GLOBAL CCS INSTITUTE

THOUGHT LEADERSHIP

NEEDS, OPPORTUNITIES AND PROSPECTS FOR CO_2 SHIPPING IN CCS PROJECTS

ANGUS GILLESPIE, Strategic Adviser

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CONTENTS

1.0 EXECUTIVE SUMMARY

CO_2 shipping today is a nascent industry with annual volumes of about 0.5 million tonnes of CO_2, serving mainly food and drink industries around northern Europe. Pipelines currently dominate CO_2 transport for CCS projects, accounting for over 95% of the global CO_2 transport capacity. The prospects for growth in CO_2 shipping for CCS do, however, look strong; more and larger CO_2 vessels are currently being built and planned, and a significant number of CCS projects in development plan to use shipping-based CO_2 transport. Three scenarios created for this paper suggest CO_2 shipping volumes could reach about 75 Mtpa, 125 Mtpa or over 600 Mtpa by 2040, the latter under highly optimistic conditions of cooperation in trade and climate action. The main regions for CO_2 shipping are the Asia Pacific, Africa and South America.

For non-owners, shipping costs are predominantly operational (or variable) rather than capital (or fixed) in nature; the opposite of pipeline costs. This means shipping should be more cost-competitive for relatively small CCS projects for distances over about 250 km, as well as short-lived projects or those with highly variable capture volumes. There are, however, still legal and regulatory obstacles to the cross-border transport of CO_2 using shipping. Still, these issues are surmountable – if sufficient political will exists.

The pressure and temperature at which cryogenic CO_2 is transported is a critical design choice for CO_2 vessels. Current ships have chosen a medium pressure design to optimise the trade-off between density (and hence cargo volumes) and costs. New ship designs are adapting from that position to allow larger cargoes or extended vessel applications, such as direct injection of CO_2 into the seabed.

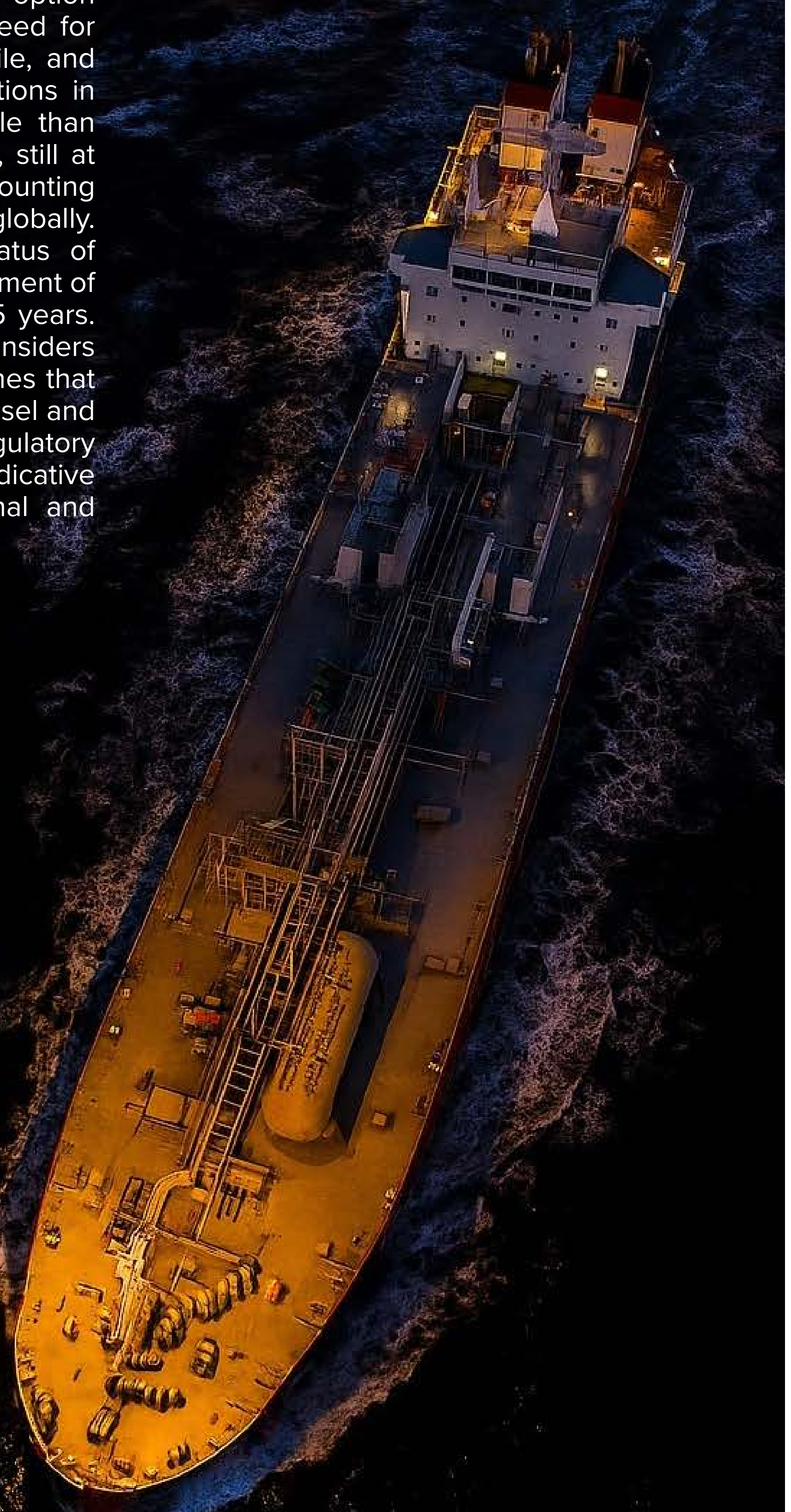
There is a healthy development pipeline of CO_2 vessels at present in design, construction or testing. The general scale of activities in the CO_2 shipping value chain is also growing, with the most active players having mostly expanded from large-scale gas transport activities. Current CO_2 shipping activities are concentrated in Europe and the Asia Pacific, which together account for about 90% of emerging CCS projects that rely on shipping for transport.

The anticipated growth in CO_2 shipping will likely mirror growth in the global CCS project development pipeline. That comes from shipping's contribution to the improved commercial and technical feasibility of more CCS projects. Its role in operationalising long-distance CO_2 transport can help address the stranded emissions dilemma facing countries lacking nearby pore space for which CCS would otherwise be a viable industrial emissions mitigation choice.

Prompted by a belief that CO_2 shipping will have a major role to play in future climate management, and especially in situations of stranded emissions where volumes of CO_2 are expected to be most significant, shipping operators appear prepared (even if mostly reactively rather than speculatively) to build (or adapt) more CO_2 vessels. This could lead to the emergence of a large and valuable new maritime business that might initially complement, and ultimately even replace, the global hydrocarbon shipping industry.

2.0 INTRODUCTION

Shipping is an increasingly attractive alternative for CO_2 transport, especially for early movers in CCS project planning. It is a flexible transport option without fixed infrastructure (albeit with a need for specialist port facilities), is scalable, versatile, and its economics are less sensitive to fluctuations in the underlying CO_2 capture volumes profile than pipelines. The shipping of CO_2 is, however, still at the very early stages of development, accounting for less than 0.5% of all CO_2 transported globally. This report provides a review of the status of shipping-based CO_2 transport and an assessment of its medium-term prospects over the next 15 years. Based mainly on a literature review, it considers the influences on future CO_2 shipping volumes that include both the technical issues around vessel and port design as well as the key legal and regulatory factors. The report closes with an indicative quantified range of scenario-based regional and global CO_2 shipping volumes.



3.0 THE ROLE OF SHIPPING IN CO_2 TRANSPORT

At its most basic, shipping CO_2 is an alternative form of transport to the orthodox use of pipelines to move liquefied CO_2 from its source to either a temporary location for consolidation or its ultimate destination for storage or use. Shipping is likely to be employed in CCS projects in preference to pipelines for economic reasons primarily related to the distance over which the CO_2 needs to be transported and/or the scale of volumes to be managed. The economics of shipping versus pipeline transport will be examined in more detail in Sections 4 and 5 below.

3.1 Estimates of current cryogenic gas shipping volumes

Shipping-based CO_2 transport[1] is limited to only four dedicated vessels at present, operating in the North Sea to largely service the food and drink industries – or CCU rather than CCS projects. Analysis for this report estimates total CO_2 volumes of up to 0.5 Mtpa. Relative to the emerging use of vessels for CO_2 transport, other, more mature, gas-based shipping markets exist. An estimate of the scale and average cargo sizes of markets for LPG and LNG are shown below.

Table 1 - Census and description of CO_2, LPG and LNG vessels (Updated from Brownsort, 2015, slide 8)

	CO_2	LPG	LNG
Number of ships	ca. 10	ca. 1,700	ca. 800
Capacity	Most <7,500m^3	Most <80,000m^3	Most <266,000m^3
Type	Semi-pressurised, refrigerated	Pressurised, Semi-pressurised, refrigerated or refrigerated	Refrigerated, atmospheric pressure
Typical Conditions	-30°C, 20 bara	Varied to -55°C, 20 bara	-161°C, 1 bara
Loading/ Unloading	In port	In port, offshore	In port, offshore

3.2 Design issues for CO_2 vessels

CO_2 carriers are categorised as low, medium, and high pressure. Historically, CO_2 has been transported in a liquid state at conditions described as medium pressure (see Figure 1). As shown in the graphic, low, medium and high (or elevated) vessel designs tend to have varying points of balance between pressure and temperature while retaining the CO_2 in a liquid phase for maximum efficiency in its transport stage.

