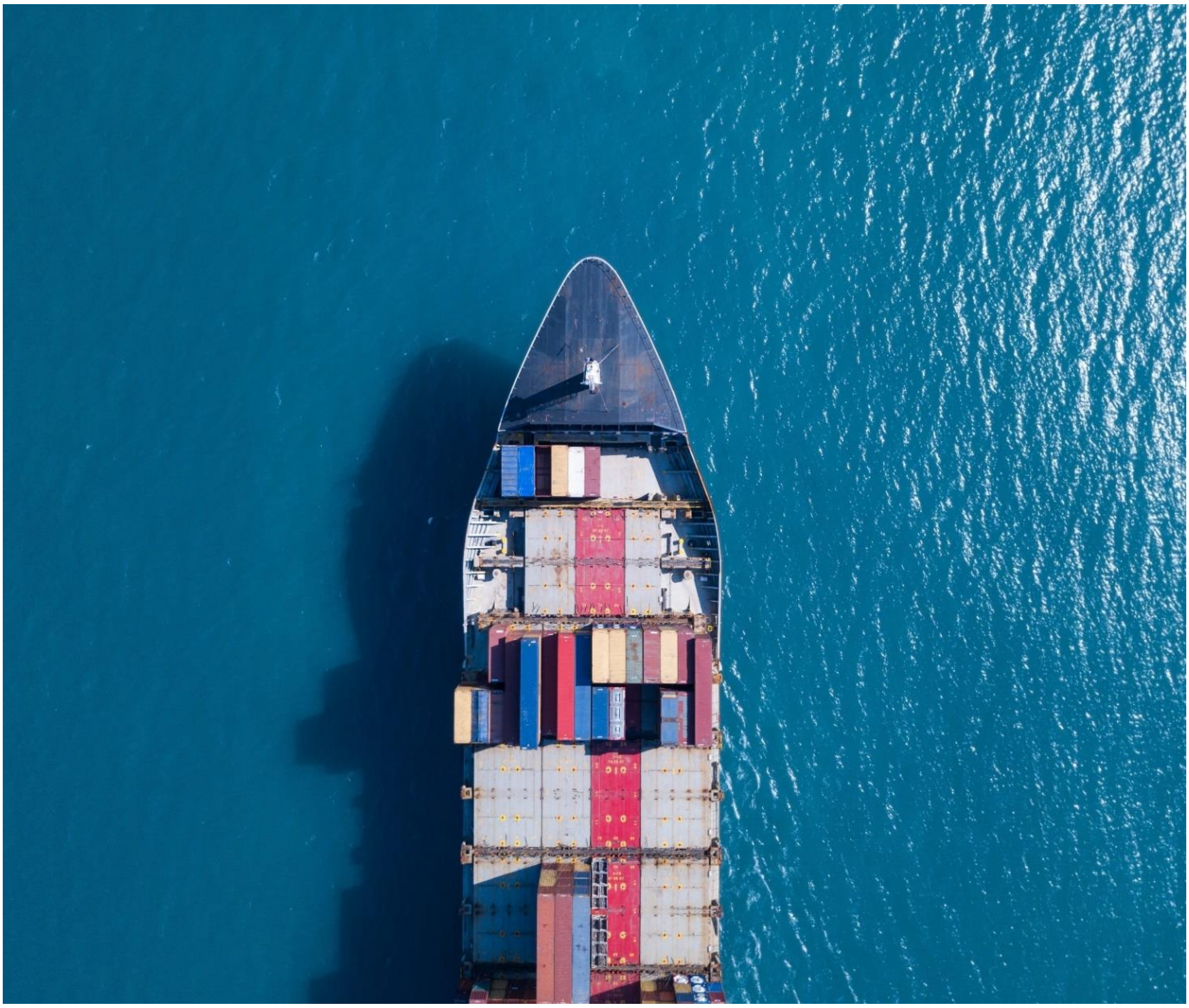
Innovation needs for decarbonization of shipping

Technical annex report, November 2021



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1. Introduction, overview of approach and summary of conclusions

Introduction

Today, international shipping accounts for around 3 percent of global emissions of greenhouse gases (GHG). The decarbonization of the industry constitutes a particular challenge. The industry relies on the availability of and access to cheap, energy intensive fuels anywhere to transport heavy freight over long distances from port to port in every corner of the world. However, the green, zero-emissions fuels we see emerging, which are needed for the transformation of the industry, are less price competitive and energy intensive. Moreover, the particular and sometimes hazardous properties of those fuels constitute risks and provide challenges to the transport and storage, as well as the use, of the fuels on board of ships.

To accelerate the transformation of the industry towards zero-emission shipping both regulatory measures and innovation are needed. While regulatory measures are needed to secure and create the right incentives for the broader uptake of green fuels, further innovations are needed to address some of the barriers – both technological and market barriers – to the wider applicability and uptake of green fuels in the industry.

The study on behalf of the DMA and the Zero-Emission Shipping Mission focuses on the innovation needs for the decarbonization of international shipping. The aim of the study has been to uncover and structure the innovations needed across the value chain to achieve commercially viable zero-emission shipping.

In this report we present and document the detailed findings of the granular assessments made of the innovation gaps and needs of green fuel options available.

In the remainder of this introductory section, we summarize our approach and the main conclusions.

Our approach: a full value chain analysis using Delphi panels to assess technologies and innovation needs

In order to identify innovation gaps and needs, a value chain approach has been applied whereby the full value chain has been broken down in its parts and subparts, cf. figure 1A. For each part and subpart of the value chain, the technologies required have been identified and assessed with regard to the innovation gaps and needs.

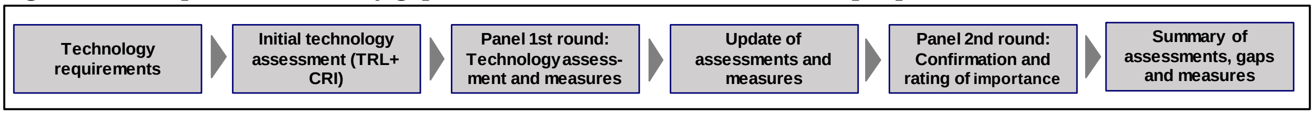
Figure 1A: Overview of the assessed value chain parts

Value chain part		Focus of the assessment
Fuel production	Feed stock	The technologies and availability of the main feedstock sources
	Fuel production and facilities	Key steps in the fuel production process and methods to manage energy supply and storage
Bunkering	Fuel transport	Methods used to transport fuels to ports
	Port and bunkering storage and supply facilities	Approaches and safety systems needed to store and bunker the fuels
Vessel operations	Ship design and building	Maturity of ship builds for different fuels and the challenges faced
	Retrofitting	Possibilities to retrofit engines to use new fuels or introduce engine replacements in existing ships
	Propulsion	The state of play of new engines, auxilliary engines and green pilot fuels
	Fuel storage and safety	Technical and economic issues related to onboard storage and maintenance
	Crew and safety management	How crew will be supported to manage new safety systems and issues connected to the different fuels
	Emissions	Availability of technologies to address emissions and if systems are in place to account for any CO2 emissions

A Delphi survey methodology has been used to peer review the technology assessments made. In doing so, we verified the gaps in the technologies concerning their development and market readiness, and the innovation needs to better deploy and scale-up the technologies across the value chain.

Three panels of in total +30 international experts, one panel for each part of the value chain, were established. The experts were recruited from academia and the industry. They were involved in two rounds of assessments of the technologies, as illustrated in figure 1B.

Figure 1B: The process to identify gaps and measures has involved two Delphi panel rounds



To identify innovation gaps, Oxford Research and Maritime DTU first performed an initial technology assessment using the Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) methodologies.[1] Then the panels validated the assessments and pointed to needed innovations. The assessments were updated and the proposed measures structured. In the second Delphi round, assessments and measures were confirmed and the measures were rated by the experts for their importance. Further information about the Delphi methodology and the list of participants in the three panels, see Annex A and B.

The focus of the study has been on green fuels, i.e. electricity-based fuels (green hydrogen, ammonia, and e-methanol), and bio-based fuels (drop-in diesel, biogas and Dimethyl ether (DME)).

