Zero Carbon Fuel Monitor

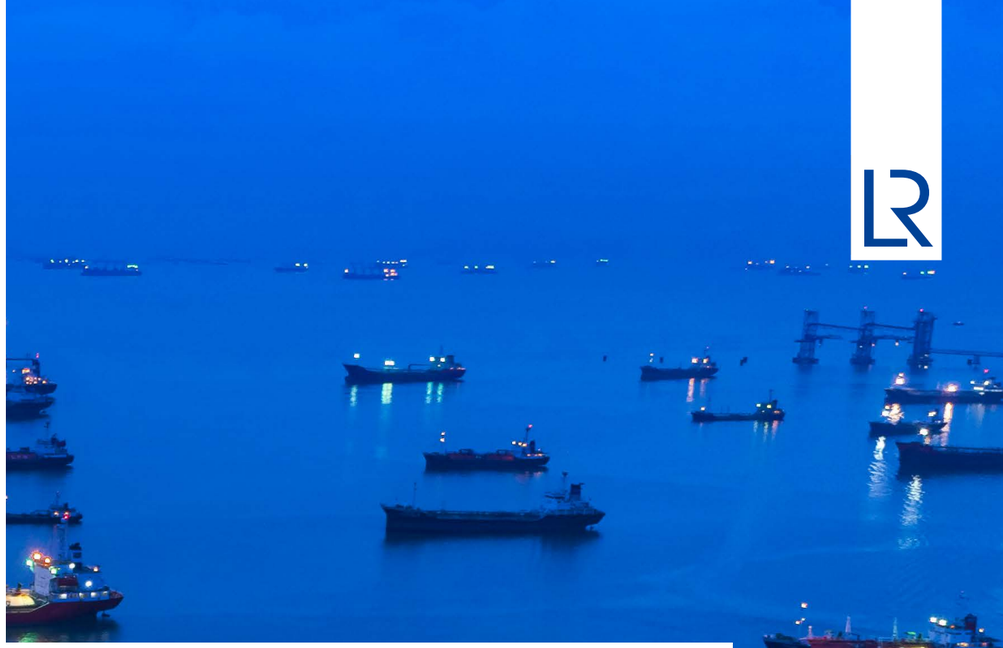
July 2022 update

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

Executive summary

Zero Carbon Fuel Monitor is an evidence-based framework assessing the readiness of the most promising zero-carbon fuels and related technologies that could play a role in transitioning the shipping industry to zero emissions by 2050. The Monitor is a publication of the Lloyd's Register Maritime Decarbonisation Hub.

This report provides a progress update on the readiness levels of zero-carbon shipping fuels from three perspectives: technology (**TRL**), investment (**IRL**) and community (**CRL**). Focusing on ammonia, hydrogen and methanol, it outlines market trends and identifies key priorities to increase readiness.



	TRL					IRL				CRL			
	Resource	Production	Bunkering	Ship storage	Ship Propulsion	Resource	Production	Bunkering	Ship	Resource	Production	Bunkering	Ship
Fuel type	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22	Jun-22
ng-Ammonia	4	4	3	3	3	2	2	1	1	2	4	1	1
re-Ammonia	7	5				2	2			5	5		
ng-Hydrogen	4	4	4	4.3	5	2	2	1	1	2	4	1	1
re-Hydrogen	7	5				2	2			5	5		
ligno-Methanol	7	3	7	8	8	2	2	2	2	2	2	3	4
ng-Methanol	4	4				2	2			2	4		
re-Methanol	7	5				3	3			5	5		

Trends have shown an average increase in readiness across all fuels and supply chain stages. Methanol is seeing small scale fleet announcements and dual-fuel deliveries. Hydrogen electrolyser capacities have increased, leading to **TRL** increases for fuel production.

CRL for renewable energy derived fuels has also seen an increase as more production facilities are given planning permission. Smaller readiness increases have been seen for other areas of the renewable energy derived fuels (re-fuels) supply chain as developments continue across the board.

Three main themes have been identified:

	Scaling technology	Stimulating investment	Ensuring sustainability
Key trends	Scale-up of re-fuels is progressing. Typical capacities for proposed production plants have increased from around 50MW in the initial release of The Monitor to more than 100MW in this latest report. However, fuel supply solutions largely remain at pilot or small-scale commercial trial. Substantial scaling is required to meet the demand expected from growth in zero emissions vessels.	We continue to see new fuel production projects and ship concept designs announced. However, many are now awaiting investment decisions, several being expected by the end of 2023. Fuel cost remains a significant barrier to investment, and the policy measures required to close the gap are not in place yet. The next twelve to twenty-four months will be crucial for progress in these areas.	The sustainability conversation continues to be high profile. Discussions are in progress at the policymaker level, including the Fit-For-55 Fuel EU Maritime proposals and the ongoing IMO process on lifecycle analysis. However, we do not yet understand these fuel's long-term impact on environment and socio-economic landscapes. Nor does the regulatory framework support sustainability reporting and certification of fuels.
Top priorities	• Electrolysers to be scaled and demonstrated producing renewable energy for marine fuels • Carbon sourcing technologies (direct air capture (DAC), biogenic source) for re-Methanol to reach maritime scale • Demonstration of carbon capture and storage (CCS) at scale for production of natural gas derived fuels • Demonstration of large-scale bunkering, particularly ship-to-ship	• Regulatory incentives to ensure price competitiveness of zero-carbon fuels • Green corridors to demonstrate fuel requirements in specific locations and drive fuel needs • Commercial scale-up fleets that enable economies of scale	• Lifecycle analysis of environmental impacts of zero carbon fuels • Regulatory standards, certification and reporting requirements applicable to fuel producers and users • Lifecycle analysis of socio-economic impacts of zero-carbon fuels • Carbon sourcing certification in place for re-Methanol production

Over the last six months the decarbonisation conversation has continued to grow in companies, the media and industry bodies. But zero-carbon fuel readiness has a long way to go to deliver shipping's increasing ambition. The Hub will continue to monitor developments and we hope to show significant progress in our next report. We will use these results to inform our own research and development projects, and hope that others in the industry will do likewise.

Contents

1. Introduction

Welcome to the first in our series of regular updates summarising the developments in the shipping industry's journey to zero-carbon fuels[1]. This report is based on research completed by the Lloyd's Register Maritime Decarbonisation Hub (The Hub) for the Zero Carbon Fuel Monitor (The Monitor).

Our initial release of The Monitor in December 2021 outlined the readiness of these zero-carbon fuels by reviewing the entire supply chain, assessing readiness levels from three perspectives: technology (**TRL**), investment (**IRL**) and community (**CRL**). It identified major shortfalls restricting immediate uptake of these fuels. Over time as research, development, and investment continue, these shortfalls change and industry knowledge advances. The Hub continuously monitors developments, re-assessing the shortfalls and the actions required to overcome them.