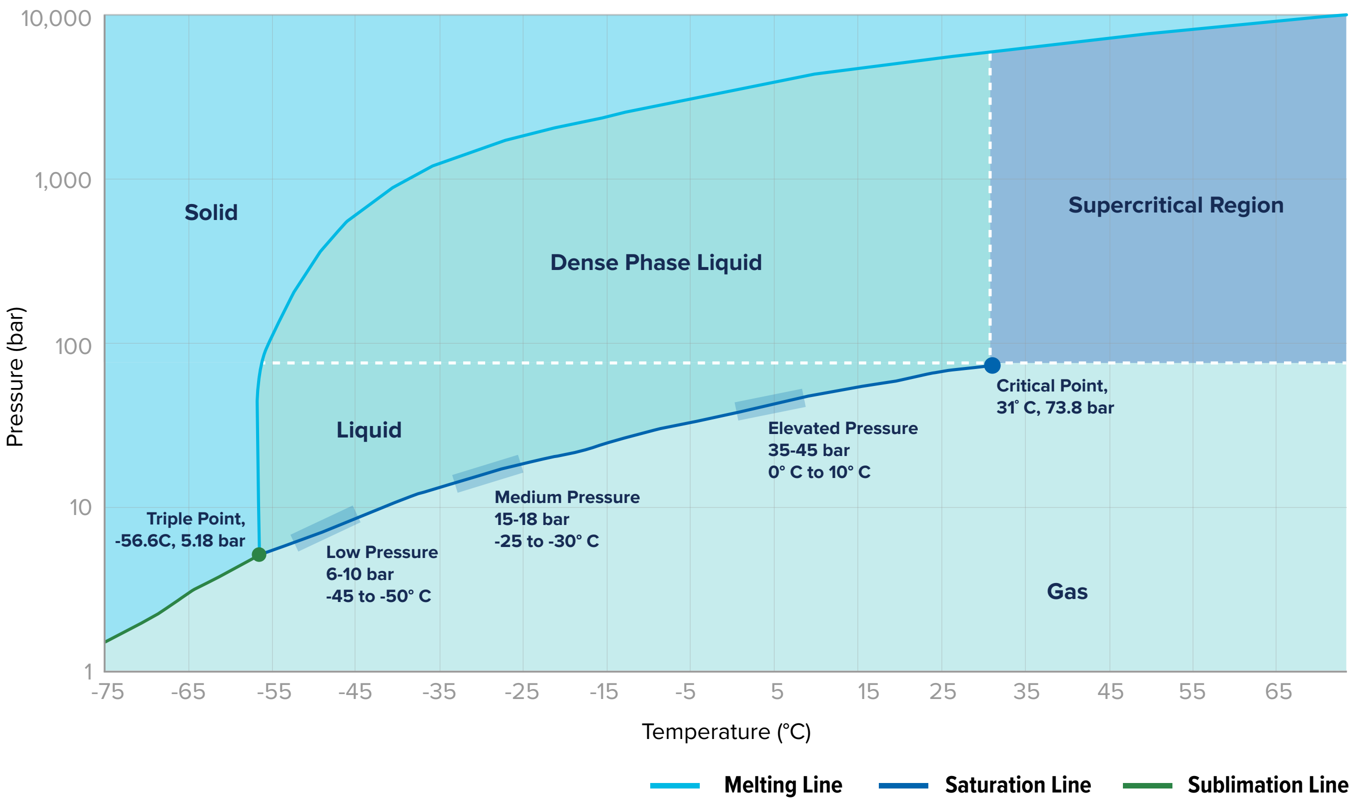
The small fleet of existing North Sea CO_2 vessels for the food and drinks industry are designed as medium pressure ships, transporting CO_2 at conditions in the range of 15-20 bara and -20 to -30°C. Their capacity is typically in the range of 1,240 m^3 to 2,000 m^3, similar to LPG carriers. Most existing CO_2 shipping vessels are operated by Larvik Shipping and were converted from dry-bulk vessels, with retro-fitted CO_2 cargo tanks[2], and that experience continues to shape the dedicated CO_2 vessels now being built. Norwegian shipping company IM Skaugen specifically designed six larger LPG carriers of 10,000 m^3 capacity to be also capable of transporting CO_2. They have been operating since 2003, although not yet for CO_2 transport.

For larger-scale CCS applications, larger ships will be required than are available today. Also, for larger CO_2 vessels, low-pressure (5-9 bara) and low temperature (-55oC) designs are proposed. As the use of CO_2 vessels extends to offer direct offshore injection, more ambitious "ambient temperature" designs might be considered to balance transport and storage conditions. Ambient temperature transport could offer some cost savings due to the lack of need for cryogenic onboard storage, although balancing that benefit may be the extra weight of the thicker tank walls to contain the higher pressure. Considerable research is currently underway on the pressure-temperature requirements of CO_2 vessels.

[1] This contrasts with ISO-approved gas container transport of CO_2 that, while only capable of much lower volumes, can be managed largely by general cargo vessels and without specialist port-handling facilities. Similarly, there are additional LPG vessels that are capable of transporting CO_2 (see Section 3.2 below) but not yet used for that purpose.

[2] Element Energy, November 2018 (p12)

Figure 1 - Pressure and temperature balance for CO_2 vessels (Advancements in CCS technologies and costs, GCCSI)



3.3 Supply chain needs for CO_2 shipping

A CCS supply chain based on shipping CO_2 has other elements to consider besides vessels. Figure 2 shows the typical process stages and associated facilities needed to support CO_2 shipping. CCS projects are typically comprised of an initial industrial CO_2 point source (or direct air capture), transportation and ultimate injection into secure geologic storage or offtake for utilisation. Inclusion of maritime transport consists of some or all of the operational components shown below. Vessels essentially serve as the "midstream" function in the CCS value chain. The ships involved can be loaded from onshore or offshore facilities and, in turn, can offload their CO_2 at one of three locations; an onshore terminal (ship-to-shore), offshore structure (ship-to-platform) or offshore from the vessel to a sub-seabed geological formation (direct injection). There are no CCS current projects in operation (or construction) that use CO_2 shipping for direct offshore injection. Several studies (e.g., Chiyoda, 2011 and CATO, 2016) have, however, shown that to be a practical design option, and the Stella Maris CCS project's development plan is based on direct injection (see Section 6.2).

3.4 Northern Lights' supply chain

Northern Lights is the transport and storage component of the Norwegian Longship CO_2 network that ships coastal CO_2 emissions to an onshore terminal for ultimate offshore storage in the Aurora reservoir via a 100 km pipeline. It opened for business in September 2024 and is the world's first open access cross-border CO_2 transportation and storage facility. The initial capture customers are both Norway based: Heidelberg Cement at Brevik and Hafslund waste-to-energy power plant in Oslo. Two new CO_2 vessels, the Northern Pathfinder and the Northern Pioneer, were delivered in the fourth quarter of 2024. Operations to transport and store the initial 1.5 Mtpa of CO_2 in the Aurora reservoir are scheduled to commence in the second half of 2025. As Figure 3 shows, third-party CO_2 will be consolidated and stored at a new onshore terminal in Oygarden before being piped 100 km offshore.

New capture customers are being added for Northern Lights. Its ambition is to store 30-50 million tonnes of CO_2 by 2035. Vessel transport, perhaps for emitters with more distant transport needs, will be complemented by a later CO_2 pipeline, the "CO_2 Highway Europe", with connections directly into Aurora's injection wells from Northwest Europe.

Figure 2 - Overview of CO_2 shipping configuration options (Opportunities for Shipping to Enable Cross-Border CCUS Initiatives, 2024, GCMD, BCG)

