Onboard carbon capture utilisation and storage

A readiness assessment for the shipping industry

The **Lloyd's Register** Maritime Decarbonisation Hub

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Executive summary

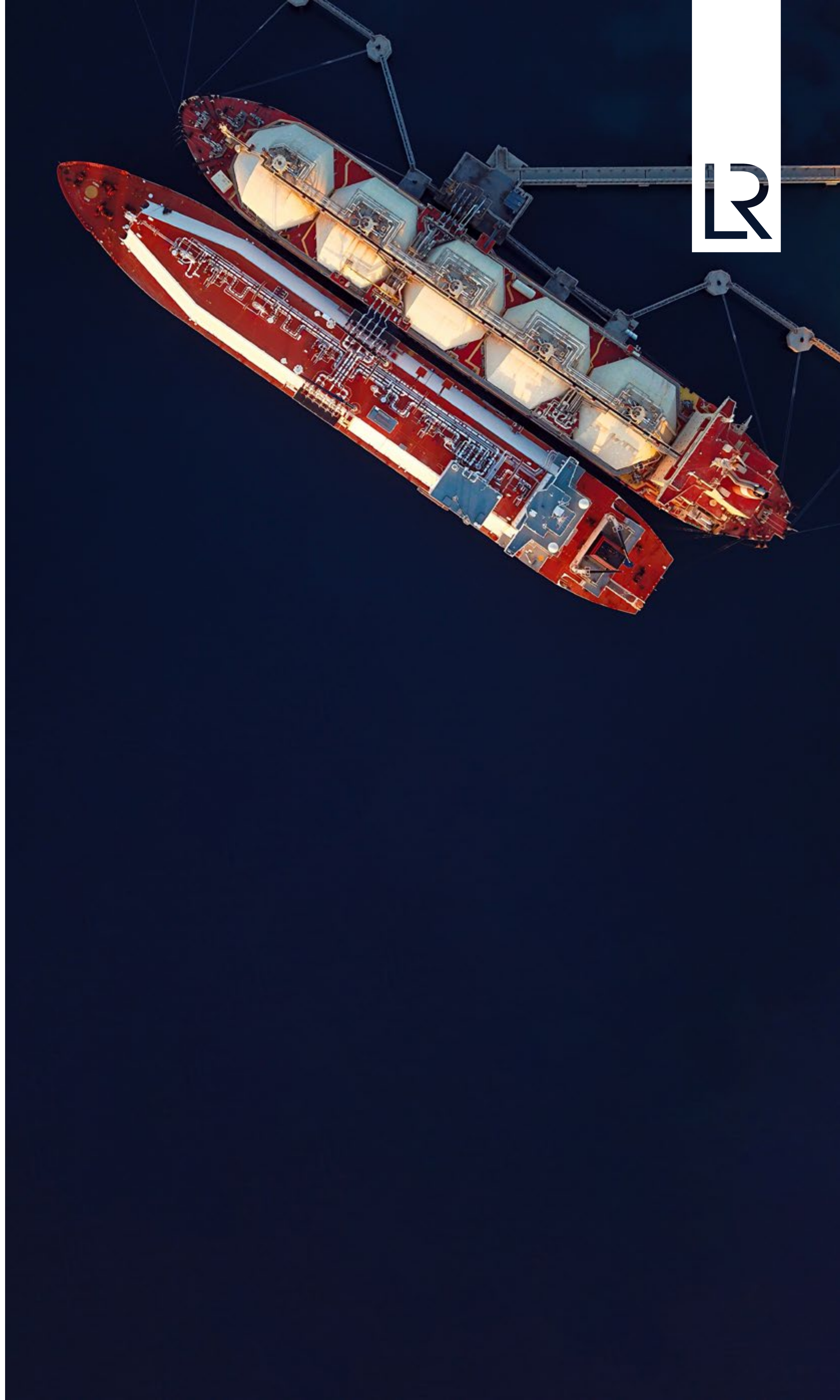
This report provides an analysis of the technology readiness level (TRL), investment readiness level (IRL) and community readiness level (CRL) of onboard carbon capture, utilisation, and storage (OCCUS) in the shipping industry. It highlights key observations and priorities that have been identified to move OCCUS adoption forward.

The OCCUS market is technology-led, and overall **TRL** across the supply chain is much higher than the **IRL** and **CRL** with technology, particularly in the storage and conversion stage, being already deployed and proven outside of the shipping industry. The **IRL** and **CRL** remain low whilst the effectiveness and economic viability of the solution are undetermined, and there is a lack of required regulation and policy.

Four key themes are identified: market maturity and economic viability, policy regulation and standards, effectiveness to deliver zero carbon, and shipping's role in the global carbon industry.

The adoption of OCCUS relies on the formation of several economic cases for the various stakeholders throughout the supply chain, and regulations need to be updated to address practical deployment challenges, including carbon accounting. There is a need for significant infrastructure scaling and investment, and to settle on a small number of onboard and offloading solutions that can become industry standards generating the required economies of scale and scope for economic viability.

The market for OCCUS is experiencing a fast rate of change as the world moves towards zero carbon, driven by the urgency to adopt solutions that will reduce emissions in line with decarbonisation milestones. Although OCCUS is expected to be a step on the decarbonisation pathway, rather than the endgame, it could play a significant role in the shipping industry's journey toward zero carbon emissions. The potential is greatest for existing vessels where conversion to zero carbon fuel is cost-prohibitive, but OCCUS provides a route to extending asset lifetime.



Contents

Introduction

The shipping industry is working to reduce greenhouse gas (GHG) emissions as it plays its part in the global energy transition. There is growing pressure on maritime to increase ambition further, going beyond the initial GHG strategy published by the International Maritime Organisation (IMO)[1]. Policymakers are pushing for alignment with the Paris Agreement to limit global warming to 1.5°C and set a pathway to zero emissions by 2050.