Summary of conclusions

Green fuel technologies have undergone considerable development already, but there are still significant obstacles and innovation needs to be addressed to support the decarbonization of international shipping. There are four main conclusions of the study.

[1] Please refer to Annex A for further detailing of the methodology including the TRL and CRI.

Firstly, it is concluded that the needed technologies across the value chain are to a large extent technologically available to support the transition towards zero-emission shipping – but they are in most instances not market ready. The technological readiness of fuel technologies is assessed as moderate to high while the commercial readiness is in general low. Innovation, together with other market supporting measures, are needed to accelerate the readiness of technologies and support the commercialization of these technologies.

Secondly, it is concluded that there is no clear green alternative fuel to fossil marine fuels at this stage, so technology neutrality is called for in innovation policies. All green fuels assessed – the three electricity-based fuels, and the three biofuels - have limitations and challenges, which needs to be addressed. Therefore, there is no single way forward for the decarbonization of international shipping. For the foreseeable future it is important to favor a technology neutral approach in innovation. In the long term, one or more fuels may emerge as commercially viable, yet for now, industry should take advantage of the different options, considering specific circumstances and needs.

Thirdly, it is concluded that systemic, cross-cutting innovations and measures are essential to address gaps that affect all fuel types and support the further development and scaling of green fuel technologies. Three cross-cutting gaps, innovations and measures are pointed to:

a. **Demonstration**: There is a lack of knowledge around the applicability and performance of the green fuel value chains in real-life operation. Hence, integrated test and demonstration in 'green corridors'[2] is suggested by experts, to seamlessly gather knowledge on performance and operation, which can guide innovation and development efforts. 'Green corridors' will enable real-life testing and across the entire value chain of zero carbon shipping, encompassing fuel production, transportation, storage, bunkering, and vessel operations.

b. **Standards**: There is a further need of approaches to address safety management and fuel quality concerns. This gap points to the needs for supporting measures in particular the development of new, and revision existing, international standards that can also underpin further innovation. The idea is that the introduction of new and revised standards could provide consistency and certainty to the market around the quality and safety of the production, bunkering and use of the green fuels, generating a clearer framework for innovation.

c. **Scaling and supply**: There is a lack of supply of renewable energy and efficient technologies needed to produce the necessary volume of green fuels, especially electricity-based fuels. This gap calls for a combination of innovation and market measures. Finally, the experts stress the need for the scaled-up supply of renewable energy to support the production of sustainable feedstock and fuels. This should be tackled through innovations to improve the efficiency of equipment used to produce renewable energy, and in the identification of production sites.

Fourthly, it is concluded that fuel specific innovations are needed in all three parts of the value chain, fuel production, bunkering infrastructure and vessel operations. The innovations needed have the general aim of improving the cost efficiency, performance as well as sustainability of the fuel value chains.

a. Regarding **fuel production**, the gaps concern the high cost and energy intensiveness of current electrolysis technologies, for instance, used in the production of green hydrogen. Therefore, innovation needs concern the energy efficiency of current technologies and the need to explore alternative approaches. Furthermore, the needs e.g. include green desalination technologies in countries with poor water supply necessary for green hydrogen production, liquefaction technologies needed to support cryogenic storage of green hydrogen, air separation to obtain nitrogen from air to produce green ammonia, and carbon capture methods necessary for e-methanol production. With respect to biomass fuels further innovation is needed to e.g.

[2] Green corridor refers to the 'greening of a fuel value chain'. A green corridor covers the entire value chain supporting production, bunkering and vessel operations for an individual green fuel.

improve access to a wider range of feedstock sources, given that supply is perceived as limited and subject to likely price increases in the long term.

b. Concerning **bunkering infrastructure**, key gaps relate to the need to transport the fuels to ports efficiently and at scale and guaranteeing safe and efficient bunkering. Specifically, innovations are called for to address the difficulties in transporting green hydrogen safely and new innovative solutions are needed to address safety and maintenance concerns.

c. Concerning **vessel designs and fuel storage systems**, adaptions to enable the safe carriage of larger quantities of alternative fuels with lower energy density are needed. And new propulsion and emission control approaches are needed to ensure good performance and mitigate negative environmental impacts. Common gaps include commercially available green pilot fuels and zero-emission auxiliary engines. An innovation push forward is needed to secure that entire vessel propulsion systems can meet zero carbon targets.

Outline of report

The technical annex report is structured in four chapters.

In chapter two, we introduce the six fuels of the study along with our overall findings.

In chapter three, we present the identified cross-cutting measures and the overall findings in terms of the measures, needs and gaps that stretch across multiple fuels or parts of the value chain.

In chapter four, we present the results for each fuel and the three overall value chain parts. The subchapters contain the assessments agreed upon by the three Delphi panels. Furthermore, the subchapters present the innovation needs and measures identified and assessed by the three panels.

The annexes to the report contain further information about the methodology of the study and information on the members of the three Delphi panels.

2. Introduction of the six fuels and overall findings on the readiness of the six fuels

The six green fuels which have been assessed in this study represent two different types of fuels: Electricity-based fuels and biofuels, cf. figure 2.

Electricity-based green fuels offer a possible zero-carbon solution. They are produced using renewable energy. In this study green hydrogen, green ammonia and e-methanol are included. Green hydrogen is a component in all three fuels reviewed.

Biofuels are produced in biorefineries using biomass materials to produce low CO_2 emitting fuels that can be sequestered into the natural carbon cycle. In this study the focus is on 2nd generation biofuels. Drop-in biodiesel, biogas and dimethyl ether (DME) are included.

Figure 2: Overview of the six green fuels

Electricity based fuels	Green hydrogen	Green hydrogen can be produced from water using electrolysis, i.e., an electrical current to separate the hydrogen from the oxygen in water. Given its low energy density, to be used as a liquid fuel, hydrogen needs to stored in cryogenic conditions. Green hydrogen has zero carbon emissions.
	Green ammonia	Ammonia is a compound of nitrogen and hydrogen produced through a process called Haber Bosch. Ammonia can be used in liquid form as a green, zero carbon fuel. However, ammonia has toxic and corrosive properties and is therefore associated with significant safety risks.
	E-methanol	E-Methanol can be produced using green hydrogen and waste CO_2 collected from industrial sites. It is a liquid at room temperature and can be handled in a similar way as existingg maritime fuels. Unlike ammonia and hydrogen, e-methanol produces CO_2 emissions although less than diesel fuel.
Biobased fuels	HVO drop in Biodiesel	HVO drop in biodiesel uses energy crops as feedstock and is produced in biorefineries. Drop in fuels do not need to be blended with diesel. HVO fuels are processed using hydrogen to make hydrocarbons that are similar to diesel. However, they produce a low level of CO_2 when burned.
	Biogas (Bio-LNG)	Biogas is a sustainable source of methane fuel. It is produced from anaerobic digestion process using food and similar waste as feedstock. Biogas has=no Sulphur or NOx emissions although does emit a small amount of CO_2.
	Dimethyl ether (DME)	Green DME can be produced from biomass using two alternate methods, gasification or pyrolysis. It could also be candidate for electricity-based production. DME is a compound of methanol molecules and is a gas under normal conditions. It has very low CO_2 emissions.

Overall assessment of the fuel pathways

Based on the input from the Delphi panels we conclude, that the needed technologies across the value chain are at a moderate to high level of development, and in some cases are being tested commercially, or are to a certain extent sold on the market. Therefore, the assessment of the current situation suggests that the transition towards zero-emission shipping is technologically possible.

However, the commercial readiness of the technologies are on average considerably lower. Further innovation is needed to improve in particular price competitiveness, efficiency, applicability and scalability of the fuel technologies, so that the preconditions for the uptake in the market – the commercialization – are in place. Moreover, there are also market supporting measures necessary to support the deployment and uptake commercially.

In table 1 below, the assessment of the technological and commercial readiness of the range of technologies for each fuel type and value chain part is summarized. A Technology Readiness Level index (TRL) with a scale ranging from 1-9 and a Commercial Readiness Index (CRI) with a scale from 1 to 6 have been used to assess the technologies, cf. annex A.

