOP's pilot capture and offloading has indicated a high level of onboard crew training, readiness and reliability, with the system being described as "crew friendly" by Evergreen. Nonetheless, OCCS training would need to be scaled from vendor-specific training toward standardized, flag-endorsed modules as adoption grows. Both aspects, safety and crew training, have been explored in greater detail in recent reports from GCMD [2] and Maritime Technologies Forum [35].

These issues, while important, appear unlikely to pose insurmountable barriers to OCCS adoption as they represent transitional hurdles rather than fundamental roadblocks. With coordinated industry and regulatory engagement, they can be effectively addressed to enable scalable OCCS deployment.

The issue of CO_2 purity however, as discussed in 4.2, is not straightforward and although it will primarily be determined by the OCCS technology providers and the CCS value chain operators, regulators have an important role to play in facilitating access to certified reception facilities for permanent CO_2 storage as specified under objective 3 of the IMO's OCCS workplan[16]. Given the critical importance of achieving the required CO_2 purity for the deployment of OCCS, regulators should support shipping in meeting these standards – whether onboard or via shore-based purification – by establishing clear guidelines on the topic. CO_2 purity should also be integrated as a key parameter in MRV schemes to ensure transparency and build confidence in the CCS value chain for CO_2 delivered from ships.

[16] MEPC 83/17/Add.1 - ANNEX 8

7 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

Container shipping currently consumes 28% of the fuel used by large ships in international trade and must transition to sustainable fuels to meet decarbonization goals by 2050. The five container liner companies CMA CGM, Evergreen, Hapag-Lloyd, Maersk, and MSC are eager to understand the potential of OCCS technology as a potential GHG abatement measure on the high-traffic NEU-Asia corridor, considering LCO_2 offloading at both major hubs Rotterdam and in Southeast Asia – as a testbed for further expansion of the technology to other trade lanes.

While still at a nascent stage, different OCCS technologies have been developed and roughly 60 vessels are equipped with the technology today, most as retrofits on smaller vessels offloading CO_2-rich amine and with unknown operational status. The orderbook points at more newbuilding installations also on larger vessels with LCO_2 beginning to be offloaded. Pilot-scale operations on and LCO_2 offloading from the container vessel EVER TOP, as well as full scale OCCS operations on the gas carrier CLIPPER ERIS are demonstrating technical feasibility. Provided OCCS proves cost-efficient from a total cost perspective and receives regulatory support, the five liners indicate interest in further investigating OCCS application on their vessels.

Currently, the value chain required to offload ship-borne LCO_2 is largely not in place – however, there is evidence that this value chain will develop: A globally developing CCS industry especially in North Europe and Asia, with projects such as CO2next and ARAMIS in Rotterdam, which are starting to acknowledge the potential of ship-borne CO_2 to utilize planned assets; the interest of owners & operators of LCO_2 barges and carrier to invest.

Modelling suggests that, under the given assumptions, use of OCCS technology on container vessels operated by the five liners along the NEU-Asia corridor could offer a cost-competitive decarbonization option to complement the use of low-GHG fuels. Under the High Uptake scenario, OCCS is projected to be used in conjunction with 60% of the total energy consumed by 2040, and 71% by 2050, resulting in 6.0 Mtpa of CO_2 abated in 2040 and 6.6 Mtpa in 2050, and 7.2 Mtpa of CO_2 offloaded in ports in 2040 and 6.9 Mtpa in 2050. These figures indicate that OCCS could bear a significant share of the GHG abatement needed as it scales up rapidly and supports maritime decarbonization over time while also providing significant potential volumes to support shore-based CCS projects.

However, the analysis also shows that OCCS uptake is highly sensitive to LCO_2 offloading cost, which yet remains uncertain: As offloading cost increases by 50%/100%, the share of energy demand OCCS accounts for decreases from 60% to 41%/19% in 2040, and from 71% to 51%/29% in 2050. CO_2 abated and volumes offloaded in ports reduce accordingly.

From an offloading value chain perspective, the capture and offloading of LCO_2 from ships presents a significant opportunity: In the High Uptake scenario, total offloading cost of 7.3 bn USD is expected to be borne by the five liners in the 2030-50 period – representing a more cost-efficient decarbonization pathway compared to competing solutions. This creates substantial revenue potential for the offloading value chain, enabling coverage of investment, operational and associated cost.