Full decarbonisation requires the replacement of fossil fuels with new, zero carbon fuels. A range of zero carbon fuels are under consideration, such as green[2] ammonia, methanol and hydrogen. However, introduction of true zero carbon fuels will take time. Propulsion solutions based on these fuels are under development and are gradually being deployed on operational vessels. The Lloyd's Register Maritime Decarbonisation Hub publishes the Zero Carbon Fuel Monitor[3], which gives an overall picture of how ready zero carbon fuel solutions are for deployment in shipping.

Whilst the updated decarbonisation trajectory is being negotiated at the IMO, short-term measures that deliver emissions and carbon intensity reductions in the next few years have been set by the IMO requiring ship owners and operators to meet interim emissions regulations. The conversation over what mid- and long-term measures will be established continues at IMO, alongside a growth in interest in interim measures, such as the use of carbon capture and storage (CCS) on board vessels to reduce onboard operational[4] carbon emissions.

In this report we have used the term CCS or CCUS to describe carbon capture (utilisation) and storage in general, either on land or at sea, whereas OCCUS refers to the specific shipping case.

[1] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx
[2] In this context, 'green' means produced using renewable energy so that carbon emissions in production are zero or close to zero.
[3] https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/zcfm/
[4] Tank to wake (TTW) emissions are all emissions related to onboard use of fuel.

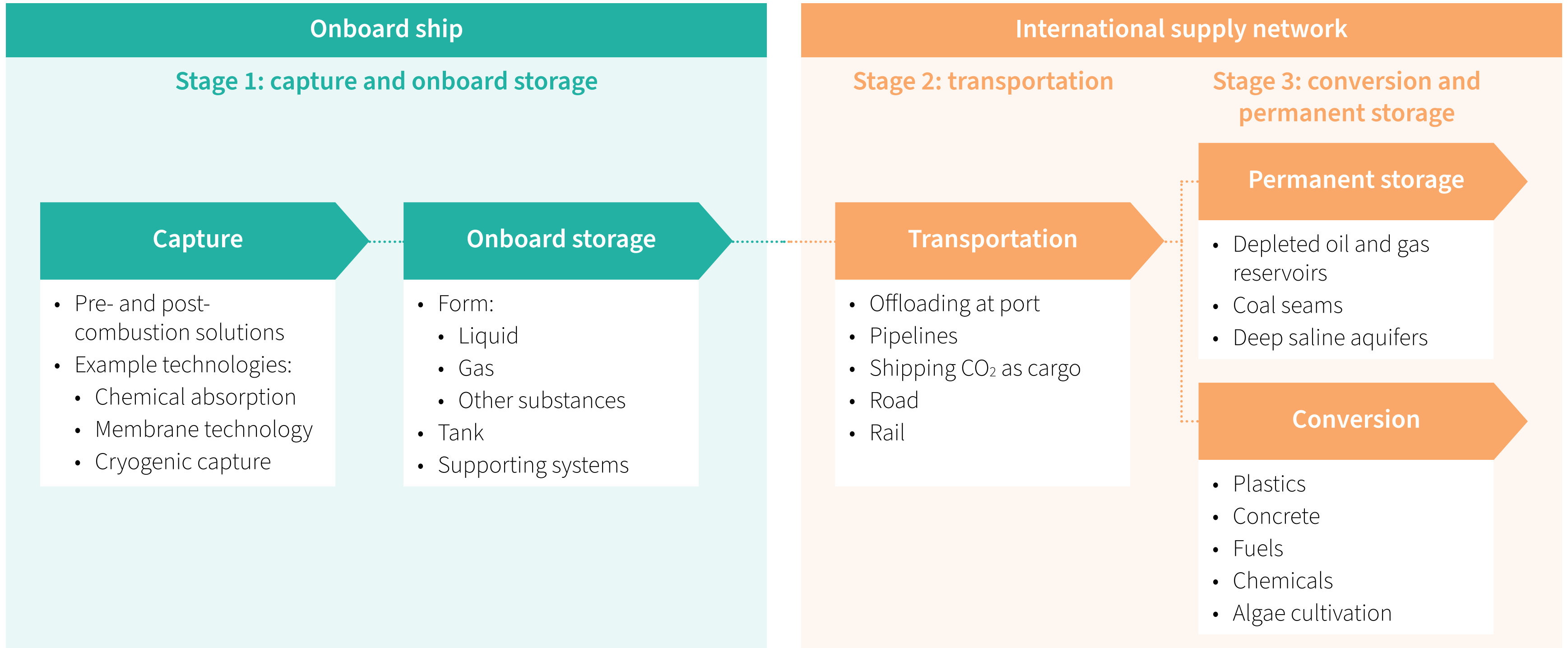
There are several alternative solutions being explored for carbon capture and storage onboard ships. Pre-combustion capture involves converting the ship's fuel into a gas and then capturing the carbon dioxide (CO_2) before combustion or removing carbon as a solid such as graphite and creating hydrogen. Post-combustion capture involves capturing CO_2 from the ship's exhaust gas by one of several mechanisms:

1. Chemical absorption: CO_2 in the exhaust is absorbed by a chemical solvent (e.g. monoethanolamine).
2. Membrane technology: selective permeation of gases in the exhaust through a physical membrane.
3. Cryogenic capture: cooling the exhaust gas to very low temperatures, which causes the CO_2 to condense into a liquid that can be stored.
4. Oxy-fuel combustion: burning the ship's fuel in an oxygen-rich environment to produce a CO_2-rich exhaust gas that is then captured.
5. Solid sorbent capture: capturing CO_2 using solid materials that adsorb CO_2 molecules from the exhaust gas.

Once the CO_2 is captured, it can be stored onboard the ship in either liquid or gaseous form, or as solid carbon. Liquid storage options include using high-pressure tanks or cooling the CO_2 into a liquid that can be stored at low pressure. Solid storage options include converting the CO_2 into a mineral form (e.g., limestone) or using solid sorbent materials that can be easily transported and stored.