The average scores of the technologies are used as an indication of the overall readiness of the six fuels. As is clear from table 1, average scores for technology readiness are high ranging from 7.1 (for vessel operations) to 8.2 (for bunkering), while the commercial readiness in general is lower ranging from 1.9 to 2.4, reflecting that competitiveness of the fuels needs to be improved through innovation and further measures are needed to support commercial deployment and uptake. We summarize the assessments for each value chain part in the following.

Table 1: Average TRL and CRI scores of technologies by value chain part and fuel type

	Fuel production		Bunkering		Vessel operations		Average by fuel	
	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*
Greeen hydrogen	9.0	2.0	6.0	1.5	6.4	1.5	6.8	1.6
Green ammonia	8.2	2.8	8.0	2.0	5.7	1.3	7.0	1.9
E-methanol	9.0	2.0	9.0	2.5	7.1	2.0	7.6	2.1
Biodiesel	9.0	2.0	9.0	3.0	9.0	3.2	9.0	2.9
Biogas	9.0	2.0	9.0	3.0	9.0	2.8	9.0	2.8
DME	5.8	1.8	8.5	1.5	7.4	1.5	7.1	1.6
Average by value chain part	7.9	2.4	8.2	2.2	7.1	1.9		

Technologies for fuel production

In relation to fuel production, the assessment of the technologies related to each individual fuel confirmed by the Delphi panels shows that, as a generalization, the current average readiness for this part of the value chain seems promising given the current Technological Readiness Level (TRL score 7.9). For example, green fuels such as hydrogen, ammonia, and e-methanol (TRL 7.0) have entered operational demonstrations, and biodiesel and biogas (TRL 9.0) are already sold commercially although are not used much by the maritime sector given their relative cost to diesel. Another possible biofuel, DME (TRL 7.0), is not used at all by the maritime industry, but some academics consider that it has potential for further development. However, one should be cautious when interpreting the TRL results. While the Delphi panel suggested that fuel production technologies are at a high level of technological readiness, it was also stressed that further innovation is needed, for example, to lower material costs and to reduce the amount of energy needed for fuel production. These two aspects should help to lower the overall costs of fuel production. In relation to biofuels, further innovation is needed to address the limited availability of biomass feedstock, for example, by diversifying possible sources.

Moreover, the average Commercial Readiness Index score for fuel production (CRI score 2.4) indicates that significant gaps remain. This is especially true with respect to the current scale of the current operations, and the limited extent of the proposed planning activities and investment in renewable energy and production sites. As we will return to below, there are important cross-cutting gaps related to the availability of and scaling of renewable energy. This is both an innovation issue and a commercialization issue.

Technologies for bunkering infrastructure

The possibilities around bunkering, again is assessed to be promising from a narrow technological perspective (TRL 8.2). This is partly due to the fact that all fuels are transported, stored and bunkered as commodities (but not as fuels with different handling and safety issues). Leading the way are bunkering systems for e-methanol and biofuels (TRL 9.0), considering that similar approaches can be used as those for diesel albeit with relatively minor modifications. Yet, while not unfeasible, bunkering systems for green hydrogen and ammonia (TRL 7.0) are not yet ready and demand further development. Generally, the commercial readiness position shows that all alternative fuels are hardly bunkered, if at all, in some cases, indicating that there is hesitancy around fuel adoption and persisting knowledge gaps around how to supply these fuels safely (CRI 2.2).

Technologies for vessel operations
With respect to vessel operations, the technological readiness is slightly lower than other parts of the value chain (TRL 7.1). However, there is variation in the scores between different fuel types.

For example, some engines already available on the market can use e-methanol and biofuels (TRL 9), although these are dual fuel solutions that also allow the use of fossil fuels. However, currently, operators using e-methanol and biofuels are doing so as part of commercial tests, and further information and experience is needed to ensure that they can be used with confidence.

Ammonia engines (TRL 8.0) and hydrogen fuels cells (TRL 7.0) are lagging and have yet to be fully developed although are expected in the coming years. At the same time, green pilot fuels and auxiliary engines (TRL 5.0) have not received the same innovation focus and are viewed as at the mid-point on the TRL scale. While improvements could be made, the technology needed to control emissions from e-methanol and biofuel is relatively strong (TRL 9.0), although solutions to address nitrous oxide emissions from ammonia (TRL 5.0) are needed.

However, the extent of commercial development of vessel operations is low (CRI 1.9). Further immediate actions are needed to ensure that vessels using green fuels can operate successfully, although some promising activities are underway. For instance, e-methanol and biofuel ships have been tested in commercial settings, and ammonia and hydrogen vessels, in particular chemical carriers, are undergoing demonstration.

Yet, to support sales, improving vessel designs to enable better storage of alternative fuels was suggested. Moreover, a key gap is the knowledge needed to operate ships that run on green fuels, so that fuel storage and propulsion systems can be maintained with confidence, and risks managed.

In table 1 the average score for the green fuel technologies for each part of the value chain is used as an indication of the readiness of the fuel technologies. The main technological gaps are presented in more detail in sections 3 and 4. As mentioned, please note that the TRL scores need to be treated with caution. While technologies such as those used for fuel production are at a late stage of development as indicated by the high TRL scores, at the same time, the Delphi panelists stressed that further innovation is needed. This is because rapid scale-up is required to address the energy needs of the maritime sector. To strengthen the business case for this process, the technologies need to be cheaper to buy, and more cost efficient to operate, so that green fuels can compete cost-wise with diesel.

3. Cross-cutting gaps and measures

The experts' assessments of the technologies across the value chain for each of the six fuels have shown that important gaps are cross-cutting i.e., they are common to all, or a group of the fuels, across a part of the value chain – or even the full value chain.

Some of these are an obstacle to innovation and need direct innovation, while others are to be addressed through supportive measures. The identified cross cutting gaps are:

- **Demonstration:** Lack of knowledge around the real-life applicability and performance of green fuels in the full value chain i.e., otherwise known as green corridors. This relates to all fuel value chains and concerns issues such as knowledge gaps around the price competitiveness of the fuel, impact on cargo space, the efficiency and safety of bunkering, the performance of engines etc. This is important for the final development of technologies.

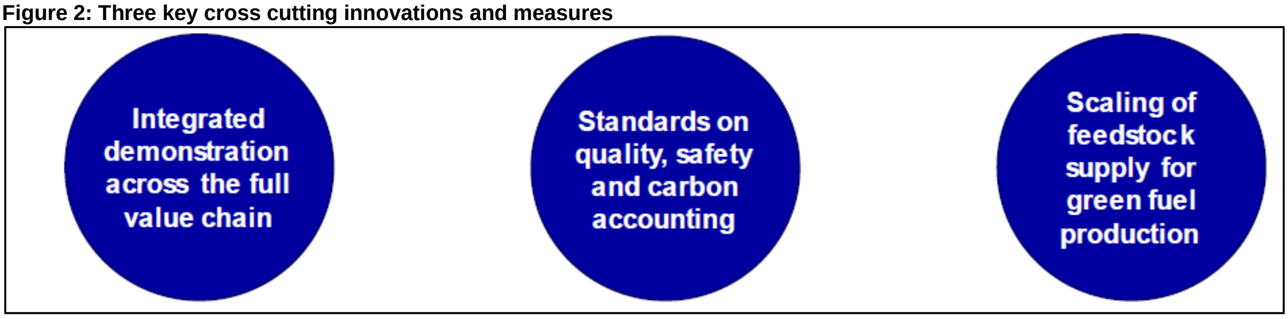
- **Standards:** Lack of established safety management approaches and certification for fuels. These gaps point to the need for supporting measures like new, or the updating of existing, international standards that can also underpin and steer further innovation. For example, standards specifying the need for technologies or procedures that ensure safe bunkering and use, and quality certification demonstrating the green credentials of the fuels.

- **Scaling and supply:** Lack of supply of feedstock, namely renewable energy and biomass needed to produce the necessary volume of green fuels. This gap calls for a combination of innovation and market measures to reduce material costs, improve the efficiency of solar and wind systems and ultimately further lower the price of renewable energy. It also demands innovation to strengthen the supply of biomass.