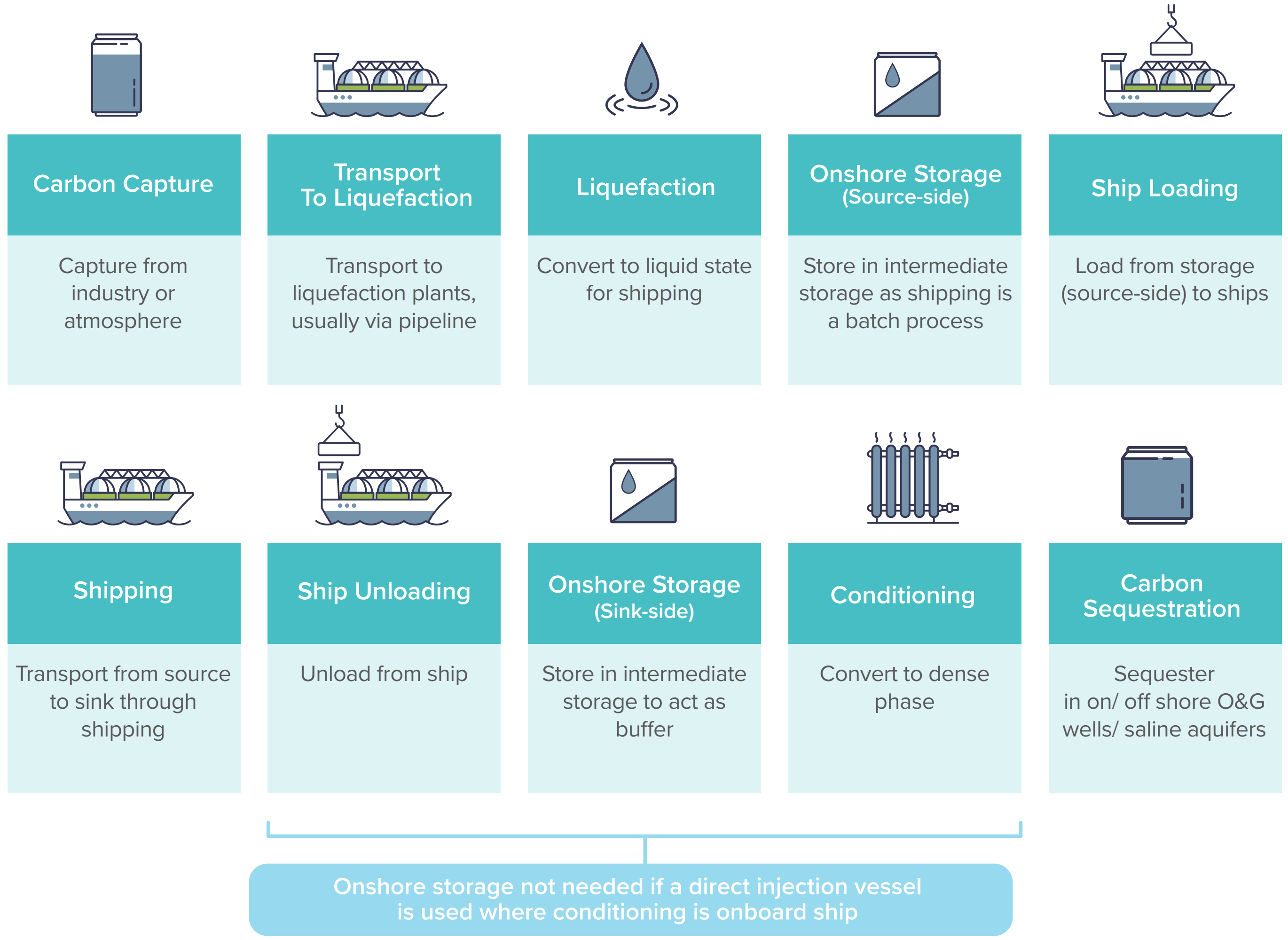
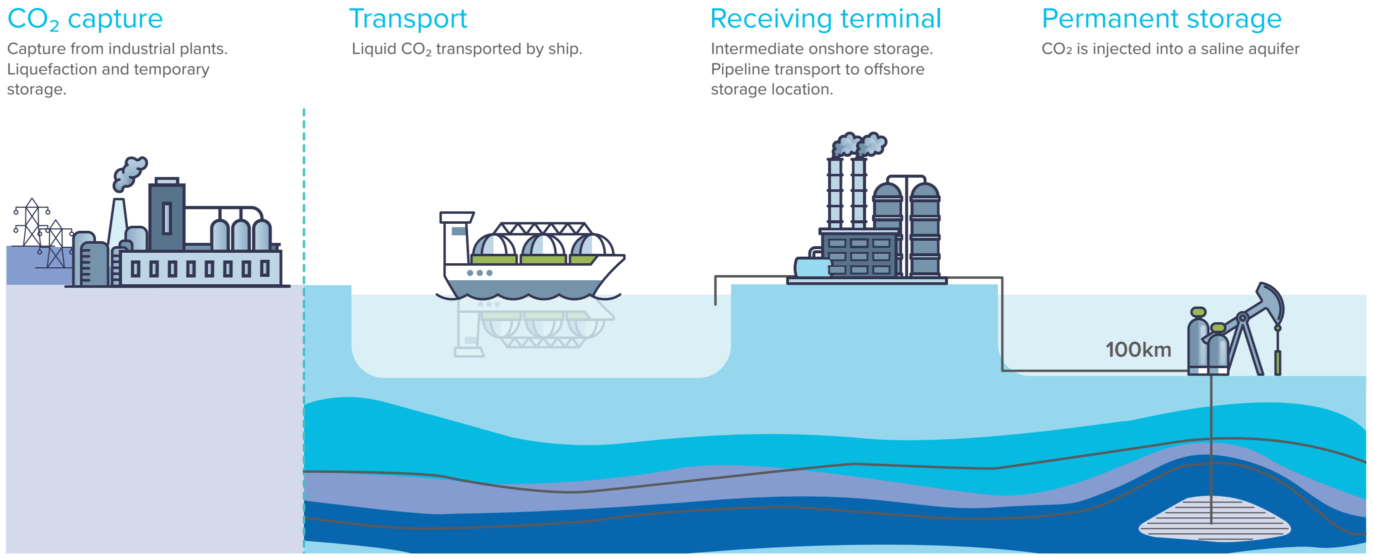


Figure 3 - CO_2 shipping infrastructure for Northern Lights (Equinor website)



4.0 ESTIMATES OF CO_2 TRANSPORT VOLUMES AND COSTS

Transportation of CO_2 from emissions sources to storage sinks can be achieved with pipelines, rail, motor carriers and ships. Each mode has different operational requirements and capacities, which impact suitability for a given project. Table 2 shows the most recent data on the relative capacities of CO_2 transport methods.

Pipeline-based CO_2 transport is by far the dominant mature technology and is the preferred method for all commercial CCS facilities. Increasingly, however, shipping is being considered by CCS projects due to its quick deployment, logistical flexibility, resilience, volume versatility, and ease of access to offshore storage sites over pipelines. Rail and road-based CO_2 transport are, and likely to remain, popular only in niche onshore operations for smaller CCS projects or small food and drink applications.

Table 2 - CO_2 transportation methods. (Al Baroudi et al., 2021; GCCSI)

TRANSPORT METHOD	CONDITIONS	PHASE	CURRENT CAPACITY
Pipelines	48-200 barg, 10 to 34°C	Dense or vapour phase	• Higher capex, lower opex costs • Low-pressure system ca.20% more expensive than dense phase transmission • Well-established for EOR use
Ships	7-45 barg, -52 to 10°C	Liquid	• Higher opex, lower capex costs • Used in food and drinks industry for smaller quantities
Motor Carriers	17-20 barg, -30 to -20°C	Liquid	• 2-30 tonnes per batch • Not economic for large-scale CCS projects
Rail	7-26 barg, -50 to -20°C	Liquid	• No large-scale systems in place • Loading/unloading and storage infrastructure required • Feasible with existing rail lines • More advantages over medium and long distances

4.1 Costs of CO_2 shipping by vessels

Table 3 summarises the Institute's research data on actual CO_2 shipping costs. As will be examined in Section 5, the influence of distance and CO_2 volumes has an important bearing on those costs, which, based on various project studies, range from $9/tonne of CO_2 (1 Mtpa over 600 km) to $50/tonne of CO_2 (5 Mtpa over 1,200km).

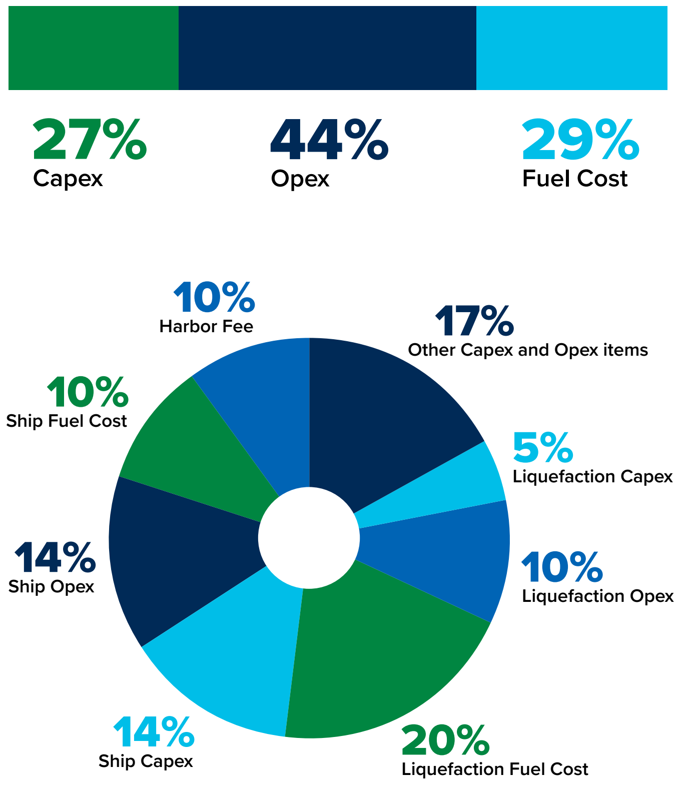
Table 3 - Summary of published shipping costs, (GCCSI)

REFERENCE	VOLUME (MTPA)	DISTANCE (KM)	COST (US$/ TCO_2)
IEAGHG (2004)	6.2	200-12,000	10-44
Aspelund et al. (2006)	Up to 2	1,500	20-30
Decarre et al. (2010)	1-3	1,000	31-42
ZEP (2011b)	2.5	180-1,500	17-24
Kang et al. (2015)	1-3	530-720	21-33
Kjärstad et al. (2016)	1-20	100-1,100	15-24
CATO (2016)	Up to 4.7	200-1,200	14-36
Element Energy (2018)	1	600	9-15
IEAGHG (2020)	1.8-1.37	1,000	41-44
Roussanaly et al. (2021)	.5-20	100 – 2,000	21-47[13]
Nogueira et al (2022)	2-5	90 - 1,200	17-50
Barrio et al (2005)	2	n/a	22-28
Norwegian CCS Study* (2020)	0.8-1.5	600-700	42-81

*The Norwegian Full-scale CCS study examines the project that is similar to Langskip (Longship)/Northern Lights. The values are estimates, as the exact capex and opex of the Northern Lights Transport and Storage project have not been publicly released.