The CO_2 stored onboard must be offloaded from the ship at a convenient port for onward transportation to a processing facility by pipeline or by cargo ship where it is processed for permanent isolation from the atmosphere. This may involve either permanent storage underground or conversion into another material that can be used in the construction, manufacturing, agriculture, or chemicals industries, where the material must not later release the CO_2 that has been captured. Any subsequent release of CO_2 would undermine the net benefit. Figure 1 illustrates the supply chain for onboard carbon capture utilisation and storage.

Figure 1: Onboard carbon capture and storage – supply chain



The second half of the OCCUS supply chain, the international supply network, is already established as there is an existing CO_2 industry. It is the onboard ship part of the supply chain that is new. However, the international supply network will need to evolve to accommodate shipping (and other industries) as CO_2 volumes increase and the requirement for offloading spreads geographically to many more locations.

Wherever CO_2 is handled throughout the supply chain, it presents major safety concerns which must be addressed through technical, operational and regulatory measures.

A wide range of regulations already apply across the supply chain. From a shipping operational perspective, some govern the ship and the wastes collected through normal operations, others govern the discharge of waste into the sea from the land. As shown in Figure 1, OCCUS is subject to both these aspects of ship regulation. In addition, a spectrum of regulations applies downstream where offloaded CO_2 in a port is then either stored (for example in sub seabed geological storage) or re-used (for example to create fuels).

This report addresses the question, "How ready is industry to use OCCUS solutions for shipping?". It is based on research done by the Lloyd's Register Maritime Decarbonisation Hub (the Hub) using the principles of the Zero Carbon Fuel Monitor (the Monitor)[5]. However OCCUS is not included in the current version of the Monitor because it is a technology used in conjunction with several fuels rather than a fuel in its own right.

The report addresses the whole OCCUS supply chain from initial capture through to the ultimate destination of either permanent storage or conversion. It identifies key priorities needed within the industry to continue to progress readiness and outlines the main trends in the developing market for OCCUS.

We welcome all feedback on the Monitor, and this report. Our website includes a contact us form[6] for contributions and discussion.

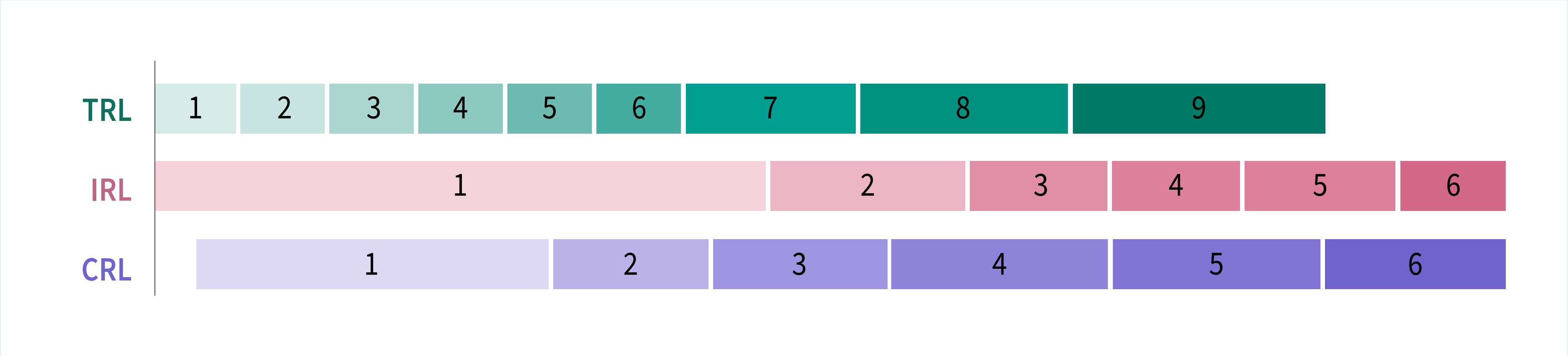
[5] https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/zcfm/
[6] https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/zcfm/dashboard/

Methodology

This report provides applies the same methodology as is used in the Zero Carbon Fuel Monitor to assess the readiness of zero carbon fuels. The entire supply chain is subjected to review, evaluating readiness levels from three perspectives: technology (**TRL**), investment (**IRL**) and community (**CRL**). The **TRL** follows the development of technology from conceptual stage (level 1) through scale-up (levels 6-8) to fully operational (level 9). **IRL** indicates the commercial maturity of a solution from initial business idea (level 1) through scale-up (levels 2-3) to reliable investment (level 6). **CRL** indicates the social maturity of a solution from the societal challenge (level 1) through to solutions proven in a relevant environment (level 6). **CRL** covers a range of aspects such as regulatory development, sustainability criteria, and community acceptance.

The appendix gives a description of all the readiness levels used. The assessment is carried out across the end-to-end supply chain, broken down into the three stages described above. The assessment method as applied to fuels, and also used for OCCUS, is fully described on the website[7]. Figure 2 gives an indication of the relationships between different readiness categories.

Figure 2: Approximate relationships between different readiness categories



[7] https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/zcfm/assessment-method/

This shows that it is unlikely that investment readiness levels will proceed beyond level 2 before the technology has been proven reliable. This does not mean that investment is not required early in the process, but that our levels recognise the change in investment maturity at scale-up level. Unlocking that investment early on is key to building the momentum required for progression. The linkages between **CRL** and **IRL** and between **CRL** and **TRL** are looser. In some cases, regulations can be formulated in anticipation of technology being developed. There are also instances where community acceptance may initially be forthcoming but then withdrawn at a later stage.

The methodology reviews readiness levels in the specific context of the maritime industry. Therefore, it may be that our readiness levels differ from those published for other industries. For example, CCUS is well established on land, so the **TRL** for carbon capture in that context could be rated at 9. However, successful deployment in shipping is less mature, therefore, the readiness levels in this report would be expected to be lower.

The approach adopted is to provide a single readiness figure for all the fossil fuels currently used in shipping, based on fuels addressed by the OCCUS solutions under development today. As solutions progress, a probable enhancement of this method would be to give separate figures for each fuel, heavy fuel oil (HFO), liquefied natural gas (LNG), very low sulphur fuel oil (VLSFO), etc.