These gaps call for different types of measures, including supporting measures like standards that can address the absence of approaches to safety management and steer development of technologies. Hence, the measures addressing the cross-cutting gaps are not exclusively related to innovation. This contrasts with the gaps related to the specific fuels, which we will discuss in the last section. These fuel-specific gaps generally warrant the introduction of innovation to strengthen their performance, efficiency, and price competitiveness.

In addressing these gaps, cross-cutting measures are needed to provide global solutions to support the development of the green fuels reviewed. The measures include integrated demonstration in real operation across the full value chain (e.g. in green corridors), the development of standards on quality, safety and GHG accounting, and scaling of renewable energy supply for green fuel production, cf. figure 2.

Figure 2: Three key cross cutting innovations and measures



The three measures are discussed in the following subsections.

Cross cutting gaps, innovations and measures: Integrated demonstration on real ships across green corridors, i.e. the complete value chain

There is a significant information gap around the operational applicability and performance of green fuels, particularly over long durations in a real-life commercial setting with other technologies and regarding the entire value chain.

Information and transparency are needed to understand how these value chains perform, and more specifically, what further innovations and technological fine-tuning are needed to address items such as the level of capital investment, operational and maintenance costs, considering also the cost impact of the displacement of cargo space due to additional fuel storage.

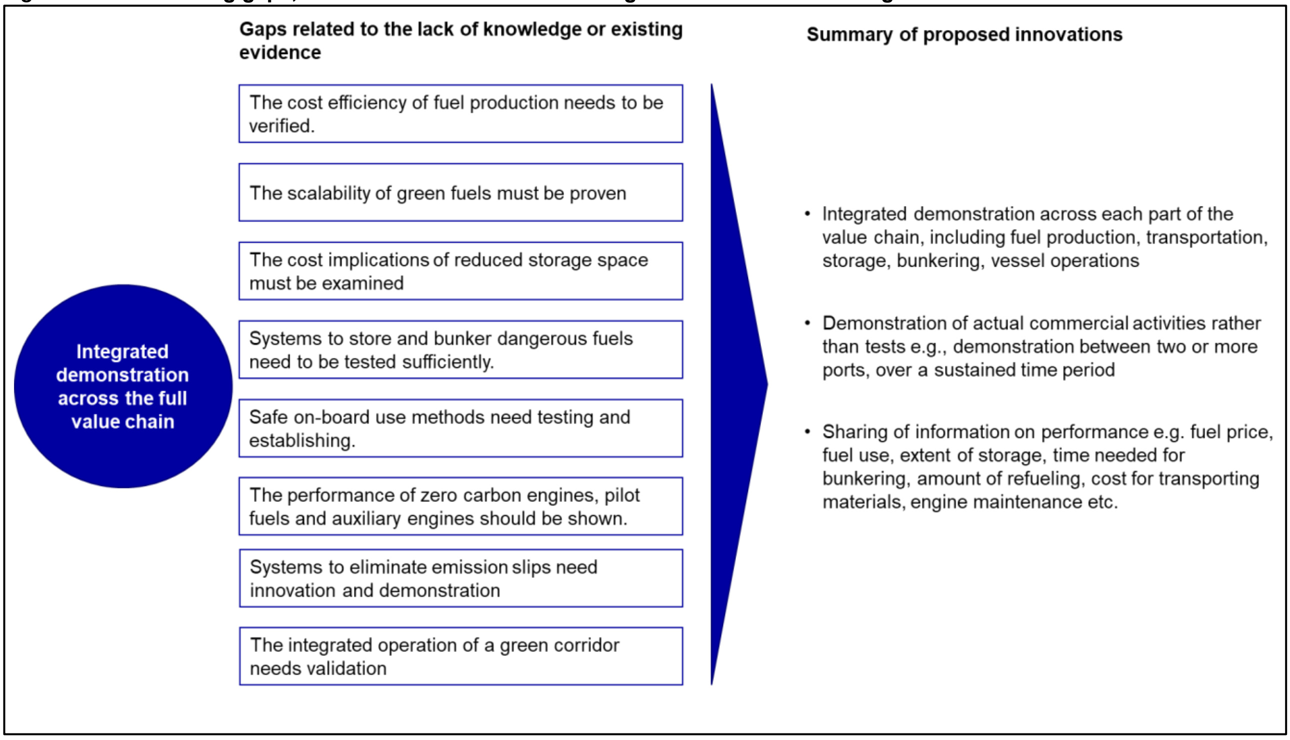
Demonstration on real ships can contribute to the needed information and transparency, while at the same supporting further innovation, such as fine-tuning of the technologies to enhance their performance and applicability, as well as learning how these technologies work alongside other existing technologies, e.g. onboard IT systems and energy efficiency technologies.

Moreover, there seems to be a lack of coordination and information sharing across the value chain with different actors waiting for technologies and market signals from other parts of the value chain, e.g. fuel producers are calling for engine manufacturers to introduce new types of engines, vessels operators mandate that bunkering infrastructure needs to change, and ports are calling for better fuel supply etc.

A solution could be coordinated demonstration on real-life ships across ‘green corridors’ i.e. the entire value chain. This would help address knowledge gaps, support development of new solutions and address questions around costs and technological challenges. The idea is that the organizations providing the value chains demonstration (fuel producers, fuel transporters, ports, vessel and engine manufacturers and operators) would provide leadership by illustrating the business case and technological readiness of using green fuels. Ultimately, the value chain demonstration, e.g., for a specific route, could support the transitioning from the test and demonstration phase to a fully mature business operation, thereby fine-tuning technologies and encouraging others to adopt.

The gaps and innovation needs pointing to the demand for integrated demonstration of green corridors are summarized in figure 3.

Figure 3: Cross-cutting gaps, innovations and measures: Integrated demonstration of 'green corridors' i.e. value chains



Cross-cutting gaps, innovations and measure: Standards on quality, safety and GHG accounting

A core cross-cutting aspect that is missing from each part of the value chain is better knowledge and recognized approaches to secure the necessary quality of green fuels, safety of bunkering and vessel operations, and also GHG accounting. New, or revisions to, existing standards offer potential in addressing these gaps.

These gaps call for other types of measures than innovation, but will at the same time support and drive forward innovation by guiding and encouraging the take up of the needed technologies i.e. for this reason, standards are typically defined as 'demand side innovation measures". The IMO is the main standardization body for the maritime sector.

For example, with the introduction or revision of standards, general safety and technological requirements can be defined specific to the alternative fuels, providing guidance to both manufacturers and users. This should support demand in the marketplace for the relevant specific solutions developed by manufacturers.

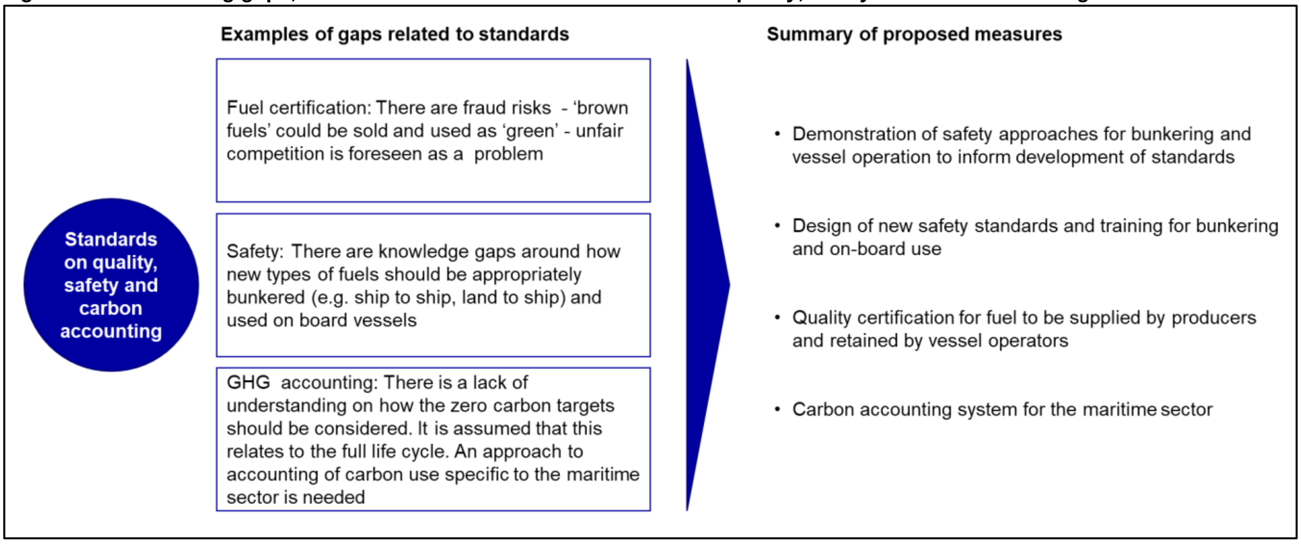
New international standards, and revisions to existing ones, to better cover new fuels and other zero-emission technologies, can be defined and implemented to address these gaps. But, ultimately these would need to be supported and enforced under existing or new regulation, and supported by penalties for non-compliance.