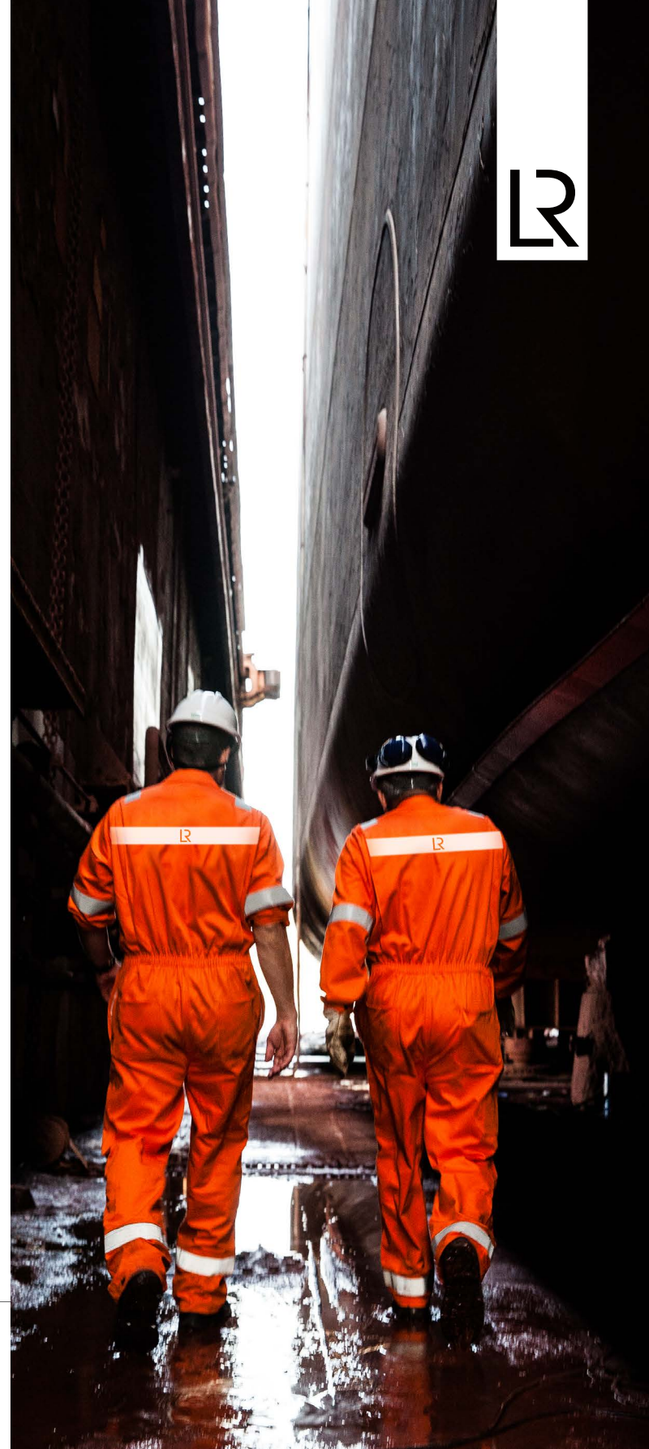
Here we review the advancements in readiness levels for re-Ammonia, re-Hydrogen and re-Methanol since the publication of The Monitor, to June 2022.

We also identify the additional developments required for further advancement in readiness levels. We have focused on three fuels for this update as they are currently showing the most long-term promise as zero-carbon fuels for the shipping industry[2].

We will continue to monitor other fuels, such as methane, biodiesel and nuclear, and will update the readiness levels for these as more evidence becomes available. The supporting evidence is contained within the dashboard and uses the best information available to LR[3].

We welcome all feedback on The Monitor, and this report. Our website includes a feedback form[4] for evidence and suggestions.

This report identifies key priorities needed within the industry to continue to progress the readiness levels and outlines the trends that we have been seeing in the developing markets for ammonia, hydrogen and methanol.

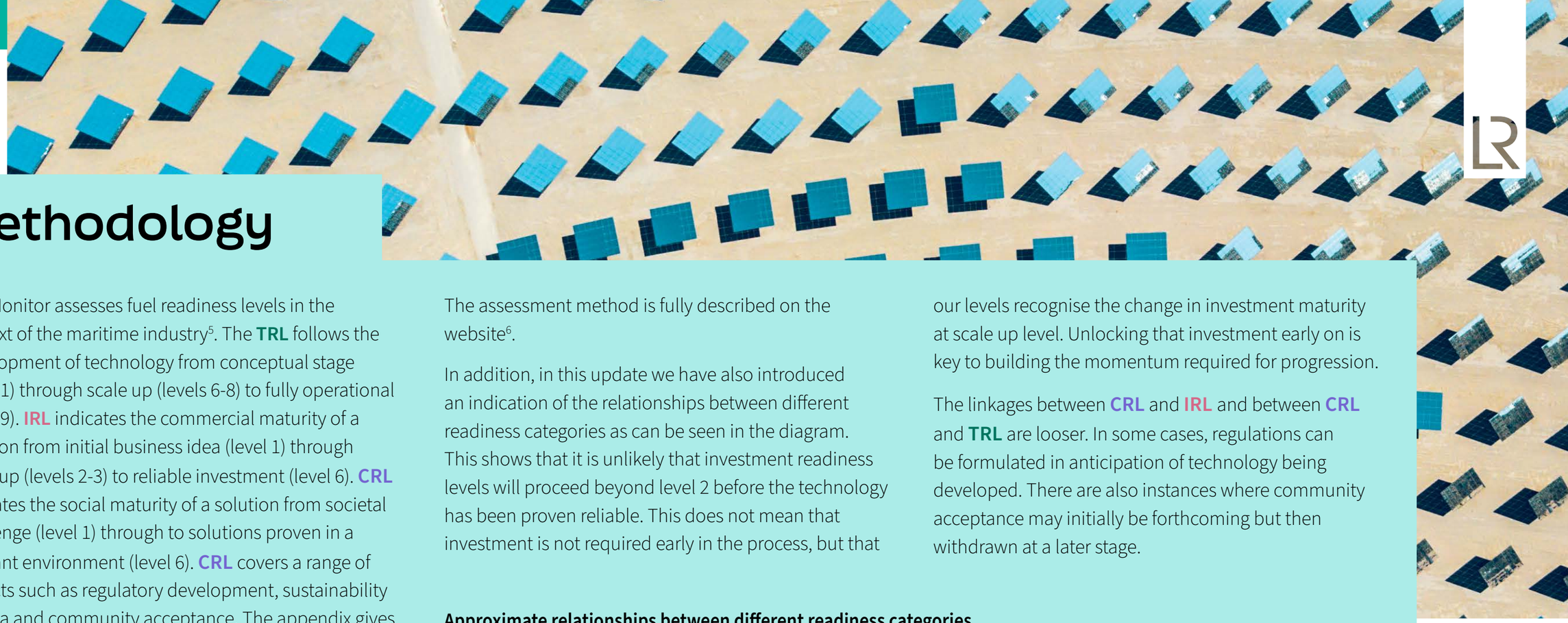


[1] Fuels that can achieve zero GHG emissions on a life cycle basis

[2] https://www.globalmaritimeforum.org/content/2021/10/A-Strategy-for-the-Transition-to-Zero-Emission-Shipping.pdf

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

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



Methodology

The Monitor assesses fuel readiness levels in the context of the maritime industry[5]. 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 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.