An estimate of the breakdown of unitised shipping costs for CO_2 transport is shown in Figure 4. The bar chart shows operating costs are the largest of the three elements. Liquefaction and ship costs, combining the capital and operational needs, along with fuel, are the biggest cost components of CO_2 shipping. Overall, shipping costs are dominated by operational costs, unlike pipelines, which are dominated by capital costs.

Figure 4 - Cost breakdown for CO_2 shipping in the UK (Source: Element Energy, 2018)



The same study that produced the cost estimates in Figure 4 found that pipelines showed much higher cost sensitivity to distance and flow rate compared to shipping. Generally, CO_2 shipping is more likely to be favoured on a costs basis over the use of pipelines when flow rates are lower, project lifetimes are shorter, and/or distances are longer. Ultimately, these relative advantages for shipping come from the domination of opex over capex in its economics compared to pipeline-based CO_2 transport.

4.2 Main companies involved in the CO_2 shipping supply chain

The strength and depth of CO_2 shipping service industries will develop if or when the underlying volume of traffic grows. Table 4 lists organisations already experienced in CO_2 shipping. Reflecting demand for CO_2 vessels, most companies are in Scandinavia and Asia – although shipbuilding is a more global activity where location reflects competitiveness rather than the need for local services. The list of supply chain participants will undoubtedly grow over the next years. Many organisations, especially from the oil and gas industry, are actively monitoring the CO_2 shipping market for opportunities, whether for sole investments or partnerships. As with any nascent industry on the threshold of significant growth, there may be first-mover advantages related to accessing the most profitable contracts, routes or partnerships; securing positions with the best-located CO_2 ports and handling facilities; developing optimum fleets of vessels; growing operational experience as well as brand credibility and, finally, gaining influence to shape emerging industry regulation.

Table 4 - Companies currently active in CO_2 shipping (Source: GCCSI)

	SHIPBUILDERS	SHIP OWNERS AND OPERATORS	SHIPPING MERCHANTS
Europe based or focused	• Frisian Shipyard • Royal Wagenborg	• Bernhard Schulte Ship Mgt (BSM) • Capital Gas Ship Mgt Co. • Knutsen OAS Shipping • Larvik Shipping AS • Stena Bulk	• Praxair • Air Liquide • Air Products • Linde group
APAC based or focused	• CSSC Jiangnan • Dalian Shipbuilding Industry Ltd • Hanwha Ocean Co Ltd. • HD Hyundai Heavy Industries • Mitsubishi Shipbuilding • Samsung Heavy Industries (SHI)	• K Line • Mitsui OSK Lines • NYK Lines • Prime Marine	
Other regions			• Ecolog

5.0 BACKGROUND TO THE RISE IN PROSPECTS FOR CO_2 SHIPPING

The previous section outlined the main conditions for CCS projects preferring shipping for CO_2 transport over pipelines on economic grounds, mainly based on smaller volumes, longer distances and/or shorter duration projects. This section uses those observations to explain the recent rise in the use of (or interest in) CO_2 shipping in CCS projects.

5.1 Economics of shipping versus pipelines for CO_2 transport

A typical distance versus volume trade-off chart for the use of shipping or pipelines for CO_2 transport is shown in Table 5. These forms of charts are very sensitive to the underlying project characteristics or assumptions. Still, based on this particular GCCSI analysis, the table's decision points range from 100 km, for volumes of less than 1 Mtpa of CO_2, to 2,000 km for the largest CO_2 volumes, in this case 10 Mtpa. An inference can be drawn that, in general, shipping can be less expensive than pipeline for CO_2 transport for distances over 250 km for small volumes and over 750 km for the largest volumes. Further, one can assume that, to underpin a growth in CO_2 shipping amongst CCS projects, smaller volumes are being moved, or there is typically a growing distance between the source of emissions and the ultimate sink. A review of projects, as summarised in Table 5 in the global CCS development pipeline tends to confirm this belief.

5.2 Regulatory and legislative barriers to CO_2 shipping

There are three areas of regulation specific to the undertaking of CCS, and therefore CO_2 shipping, that have a material economic impact on the commercial viability of CCS projects. These are the regulation of geological storage of CO_2, the transboundary shipment of CO_2, and the recognition and monetisation of abatement delivered by CCS.

It is very difficult to develop CCS projects in jurisdictions without clear and predictable regulations covering the geological storage of CO_2, unless authorised under petroleum exploration and production legislation. The absence of clear regulation creates an unmanageable compliance risk for the project developer and fails to provide the developer with clear property rights to use storage resources. Clear regulation of CO_2 storage is a critical requirement of all CO_2 value chains, including those designed around shipping-based CO_2 transport.

International marine legal agreements aimed at protecting the world's oceans are central to the legality of offshore CCS operations. The 1972 London Convention and its 1996 Protocol, which seek to protect the marine environment from the unauthorised disposal of wastes, was an initial obstacle to CCS activities by excluding CO_2 from the list of substances that could be 'dumped' at sea or stored in the seabed. In 2006, during the first meeting of the Contracting Parties to the London Protocol, an amendment was adopted to include "CO_2 streams from CO_2 capture process for sequestration"

Table 5 - Indicative preferred CO_2 transport based on capacity and distance (Internal JCCS, table 39)

DISTANCE (KM)	FLOW 1 MTPA	FLOW 2.5 MTPA	FLOW 5 MTPA	FLOW 7.5 MTPA	FLOW 10 MTPA
100km	PIPE	PIPE	PIPE	PIPE	PIPE
250km	PIPE	PIPE	PIPE	PIPE	PIPE
500km	SHIP	PIPE	PIPE	PIPE	PIPE
750km	SHIP	SHIP	SHIP	SHIP	PIPE
1000km	SHIP	SHIP	SHIP	SHIP	SHIP
1500km	SHIP	SHIP	SHIP	SHIP	SHIP
2000km	SHIP	SHIP	SHIP	SHIP	SHIP

● PIPE ● SHIP

within the categories of wastes which may be considered for dumping. The amendment provides a legal basis for offshore CO_2 storage operations that include CCS activities. Another amendment was proposed to Article 6 of the Protocol that previously prevented the transboundary transport of CO_2 for geological storage. That was adopted in 2009 to allow "… the export of CO_2 streams for disposal … provided that an agreement or arrangement has been entered into by the countries concerned". Any such agreement must ensure that the permitting, risk assessment and environmental protection standards of the Protocol are fully met.

The 2009 amendment will enter into force only after two-thirds of the signatories have ratified it. Currently, however, ratification has only occurred in Austria, Australia, Belgium, Denmark, Estonia, Finland, Iran, the Netherlands, Norway, South Korea, Sweden, Switzerland and the UK. Countries not signatory to the London Protocol are able to transport CO_2 across their borders if both are not signatories. The transboundary shipment of CO_2 across the borders of parties to the London Protocol, however, requires them to provide a declaration of provisional application and notification of any arrangements or agreements to the IMO. This is not a trivial process, demanding significant government-to-government cooperation and agreements.

Business models for CCS value chains rely upon the value created through capturing and storing CO_2 rather than emitting it to the atmosphere. Carbon accounting, and schemes that attach a financial value to CO_2, must recognise the abatement provided by CCS to underwrite CCS project developers' business case. Until recently, this was not the case for shipping of CO_2 under the EU ETS. Monitoring and reporting regulations meant it was unlikely that CO_2 moved by ship would count as "verified transported" and would instead be treated as "emitted" and the obligation to surrender allowances for that CO_2 would remain. However, effective January 2025, the EC revised the EU ETS to include the maritime sector by effectively recognising all means of CO_2 transport, where that is for the purpose of geological storage. The UK ETS is still in the process of making similar revisions to recognise CO_2 shipping for CCS projects. Although the UK ETS changes are still in consultation (as of July 2025), there could be a key difference from the EU approach. In Europe, liability for surrendering EU ETS allowances is transferred at each stage of the CCS value chain (i.e., capture, transport and storage). By contrast, the UK has expressed a preference for having the emitter retain liability for the CO_2 until it reaches its storage site.

Another point of conflict between the UK ETS and EU ETS is that, at present, the EU does not recognise EU emissions as securely stored if exported to UK pore space. In those cases, a European emitter still needs to surrender allowances if, for example, its CCS project ships the CO_2 to a UK-based reservoir or aquifer. Improved coordination of ETS (or tax) regimes will be needed across countries exporting and importing CO_2 to avoid regulatory blockers to cross-border CCS schemes.