When considering technology solutions, readiness levels have been based on the most-ready technology – for onboard capture, for example, this is post-combustion chemical absorption of HFO.

Although enhanced oil recovery (EOR) is a well-established use of carbon, it is out of scope for this report as it relates to production of further fossil fuels and ultimately increased well-to-wake (WTW) emissions[8].

[8] Well-to-wake emissions means the total emissions across the whole shipping fuel production and usage cycle.

Readiness assessment

The results of the readiness assessment can be seen in Figure 3.

Figure 3: Onboard carbon capture and storage – readiness assessment

		Supply chain stage		
	Scored out of	Capture and onboard storage	Transportation	Conversion and permanent storage
TRL rating	9	6	5	8
IRL rating	6	2	2	3
CRL rating	6	3	2	2

Across all parts of the supply chain, **TRL** is significantly higher than **IRL** and **CRL**. This is largely due to technology having been developed and in increasing use outside of the maritime industry, however adaption for the maritime OCCUS use case is necessary and significant scaling of existing infrastructure will be required to meet forecast demand.

Overall **IRL** and **CRL** ratings are heavily impacted by the effectiveness and economic viability of the solution, and the lack of required regulation and policy for OCCUS.

Please note that the **TRL** scores are out of 9, whilst **IRL** and **CRL** scores are out of 6. More information on the meaning of each readiness level is given in the appendix.

Capture and onboard storage

TRL

Capture and storage solutions from several vendors have reached the pilot stage of development. For example, Value Maritime's onboard CO_2 capture and storage unit, using post-combustion chemical absorption of HFO in an onboard tank, is gaining market traction and has been awarded an Approval in Principle (AIP) by LR.

The Value Maritime carbon capture solution is now being installed onboard on vessels, for example X-Press Feeders /Eastaway is in the process of commissioning a two-vessel pilot. On an Eastern Pacific Shipping managed vessel (M/T Pacific Cobalt), the solution is anticipated to be able to capture up to 40% of the vessel's main and auxiliary engine emissions[9]. At this stage there is insufficient evidence to validate the real-world performance of these systems or the systems from other vendors.

The **TRL** has been assessed to be 6 as leading solutions are in early deployments, and progression to **TRL** 7 will be dependent on validated capture rates.

IRL

The economic viability of capture and onboard storage solutions is thus far unproven. Higher capture rates require higher capital and operating expenditure and consume higher levels of energy. Additionally, cargo space may be taken up by CCS equipment, reducing total revenue. As a result, there are potential diminishing returns and potential additional carbon emissions associated with higher capture rates. Furthermore, lack of clarity as to measurement and reporting standards creates uncertainty over how owners can benefit economically from captured carbon.

Whilst the economic viability needs to be determined and ongoing commercial trials are small-scale, the **IRL** sits at 2.

CRL

Storage of CO_2 onboard presents safety challenges that need addressing from technical, operational and regulatory standpoints. Exposure to high levels (above 10%) of CO_2 can lead to asphyxiation and a severe hazard of pressurized CO_2 is the boiling liquid expanding vapour explosion (BLEVE). It should therefore be handled as a dangerous substance.

MARPOL (the international convention for the prevention of pollution from ships) is the main international regulation which aims to prevent the pollution of the marine environment by ships from operational or accidental causes. However, MARPOL does not currently include CO_2 captured onboard a ship as a waste product, thus leaving it as a grey area. As such there are no internationally adopted regulations or guidelines for CO_2 waste reception facilities within ports or considerations for ship design, transport and offloading of CO_2.

Carbon accounting onboard remains under development. A raft of legislation and policy initiatives in the EU are now incentivising the growth of CCS and OCCUS in shipping. With the gradual introduction of shipping into EU ETS these incentives will increase. However the question of how OCCUS will play a role in a WTW LCA[10] of fuel remains unanswered. Discussions at the IMO around including carbon capture technologies in the IMO regulatory framework to reduce GHG emissions from ships continue to progress, albeit slowly. Inadequate evidence on real-world capture rates means there is limited information available to convince communities of the effectiveness of this technology. Given these challenges, the **CRL** is rated at 3.

[9] https://valuemaritime.com/news/eps-and-value-maritime-install-first-of-its-kind-fully-integrated-carbon-capture-solution-onboard-mr-tanker/
[10] Lifecycle analysis – calculation of total emissions across the entire lifecycle of a fuel

Transportation

TRL

Port based terminals to receive CO_2 are in development, including at Ports of Antwerp, Gdansk, Gothenburg, Dunkirk harbour and German BlueHyNow project. There are several approaches to offloading CO_2. For example, Value Maritime has developed a containerised "CO_2 battery" that can be removed, transported, processed and returned.

Globally, multi-use CO_2 pipeline networks are being developed to further transport CO_2 to end users and into CO_2 sequestration networks. Examples of such networks include the Mid-west Carbon Express (US), an offshore pipeline connecting Belgium with Norway, and the Delta Corridor connecting parts of Germany and the Netherlands.

OCCUS transportation is rated at **TRL** 5 whilst offloading prototypes are still being tested and industry standards will need re-evaluation to deal with the volumes generated by shipping and other industries.

IRL

The most advanced technology in commercial trial (the Value Maritime CO_2 battery system) is still in early stages, with the attractiveness to CO_2 consumers of this containerised solution unknown, and although government support for CO_2 transport and storage infrastructure is growing in several countries, pilots at ports for CO_2 offloading remain in early stages. As a result, the **IRL** sits at 2 at this stage.

CRL

The **CRL** is rated at 2 as existing safety and environmental regimes need re-evaluation to address large volumes of CO_2, particularly noting safety concerns that exist around CO_2 pipeline transportation as compressed CO_2 released from a leaking or ruptured pipeline is extremely hazardous. At present, communities are largely uninformed about the overall risks and benefits.

Conversion and permanent storage

TRL

For storage to be effective in terms of climate change, the captured CO_2 needs to be locked away for climatically significant geological timescales. The definition of this timescale and whether the storage can meet this need has not yet been addressed.