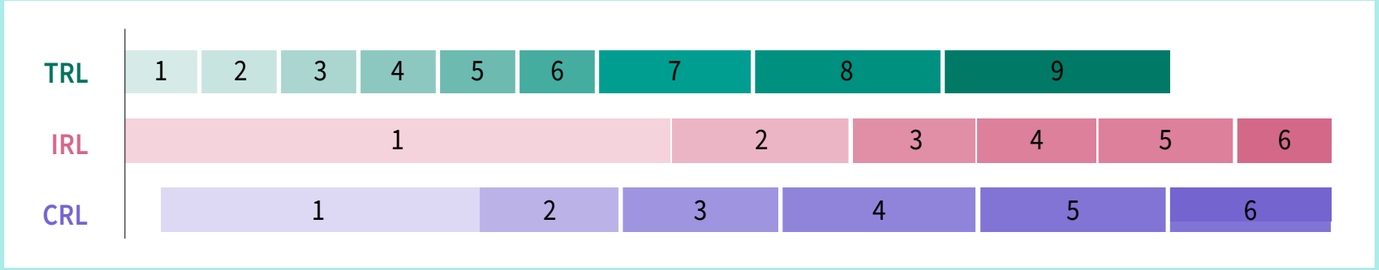
The assessment is carried out across the end-to-end fuel supply chain, broken down into five main stages. These stages are resources, production, bunkering, onboard storage and propulsion. In some cases, the onboard ship stages (onboard storage and propulsion) are combined into a single category, ship.

The assessment method is fully described on the website[6].

In addition, in this update we have also introduced an indication of the relationships between different readiness categories as can be seen in the diagram. 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.

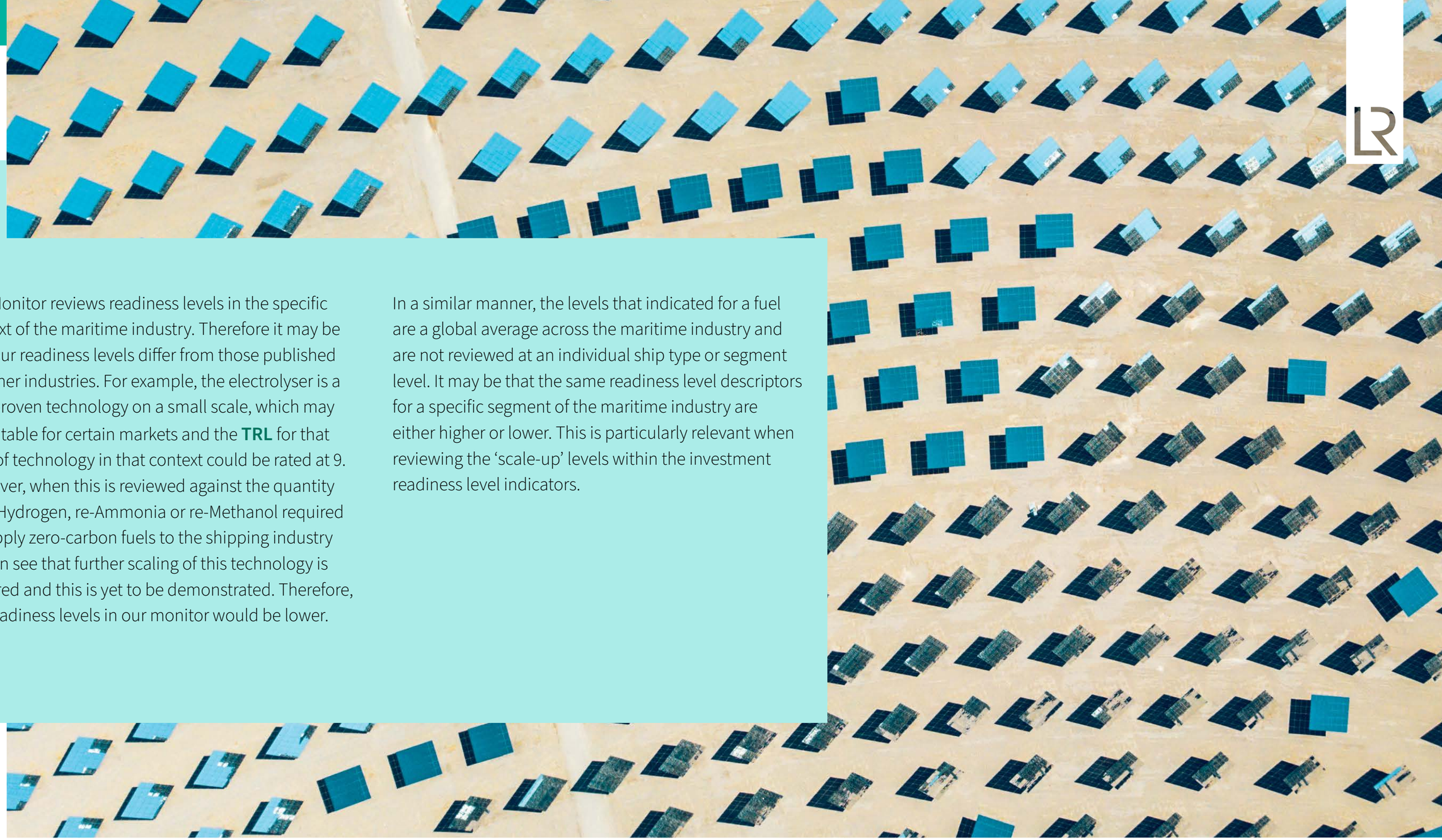
The linkages between **CRL** and **IRL** and between **CRL** and **TRL** are looser. In some cases, regulations can be formulated in anticipation of technology being developed. There are also instances where community acceptance may initially be forthcoming but then withdrawn at a later stage.

Approximate relationships between different readiness categories



[5] Zero-carbon fuels assessment method (lr.org)

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



The Monitor 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, the electrolyser is a well proven technology on a small scale, which may be suitable for certain markets and the **TRL** for that item of technology in that context could be rated at 9. However, when this is reviewed against the quantity of re-Hydrogen, re-Ammonia or re-Methanol required to supply zero-carbon fuels to the shipping industry we can see that further scaling of this technology is required and this is yet to be demonstrated. Therefore, the readiness levels in our monitor would be lower.

In a similar manner, the levels that indicated for a fuel are a global average across the maritime industry and are not reviewed at an individual ship type or segment level. It may be that the same readiness level descriptors for a specific segment of the maritime industry are either higher or lower. This is particularly relevant when reviewing the 'scale-up' levels within the investment readiness level indicators.

2. Emerging trends

This section examines the changes in readiness levels across fuels and by supply chain stage to highlight emerging trends.

Figure 2-1 identifies changes compared to the previous release.

Figure 2-2 shows the actual changes in level. The appetite of the industry to progress the transition to zero-carbon fuels is visible in these changes of level.

To highlight emerging trends and find areas for development, the data in Figure 2-1 and Figure 2-2 have been reviewed to reveal patterns. We have compared the data by fuel, by supply chain stage and by readiness levels to see where trends are emerging.

	TRL										IRL								CRL							
	Resource		Production		Bunkering		Ship storage		Ship Propulsion		Resource		Production		Bunkering		Ship		Resource		Production		Bunkering		Ship	
Fuel type	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22	Dec-21	Jun-22
ng-Ammonia	3	4	4	4	2	3	3	3	3	3	2	2	2	2	1	1	1	1	2	2	4	4	1	1	1	1
re-Ammonia	7	7	5	5							1	2	2	2					4	5	3	5				
ng-Hydrogen	3	4	4	4	2	4	4.3	4.3	5	5	2	2	2	2	1	1	1	1	2	2	4	4	1	1	-	1
re-Hydrogen	7	7	4	5							1	2	2	2					4	5	3	5				
ligno-Methanol	7	7	3	3	6	7	8	8	7	8	2	2	2	2	1	2	1	2	2	2	2	2	2	3	3	4
ng-Methanol	3	4	3	4							2	2	1	2					2	2	4	4				
re-Methanol	7	7	3	5							3	3	3	3					4	5	3	5				

Figure 2-1: Comparison of readiness levels across the supply chain for hydrogen, ammonia and methanol between December 2021 and June 2022.