5.3 Current CCS projects based on CO_2 shipping

Northern Lights is the only CCS project at present that ships CO_2. In September 2022, however, another nine CCS projects, in the early or late stages of development, had identified shipping as their planned CO_2 transport method. That number grew more than five-fold to 48 by July 2024. Around 70% of those are in Europe and 20% are in the Asia Pacific. Early development is defined as having at least started a Feasibility or Pre-Feasibility study.

6.0 ADVANTAGES OF AN EXPANDED ROLE FOR CO_2 SHIPPING

The ultimate main societal benefit of a significant growth in shipping-based CO_2 transport is likely to be a complementary rise in the number of CCS projects and proportionate reduction in emissions. This section examines how a rise in CO_2 shipping to that growth in CCS project numbers.

6.1 Lower CO_2 transport costs

As discussed in Section 5.1, for CCS projects with lower, short-lived and/or variable CO_2 volumes, and with longer distances to their sinks, shipping should be a less expensive form of transport than pipelines. The implied typical savings for a 2.5 Mtpa flow rate of US$12 (for 500 km) to US$40 (for 1,500 km) per tonne[3] of CO_2 could help make more CCS projects economic. Current estimates[4] are that transport accounts for between about 10% and 20% of total CCS costs, depending on variables such as the underlying emitting activity (specifically its CO_2 density), the distance to the sink and the characteristics of that reservoir or aquifer. The larger the importance of the transport activity to a project's total CCS costs, the greater is the potential contribution to its business case from an expansion in CO_2 shipping.

Besides reducing transport (and thus overall) costs for stand-alone CCS projects, reduced CO_2 transport costs from shipping can also improve the business case for offshore CO_2 storage networks, sometimes referred to as "CCS hub and clusters". An expanded CO_2 shipping capacity extends the potential customer capture area for network operators and, with associated economies of scale from larger CO_2 vessel capacities, could help reduce the transport rates offered to emitters.

On a lifecycle basis, CO_2 shipping has several advantages over pipelines when a CCS project ends and the associated infrastructure needs to be decommissioned. As well as the relative speed and ease of restoring the associated subsurface facilities to their previous state compared to pipelines, ships have the subsequent advantage of re-deployment potential, including to LPG operations. The CO_2 vessels serving one CCS project can be quickly reallocated to other operating projects. This feature reduces the post-closure cost implications of storage operations served by ships rather than pipelines. Research on this topic for CCS projects is limited but, as an analogue, decommissioning costs for offshore oil and gas fields can account for around 5% to 15% of total lifetime project costs[5].

6.2 Expansion of CO_2 shipping role to include direct injection

There is a general aspiration for CO_2 shipping to ultimately operate in CCS projects without the need for a complementary pipeline from shore, often a port, to the injection well. That both reduces costs and enhances flexibility. Studies have suggested this is a practical solution[6]. The two main configurations are either direct injection from the vessel or via unloading to a fixed platform, or a secondary vessel, where intermediate storage and injection equipment are located. While the preference for a continuous injection flow favours the platform-related option, direct injection is likely to be less expensive, given the additional expense of building and maintaining an operational platform[7]. A major Joint Industry Project (JIP) is underway in 2025 to establish common appraisal practices, as well as best practices and knowledge gaps, to help progress direct CO_2 injection projects. Partners involved in this JIP are Shell, Aker BP, Total, Harbour Energy, Woodside, K-Line and Mitsui OSK Lines[8].

The most advanced development plan to test ship-based CO_2 injection is underway in Norway. Yinson Production acquired the Stella Maris venture in February 2025, which is developing a large-scale floating solution for the direct injection of CCS-related CO_2 into the seabed. Many of the same FPSO technologies are being applied for injection rather than extraction purposes. Under the previous (Altera) leadership, Stella Maris was provisionally awarded EUR22.5 million from the EU Innovation Fund in October 2024 that, together with grant support from Gassnova, will be used to develop the breakthrough concept. Phase 1 of the outline plans is to inject up to 10 Mtpa of CO_2 into the Havstjevne in Norwegian waters by shuttling batches of about 50,000 m^3 of CO_2 from multiple industrial sources to the floating injection system.

[3] ZEP costs report, 2011
[4] GCCSI research, 2020
[5] Median value (or P50 case) is 8.8%. From TSB Offshore, Inc., 2014
[6] Chiyoda, 2011, and TNO CATO, 2016
[7] Chiyoda, 2011
[8] Described in DNV bulletin, 2024 – *link here*

6.3 Increased flexibility for CCS projects

Due to its lower need for subsea capital infrastructure, shipping-based CCS projects have the potential to be more quickly designed and built than those relying on pipelines for CO_2 transport. Even CCS projects planning to redeploy retired oil and gas pipelines still have work to refurbish and prepare those for reverse flows of CO_2. Assuming excess CO_2 shipping capacity (which is likely in a growing market), transport can be arranged relatively quickly. As well as helping shorten overall CCS project development timelines, the use of shipping over pipelines likewise probably reduces delay risks in the construction and testing phases.

The inherent versatility of the marine industry and its traffic management offers several advantages to CCS project developers and operators using CO_2 shipping. Changes, and especially increases, in the underlying emissions profile, both in the short-term due to unforeseen operational needs or long-term growth in underlying industrial production, can be accommodated more easily and quickly with vessels rather than pipelines. Besides the natural redundancy margin with multiple vessels, changes in the size and/or number of CO_2 ships serving the emitter can be more quickly organised, especially as the overall size of the CO_2 fleet expands.

Again, CO_2 storage network operators can benefit from the versatility of shipping. The ability of a range of (themselves variable) CO_2 volumes to be managed, in terms of both varied vessel cargoes and traditional maritime scheduling practices, expands the potential customer base. Supply routes can be actively altered, adjusted and overall optimised as the volumes of CO_2 grows. The capacity of complementary intermediate onshore CO_2 storage facilities (as shown in Figure 2 in Section 3.3) can likewise be adjusted to reflect ongoing changes to networks' supply routes.

Overall, the flexibility in CO_2 transport afforded using shipping, which increases in line with the size of the global CO_2 vessel fleet, helps both the economic and technical feasibility of prospective CCS projects. The latter issue is especially relevant as distances between emission sources and their sinks increases, sometimes rendering CCS ambitions technically unachievable. Extreme situations, where local storage options are absent or CO_2 pipelines are impractical, can even lead to the phenomenon of "stranded emissions". That issue is examined in the next section.

6.4 Helps manage stranded emissions

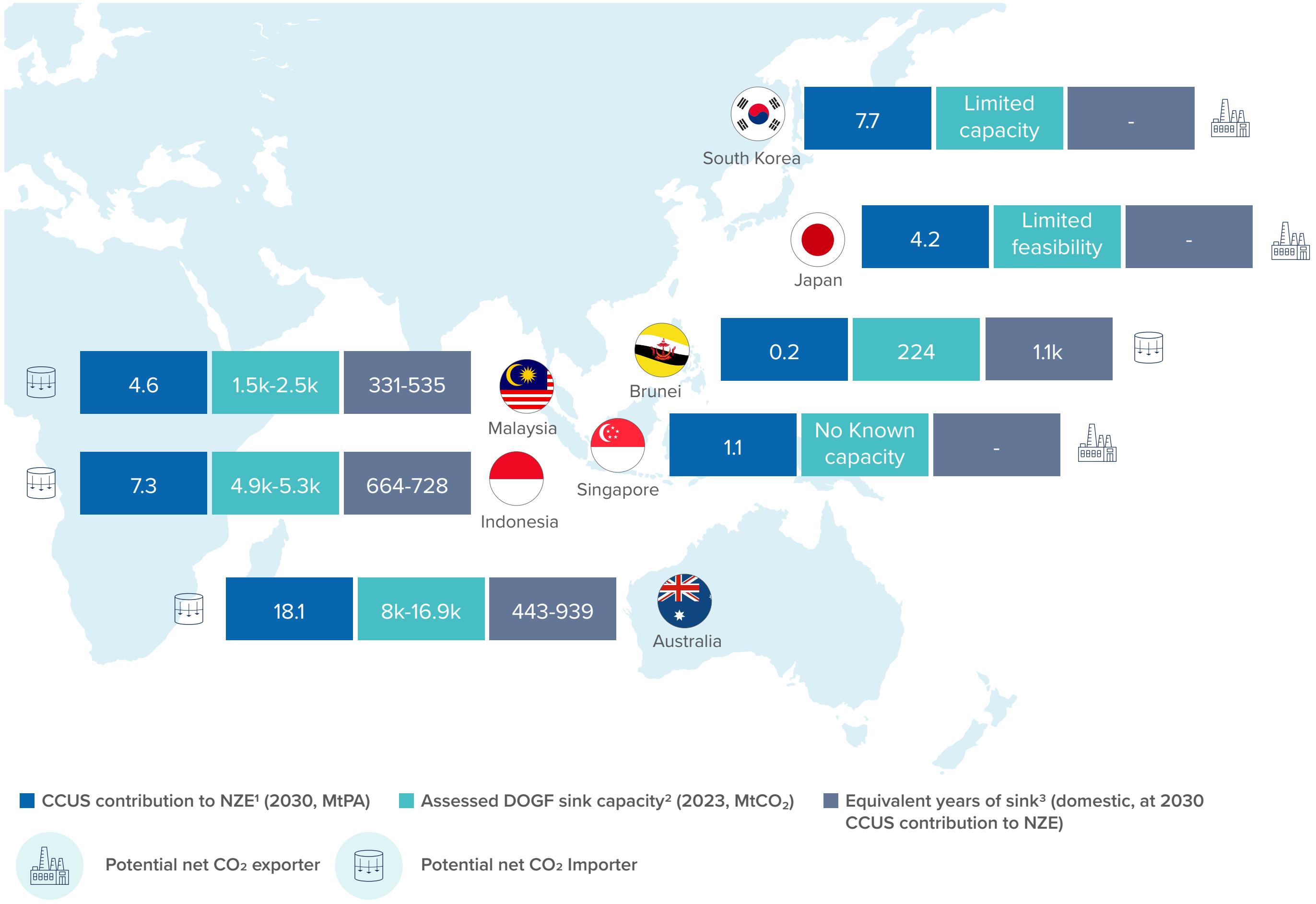
There are regions of the world that host industrial operations with significant CO_2 emissions and for whom CCS is unavailable as a mitigation option due to the absence or unsuitability of nearby pore space for safe storage of its CO_2. The most often used examples of such locations include Japan, South Korea, Singapore and some regions in Russia and China[9]. Regional and, at times, national geological characteristics mean that CCS had traditionally been considered as technically unfeasible due to excessive CO_2 transport needs (and costs) to reach suitable storage resources, and for which pipelines are an impractical solution.