As upfront investment requirements needed to implement OCCS are high both on board of ships as well along the LCO_2 offloading value chain, stakeholders involved will only invest in case of fundamental belief in scale and economic sustainability of the solution. The analysis indicates that scale can be achieved if offloading cost remains reasonable. Conversely, higher offloading cost would erode the relative attractiveness of OCCS from a liners' perspective and may prevent the LCO_2 offloading value chain from reaching critical mass.

Regulation for OCCS is still developing. At IMO, a work plan adopted in 2025 targets a regulatory framework by 2028 to address safe CO_2 handling, certified reception facilities, and transparent reporting. LCA guidelines exist but require OCCS-specific methods for parasitic energy and Ship-to-Storage emissions. Verification standards and recognized sequestration schemes are absent. In the EU, OCCS is not yet a compliance option under FuelEU Maritime, and ETS lacks comprehensive maritime-specific guidance although it theoretically allows for onboard CO_2 capture and sequestration. Globally, legal uncertainty persists under the London Convention and Protocol regarding cross-border CO_2 transport, and classification of CO_2 as waste versus commodity remains unresolved, creating investment and operational ambiguity.

7.2 Recommendations

The main prerequisite to unlock OCCS as a credible decarbonization measure at scale is a **timely, supportive, harmonized, and predictable regulatory framework** to enable investment across the Ship-to-Storage value chain. At the IMO level, clarifying the treatment of emissions captured on board (ecc) in the LCA Guidelines, establishing guidance for ecc measurement and CO_2 offloading verification, and defining certified sequestration and verification schemes are essential next steps. At the EU level, further maritime-specific guidance under the ETS and inclusion of OCCS in the FuelEU Maritime regulation are needed. On the legal side, IMO must provide clarity on the London Convention/London Protocol applicability and CO_2 receiving national governments should implement legal carve-outs and definition of CO_2 as non-waste.

Given the high sensitivity of the OCCS business case to LCO_2 offloading costs, excessive cost levels hinder large-scale deployment. It is therefore critical that the CO_2 value chain ensures **consistently low offloading costs across all major hubs** to enable OCCS to scale effectively.

Positioning OCCS as a substantial contributor to shipping decarbonization requires **cooperation and eventually collaboration of previously unconnected stakeholders along the entire CO2 value chain** – container liners, ports, LCO_2 barge and carrier operators, and operators of LCO_2 intermediate (terminals) and permanent storage facilities in more than one geographic location, Rotterdam and Singapore in this case. Hence, is it recommended that the shipping industry and CO_2 value chain stakeholders intensify their information exchange, through formalized fast-moving groups, addressing agenda points such as status and outlook of FID, LCO_2 specification requirements, maritime regulation, LCO_2 volume projections, etc.