Looking at just renewable energy derived fuels (re-fuels), we can see that community readiness levels for the resource and production have increased for all these fuels as shown by the dotted blue boxes In figure 2.2.

Looking at a single fuel such as hydrogen, we can see **TRL** increase of 2 for bunkering as described in section 2-1.

Figure 2-2: Increase in readiness levels for ammonia, hydrogen and methanol fuels December 2021 to June 2022.

	TRL					IRL					CRL				
	Resource	Production	Bunkering	Ship storage	Ship Propulsion	Resource	Production	Bunkering	Ship storage	Ship Propulsion	Resource	Production	Bunkering	Ship storage	Ship Propulsion
ng-Ammonia	1	-	1	-	-	-	-	1	-	-	-	-	-	-	-
re-Ammonia	-	-	1	-	-	1	-	1	-	-	1	1	-	-	-
ng-Hydrogen	1	-	2	-	-	-	-	-	-	-	-	-	-	1	-
re-Hydrogen	-	1	2	-	-	1	-	-	-	-	1	2	-	-	-
ligno-Methanol	-	-	1	-	1	-	-	1	1	1	-	-	1	1	1
ng-Methanol	1	1	1	-	1	-	1	1	1	1	-	-	1	1	1
re-Methanol	-	2	1	-	1	-	-	1	1	1	1	2	1	1	1

2.1 Emerging trends by fuel

Methanol TRL is starting to move from 'pilot and demonstration' to 'initial market introduction'.

Six vessels have been delivered with methanol capability, including two dual-fuel tankers for Waterfront Shipping in Canada[7]. Waterfront Shipping has an additional six tankers expected to be delivered by 2023.

These projects along with the publication of rules and regulations from three classification societies and IMO Guidelines under MSC.1/Circular.1621[8] have led to the increase in readiness levels for all three readiness categories at the ship storage and propulsion supply chain stages.

The increase for methanol bunkering has been driven by the demonstrations carried out by Waterfront Shipping in Rotterdam; the continued methanol refuelling of vessels such as the Stena Germanica[9]; and bunkering guidance notes from LR and the Methanol Institute[10].

The scaling of DAC for re-Methanol production has made progress in the last few years with additional projects such as Flagship One[11] expected to capture and recycle 70,000 t of CO2 per year. The Orca Plant in Iceland[12] is demonstrating units which can each collect 500 t of Carbon per year. These developments have contributed to the increase in **TRL** levels at the production stage.

Methanol IRL has moved 'from hypothetical commercial proposition' to 'commercial trials' but mainly only for shipping and bunkering; whereas production remains unchanged.

The momentum has begun to build with three announcements of small-fleet dual fuel vessels, with twelve container ships to be delivered to Maersk[13], eight feeder ships to X-press feeders[14], and six multi-purpose vessels for AAL Shipping[15]. Additionally, further engines to support other ship types are being developed by manufacturers such as Rolls Royce[16], and boilers are being modified to run on methanol by Alfa Laval[17].

This is showing that at an investment level, the prospect for small scale commercial trials has been verified.

[7] https://www.waterfront-shipping.com/news/2020/11/shipping-industry-welcome-new-lower-emission-methanol-dual-fuel-vessels

[8] https://www.register-iri.com/wp-content/uploads/MSC.1-Circ.1621.pdf

[9] https://www.methanex.com/news/industry-celebrates-five-year-anniversary-world%E2%80%99s-first-methanol-powered-commercial-vessel

[10] https://www.lr.org/en/latest-news/lr-methanol-institute-guidance-on-methanol-bunkering/

[11] https://www.liquidwind.se/emethanol

[12] https://climeworks.com/roadmap/orca

[13] https://www.maersk.com/news/articles/2021/12/08/designing-the-future-of-our-customers-supply-chains

[14] https://www.x-pressfeeders.com/news/new-build-purchase

[15] https://aalshipping.com/aal-shipping-increases-order-of-its-innovational-third-generation-newbuildings/#:~:text=The%20Super%20B%2DClass%20will%20be%20dual%20fuel%20and%20methanol,service%20speed%20of%2014.5%20knots.

[16] https://www.mtu-solutions.com/eu/en/stories/marine/how-does-shipping-go-green.html

[17] https://www.alfalaval.com/media/news/2021/abs-grants-alfa-laval-the-marine-industry-s-first-approval-in-principle-aip-for-firing-boilers-with-methanol/

Methanol CRL for bunkering and shipping has progressed from 'validation' to 'demonstration' in a relevant environment.

CRL levels are a combination of both regulatory criteria and sustainability criteria. For methanol, we have seen the publication of bunkering guidance notes and ship classification rules and regulations, as well as interim guidelines from the IMO for ships using methanol as a fuel. The use of these rules and regulations in the design of new vessels, and the validation of the safety regulations, have led to an advance in **CRL** levels.

Hydrogen TRL for bunkering has moved quickly from 'concept' to 'prototype' in test environment

The increase in hydrogen **TRL** has been led by four vessels now demonstrating the bunkering of hydrogen in compressed gas format. One of the vessels, the Hydrocat 48[18] currently demonstrates daily refuelling of 200kg of compressed gas. Additionally, the first multimodal hydrogen refuelling station[19] in Antwerp has now been running for almost a year, providing hydrogen for port applications.

Ammonia TRL for bunkering has increased from 'concept' to 'first assessment' of feasibility

The ammonia bunkering **TRL** has been advanced to feasibility concept and technology level (**TRL** 3) for feasibility concepts following four studies on ammonia bunkering safety including the joint study being carried out in Singapore[20]. Additionally, Yara International has pre-ordered fifteen floating bunkering terminals[21] for ammonia fuelling.