Several countries in the Asia Pacific region are actively investigating the use of CO_2 shipping to manage stranded emissions. Figure 5 shows the degree of challenge faced by Japan, South Korea and Singapore, with the potentially balancing capabilities of Indonesia, Malaysia, Brunei and Australia to store those surplus CO_2 volumes in future, enabled by CO_2 shipping. It is, of course, no coincidence that the region's potential net importers of CO_2 are those with a traditional offshore oil and gas industry that allows subsequent access to redundant reservoirs or natural aquifers.

Still, at this stage, without more impactful climate legislation, CCS lacks a sufficient economic incentive across most of the Asia Pacific region to drive private sector investment. In April 2024, for example, the net "carbon price" (the regulatory cost of CO_2 emissions), where it existed at all, ranged from around US$1 per tonne of CO_2 in Indonesia to US$22 per tonne in Australia[10]. Meanwhile, the comparable cost of building transboundary regional export capacity for CO_2 ranged from US$140 to US$290 per tonne of CO_2[11]. That leaves a significant value gap. Nevertheless, in anticipation of the need to manage their stranded emissions in the future, several pilot CCS projects and CO_2 shipping trials are already underway in net-export countries.

[9] Based on countries' "carbon ratios", comparing national pore space and emissions, ABS, 2023 (p103)
[10] GCMD, 2024 (p38)
[11] GCMD, 2024 (p32)

Figure 5 - Mismatch of CCS ambitions and storage capacities in Asia Pacific (GCMD, 2024, p23)



6.5 Possible inland waterway CO_2 routes in Europe

A practical extension of CO_2 shipping would be to connect contiguous national and international waterways with major ports capable of accommodating CO_2 tanker vessels. Thinking on this multi-modal transport model is most developed in Europe. There, the existing network of international canals and rivers could be used to develop a feeder system of barges to export consolidated CO_2 from, for example, Antwerp or Rotterdam. This would be akin to a secondary CO_2 collection network, even using small-scale trucks, trains or pipes from industrial CO_2 capture points to waterside locations.

ZEP developed a provisional model for a European waterways CO_2 transport system in its 2024 paper[12]. It identified 26 practical CCS capture locations along the European rivers and canals network that could ultimately collect 50 Mtpa of CO_2, using 10-20 vessels. Its modelling was based on exporting about 1 Mtpa of CO_2 for every 20,000 tonne vessels on weekly round trips.

The ZEP work identified several areas of work needed to realise its multi-modal CO_2 transport model. Besides having sufficient CO_2 vessel capacity, it recommended that all European signatories to the London Protocol deposit a notice to the IMO to apply the Article 6 Amendment, also signing bilateral agreements where needed. CCS subsidy schemes have to be amended to avoid any prejudice to CO_2 shipping and standardisation is needed for CO_2 specification in shipping, liquefaction and onshore storage. Finally, the paper suggests public authorities create new mechanisms to incentivise investment in both CO_2 vessels and appropriate port-side handling facilities.

The European inland waterways CO_2 network concept extends the application of CO_2 shipping to landbound countries that might otherwise face the issue of stranded emissions discussed previously (see Section 6.4). The same model could have other applications in, for instance, Africa or North America. By extending the technical feasibility of CO_2 transport and storage, CO_2 shipping can further support the global development rate of CCS projects.

[12] ZEP and CCSA - "Achieving a European Market for CO2 Transport by Ship", January 2024

A JOINT PUBLIC-PRIVATE APPROACH IS NEEDED TO ENCOURAGE COUNTRIES WITH SURPLUS PORE SPACE TO DEVELOP NEW CO_2 NETWORKS.

7.0 FOCUS AREAS TO SUPPORT GROWTH IN CO_2 SHIPPING TO 2040

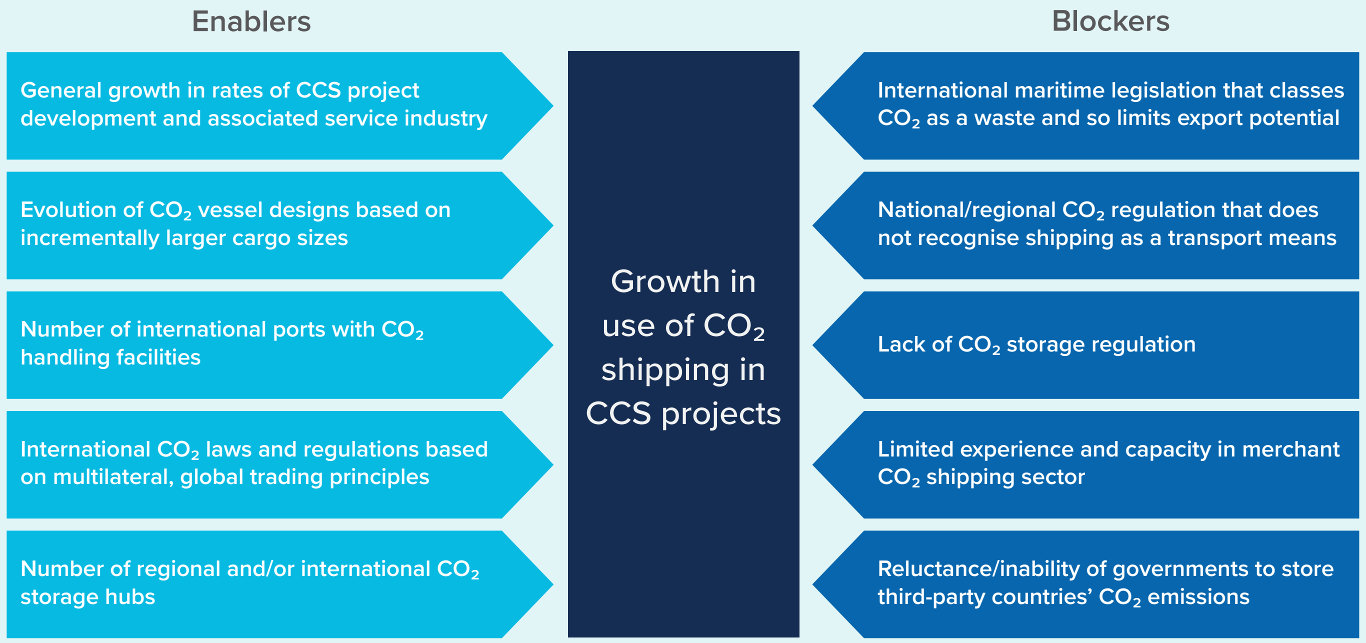
This section consolidates this paper's main observations to suggest points of leverage for policy or commercial efforts to underwrite or accelerate the prevailing, already positive, outlook for the use of CO_2 shipping in CCS projects. The force field graphic in Figure 6 consolidates the key actions on developments influencing the rate of growth in CO_2 shipping. There are many co-dependencies and interrelationships across the highlighted variables, not least in that all the other factors will affect the ultimate growth rate in general CCS projects – the top listed enabler.

The separate listing of influences reveals several insights. Most blockers, for example, are intangibles, based on the constraints created by the absence of legislation and regulation that is accommodating to both national and international movements of CO_2 by ship. By contrast, enablers are mostly tangible, such as vessel capacities and fleet sizes, port-handling facilities and CO_2 networks. These generally imply significant investment costs and lead times. Thus, removing blockers could act as a quicker acting stimulant to CO_2 shipping prospects than the physical building of scale. Of course, ideally, removing (or reducing) blockers and creating (or growing) enablers should be done in parallel.

The different mechanisms by which blockers and enablers work in practice is itself revealing. Some of the possible actions listed above have a universal stimulating effect on all CCS projects. This will help CO_2 shipping on the principle that "a rising tide raises all boats". Others, such as building port facilities, CO_2 networks or developing marine-focused CO_2 regulations, extend the technical feasibility for vessel-based CO_2 transport. The final class improves the overall cost base, and ultimately competitiveness, of CO_2 shipping in CCS projects and so covers CO_2 vessel capacities, fleet sizes and general maritime experience.