With respect to safety standards, these provide guidance and certainty on requirements for the necessary innovative solutions and approaches needed when bunkering and operating vessels. Ultimately, they would contribute to maintaining safe working environments for port staff and crew, as well as addressing safety concerns of local residents near ports. The standards would indicate the necessary features of the technologies needed, as well as working methods and maintenance protocols.

Although not an innovation, experts have pointed to the need for supporting measures related to certification of green fuels to reduce the possibility of fraud, and the ability of operators to calculate and demonstrate their carbon footprint, especially in a transition period. It should be noted that life cycle assessment approaches, including certification, are currently being negotiated at the IMO, and the end results should address the concerns in these areas. Again, these measures are to boost demand and create better market certainty.

The gaps pointing to the need for standards for quality, safety and GHG accounting are summarized in figure 4.

Figure 4: Cross cutting gaps, innovations and measures: Standards for quality, safety and GHG accounting



Cross-cutting gaps, innovations and measure: Innovation is needed to secure higher efficiency as well as scaling of renewable energy supply for green fuel production and also biomass supply

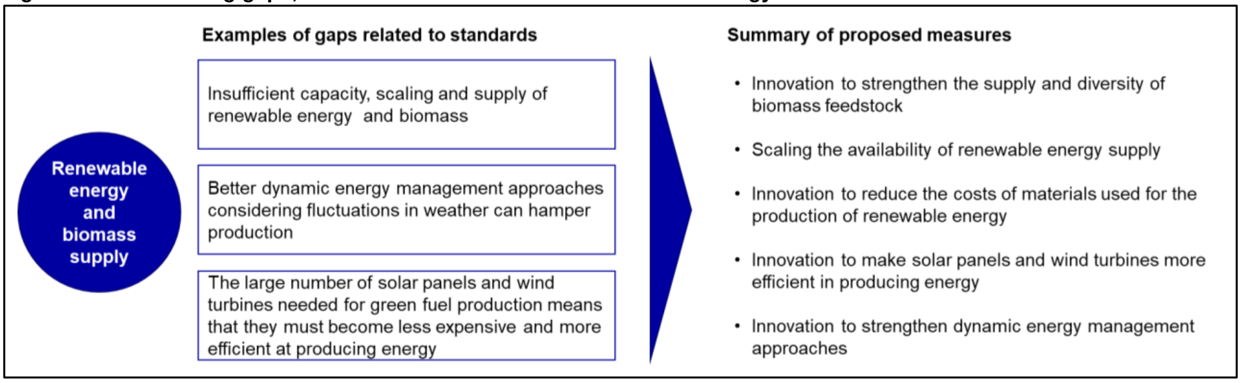
Innovation is needed to strengthen the supply of essential feedstock, namely renewable energy and biomass.

The supply of cost-efficient renewable energy is key for zero carbon fuel production Renewable energy systems (solar, wind, hydropower and geothermal) are at a high level of technological development given their existing use in commercial settings.

Although renewable energy systems are technologically mature, it should be recognized that further innovation is needed to reduce the cost of solar panels and wind turbines i.e. to reduce capital costs. Improvements to their operational efficiency would also be beneficial in reducing green fuel production costs, along with improved energy storage systems. The supply of renewable energy to produce green fuels is limited, representing a cross-cutting gap. This could be addressed mainly by innovations aiming to lower the cost of wind and solar power technologies and improving their efficiency in producing energy. Improved fuel production facilities that can dynamically manage changes in the supply of renewable energy due to weather fluctuations were also recommended.

At the same time, biomass supply is considered as insufficient to produce the extent of energy needed for the maritime sector. Competition for biofuels will likely grow in the future. Innovations are needed to strengthen and diversify the supply.

Figure 5: Cross-cutting gaps, innovations and measures: Renewable energy



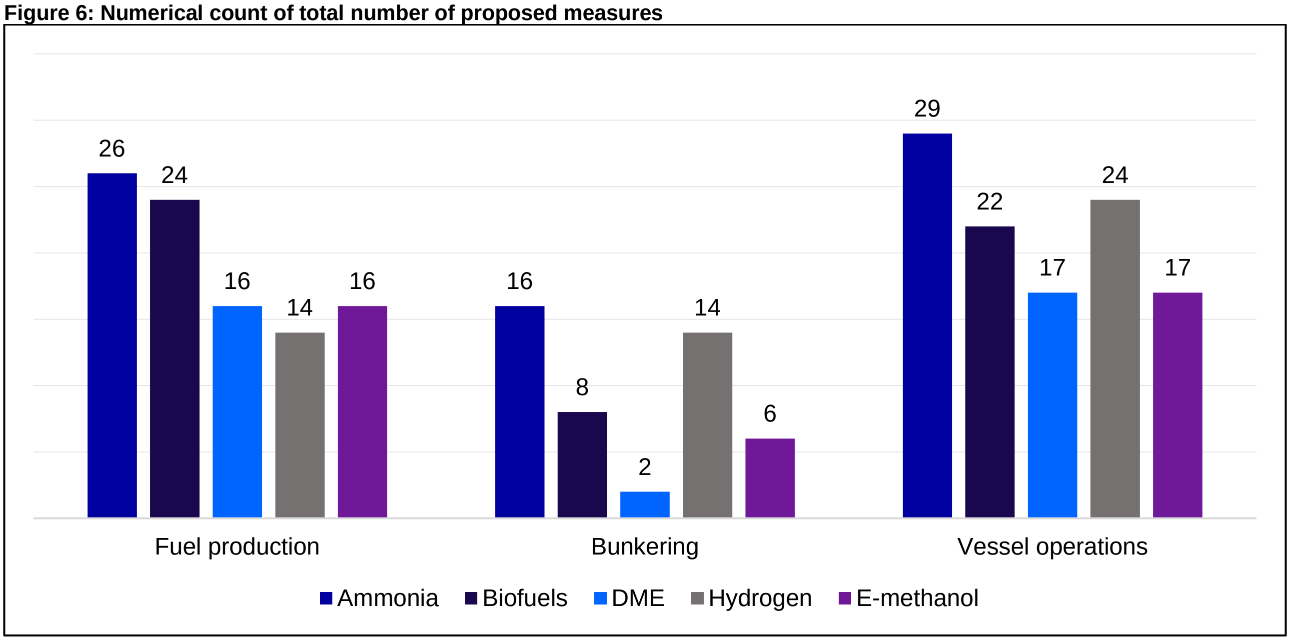
4. Fuel-specific gaps and measures

The purpose of this chapter is to present and explain the assessments of technological and commercial readiness and the selected innovations and market supporting needs, which address the identified technological and commercial gaps. The chapter is divided into six parts; one for each of the fuels investigated in the study. These parts are further subdivided into three; one for each part of the value chain.

The measures listed in tables 2 to 61 stem from a larger pool of innovation and commercialization measures, which have been proposed by the Delphi panelists in the first round, and then processed by the project team. Lastly, the measures have been assessed and evaluated by the Delphi panelists. The aim in this round was to get an indication from the panels on how important the particular measure was for the further development of the fuel as a viable way forward for the maritime industry. The listed measures in tables 2-61 have been selected from the larger pool of measures. The measures have been selected based on how high their scoring was. The highest scoring measures, indicating the most important and crucial innovation and commercialization needs, have been included in tables 2-61. More detailed information about the methodology and phases for the two Delphi rounds in each of the three expert panels can be seen in Annex A.