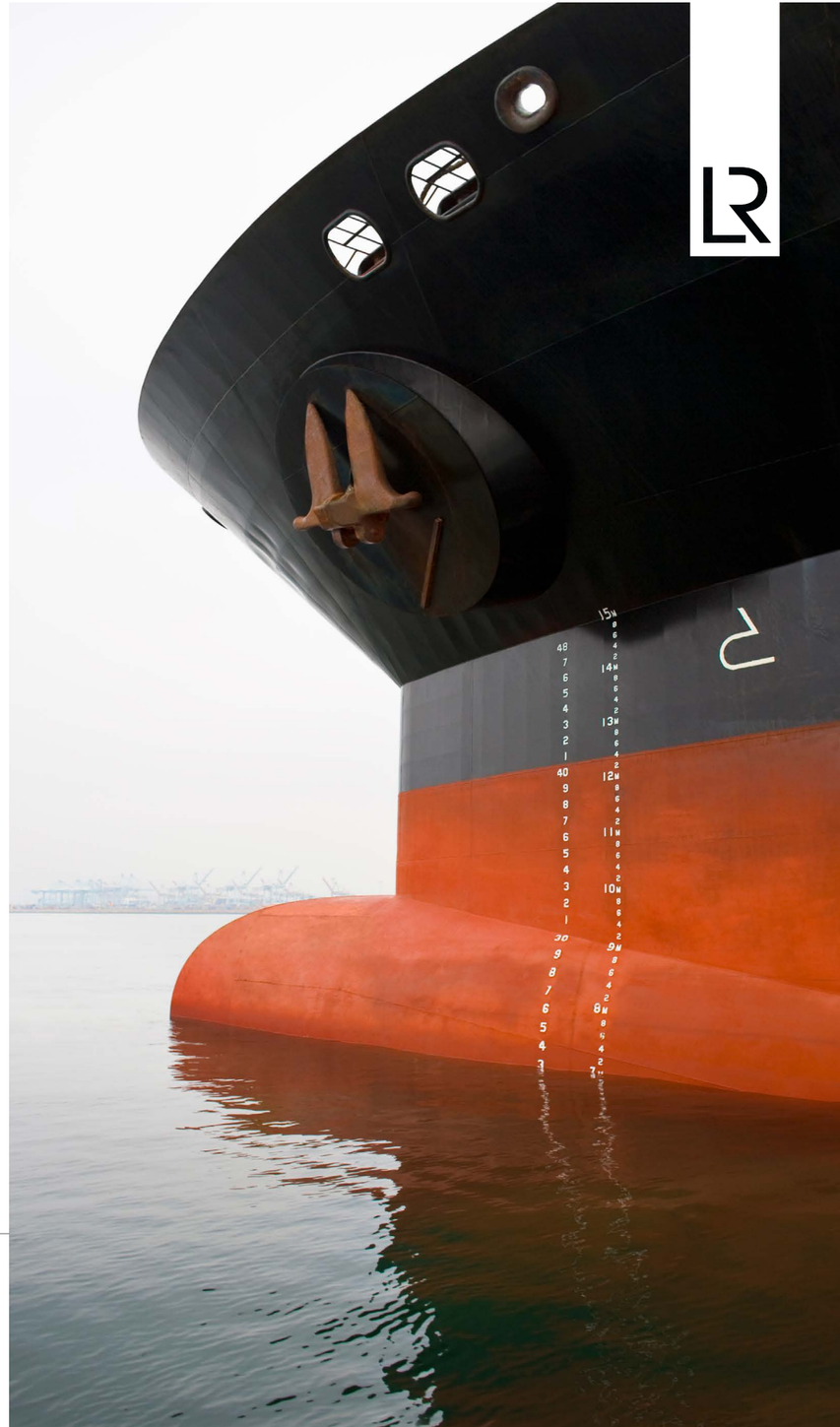
[18] https://cmb.tech/divisions/marine/hydrocat
[19] https://cmb.tech/divisions/h2-infra/antwerp-refuelling-station
[20] https://www.itochu.co.jp/en/news/news/2022/220406.html
[21] https://www.yara.com/news-and-media/news/archive/news-2022/yara-international-and-azane-fuel-solutions-to-launch-worlds-first-carbon-free-bunkering-network-delivering-green-ammonia-fuel-to-the-shipping-industry/

2.2 Emerging trends across the supply chain and all fuels

TRL and CRL are progressing faster than IRL, although IRL is making progress through green corridors initiatives

Whilst government funding partnerships such as the CMDC in the UK[22] and Norway's Pilot-E program help to initiate projects within the industry, the linking of supply chains together with appropriate investment remains limited. At COP26, the initiation of the Clydebank Declaration recognised this, and that international cooperation is key to unlocking the new level of investment required to reach the industry's goals. The signatories to the Clydebank Declaration have helped spur several green corridor initiatives.

Green corridor projects are seen as a way to create markets for new fuels and unlock potential investment. We are tracking nine of these initiatives, with more projects being announced each day, including The Silk Alliance[23], The Shanghai-LA Green Corridor, The European Green Corridors[24] Network, and The Montreal-Antwerp pledge[25]. Together these show how bringing together different aspects of the supply chain under aligned decarbonisation goals can deliver effective change. As more of these cross-collaboration projects emerge, we expect momentum to continue building.



[22] Clean maritime demonstration competition (CMDC) - GOV.UK (www.gov.uk)

[23] LR and partners unveil 'Silk Alliance' green corridor project.[24] The Port of Antwerp and the Port of Montreal pledge to create a green shipping corridor (portofantwerpbruges.com)

[25] The Port of Antwerp and the Port of Montreal pledge to create a green shipping corridor (portofantwerpbruges.com)

2.3 Emerging trends by specific stage of the supply chain

The CRL of renewable energy derived fuels is moving from validation to piloting and planification

The increase can be attributed to the regulatory environment of developed countries where we can see infrastructure development go through multiple levels of approval and community consultation before being built. Projects such as North of Scotland Hydrogen Programme[26] have demonstrated how the public consultation process, working with governments and local industry can produce a positive outcome. In other areas, such as the Pilbara region of Western Australia[27], a negative outcome for the production plant was achieved, but the overall demonstration of regulatory and planning framework, and community engagement was mature.

CRL for re-Methanol and re-Hydrogen have increased by two levels, whereas re-Ammonia by one level. The CRL of re-ammonia production lags that for re-Methanol and re-hydrogen due to questions about community acceptance of ammonia given its toxicity.

The TRL for a marine renewable fuel electrolyser is now being demonstrated in an at scale user environment

The phase 2 results of the Gigastack project[28] have demonstrated that scaling electrolysers to 100MW is possible. This project is now awaiting investment and funding decisions before moving on to phase 3. Moreover, announcements from other projects show that scaling beyond this stage is also possible.

Of the twelve production plants announced that have given electrolyser size, nine of these have power levels over 100MW, with projects such as The Orsted US Gulf Coast Power-to-X facility[29] expected to scale to 1.2GW and the FFI Gladstone Electrolyser[30] expected to scale to 2GW by 2030.

[26] https://pocf.co.uk/2021/07/23/cromarty-firth-ideal-location-for-the-uks-largest-green-hydrogen-electrolyser/

[27] https://www.reuters.com/business/sustainable-business/australia-rejects-36-bln-wind-solar-hydrogen-project-2021-06-21/

[28] https://gigastack.co.uk/about/renewable-hydrogen/

[29] https://orsted.com/en/media/newsroom/news/2022/03/20220310491311

[30] https://ffi.com.au/news/construction-commences-on-world-leading-electrolyser-facility-in-gladstone-queensland/

3. Key priorities for progression of readiness levels

In this section of the report, we have outlined the areas which require development, or further research to enable readiness levels to continue to progress.

In the same way that trends were reviewed, we have identified areas where readiness levels are lagging behind. We have reviewed this by individual solution, across specific fuels, by readiness level categories and across all categories and supply chain stages.

For example, as can be seen in Figure 3-1, investment readiness levels are low across all fuels and supply chain stages (A). The research and development and requirements for increasing these levels is outlined in section 3.2. Additionally, **TRL** levels for fuel production are low across the board (B) – despite resources being available for some of these. Section 3.1 outlines what now needs to be demonstrated to increase **TRL** levels.

Figure 3-1: Overview of readiness levels across all fuels and supply chain stages, June 2021. Darker numbers indicate higher readiness levels.

	TRL					IRL					CRL				
	Resource	Production	Bunkering	Ship storage	Ship Propulsion	Resource	Production	Bunkering	Ship storage	Ship Propulsion	Resource	Production	Bunkering	Ship storage	Ship Propulsion
ng-Ammonia	4	4	3	3	3	2	2	1	1	1	2	4	1	1	1
re-Ammonia	7	5	3	3	3	2	2	1	1	1	5	4	1	1	1
ng-Hydrogen	4	4	4	4.3	5	2	2	1	1	1	2	4	1	1	1
re-Hydrogen	7	5	4	4.3	5	2	2	1	1	1	5	5	1	1	1
ligno-Methanol	7	3	7	8	8	2	2	2	2	2	2	2	3	4	4
ng-Methanol	4	4	7	8	8	2	2	2	2	2	2	4	3	4	4
re-Methanol	7	5	7	8	8	3	3	2	2	2	5	5	3	4	4

B A

3.1 Key priorities by fuel

Ammonia TRL for bunkering and onboard vessels is waiting for the safety components to be identified and tested

Three classification societies have published rules and regulations for ammonia fuelled vessels, with a proposal presented to the IMO for consideration[31].