A proactive use of the force field summary would be to derive recommendations for governments and the general CO_2 shipping supply chain. Thus industry focus areas are improved CO_2 vessel designs and extending the number of ports installing CO_2 handling facilities. Government policy could be directed at ensuring adequate CO_2 regulations for vessel transport and, at a macro scale, easing the international movement of CO_2 cargoes for storage. A joint public-private approach is needed to encourage countries with surplus pore space to develop new CO_2 networks. The associated demand for long-distance CO_2 transport of stranded emissions will stimulate growth in CO_2 shipping.

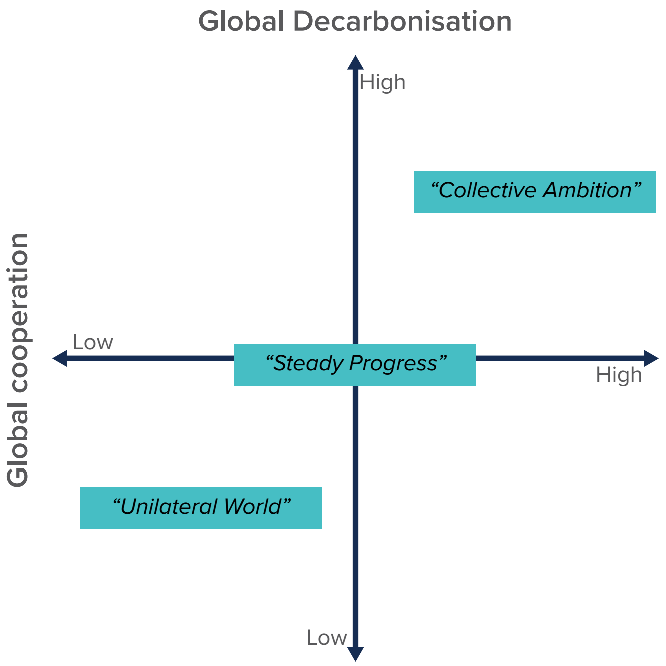
Figure 6 - 'Force field' behind potential growth in CO_2 shipping (Source: GCCSI)



8.0 POSSIBLE SCENARIOS FOR CO_2 SHIPPING VOLUMES TO 2040

Scenarios are often preferred as a basis for quantifying future industry growth rates over straightforward forecasts, or projections, in situations of high uncertainty. Work for this paper suggests the two most critical ultimate uncertainties affecting CO_2 shipping are the levels of global decarbonisation efforts and the extent of international cooperation on marine legislation and general trading. That assumption shaped three scenarios that, by employing GENZO, the Global CCS Institute's proprietary Global Emissions and Net Zero Optimisation model[13], produced a range of future CO_2 shipping volumes. Derivation of the three scenarios is shown schematically in Figure 7.

Figure 7 - Three scenarios for future growth in global CO_2 shipping (Source: GCCSI)



8.1 Scenario narratives

The next stage in scenario development is to create a plausible narrative to help understand how such futures might develop in practice and to associate that description to the applied implications, in this case for CO_2 shipping. This stage is summarised below for each of the three emerging scenarios.

Collective Ambition – A series of highly destructive climate events (e.g., storms, floods, droughts) drives an urgent and focused series of actions on CO_2 management. Targeted pressure builds on the top tier of emitting countries to more immediately reduce their emissions. The UNFCCC is strengthened to become an effective coordinator of global cooperation to accelerate programs to reduce CO_2 emissions. A revised objective to achieve net zero by 2050 is widely supported and endorsed. The overall rate of CCS project development increases, even showing signs of closing the CCS deployment gap in the ambitious IEA Net Zero scenario. Significant short-term increases in prevailing carbon prices also kick-start CCS in countries lacking national pore space. Some countries with significant CO_2 storage capacity surpluses develop new or expanded CO_2 networks. A larger, more sophisticated CO_2 vessel fleet emerges to service a material international CO_2 transport sector.

Steady Progress – Climate policies continue to grow at a relatively incremental pace. Continued growth and expansion (in terms of new applications) of CCS projects drives a reduction in unit costs. That saving is due to both economies of scale as well as ongoing technology and process innovation. Short-term impediments to global climate efforts continue, driven by either political changes or economic cycles. Regardless, the long-term climate trend continues to suggest global achievement of net zero, albeit maybe in the first half of the 2100s. The majority of CCS projects in the current development pipeline will reach operational status. Beyond that, the "feed rate" of new CCS proposals increases as cost reductions improve general CCS project economics. The steady trend towards increasing carbon prices across the world gives a later "second boost" to the underlying CCS growth rate. Expansion in the use of Cross-Border Adjustment Mechanism (CBAM) CO_2 policies drives industrialised countries to pursue CCS opportunities, even when that needs significant CO_2 exports.

Unilateral World – A trend towards populism drives an era of political unilateralism. Levels of international cooperation reduce as countries seek more independence in policy and trade. Action on climate change is reduced, suspended or even abandoned in favour of undiluted industrial growth in domestic economies. Increasing numbers of countries withdraw from the UNFCCC or significantly reduce ambition in their NDCs. Experts forecast that the net zero goal is unlikely to be achieved by the end of the century. CCS projects in the early stages of development suffer a high (>25%) attrition rate. Those already under construction continue to reach actual operation. CBAM CO_2 regimes gain traction and are used to protect industrial competitiveness as well as to manage national CO_2 emissions. Negotiations to reduce cross-border legislative and regulatory trade barriers falter.

[13] Details of the GENZO model are available via this link.

8.2 Scenario results

The Institute's GENZO CCS optimisation model was used to further operationalise the scenario descriptions by interpreting the implications for the model's key parameters. A series of simulations were then run to quantify the scenarios' impact on regional and global CO_2 shipping volumes, measured in Mtpa, through to 2040. The key results, in terms of average annual global shipping volumes, are shown in Table 6.

Table 6 - Scenario-based projections of annual CO_2 shipping volumes (Source: GENZO, GCCSI)

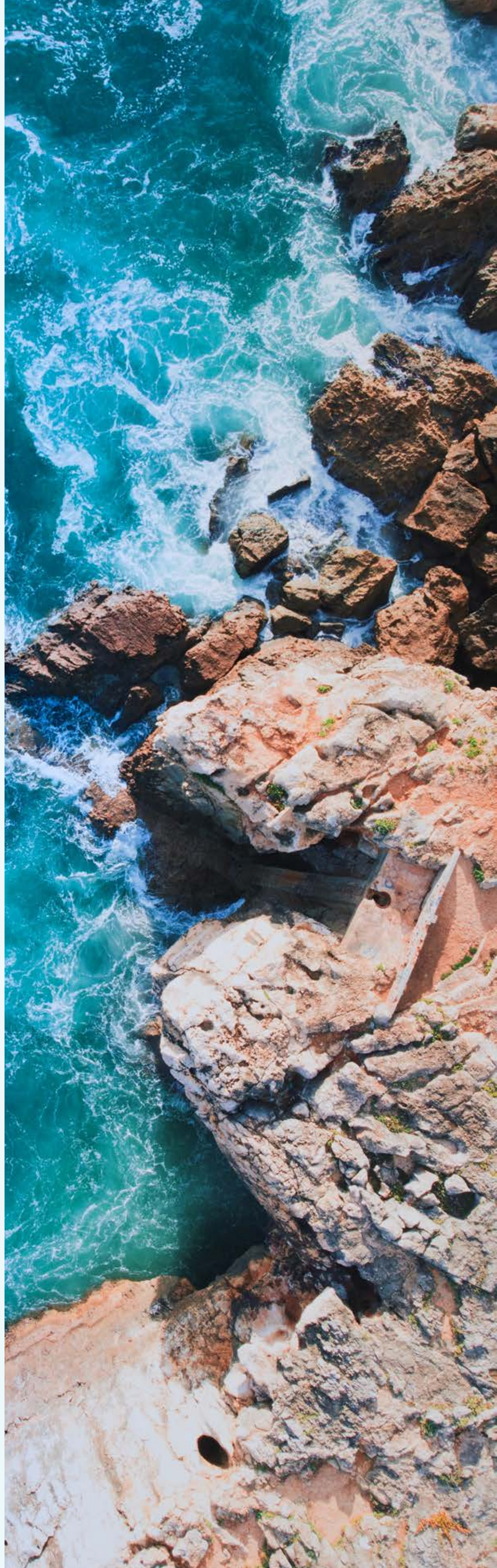
	Average Mtpa of global CO_2 shipped during five year periods*		
	2025-2030	2030-2035	2035-2040
Steady Progress	15	60	75
Unilateral World	20	65	125
Collective Action	25	145	625

** All figures rounded*

The suggested range of annual volumes of CO_2 shipped globally by GENZO is between 75 Mtpa and 625 Mtpa by 2035 to 2040. Either end of that range represents a substantial increase on the estimated 0.5 Mtpa of CO_2 transported in 2024. Although it was not designed as such, the Collective Action scenario produces CCS activity that gets close to levels seen in the IEA Net Zero scenario. On that basis, and perhaps unsurprisingly, given the underlying levels of global commitment and cooperation, Collective Action implies more than eight-times the shipping volumes than Steady Progress. More surprising, perhaps, is the relatively large scale of CO_2 shipping under Unilateral World. Closer examination of the GENZO model output explains this anomaly by its emphasis on domestic industrial competitiveness that encourages industrial CCS to avoid export-market CBAM policies, as well as the development of CO_2 networks to build new export markets for third-party CO_2 management.