In figure 4 the total numerical count of the proposed innovation and commercialization measures are visualized. For large parts of the measures regarding the two bio-based fuels, labelled ‘biofuels’, it is not possible to distinguish between bio-LNG and biodiesel, hence they are combined for the visualization below.

Figure 6: Numerical count of total number of proposed measures



4.1 Green hydrogen

Green hydrogen as a fuel is being considered by multiple industries and sectors and can be produced via several conversion pathways, including electrochemical conversion. The idea of green hydrogen as an emission free fuel has been a dream and vision for many years and the principle of green hydrogen is appealing and simple, as it can be made from a readily available and cheap resource, water. Due to the low energy density, green hydrogen will currently require too much storage room for intercontinental shipping.

Green hydrogen is needed for the production of other fuels, i.e. green ammonia, e-methanol and HVO drop-in diesel, and can thus be assessed both as a feedstock and as a fuel itself. The increase in technological readiness for hydrogen will therefore have positive effects for other alternative fuels.

Box: Characteristics of green hydrogen fuel

Green hydrogen can be produced from H_2O using electrolysis i.e. an electrical current to separate the hydrogen from the oxygen in water. The process does not produce any CO_2. However, there are major challenges around competitive pricing, safe and efficient storage, and the issue of the space needed to carry large amounts of fuel. The possibilities for propulsion include fuel cells and green hydrogen engines.

Based on the consolidated assessments in table 2, green hydrogen can be viewed as a fairly mature fuel across the value chain.

Table 2: Average TRL and CRI scores of technologies for green hydrogen by value chain part

	Fuel production		Bunkering		Vessel operations		Average	
	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*
Green hydrogen	9.0	2.0	6.0	1.5	6.4	1.5	6.8	1.6

The highest technological readiness is for the production of hydrogen, which is in part due to hydrogen being produced from simple methods and feedstocks. Clean water is used as feedstock and hydrogen is obtained via the electrolysis process, but this is an energy intensive process, which bears most of the production costs. The main technological challenge for the production is supplying sufficient amounts of renewable energy at a low cost.

There are issues with the space needed for storage compared to traditional liquid fuels. The bunkering of hydrogen fuel is subject to lower technological readiness and thus requires more innovation. There is a pressing need for demonstration of bunkering for hydrogen to address the technological challenges and the issues regarding the safe handling and operation. Due to the lower technological readiness, the commercial aspects of hydrogen bunkering are in the early stages. In sum, the bunkering of hydrogen still needs technological development and commercial scaling for it to be viable, cf. table 2.

When assessing the operations of vessels powered by hydrogen, there are both technological and commercial gaps to be filled, as indicated by the consolidated scores in table 2. To be used as a fuel, hydrogen needs to be stored as a liquid (at -253°C). Hence, there is a need for on-board refrigeration and insulation systems, which are bulky and consume energy. Some panelists argued that this reduces the feasibility of using hydrogen on ships. The assessment points to a low technological readiness for the cooling systems.

Using green hydrogen as a fuel has zero carbon emissions and low NOx emissions that can be eliminated. Hydrogen slips are risky (explosive, suffocation in confined spaces), but it is not toxic or corrosive like ammonia.

Hydrogen as a fuel has been demonstrated in internal combustion engines and fuel cells. Nevertheless, significant technological advances are needed before hydrogen can be considered a viable fuel option. It is not bunkered or used as a fuel, and there are gaps in safety training and standards. This is reflected in the assessment made by the panels. The scores reflect that there is a general need for demonstration projects to strengthen the market knowledge on the operational behavior of hydrogen across the value chain, cf. table 2.

In the following parts we summarize the results of the assessments for hydrogen for each part of the value chain and the corresponding sub parts.

4.1.1 Fuel production

Key requirements for green hydrogen fuel production

Feedstock

The electrochemical production of hydrogen fuel requires two main feedstock components:

I. Clean water. This may be a challenge in some parts of the world. Therefore, green desalination plants are needed.
II. Renewable energy

Fuel production

The production of green hydrogen requires the electrolysis of water using renewable electricity and an electrolyzer. The energy requirement and cost of the electrolyzer make hydrogen production expensive, therefore identification of efficiencies and scale up are needed. Projects to further the development of the needed infrastructure and facilities to produce green hydrogen are planned or already being demonstrated, cf. box 2.

Box 1: Selected examples of the readiness of the technologies

In line with Mission Innovations mission on zero-emission shipping. A mission focused on clean hydrogen was launched in 2021. Clean Hydrogen Mission – Mission Innovation (mission-innovation.net)

Access to clean water may vary geographically. Development of green salination plants are in the planning. For example:

- There are plans to install a desalination plant, which is to operate only on renewable energy, in Egypt. EGYPT: Cairo bets on green energy desalination plants | Afrik 21
- A small green desalination plant is operational in Kenya. Tesla's Solar Panels Are Turning Saltwater into Drinking Water for 35,000 Kenyans (returntonow.net)
- Large-scale production facilities have yet to be established, although some are in use and others are planned (small-scale sites are in operation).
  Norsk Hydro plant, which used hydro power. Norsk Hydro Rjukan - Wikipedia
- Power to X systems that use renewable energy to produce green hydrogen are in use (e.g. **Shell's Refhyne** project that is estimated to produce 200MW of hydrogen using a ~1-10MW electrolyzer). About – REFHYNE
- **LHYFE (FR)** will build a 24MW ´green hydrogen site in Denmark. Lhyfe to install a hydrogen production site in Denmark - Offshore Energy (offshore-energy.biz)
- **Green Hydrogen (DK)** has received grant funding to develop a 100 MW project using a novel multi-MW-range alkaline electrolyzer.
- **Enegix (Brazil)** has plans to build the world's largest green hydrogen production facility that will harness 3.4 GW of combined wind and solar power.
- **Ørsted (DK)** plans to develop a 1 GW electrolyzer supplying industrial demand for renewable hydrogen in the Netherlands and Belgium by 2030.
- **Ørsted (DK)** has made plans to develop a 1GW green hydrogen plant. Ørsted to develop one of the world's largest renewable hydrogen plants to be linked to industrial demand in the Netherlands and Belgium (orsted.com)
- **Port of Rotterdam (NL)** is considering construction of a green hydrogen plant. Uniper, Port of Rotterdam mull green hydrogen plant (argusmedia.com)

Technological assessment and gap

The feedback from the panel indicated a need for innovation of the electrolysis processes despite it being mature (TRL 9.0 and CRI 2.0). The technological readiness of the electrolysis was stressed using the active Shell Refhyne project with 200MW of green electrolyzer production as an example. Some of the feedback from the panelists indicated a higher commercial readiness for the electrolysis, when considering the Norsk Hydro plant and the Aswan dam electrolyzer that produces green hydrogen using hydropower. The main issue is, however, related to the readiness when produced from other renewable energy sources, hence our scoring of a CRI 2.0. Innovation could explore how production costs can be reduced by developing alternative electrolysis methods (as opposed to alkaline methods).

In some countries, clean water may not be available. Desalination is a well-known technology, but green desalination plants need further development (TRL 9.0 and CRI 2.0). Of the several technologies, reverse osmosis is enabled through a pump which can be powered by any energy source, and many of which are electrified. Changing the electricity supply to renewable electricity is not something which should require further innovation. The process does, however, need innovation in terms of reducing the amount of electricity and the costs of the electrolyzer.

In sum, the technologies are generally ready, but they could be made more efficient given the energy needs of the maritime sector.

Commercial assessment and gap:

The main issues for the production of green hydrogen relate to identifying, and investing in, new sites to support upscaling of production. Connected to this, is the need for standards to certify the green credentials of hydrogen fuel. Some of the panelists raised concerns about the commercial readiness being low when considering the total energy needs of the maritime sector.

In the tables below are the assessment and the main proposed innovation and commercialization measures, summarized.