Additionally, safety studies are underway for ammonia fuelled ships[32] and several bunkering studies have been announced including one in Singapore[33]. However, at this stage, these do not warrant increase of the **TRL** levels beyond the current level. Once reports such as these have published results outlining safety requirements, and the practices are verified in a user environment then these results will be able to further inform the readiness levels.

Further advancements for ammonia onboard **TRL** are waiting on the development of ammonia fuelled engines. Companies such as MAN and Wartsila, who are developing two stroke slow speed engines and medium speed engines to run on ammonia, expect to have these available for use on-board by 2024[34]. Until these engines become available, and pilot projects can be successfully demonstrated with all safety components in place, we do not expect to see any significant change in the readiness levels for ammonia fuelled vessels.

Re-fuel TRL for production needs multiple electrolysers at scale to demonstrate pilot production for marine applications

Although production facilities have been announced, the announced projects are currently awaiting the final investment decision, including the Gigastack Project and Orsted facility. Building and demonstration of production facilities will bring the next stage of **TRL** increase, as the scaling potential of electrolyser technology is physically demonstrated at the required scale for the maritime industry.

[31] MSC-104-15-9-Development-of-non-mandatory-guidelines-for-safety-of-ships-using-ammonia-as-fuel-Japan-Singapore-ICS-and....pdf (ics-shipping.org)

[32] https://www.lr.org/en/latest-news/industry-leaders-collaborate-to-develop-guidance-on-the-safe-use-of-ammonia-as-a-shipping-fuel/

[33] https://www.itochu.co.jp/en/news/news/2022/220406.html

[34] https://www.man-es.com/discover/two-stroke-ammonia-engine

Re-Methanol TRL for production also needs carbon sourcing at scale to demonstrate pilot production for marine applications

Re-Methanol has the additional step of direct air capture required within the production process. Although some projects have been announced, as for the electrolyser requirements above these are yet to be built and demonstrated. Direct air capture with an associated facility demonstrating scale-up of the technology to a level to be able to supply the shipping industry is required to progress these levels further.

Bio-Methanol TRL for production requires demonstration of supply at scale for marine applications

The bio-Methanol facilities announced in the past six months are either not expected to be used for production of fuels for the maritime industry or are at a scale too small to be capable of producing incidental fuel for small fleets such as those announced in the Maersk agreements with fuel producers. At this stage, we have not seen announcements or project demonstrations showing that this technology and resource are available to supply the maritime industry at scale. This will be required for further advancement of readiness levels.

Hydrogen TRL for onboard storage remains a challenge and solutions need to be validated and tested

Of the nine launched hydrogen-capable vessels that we are tracking: two are currently undergoing trials; two are undergoing fit out for hydrogen; one is operating on battery mode awaiting liquid hydrogen availability; and four are operating with compressed gas including the Hydrocat 48[35] which is operating out of the UK.

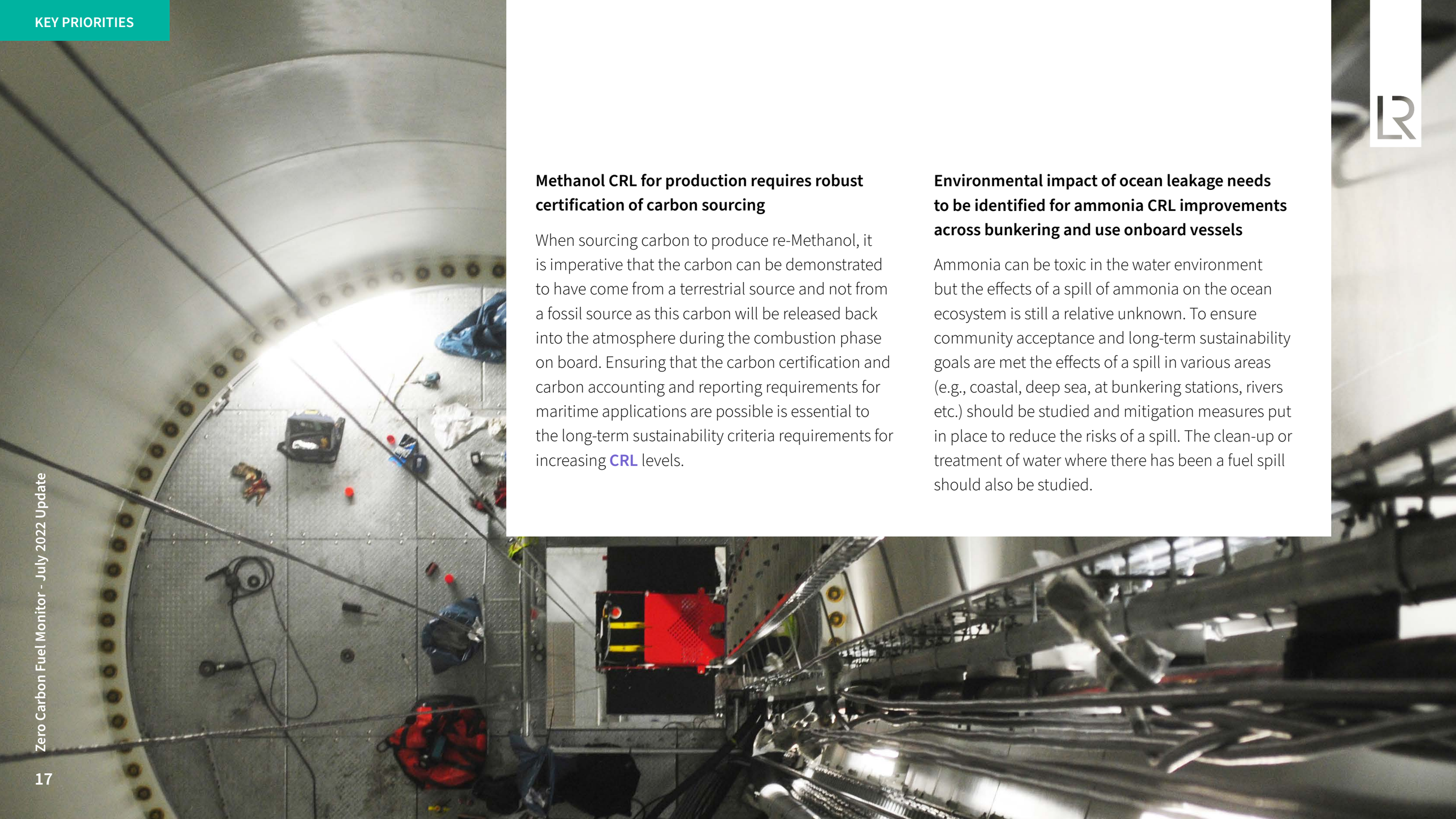
As we continue to track the progress of pilot projects, to achieve further increases in **TRL**, we would expect to see scaling of size or number of vessels; demonstration of the different onboard storage and propulsion technologies, including liquid and gas storage, internal combustion engines and fuel cells; publication of rules and regulations covering the different storage and technologies; and increased crew training.