Corresponding GENZO-generated CO_2 vessel numbers in 2040 ranged from about 100 in Steady Progress to around 1,000 under Collective Action. The latter estimate coincidentally calibrates with other projections, such as the ZEP figure[14] of 600 CO_2 ships needed to service European CO_2 shipping needs in 2050 to accommodate the IEA Net Zero scenario. A review of GENZO's projections of pipeline-based global CO_2 transport under the three scenarios shows similar growth to CO_2 shipping, with a range of 100 Mtpa under Steady Progress to 450 Mtpa in Collective Action. Looking at the comparison of CO_2 shipping to CO_2 pipeline volumes, Collective Action has the highest proportion of ship-based movements, at around 60%

[14] EU Zero Emissions Technology and Innovation Platform Study Estimates", 2018

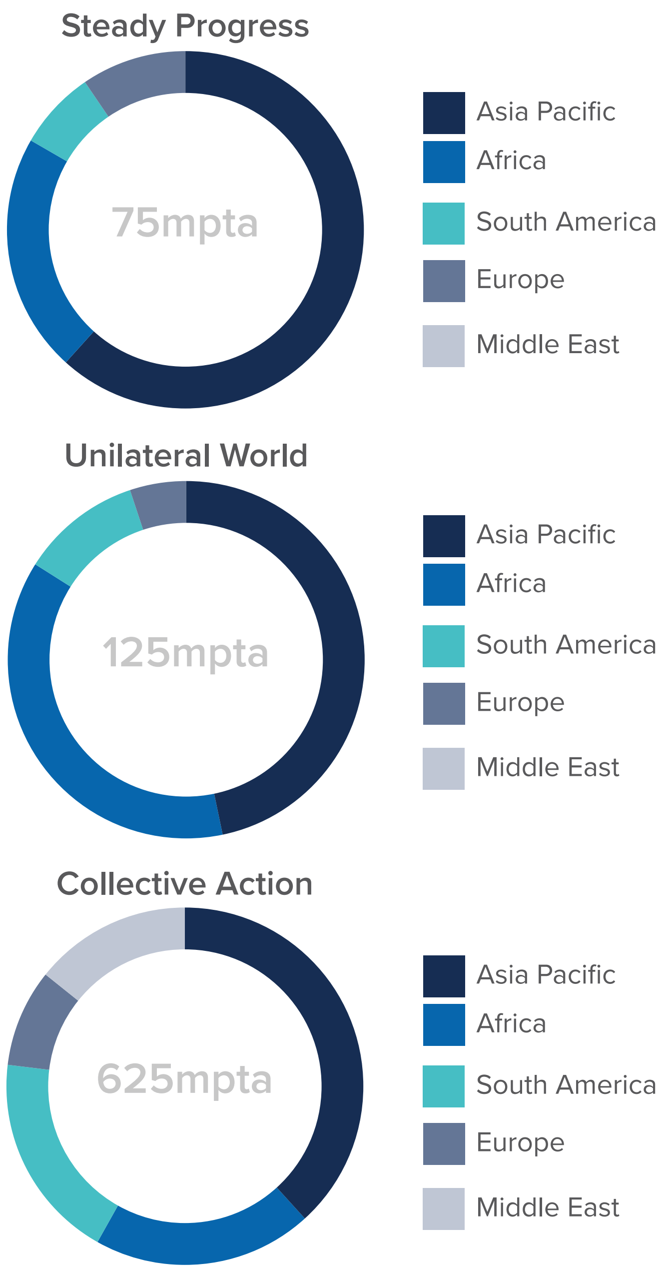


and Steady Progress has the lowest proportion at about 40%. The explanation for the domination of shipping over pipelines for CO_2 transport in Collective Action relates to the large scale of (mostly very long-distance) movements to manage stranded emissions, for which pipelines are inappropriate. Indeed, closer examination of the GENZO results shows that, even under that scenario, pipelines remain more important than shipping in Europe, some regions of South-East Asia and in North America.

A comparison of the regional breakdown of the global CO_2 shipping volumes by each of the three scenarios in 2040 is shown in Figure 8. In all three cases, Asia Pacific dominates global CO_2 shipping activities, accounting for 40-60% of trade across the three scenarios, followed by Africa, based on most CO_2 traffic arising from the future management of stranded emissions. The Middle East appears as a significant maritime exporter of CO_2 only under Collective Action, when global mitigation activities – as well as underlying carbon prices – are at their highest levels.

Although this paper has followed a scenario-based approach to generating medium term CO_2 shipping volumes, rather than a more incremental forecasting model, the implications of the GENZO model output are important and insightful. It appears that CO_2 shipping is likely to grow by at least 75 Mtpa, and maybe, under admittedly extreme conditions, to 625 Mtpa, by 2040. Either end of that range represents impressive growth. One can understand others reading similar market signals and now building (or adapting) more CO_2 vessels, expanding the number of ports equipped to manage CO_2 tankers, and developing more CCS projects that use vessels for their CO_2 transport needs.

Figure 8 - Scenario-based CO_2 shipping volumes from and within regions in 2040 (Source: GENZO, GCCSI)



9.0 CONCLUSIONS AND RECOMMENDATIONS

CO_2 shipping today is a nascent industry with current annual volumes transported of about 0.5 million tonnes of CO_2, serving mainly food and drink industries around northern Europe. Pipelines presently have overwhelming domination in CO_2 transport for CCS projects. They currently account for over 95% of global CO_2 transport capacity. The prospects for growth in CO_2 shipping for CCS do, however, look strong; more and larger CO_2 vessels are currently being built and planned, and a significant number of CCS projects in development already plan to use shipping-based CO_2 transport. Three scenarios created for this paper suggest CO_2 shipping volumes could reach about 75 Mtpa, 125 Mtpa or over 600 Mtpa by 2040, the latter under highly optimistic conditions of cooperation in trade and climate action. The main regions for CO_2 shipping are Asia Pacific, Africa and South America.

For non-owners, shipping costs are predominantly operational (or variable) rather than capital (or fixed) in nature, the opposite of pipeline costs, meaning shipping should be more cost-competitive for relatively small CCS projects for distances over about 250 km, as well as short-lived or highly variable capture volumes. There are, however, still legal and regulatory obstacles to the cross-border transport of CO_2 conducive to shipping. Still, these issues are surmountable – if sufficient political will exists.

The pressure and temperature at which cryogenic CO_2 is transported is a critical design choice for CO_2 vessels. Current ships have chosen a medium-pressure design to optimise the trade-off between density (and hence volumes) and costs. New ship designs are adapting from that position to allow larger cargoes or extended vessel applications, such as direct bed injection of CO_2 into the sea.

There is a healthy development pipeline of CO_2 vessels at present in design, construction or testing. The general scale of activities in the CO_2 shipping value chain is also growing, with the most active players having expanded from large-scale gas transport activities. Current CO_2 shipping activities are concentrated in Europe and the Asia Pacific, which together account for about 90% of the emerging CCS projects that rely on shipping for transport.

The anticipated growth in CO_2 shipping will likely mirror growth in the global CCS project development pipeline. That comes from shipping's contribution to the improved commercial and technical feasibility of more CCS projects. Its role in operationalising long-distance CO_2 transport can help address the stranded emissions dilemma facing countries lacking nearby pore space, for which CCS would otherwise be a viable industrial emissions mitigation choice.

Prompted by a belief that CO_2 shipping will have a major role to play in future climate management, and especially in situations of stranded emissions where volumes of CO_2 are expected to be most significant, shipping operators appear prepared (mostly reactively rather than speculatively) to build (or adapt) more CO_2 vessels. That could lead to the emergence of a large and valuable new maritime business that might initially complement, and ultimately even replace, the global hydrocarbon shipping industry.

A series of recommendations to underwrite and accelerate the rate of growth in CO_2 shipping emerges from this paper, which are categorised below by the most relevant action parties.

Shipping industry efforts are best directed towards:

- Continued work on improved CO_2 vessel designs, both for larger capacities and for extended CCS applications, such as direct injection activities.
- An associated expansion in the size of the CO_2 fleet and experience in their traffic management and development of handling facilities for CO_2 tankers at more ports.

Government policy actions are best targeted at:

- Ratification of London Protocol amendments and negotiation of bilateral agreements between CO_2 exporting and importing nations.
- Revision of existing and planned CCS regulatory regimes (from monitoring and reporting to emission trading schemes) to recognise non-pipeline CO_2 transport.

Joint industry and government efforts are most productive in:

- Development of international CO_2 networks, and associated business models, in countries and regions with suitable surplus CO_2 storage space.
- Planning (even contingency) work on CO_2 export practices and routes for industrialised countries that lack accessible pore space, but for whom CCS is a practical mitigation mechanism.

Prompted by a belief that CO_2 shipping will have a major role to play in future climate management, and especially in situations of stranded emissions where volumes of CO_2 are expected to be most significant, shipping operators are already building (or adapting) CO_2 vessels. That could lead to the emergence of a large and valuable new maritime business that might initially complement, and ultimately perhaps even replace, the global hydrocarbon shipping industry.

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GLOBAL CCS INSTITUTE

Global CCS Institute
Level 23, Tower 5,
727 Collins Street
Docklands VIC 3008 Australia

globalccsinstitute.com

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