8 APPENDIX

8.1 Emissions intensity calculation: breakdown and assumptions

		All in gCO_2e/MJ	LFO	HFO	B46 (HFO+ B100)	B100 (UCO)	LNG Diesel DF slow speed	Bio-LNG Diesel DF slow speed (manure & maize)	Bio-methanol (waste wood)
1	**Well-to-Wake**	WtT CO_2e	13.2	13.5	-20.8	-61.7	18.5	-40.4	-55.6
		TtW CO_2	76.9	76.9	76.8	76.6	55.9	54.9	69.1
		TtW N_2O+CH_4	1.3	1.4	1.4	1.5	1.7	1.7	2.8
		Subtotal	**91.4**	**91.7**	**57.3**	**16.4**	**76.1**	**16.1**	**16.3**
2	**Parasitic loss**	WtT CO_2e	2.6	2.7	-4.2	-12.3	3.7	-8.1	-11.1
		TtW CO_2	15.4	15.4	15.4	15.3	11.2	11.0	13.8
		TtW N_2O+CH_4	0.3	0.3	0.3	0.3	0.3	0.3	0.6
		Subtotal	**18.3**	**18.3**	**11.5**	**3.3**	**15.2**	**3.2**	**3.3**
3	**Well-to-Wake w/ parasitic loss** (=1+2)	WtT CO_2e	15.8	16.2	-25.0	-74.0	22.2	-48.5	-66.7
		TtW CO_2	92.2	92.3	92.1	91.9	67.1	65.9	82.9
		TtW N_2O+CH_4	1.6	1.6	1.7	1.8	2.0	2.0	3.3
		Subtotal	**109.7**	**110.1**	**68.8**	**19.7**	**91.3**	**19.4**	**19.5**
4	**CO_2 captured**	**TtW CO2**	**69.2**	**69.2**	**69.1**	**68.9**	**50.3**	**49.4**	**62.2**
5	**Well-to-Wake w/ OCCS** (=1+2-4)	WtT CO_2e	15.8	16.2	-25.0	-74.0	22.2	-48.5	-66.7
		TtW CO_2	23.1	23.1	23.0	23.0	16.8	16.5	20.7
		TtW N_2O+CH_4	1.6	1.6	1.7	1.8	2.0	2.0	3.3
		Subtotal	**40.5**	**40.9**	**-0.3**	**-49.3**	**41.0**	**-30.0**	**-42.7**
6	**Wake-to-Storage** Rotterdam	Barge	0.11	0.11	0.11	0.11	0.08	0.08	0.10
		Intermediate storage	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00
		Pipeline	0.02	0.02	0.02	0.02	0.02	0.02	0.02
		Permanent storage	0.16	0.16	0.16	0.16	0.11	0.11	0.14
		Subtotal	**0.29**	**0.29**	**0.29**	**0.29**	**0.21**	**0.21**	**0.26**
7	**Well-to-Storage** Rotterdam (=1+2-4+6)	WtT CO_2e	15.8	16.2	-25.0	-74.0	22.2	-48.5	-66.7
		TtW CO_2	23.1	23.1	23.0	23.0	16.8	16.5	20.7
		TtW N_2O+CH_4	1.6	1.6	1.7	1.8	2.0	2.0	3.3
		WtS CO_2e	0.29	0.29	0.29	0.29	0.21	0.21	0.26
		Total	**40.8**	**41.2**	**0.0**	**-49.0**	**41.2**	**-29.8**	**-42.4**
8	**Wake-to-Storage** Singapore	Barge	0.11	0.11	0.11	0.11	0.08	0.08	0.10
		Intermediate storage	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00
		Shipping	0.54	0.54	0.54	0.54	0.39	0.39	0.49
		Pipeline	0.01	0.01	0.01	0.01	0.01	0.01	0.01
		Permanent storage	0.16	0.16	0.16	0.16	0.11	0.11	0.14
		Subtotal	**0.82**	**0.82**	**0.82**	**0.81**	**0.59**	**0.58**	**0.73**
9	**Well-to-Storage** Singapore (=1+2-4+8)	WtT CO_2e	15.8	16.2	-25.0	-74.0	22.2	-48.5	-66.7
		TtW CO_2	23.1	23.1	23.0	23.0	16.8	16.5	20.7
		TtW N_2O+CH_4	1.6	1.6	1.7	1.8	2.0	2.0	3.3
		WtS CO_2e	0.82	0.82	0.82	0.81	0.59	0.58	0.73
		Total	**41.3**	**41.7**	**0.5**	**-48.5**	**41.6**	**-29.4**	**-41.9**

Table 2: GHG intensity of selected fuels @ 20% parasitic loss, 75% capture rate (gCO_2e/MJ) [2, 3, 4][17]

[17] The GHG intensity analysis follows IMO LCA Guidelines (MEPC.391(81)), assuming a 75% gross capture rate and 20% energy penalty. Carbon factors are taken from FuelEU Maritime (Regulation (EU) 2023/1805, amending Directive 2009/16/EC). Exemplary emission factors for biodiesel (B100) from used cooking oil (UCO), for bio-methanol from waste wood, and for bio-LNG from 60% manure and 40% maize in combination with close digestate, off-gas combustion technology follow default values from Directive (EU) 2018/2001. These emission factors and biomass types were selected as examples of representative production pathways. The FuelEU Maritime carbon factors were chosen for this comparison since they offer more detailed values for different biofuel types compared to the broader default factors in IMO guidelines. Pilot fuels are not considered.