Hydrogen and ammonia CRL for bunkering and onboard vessels remains very low due to a lack of identified problems and proposed solutions

With little previous experience in the use of ammonia and hydrogen as a fuel within the shipping industry, the December 2021 release of The Monitor acknowledged that assessment of safety for these fuels would require a return to first principles. This would involve understanding the risks and establishing the technical measures, procedures, and standards to mitigate them. At this stage, **CRL** levels for these fuels at the bunkering and onboard vessels have stagnated.

Progress needs to be made in safety assessments, rule development and community acceptance of these fuels. The risks associated with bunkering, onboard storage and potential accidents need to be understood and solutions proposed and validated.

[35] https://cmb.tech/divisions/marine/hydrocat



Methanol CRL for production requires robust certification of carbon sourcing

When sourcing carbon to produce re-Methanol, it is imperative that the carbon can be demonstrated to have come from a terrestrial source and not from a fossil source as this carbon will be released back into the atmosphere during the combustion phase on board. Ensuring that the carbon certification and carbon accounting and reporting requirements for maritime applications are possible is essential to the long-term sustainability criteria requirements for increasing **CRL** levels.

Environmental impact of ocean leakage needs to be identified for ammonia CRL improvements across bunkering and use onboard vessels

Ammonia can be toxic in the water environment but the effects of a spill of ammonia on the ocean ecosystem is still a relative unknown. To ensure community acceptance and long-term sustainability goals are met the effects of a spill in various areas (e.g., coastal, deep sea, at bunkering stations, rivers etc.) should be studied and mitigation measures put in place to reduce the risks of a spill. The clean-up or treatment of water where there has been a fuel spill should also be studied.

3.2 Key priorities across the supply chain and all fuels

Compared to TRL and CRL, IRL still remains insufficient to unlock the required scale of investment

IRL levels are still trailing other readiness categories. In some cases, this is due to the higher cost of zero-carbon fuels but may also be due to a lack of scalable technology. A lack of investment will impact both **TRL** and **CRL** considerably as progress in both these readiness level categories requires investment. As the technology matures, further investment at greater levels is required to achieve scale-up.

Whilst project announcements are positive indicators of intent, a major concern is a lack of investment which can lead to projects stagnating. If these projects do not proceed, we are unlikely to see the required change for the shipping industry to its journey to zero-carbon fuels.

It is expected that as regulation and incentives through carbon pricing or other methods become commonplace, the drive for the technologies and fuels will begin to ramp up, further releasing investment. However, for the first movers it is possible that investment can be unlocked in several ways. The take-off agreements signed by Maersk[36] with several producers to fuel new methanol vessels has shown that this is possible where there is significant interest. Additionally, green corridors and small-scale fleet announcements will start to signal the demand for fuel, leading to the establishment of more secure supply chains.

The lack of certifications and regulations for the sustainability elements of CRL (LCA, environmental and socio-economic impacts) is preventing the validation of all proposed fuels

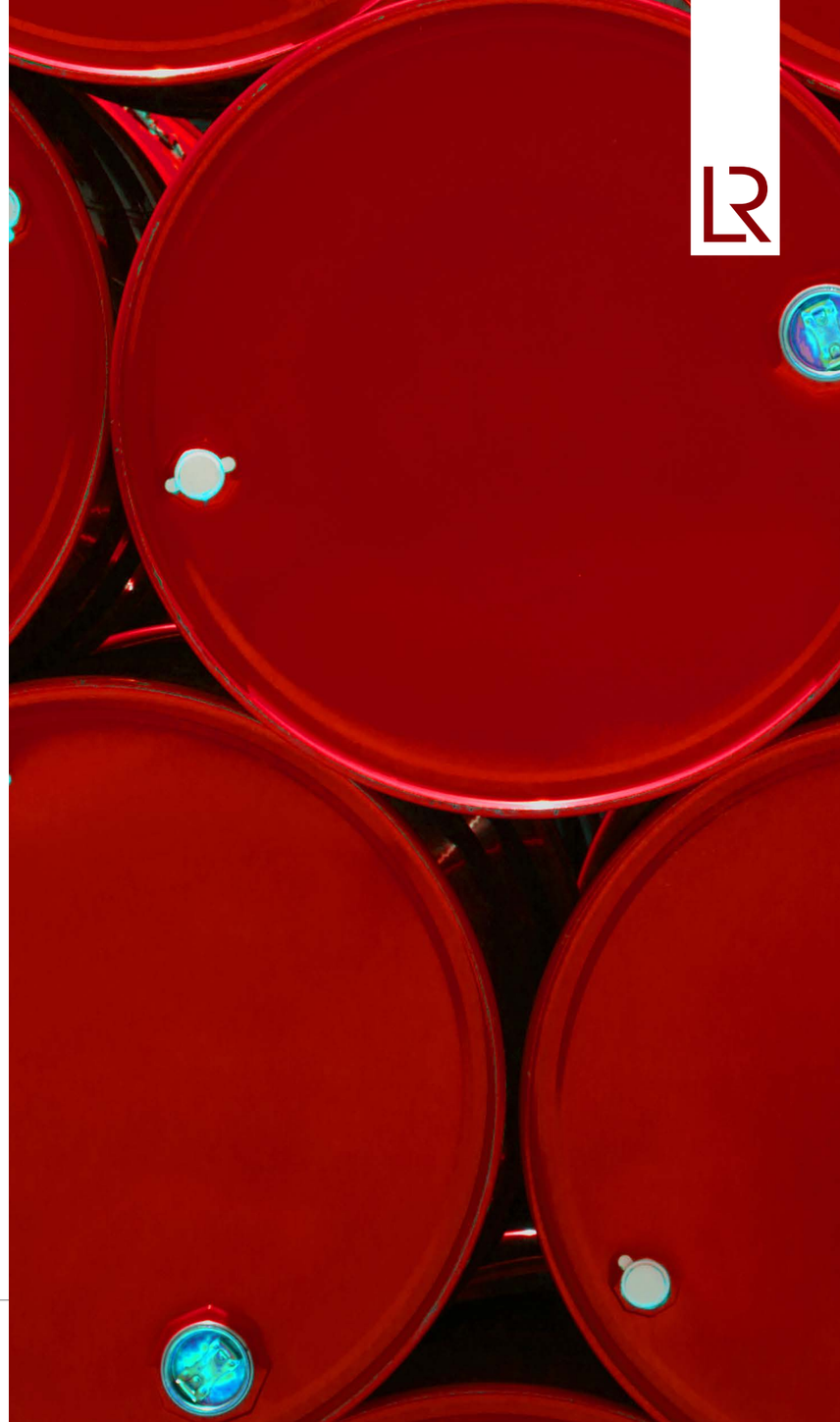
CRLs are higher in the zero-carbon fuels produced from renewable electricity (re-fuels) than those produced from natural gas (ng-fuels), attributable to the concerns surrounding long term underground storage of captured carbon. Additionally, the lack of full lifecycle analysis, reporting policies and analysis of environmental impact over several years means that the sustainability of the fuels is still under investigation, which is limiting **CRL** increases across all supply chain stages.