The 1996 Protocol to the Convention of the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (the London Protocol) provides a regulatory framework for CO_2 being sent from a port to an offshore location for geological sub seabed storage. When the Protocol entered into force OCCUS was not an in-use technology. As this technology has matured it became clear that the Protocol prevented both the geological sequestration of CO_2 into sub seabed formations and the transboundary movement of CO_2 as a waste product, noting that not all countries have their own suitable geological formations for CO_2 storage.

Today the London Protocol has been amended to permit CO_2 captured for geological storage and the transboundary movement of CO_2. However, for the amendments to allow transboundary movement of CO_2 to come into effect two thirds of contracting parties to the Protocol must accept them and they are not yet in force. As such, unless CO_2 is being moved from the land (port) to sub seabed geological storage within the same nation's territorial waters, its movement is prohibited under the London Protocol. In 2019, a resolution was published which allows for contracting parties to provisionally accept the adopted (but not yet accepted) amendments to the London Protocol to allow transboundary movement of CO_2 as waste. So far only UK, Netherlands and Norway have provisionally accepted these amendments. However, in September 2022, Denmark and Flanders signed the first bilateral agreement for CO_2 transport for the purpose of offshore storage. This is a key enabler for the transportation market, which we expect to grow as other agreements are made[11].

The conversion and permanent storage of CO_2 has reached **TRL** 8 because storage facilities are in full production today. However, capacity is limited with facilities for just 10Mt CO_2 per year in full production today[12], and significant further scaling of the infrastructure and storage is required to meet forecast demand. For reference, the shipping industry alone emits approximately 1,050Mt CO_2 per year[13].

IRL

Plans for increased CO_2 storage globally are now underway. For example, in the UK the North Sea transition authority is organising a licensing round, with new carbon storage licenses expected to be announced in 2023 and first injection potentially in 2027. In March 2023, Project Greensand saw CO_2 from Belgium being shipped and injected into a depleted oil field in the Danish North Sea.

Despite these efforts, world planned CO_2 storage capacity is just 17% of that required solely to be on track in 2030 for zero carbon shipping in 2050, and the shipping industry is not yet engaged with these facilities to deliver the capacity required for the industry to adopt OCCUS at scale. Additionally, the locations of storage hubs may create potential challenges for the industry as regional capacity constraints could cause increased emissions through further transport of the CO_2.

As well as regional capacity constraints, there are also regional variations allowing, or otherwise, the export of CO_2 for the purpose of storage offshore as described above.

[11] https://www.iea.org/reports/CO2-transport-and-storage → international collaboration
[12] https://www.iea.org/reports/CO2-transport-and-storage
[13] https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20Executive-Summary.pdf

Due to the storage constraints and prohibitive costs to supply and use the CO_2 in CO_2-derived products (see **CRL** below), the **IRL** rating is 3.

CRL

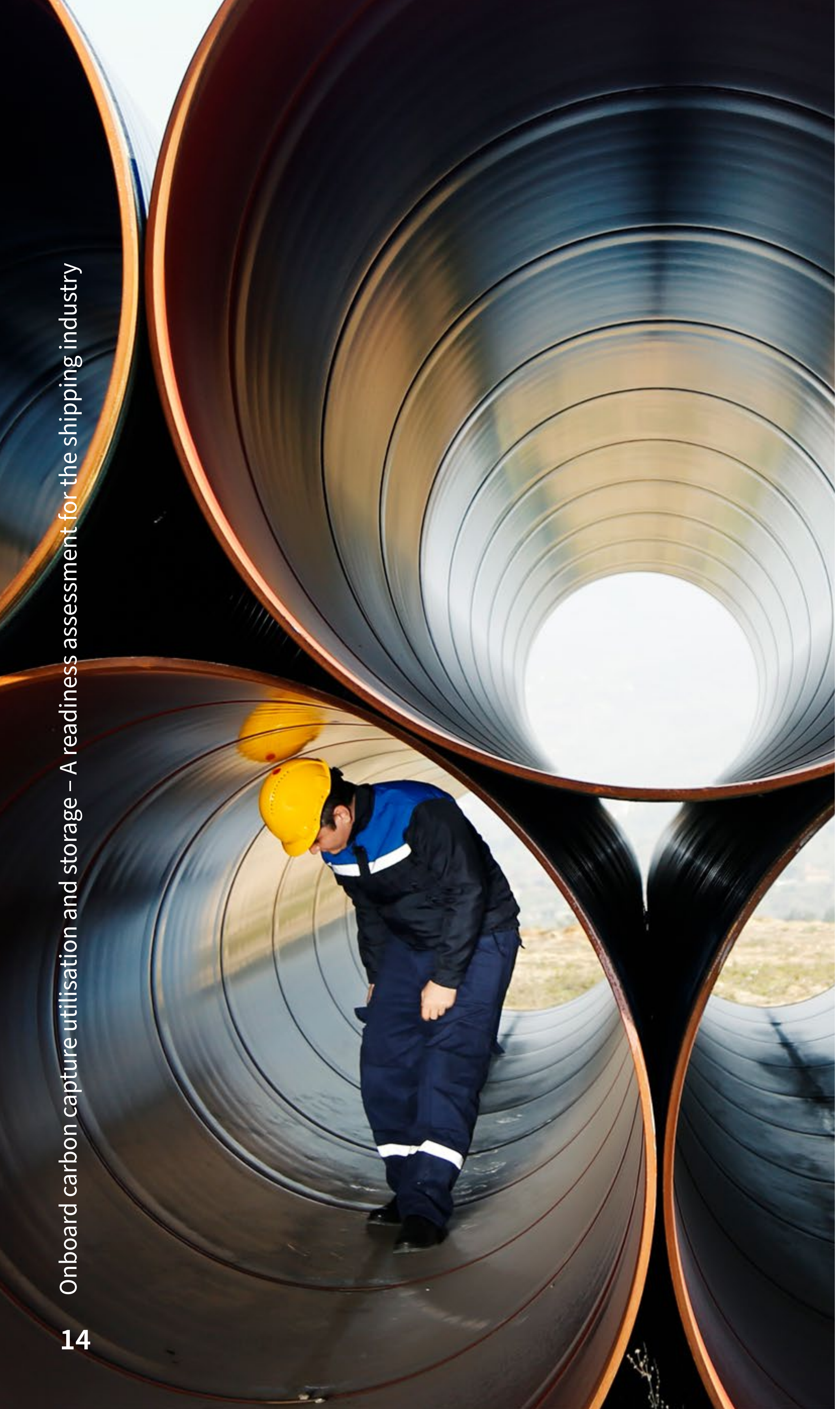
For communities to be convinced and accepting of CCS in general, there needs to be evidence that the carbon can be stored permanently and in a safe manner without release, followed up with better awareness and education. The question of who accepts sovereign liability of the storage, particularly when storage is in international waters, remains unanswered.