Table 3: Assessments and measures related to feedstock for fuel production of hydrogen

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Feedstock	Green desalination	9.0	2.0	Clean H2O is needed. This may be a challenge in some parts of the world. Therefore, green desalination plants are needed. The estimated technological readiness for green desalination is TRL 9 and the commercial readiness is CRI 2. It seems that there is currently commercial testing of such systems in countries with water supply challenges, such as those in the Middle East.	No measure was provided. However, the Delphi panelists agreed that the production of hydrogen from green desalination is technologically mature at TRL 9, but still needs commercial scaling at CRI2.	

Table 4: Assessments and measures related to fuel production and facilities for hydrogen fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel production and facilities	Green electrolysis of hydrogen	9.0	2.0	Green hydrogen requires the electrolysis of water using renewable electricity. The energy requirement makes hydrogen production expensive, therefore identification of efficiencies and scale up are needed. It was noted that desalination is a mature technology. Of the several techs, reverse osmosis is enabled through a pump which can be powered by any energy source, and many of which are electrified. Changing the electricity supply to renewable electricity is not something which should require further innovation. The technological readiness level of the green electrolysis of hydrogen is TRL 9 and its commercial readiness is CRI 2, as small-scale sites are in operation and large-scale production is planned.	Further demonstration of green electrolysis e.g. in terms of scalability and durability.	4.7
					Further research and testing of Polymer electrolyte membrane (PEM) electrolyzers.	4.3
					Further research and testing of Anion exchange membrane (AEM) electrolyzers.	3.5
					Engineering of membranes and to strengthen the ion conducting polymers for use at high temperatures in water (by reinforcing them with a porous support).	4.3
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Further research and development into the adhesion of catalysts to the support/porous transport layer, due to the loss of catalysts.	3.5
					Further research into optimization of heat and mass transfer (gas/liquid transport and separation).	4.0
					Demonstration projects of efficient liquefaction technologies.	4.0
					Improvement of cost competitiveness (e.g. better storage 10 MW+).	4.3
					Commercialization measure: Identification of local production sites for H2.	3.5

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
					Commercialization measure: Upscaling of the production.	4.3
					Commercialization measure: Quality standards and certification systems for green hydrogen maritime fuel.	4.0

4.1.2 Bunkering

Hydrogen gas and liquid are commercially demanded commodities that are already transported to, stored and bunkered in ports. As a gas, hydrogen can be transported using pipelines or pressurized cylinders carried by truck. As a liquid, hydrogen can be transported in refrigerated cylinders by truck. There are existing research projects that combine hydrogen with an oil-like liquid to make transportation easier.

However, with respect to hydrogen as a maritime fuel, there is no major bunkering infrastructure yet. There are plans to develop some test sites. Bunkering hydrogen fuel would need to meet high safety standards to allow simultaneous loading of cargo.

Where green hydrogen is converted to a liquid, given its low energy density, it will need to be kept at –253C in cryogenic tanks. The fuel is highly flammable. Innovation is needed to develop efficient and safe storage and fuel bunkering systems.

Projects to further the development of the needed infrastructure and facilities to bunker green hydrogen are planned or already being demonstrated, cf. box 2.

Box 2: Examples of hydrogen sites at the planning or development stage include

Hydrogen liquid and gas transportation are well defined regulated markets

- Liquid Hydrogen Delivery | Department of Energy (US)
- Gaseous Hydrogen Delivery | Department of Energy (US)

There are plans to launch hydrogen fuel bunkering

- Some companies like **KHI** in Japan have developed the containment system and built a trial vessel for demonstration projects, but not much technological information has been disclosed Japan's KHI develops marine hydrogen tank system (argusmedia.com)
- **Moss Maritime** (Norway) have released a design of a liquified hydrogen bunkering vessel. New Design Makes Liquefied Hydrogen Bunker Vessels A Reality - FuelCellsWorks
- **Voyex** (the Netherlands) is planning a test floating bunkering infrastructure that uses solar energy. This will combine the hydrogen to an oil-like liquid to make transportation easier. A Dutch first: Refueling ships with hydrogen at floating solar islands - Offshore Energy (offshore-energy.biz)

Technological assessment and gap

Hydrogen gas and liquid are commercially demanded commodities that are already transported to, stored and bunkered in ports as a commodity. However, a problem is whether the current transport system is optimised given the low energy density of hydrogen and the volumes of hydrogen that need to be transported for the maritime sector (TRL 7.0 and CRI 2.0). There is no major fuel bunkering infrastructure yet. There are plans to develop some sites and some demonstrations are underway, cf. box 2 (TRL 5.0 and CRI 1.0).

Commercial assessment and gap

The feedback from the panel indicates that transporting and storing hydrogen as a liquid could be costly. Likewise, it is stated that there currently exist knowledge gaps on how to bunker hydrogen safely and also in terms of dealing with the risks related to possible spills. This is a barrier for further commercial development of hydrogen fuel.

Table 5: Assessments and measures related to fuel transport of hydrogen fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel transport	Systems needed to transport and store hydrogen - as liquid and as gas	7.0	2.0	The systems needed to transport and store hydrogen liquid and gas are at TRL 7, given their existing extensive use in the trade of hydrogen as a commodity. The commercial readiness to store and transport hydrogen as a fuel is CRI 2, given the need to scale up the existing infrastructure to meet future fuel demands.	Optimization of transportation and storage of H2.	4.2
					Research into conversion of the gas grid for the transport of hydrogen is possible and to what extent.	3.8
					Optimization of transportation and storage of H2.	4.2
					Research in transporting hydrogen as ammonia.	3.3

Table 6: Assessments and measures related to port and bunkering storage and supply facilities for hydrogen fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Port and bunkering storage and supply facilities	Bunkering hydrogen fuel	5.0	1.0	In terms of bunkering hydrogen as a fuel, there is an engineering challenge related to safety and commercial testing, though the innovation requirement is low. Therefore, the current stage of development is TRL 5. Currently, there are plans to test commercial hydrogen bunkering, but these have not been launched yet. Therefore, bunkering of hydrogen fuel remains a hypothetical proposition and is at CR 1.	Bunkering hose system suitable for LH2 is essential for ship-to-ship bunkering, in order to absorb the ship's movement by wave/wind/tide and difference of manifold height.	4.2
					Further development and simulation of the bunkering infrastructure, including reductions of costs across this part of the value chain.	5.0
					It would be interesting to assess how to purge or effectively drain the trapped LH2 in the connection system between the ship and truck/shore/ship when disconnected.	4.4
					Commercialization measure**:** Development of regulations on how to bunker hydrogen quickly and safely.	4.6
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Investigating potential of Liquid Organic Hydrogen Carriers (LOHC) for storage.	3.5
					Measures are needed to minimize the gas/liquid leak from valve, piping, gauges, blanks and handling machinery, like pump, compressor and heat exchanger.	4.8
					Commercialization measure: Risk analysis of the impacts when hydrogen is leaked in confined spaces.	4.2
					Commercialization measure: Research and testing into the effects and impacts for supply chains of vessels having to bunker more frequently.	4.2

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
					Commercialization measure: Research and development of the methods for the safe handling of the fuel. Both onboard vessels and in ports.	4.8

4.1.3 Vessel operations

Key requirements for onboard fuel storage, safety and emissions of hydrogen

The current state of technology for the onboard storage of liquid hydrogen faces challenges concerning the large volume of fuel that must be stored, its weight, and the energy needed to maintain the fuel at –253℃. There were minor disagreements in the panel, in terms of whether insulation or energy is the primary and/or most efficient method to maintain the low temperature.

Related considerations for gaseous hydrogen include the insulation, boil-off gas to keep hydrogen cool, and the fuel storage for the auxiliary engines. The need for hydrogen to be compressed to 300 bars requires a significant amount of energy. These coolers are not a ready technology to be used in the maritime sector. There is a technological and commercial challenge to be overcome in this regard.

Key safety issues for the storage of hydrogen include the need for installation of detectors to prevent slips, ventilation, remotely operated isolation valves, route piping at sufficient distance from the side shell and piping in separate unmanned space.

To ensure safe handling of hydrogen, fuel crews will need to be trained to handle it in a responsible manner. It is likely that new regulations and standards will need to be introduced to ensure safe onboard management.

Hydrogen can be produced from diverse resources with the potential for near-zero greenhouse gas emissions. Once produced, hydrogen generates electrical power in a fuel cell, emitting only water vapor and warm air.