[36] https://www.maersk.com/news/articles/2022/03/10/maersk-engages-in-strategic-partnerships-to-scale-green-methanol-production

There are many aspects of fuel sustainability which require assessment and regulation to ensure that the decarbonisation of the industry continues to do long term good. These include:

- Lifecycle analysis of environmental impacts of the fuel, at all stages from feedstock to use on board, covering air quality, ecological impact, water, land-use, and sustainable resource use.
- Lifecycle analysis of socio-economic impacts of the fuel, at all stages from feedstock to use on board, covering human, labour, and welfare rights.
- Regulatory policy defining the required outcomes of the above, the standards that need to be met by fuel producers and users, and the reporting requirements.

Discussions are in progress at the regulatory level, including the ongoing IMO process[37] and the Fit-For-55 Fuel EU Maritime proposals[38], which have already led to certification schemes for hydrogen in Europe. However, without an established regulatory framework and without full lifecycle assessments, **CRL** levels for all fuels will continue to stagnate.



[37] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx
[38] https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2021)698808

3.3 Key priorities for all fuels for a specific stage of the supply chain

TRL for bunkering needs to be demonstrated technically and operationally

For all fuels, bunkering **TRL** is lagging the ship onboard storage and production stages. The bunkering demonstrations that have led to the increases seen in this update of The Monitor have been driven by individual ships using bunkering as one-off demonstrations, or bunkering methods specific to that vessel. However, bunkering on a larger scale including all safety requirements, training for personnel involved in the operation, and standard practices across the industry require demonstration to make further progress.

It is expected that ship-to-ship bunkering will become a more common operation for some zero-carbon fuels at more ports where this may be less common for fossil fuels. Ship-to-ship bunkering for new fuels, including the safety and critical components required will need to be demonstrated technically and operationally to progress bunkering readiness levels further.

IRL for bunkering needs to demonstrate potential synergies with other port energy systems and multimodality

Enabling efficient use of fuels within the port environment will help unlock potential investment opportunities and increase **IRL** levels. To accomplish this, it is important that all aspects of fuel use in areas such as ports is explored and demonstrated. This will enable efficient use of fuels within the port environment, which may include using the fuel to create power for the port, or to fuel land transport in the area.

CRL for bunkering needs standard regulations across different ports

In most cases the bunkering of ammonia, hydrogen and methanol at this stage are only small individual demonstrations. Demonstrating the bunkering of any of these fuels at scale in the ports will require storage solutions, transport, and bunkering (from shore or through ship-to-ship), safety and regulatory framework in place, and significant investment to see these developed.

In particular the bunkering of ammonia and hydrogen in its different forms (gas and liquid) require further safety assessments and practical demonstrations to ensure safety and sustainability criteria can be achieved before any further increases will be seen in their readiness levels.

Ng-fuel readiness levels for production require confirmation of CCS viability at scale

Ng-Hydrogen, also known as blue hydrogen, is also a key component for ng-Ammonia and ng-Methanol. These fuels may play an important role, especially if renewable electricity fuels cannot scale at the pace and costs needed. All ng-fuels suffer from a limited readiness of CCS. There is a lack of evidence regarding the actual global capacity for permanent storage (**TRL**); a lack of environmental and socio-economic impact analysis of long-term carbon underground storage (**CRL**); and lack of proven permanence of carbon storage solutions (**CRL**).

3.4 Key priorities - summary

The key priorities for progression of readiness levels in a timely manner largely fall into three themes: scaling technology, stimulating investment and ensuring sustainability. These key priorities can be addressed now, which will go a long way to making significant progress in the journey to zero emission vessels.

Figure 3-2: Summary of key priorities

	Scaling technology	Stimulating investment	Ensuring sustainability
What is the issue?	Technology is not yet being scaled to a level which will achieve impact within the wider maritime environment.	Investment readiness levels are still significantly lagging other readiness levels across all fuels and supply chain stages.	Community readiness levels are being held back by the lack of clarity on long term sustainability of the fuels and technologies used to make them.
Why is it important?	If fuel supply technologies are not scaled up soon, the fuel will not be available at scale for the growing uptake of zero emission vessels. This includes technologies related to the energy resources, production, and bunkering stages.	Lack of investment can lead to projects stagnating, meaning we are unlikely to see the required change for the shipping industry to progress its journey to zero-carbon fuels. Investment in the technologies, scaling-up of fleets, and establishing supply chains are key to advancing not only **IRL**, but **TRL** levels also.	There are many aspects of fuel sustainability which require assessment and regulation to ensure that the decarbonisation of the industry continues to advance.
Key priorities	• Electrolysers to be scaled and demonstrated producing renewable energy for marine fuels • Direct air capture technology (or other carbon sourcing technology e.g., biogenic source) to be scaled for production of re-Methanol at scale for maritime industry • Demonstration of CCS at scale for production of natural gas derived fuels. • Bunkering on a larger scale, particularly ship-to-ship bunkering to be demonstrated	• Establishment of regulatory incentives to ensure price competitiveness of zero-carbon fuels. • Establishment of green corridors to demonstrate fuel requirements in specific locations and drive fuel needs • Establishment of commercial scale-up fleets to enable economies of scale.	• Lifecycle analysis of environmental impacts of the fuels • Lifecycle analysis of socio-economic impacts of the fuels • Regulatory policy defining the standards that need to be met by fuel producers and users, and reporting requirements • Carbon sourcing certification to be in place for re-Methanol production.
What else can contribute?	• Standard procedures and regulations for bunkering worldwide • Ammonia and hydrogen on board storage and propulsion solutions to be validated and tested for larger vessels.	• Reviewing synergies with other operations (e.g., land-based vehicle fuel use and ship bunkering at ports)	• Effects of possible ammonia spill to be determined and risks mitigated to ensure community acceptance. • Risks and technical measures, procedures, and standards to mitigate these risks; to be identified for bunkering ammonia and hydrogen.

4. Conclusions

This update to the Zero Carbon Fuel Monitor has been undertaken to continue the tracking and advancement of potential zero-carbon fuels in the context of the maritime industry. By tracking, we can identify trends and key priorities to ensure that the industry remains on course to reach its decarbonisation goals.

Trends have shown an average increase in readiness across all fuels and supply chain stages. Methanol is seeing small scale fleet announcements and dual-fuel deliveries. Hydrogen electrolyser capacities have increased, leading to **TRL** increases for fuel production. **CRL** for renewable energy derived fuels has also seen an increase as more production facilities are given planning permission. Smaller readiness increases have been seen for other areas of the re-fuels supply chain as developments continue across the board.

In reviewing the trends and development topics, we have noted that the key priorities to progress readiness levels in a timely manner fall generally into three themes:

- Scaling technology: Technology is not yet being scaled to a level which will achieve impact within the wider maritime environment. This includes technologies such as electrolyser, DAC, CCS, and bunkering.
- Stimulating investment: Investment readiness levels are still significantly lagging other readiness levels across all fuels and supply chain stages. This includes regulatory incentives and commercial scale up.
- Ensuring sustainability: Community readiness levels are being held back by the lack of clarity on long term sustainability of the fuels and technologies used to make them. This includes LCA, environmental socio-economic impacts and certifications.

We will use these results to inform our own projects and research and development, and hope that others will also be able to use them to stimulate ideas. We appreciate all comments and feedback that help develop the tool and increase its impact in achieving zero-carbon shipping by 2050. Please do get in touch using the feedback form at **www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/zcfm**.

Appendix – 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 commerical proposition
Trial	2	Commercial trial, small scale
Scale up	3	Commercial scale up
Adoption	4	Multiple commerical 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

The Maritime Decarbonisation Hub

Get in touch

www.maritimedecarbonisationhub.org

To find about more information please visit **www.lr.org/zcfm**

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