The alternative to long-term storage, processing for usage, also comes with its own challenges, which would result in a lower **TRL** than the permanent storage route. The CO_2 commodity market today is small and mature, consisting largely of food and beverage applications (in which the CO_2 is not permanently stored) and agricultural and construction uses. Many people advocate a truly circular economy solution, in which carbon capture is fully reused and stored permanently in its new form, however at present most derived products are more expensive to manufacture utilising CO_2 than utilising fossil-fuel-derived incumbents[14].

For CO_2 to be converted for use rather than placed into storage hubs, it will need to meet CO_2 purity requirements applicable to the end usage. Therefore, costs associated with supplying CO_2 as a by-product for specific use cases (rather than producing CO_2 as a waste product) need careful evaluation if a robust economic case is to be created.

CRL is rated at 2 whilst existing safety and environmental regimes do not accommodate CO_2 storage and usage at scale from OCCUS, and although awareness is growing, communities remain largely uninformed of the risks and benefits of CCS.

[14] https://nap.nationalacademies.org/catalog/26703/carbon-dioxide-utilization-markets-and-infrastructure-status-and-opportunities-a



Overall observations

Market maturity and economic viability

Large scale adoption of OCCUS will depend on the overall market maturing, significant capital expenditure particularly on infrastructure across the supply chain, and definition of a robust economic case for all stakeholders. Key factors heavily impacting the economic case are unproven onboard technology performance, the need for significant infrastructure scaling and some unresolved key trade-offs related to the operational economic viability.

Funding and incentives

Industry is experiencing a fast rate of change in this area as the world is transitioning towards zero carbon. With milestones for this transition already set, governments are directing funding to development and incentives that will move industry on the steps to low emission and zero carbon solutions in the given timeframes.

Funding for CCS, and now also specifically OCCUS, is emerging. This will accelerate the market maturity for OCCUS and is strengthening the economic case, as the funding makes it financially more attractive for industry stakeholders across the supply chain to adopt OCCUS for long-term use. However, we believe the government will need to invest further to make this a viable solution.

As an example, in the UK Government's Budget in March 2023, it was announced that the funding to support the development of CCUS in the UK would be increased to £20 billion, showing the UK's commitment to carbon offsetting through the CCUS route. In Scotland, a Scottish cluster (Acorn CCS) has benefitted funding from Connecting Europe Facility (CEF) from the European Commission, as well as the UK & Scottish Governments. The goal of Acorn is to develop a major hydrogen and CCS hub at St Fergus gas terminal, together with the required infrastructure and international storage hub in the North Sea with growth potential[15]. Critically, the cluster is also working to a defined revenue model for all stakeholders.

Land-based incentives are emerging, and these are likely to benefit the maritime industry OCCUS due to overall growth in the market and infrastructure

[15] https://www.theacornproject.uk/projects

investment. For example, changes to the US 45Q tax credit made by the Inflation Reduction Act of 2022 have improved the attractiveness of CCUS schemes, increasing the value per ton of carbon captured by 70% to $85 per ton[16]. This will make CCUS a more economically appealing option in more industries.

Demand driving growth

The growing commercial and consumer demand for solutions to reduce environmental impact is accelerated by social and political pressures, with many corporations having pledged emission reductions. For example, AstraZeneca has committed to net-zero carbon by 2025 and negative by 2030[17], whilst Microsoft plans to become carbon negative by 2030[18]. Corporations are seeking to be sustainable and prove it and CCS is one way they can demonstrate their environmental credibility.

As a result, the overall carbon capture market is growing and Q2 of 2022 saw the highest-ever venture capital investment in carbon capture start-ups with $841.5 million invested across 11 deals[19]. As the market grows so will the infrastructure that is required for wider adoption of OCCUS.

Challenges to implementation of complete OCCUS solutions

The OCCUS market is currently largely technology led, as several technological solutions exist, but few products. To progress wider adoption, the market will need to settle upon a small number of onboard and offloading solutions that have sufficient evidence of real-world performance and can become the industry standards that will generate the required economies of scale and scope to be economically viable.

Another challenge that shipowners are facing in adoption is the fragmented approach applied across the supply chain, with technology providers working on the onboard technology typically not fully engaged with the other supply chain members such as ports, transportation and end users or storage facilities of the captured CO_2. This is resulting in gaps in creating a complete and circular solution for shipowners. Shipowners may, however, still decide to adopt OCCUS whilst these challenges are still unresolved as shipowners adopting sulphur oxides (SOX) scrubbers may see benefits in installing CO_2 technology onboard at the same time for future-proofing the vessel.

Further on in the CCUS supply chain additional development and scaling is also required. Port infrastructure is essential and currently a major gap within the supply chain, however ports first need to see evidence of demand for offloading in order to invest, and the question of where in the supply chain processing facilities for liquefaction should sit – onboard or in port – remains unanswered. It is anticipated that investment requirements for infrastructure on land will be the bulk of the challenge and slower to move than onboard.

Defining the economic case

The adoption of OCCUS relies on the formation of several economic cases for the various stakeholders throughout the supply chain, for example, shipowners, charterers, port infrastructure, transportation infrastructure and as part of wider global initiatives, storage facilities and business models for reuse.