8.2 LCA and double counting of Emissions from parasitic loss (ecc)

Assumptions:

$$GHGWtT: Well\text{-}to\text{-}Tank\ total\ greenhousegas\ intensity$$
$$GHGTtW: Tank\text{-}to\text{-}Wake\ total\ greenhouse\ gas\ intensity$$
$$\text{csc [gCO2eq/MJ]} = \text{CfCO2 x CR / LCV}$$
$$\text{pen [\%]} = \text{parasitic energy from using additional fuel}$$

From the LCA formula it is known that:

$$\text{GHGWtW [gCO2e/MJ]} = \text{GHGWtT} + \text{GHGTtW}$$

For a case where OCCS is used, the LCA formula can be simplified into (assuming et, est, ex as 0 for simplicity):

$$\text{GHGWtW (with capture)} = \text{GHGWtW (w}_\text{o}\text{capture)} - (\text{csc} - \text{ecc})$$

Since ecc is the total emissions less captured emissions multiplied by the penalty, taking into account that also part of emissions from the additional energy is captured:

$$\text{ecc [gCO2e/MJ]} = (\text{GHGWtW(w}_\text{o}\text{capture)} - \text{csc) x pen}$$

Therefore, substituting the ecc value gives:

$$\text{GHGWtW (with capture)} = \text{GHGWtW(w}_\text{o}\text{capture)} - (\text{csc} - (\text{GHGWtW(w}_\text{o}\text{capture)} - \text{csc) x pen))}$$

$$\text{GHGWtW (with capture)} = \text{GHGWtW(w}_\text{o}\text{capture)} + \text{GHGWtW(w}_\text{o}\text{capture) x pen} - (csc + \text{csc}\ x\ pen)$$

$$\text{GHGWtW (with capture)} = (\text{GHGWtW(w}_\text{o}\text{capture)} - \text{csc) x (1 + pen)}$$

This confirms that the current LCA formula correctly accounts for parasitic emissions. The method is equivalent with including the total Well-to-Wake emissions minus the captured and stored CO2 emissions and divided by the total energy used excluding the parasitic energy needed for the capture and onboard storage.

The alternative where ecc is not considered would result in the following:

$$\text{GHGWtW (with capture)} = (\text{GHGWtW(w}_\text{o}\text{capture)} - \text{csc)}$$

In this case the total WtW emission is divided by the total energy use including parasitic energy use, thereby not accounting for parasitic emissions or energy arising from OCCS.

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10 GLOSSARY

B46	Biodiesel blend with 46% biodiesel
B100	100% biodiesel
bn	Billion
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CII	Carbon intensity indicator
CO_2e	CO_2 equivalent
DCS	(IMO's) Data Collection System
DF	Dual fuel (engines being able to use another fuel next to HFO, (V)LSFO and MGO, i.e. Methanol, LNG, or Ammonia)
DWT	Deadweight tons
EE	Energy efficiency and logistics improvements
EM	Electric motor
EUAs	European Union Allowances
EU ETS	European Union Emission Trading System
FC	Fuel cell
FEED	Front-end engineering design
FID	Final investment decision
GFI	Greenhouse gas fuel intensity
GFS	GHG Fuel Intensity Standard
GHG	Greenhouse gas
GT	Gross tons
HFO	Heavy fuel oil
ICE	Internal combustion engine
IMO	International Maritime Organization
ISM Code	International Safety Management Code
KPI	Key Performance Indicator
LCA	Life cycle assessment
LCO_2	Liquid CO_2
LFO	Light fuel oil
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MEPC	Marine Environmental Protection Committee
MF	Mono fuel
MGO	Marine gas oil
mn	Million
Mtoe	Mn tons of oil equivalent
Mtpa	Mn tons per annum
nm	Nautical mile
OCCS	Onboard carbon capture and storage
OPEX	Operational expenditure

TEU	Twenty-foot equivalent unit
TtW	Tank-to-wake
UCO	Used cooking oil
VLSFO	Very low sulphur fuel oil
WtS	Well-to-(permanent) storage
WtT	Well-to-tank
WtW	Well-to-wake
ZNZ	Zero and near-zero (fuels)

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