The case for shipowners depends on factors such as the trade-off between high capture rates and higher costs due to increased fuel consumption, as well as reduced cargo space or frequent port stops due to fuel

[16] Postcombustion Carbon Removal, Pitchbook, September 2022
[17] "Ambition Zero Carbon," AstraZeneca, January 22, 2020
[18] "Operating to Drive Global Change," Microsoft, 2022
[19] Postcombustion Carbon Removal, Pitchbook, September 2022.

and CO_2 storage space requirements and limitations. This case will not be a one-size-fits-all as the ship operating profile has a major impact on the chosen solution, for example tank size, locations of offloading points, and energy budget onboard the vessel all affect the economic viability of solutions. The case will be stronger for existing vessels that face possible scrappage due to energy efficiency regulations such as Carbon Intensity Indicator (CII) unless they can be converted to zero carbon fuels at costs that could be prohibitive. Different technological solutions will suit different situations, depending on the cost of installation, flue gas composition and properties, desired purity of the CO_2 and integration with the existing facility.

Low pressure ships transporting CO_2 may not be economically viable as the costs to transform the CO_2 into a state stable for storage in high-pressure saline aquifers and hydrocarbon reservoirs are high. Low-pressure ships may be a practical option for transporting CO_2 long distances, whilst high-pressure ships may be better suited for shorter trips to sites where the CO_2 can then go straight from the ship to geological storage without high conversion costs, although the higher capital and operational costs of these ships must be taken into consideration.

The knowledge gap for decision making

We believe that, as in any market with the introduction of new technology, it is likely that there is a significant knowledge gap between well-funded, heavily resourced major players and other players who are placed in a more reactive position, increasing the risk of ill-informed investment choices. In the case of OCCUS, this risk is compounded by time pressure to make investment decisions that will ensure companies meet intermediary decarbonisation milestones on their path to zero carbon, whilst the future fuels and technology outlook is continuously changing and developing.

Policy, regulation and standards

As is often the case, regulations are lagging technology development and the publication of relevant regulations will be critical to investment and safe, sustainable market adoption of OCCUS.

In the absence of global regulatory frameworks, adoption and agreement of amendments to regulate CCS and OCCUS, safety and environmental regimes will vary significantly by region. Such regional approaches will need re-evaluation and consistency to address the challenges of onboard carbon capture, offloading, carbon accounting and permanent storage in large volumes. For example, measuring and recognising collected and transferred CO_2 is not currently covered and the existence of carbon tax, and cap and trade schemes varies by region and country. Additionally, classification societies will need to develop rules to cover OCCUS.

Effectiveness to deliver a zero carbon solution

Although there is insufficient evidence of existing solutions' capture rates in real-world scenarios, realistic capture rates are expected to be insufficient to reach zero emissions targets.

Even if, in the future, a technology is proven to achieve 100% capture rates, it is unlikely that such a solution will be economically viable. There may be an optimal capture rate (or several optimal capture rates, by application) taking into account key factors such as finance, energy consumption and sustainability, and these will limit the role of OCCUS as a tool to tackle shipping's decarbonisation.

For this reason, CCS are solutions likely to be a step on the decarbonisation pathway, rather than the endgame, as is also reflected in the **IRL** and **CRL** ratings across the supply chain.

Shipping's role in the global carbon industry

The market for CO_2 transportation already exists, primarily using a combination of pipelines for high volumes and short distances, and shipborne for smaller volumes and more disparate geographies. Transportation by pipeline tends to be the lowest cost where sufficient volumes of CO_2 are available, however shipping is more flexible for geographically spread, lower volume CO_2 transportation.

Geographical dislocations of CO_2 and varying carbon prices are likely to drive further growth of the CO_2 shipping market, which up to now has been mainly used for relatively small volumes ($800m^3$-$1000m^3$) for the food and beverage industry. However, increased CO_2 shipping capacity will be required for much larger volumes produced through CCUS and standards for large volume CO_2 shipping have not yet been settled on.

The emergence of a large-scale carbon sequestration market (of which shipping may be a relatively small part, sectors such as steel and cement may ultimately be the key drivers) will transform the existing CO_2 market.

Reuse is currently largely driven by the food and beverage, agriculture, manufacture and construction industries, but there is potential for other new uses of CO_2, for example in renewable fuels production. Today the CO_2 market is approximately 230Mt per year. To bring perspective, shipping produces approximately 1,050Mt per year, and there are many other industries likely to produce additional CO_2. This market is likely to evolve with the new uses as not one market but a series of interconnected smaller markets with different CO_2 demand and purity requirements.

The ultimate end-product influences the shape of the upstream supply chain and technology used for onboard carbon capture and subsequent processing, subject also to commercial and technical constraints. Therefore, a key challenge for shipping to contribute to fulfilling the carbon requirements from other industries is finding a way to economically produce CO_2 that meets purity and quality requirements for end-uses.

Key priorities

Real-world performance needs to be proven

Potential capture rates in the region of 70% to 80% are discussed, but so far, few pilots and trials have published verified results. The industry needs to publish the results of trials and create the evidence that will support the investment case.

Actual capture rates will be based on the full range of vessel design, economic and operating parameters and may be below the theoretical maximum, possibly in the range of 30% to 50% or lower. As practical operational experience builds, optimal capture rates for technical and commercial viability will become clear. This will provide the evidence needed to show what role CCS can play in energy transition pathways to zero and to support larger scale investment decisions.

Shipping must interconnect with the wider carbon industry

The mature carbon dioxide market will be disrupted by the emergence of new supply from shipping and other sectors, and the needs and eligibility (permanent CO_2 conversion for use) of the existing market must be understood by the new suppliers.

Ship operators will need to understand the carbon products and purity and quality requirements of for the different market segments to determine what technologies, solutions and business models to use. These will in turn determine the requirements for certification and verification that will be needed.

The shipping industry needs to be part of cross-sector carbon transportation utilisation and storage discussions so that maritime requirements are included in wider investment and planning decisions, for example to ensure that forecast volumes are considered when sizing facilities.

Additional policy measures and regulations are required

Successful adoption of OCCUS requires a combination of policies and regulations to incentivise investment, ensure safety and compliance, and promote ongoing research and development. This goes beyond the revised strategy for the reduction of GHG emissions from ships, currently being worked on by the IMO, although that is a prerequisite that will create the right environment for OCCUS.

As bi- and multi-lateral agreements are established to transport and store captured carbon between contracting parties to the London Protocol, governments should also consider (provisionally) agreeing to the 2009 amendments allowing the transboundary movement of CO_2 as a waste for geological sub seabed storage.

The IMO does not currently regulate OCCUS, however it is a topic of discussion at IMO[18]. Review of the regulatory framework will be required to standardise approaches to OCCUS and ensure that there is a robust regulatory framework which:

- Defines requirements for ships with carbon capture technology onboard.
- Defines requirements for the characterisation of the CO_2 captured onboard a ship (noting different geological storage sites have individual specifications for acceptable CO_2 which port reception facilities will require at the point of offloading CO_2 and ahead of its transport to storage sites).
- Develops guidance on how administrations should issue exemptions from MARPOL Annex VI for ships trialling OCCUS technology to ensure a consistent approach.
- Clarifies how the use of carbon capture technology on board ships is reflected in the relevant requirements of EEDI/EEXI[21] and CII.

The regulatory and policy framework for carbon trading needs to mature. We need to see effective market-based measures such as carbon taxes or cap-and-trade schemes. Standards will be needed for measuring and recognising collected and transferred CO_2, and monitoring, reporting and verification methods, backed up by strong regulation.

Investment needs to be stimulated, particularly in onshore infrastructure

Adoption of OCCUS will require significant additional capital and operating expenditure both on ships and on land. To address low **IRL**s across the supply chain we need to reduce risks and uncertainties to make it easier to secure financing for CCS projects. The industry needs to determine how the CO_2 will be transported to determine the port infrastructure required as vessel investors need to see this offloading infrastructure and onward supply chain in place, whilst ports need to see volume demand from vessel operators. The economic case needs to be determined for all stakeholders across the supply chain so that bottlenecks are not created.

Port readiness is only partly about equipment, it is also about the business process, people and safety procedures. Where infrastructure can be put to multiple uses, investment will be more future proof for example by using pipes that can carry either hydrogen or CO_2. State-sponsored clusters such as the Acorn project in Scotland are one way to create the critical mass to drive growth.

[20] Norway (MEPC 79/7/16) Carbon capture and storage on board ships.
[21] Energy efficiency design index (EEDI) and energy efficiency existing ship index (EEXI) are measures of the energy efficiency of a ship design

Conclusions

The adoption of OCCUS depends on the formation of viable economic cases for each player in the supply chain, the creation of evidence to validate real-world performance of onboard capture technology, the publication of relevant required regulations and policy, and the development and scaling of infrastructure for storage and usage.

OCCUS is not the only solution for reducing carbon emissions from existing vessels. Other options include retrofit to a zero-carbon fuel or adoption of energy saving technologies (for example hull coatings, slow steaming, air lubrication, etc.). The viability of OCCUS versus these alternatives will vary by ship type and operational profile. Further assessment for an individual ship should address all aspects, **TRL**, **IRL** and **CRL**.

Government stimulation will help to accelerate overall readiness, although it will take time to build up the infrastructure to handle CO_2 in large volumes and the shipping industry needs to engage without delay if OCCUS is to be adopted at scale so that sufficient infrastructure and storage capacity can be created to accommodate this adoption. The shipping industry also needs to interconnect with the wider carbon markets and can start engaging through emerging government-funded CCS clusters to start moving in this direction.

OCCUS across the supply chain has a high **TRL**, particularly for conversion and storage, as the technology is proven and in use today outside of the shipping industry. It presents an opportunity to move the shipping industry to reduced emissions on the decarbonisation pathway to zero carbon. However, this technology is unlikely to practically provide a zero-carbon solution and until further operational experience is achieved and regulations published, **IRL** and **CRL** remain low.

The market for OCCUS is experiencing a fast rate of change as the world moves towards zero carbon, driven by the urgency to adopt solutions that will reduce emissions in line with decarbonisation milestones. Although OCCUS is expected to be a step on the decarbonisation pathway, rather than the endgame, it could play a significant role in the shipping industry's journey towards zero carbon emissions. The potential is greatest for existing vessels where conversion to zero carbon fuel is cost-prohibitive, but OCCUS provides a route to extending asset lifetime.

Appendix

Zero Carbon Fuel Monitor readiness scales

Technology readiness level

TRL	Level	Level description
Idea	1	Basic principle observed
Concept	2	Commercial trial, small scale
Feasibility	3	First assessment feasibility concept & technologies
Validation	4	Validation of integrated prototype in test environment
Prototype	5	Testing prototype in user environment
Product	6	Pre-production product
Pilot	7	Low scale pilot production demonstrated
Market introduction	8	Manufacturing fully tested, validated and qualified
Market growth	9	Production & product fully operational

Investment readiness level

IRL	Level	Level description
Idea	1	Hypothetical commercial proposition
Trial	2	Commercial trial, small scale
Scale up	3	Commercial scale up
Adoption	4	Multiple commercial applications
Growth	5	Market competition driving widespread development
Bankable asset	6	Bankable asset class

Community readiness level

CRL	Level	Level description
Challenge	1	Identifying problem and expected societal readiness, formulation of possible solution(s) and potential impact
Testing	2	Initial testing of proposed solution(s) together with relevant stakeholders
Validation	3	Proposed solution(s) validated, now by relevant stakeholders in the area
Piloting	4	Solution(s) demonstrated in relevant environment and in co-operation with relevant stakeholders to gain initial feedback on potential impact
Planning	5	Proposed solution(s) as well as a plan for societal adaptation complete and qualified
Proven solution	6	Actual project solution(s) proven in relevant environment

Maritime Decarbonisation Hub

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