Key requirements for ship design, propulsion and retrofitting of hydrogen

The naval architecture for ships fueled by hydrogen requires design, engineering and safety adaptations, given the need to carry a higher volume of fuel, account for the risks associated with carrying and using hydrogen, and meanwhile ensure sufficient cargo space.

The development of new hydrogen engines and/or hydrogen fuel cells are needed. Hydrogen fuel cells are however available currently, but are not directly compatible for marine purposes. Demonstration projects and tests of vessels powered by hydrogen fuel cells are currently underway or being planned for the foreseeable future, cf. box 3. Hydrogen engines require further innovation, given the energy and safety issues. Despite the lacking proof of concept in marine environments for hydrogen fuel cells, they are still preferred by the Delphi panel over hydrogen engines. Although hydrogen engines are green in terms of CO_2, NOx would still be an issue in an internal combustion engine. The ability to retrofit an existing vessel with a fuel cell system is important, as it does not require designing and building a new ship. Fuel cells are lighter and require less volume than a diesel engine at an equivalent power output. Auxiliary engines may require innovation, as there seems to be less reported developments in this area.

When dealing with retrofits, the possibilities for retrofitting requires the commercial availability of green hydrogen engines or fuel cells that can be installed into the existing ship stock. Technical solutions and installation services will need to be made available. Retrofitting would essentially mean removing the combustion engine and introducing a new hydrogen system. It is not possible to modify existing diesel engines to use hydrogen as a fuel and, therefore, this possibility is not explored further in the study.

Projects to further the development of the needed technological and commercial availability are being developed over the coming years, cf. box 3.

Box 3: Examples of hydrogen sites at the planning or development stage

- **ULSTEIN** (Norway) The SX190 is a design for a proposed support vessel that uses green hydrogen and will be trialed in 2022. The ship uses existing technologies and fuel cells.
  Ulstein
- **Egil Ulvan Rederi** (Norway) has been awarded a contract to build the first hydrogen cargo ship. It is planned for operation in 2024.
- **Shell** (Singapore) in 2021 announced a trial to install a hydrogen fuel cell for an auxiliary power unit on an existing roll-on/roll-off vessel. Shell's maiden trial for hydrogen fuel cell in ships to aid Singapore's clean fuel ambitions | S&P Global Platts (spglobal.com)
- **Wilhemsen** (Norway) announce plans to build a hydrogen carrier powered by hydrogen fuel cells to be operational by 2024. HySHIP: inside Europe's flagship hydrogen vessel demonstrator project (ship-technology.com)
- A **Japanese** consortium including Kawasaki announced the development of 4 and 2 stroke hydrogen engines, including auxiliary engines and fuel storage systems for the maritime sector. Japanese Manufacturers Cooperate On Development Of Hydrogen Fueled Marine Engines (fuelcellsworks.com)
- In 2021, the **China Classification Society** provided a first type-approval for a hydrogen marine fuel cell that will be tested on a purpose-built bulk carrier of 2,100DWT. Manifold Times | China Classification Society awards first type approval for hydrogen marine fuel cell
- **ABB (Switzerland)** has announced plans to manufacture hydrogen fuel cells for ships. ABB to Develop Hydrogen Fuel Cell for Ships - Ship & Bunker (shipandbunker.com)
- A hydrogen carrier has been launched between Japan and Australia.
  World's first liquefied hydrogen carrier launched in Japan | Recharge (rechargenews.com)
- A new hydrogen fueled ferry is under development.
  CMAL Caledonian Maritime Assets LtdCONTRACT AWARDED FOR CONCEPT DESIGN OF EMISSONS-FREE FERRY - CMAL Caledonian Maritime Assets Ltd (cmassets.co.uk)
- **Norled** hydrogen ferry, Norway. Norled and partners in FLAGSHIPS receives EU-funding: - Norled
- **The Sea Change** (formerly called the Water Go Round) has been constructed. It uses hydrogen fuel cells for essentially all propulsion power. It will soon undergo sea trials. It is being constructed in Seattle WA and will be deployed in San Francisco, CA. SW/TCH Maritime (switchmaritime.com)

Technological assessment and gap

The technologies needed to ensure safe storage of hydrogen require some development, given the cost and safety challenges of storing high volumes at low temperatures, and related risks such as metal brittleness. (TRL 7.0 and CRI 2.0). The cooling to –253℃ is energy intensive and needs further innovation to improve efficiencies (TRL 4.0 and CRI 2.0). The feedback suggested that NOx and particle emissions can be prevented using fuel cells. There is, however, still room for technological improvement (TRL 7.0 and CRI 1.0).

Hydrogen fuel cells are the most technologically ready propulsion technology available (TRL 7.0 and CRI 2.0). Likewise, it was stated that there is a need for technological improvements into auxiliary engines and pilot/ignition fuels (both TRL 7). Hydrogen internal combustion engines are far from ready (TRL 4.0 and CRI 1.0). In terms of designing and constructing the vessels, there are initial developments demonstrations proposed (TRL 7 and CRI 2). The ability to retrofit current engines to use hydrogen fuel was suggested as possible (e.g. MAN ES ME-C engines), but there are still technological advancements to be made (TRL 5 and CRI 2.0).

Commercial assessment and gap

The panel points to the gap around formulating the necessary safety requirements for crews handling hydrogen **(CRI 1)** and, in the same way as the bunkering panel, assessment of the impact on increased fueling patterns was suggested. The general emphasis by the panels is placed upon developing regulations and standards, and demonstrations of the business case and feasibility.

Table 7: Assessments and measures related to ship design of hydrogen-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Ship design and building	Ship design and building	7.0	2.0	Currently green combustion engines have yet to be developed. There are developments underway to launch vessels using hydrogen fuel cells in the coming years.	Further development and demonstration of LH2 tanks optimized for ships.	5.0
					Research in challenges with storage is needed.	5.0
					Research and thorough testing and demonstration of lifetime of the components and costs.	4.5
					Testing of material compatibility and thermal cycle tests for fatigue stress.	4.3
					Commercialization measure: Demonstration of vessel operation patterns and duration consideration storage constraints.	3.8
					Commercialization measure: Development of regulations and standards for vessel building to provide guidance.	4.5

Table 8: Assessments and measures related to retrofitting of hydrogen-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Retrofitting	Retrofitting	5.0	2.0	It may be a possibility for hydrogen carriers, but there may be challenges in retrofitting nonchemical carriers. Such services are not widespread. The technology readiness level is TRL 5. Due to the lack of commercial projects, the commercial readiness level is CRI 2. One panelist mentioned that The MAN ES ME-C engine could be modified to run on hydrogen.	No measure was provided, but the Delphi panelists agreed that there is a need for technological development and commercial scaling.	

Table 9: Assessments and measures related to propulsion of hydrogen-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Propulsion	Hydrogen engines	7.0	1.0	Hydrogen engines are at an initial research level, but not for ships, although there is some interest in Japan. For hydrogen engines the technology readiness level is TRL 7. Sine there is no actual ongoing demonstration projects, the commercial readiness level is CRI 1.	No measure was provided but the Delphi agreed that there is a need for technological development and commercial scaling.	
	Design of pilot/ignition used by hydrogen engines	7.0	N/A		No measure was provided but the Delphi agreed that there is a need for technological development.	
	Hydrogen fuel cells	7.0	2.0		Innovation and demonstration for H2 fuel cells as well as new engine designs to accommodate the volumes and pressures and safety comes with this new fuel.	4.6
					Research and development of solid oxide fuel cells (SOFC) technology compatible with H2.	4.7
					Improvement in power density of the fuel cell system (equal to or larger than current engines).	4.0
	Hydrogen auxiliary engines	7.0	N/A	The provided feedback points to the fact that auxiliary engines in practice would be fuel cells, which are at TRL 7.	No measure was provided, but the Delphi agreed that there is a need for technological development.	
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Demonstrations on shorter routes are to be investigated further, for instance, through a small-scale project like tender boat or commuting boat, for verification of fuel and bunkering system feasibility.	4.3
					Demonstration of real-life shipping route moving cargo fueled by a hydrogen engine or fuel cell.	4.3

Table 10: Assessments and measures related to onboard fuel storage and safety for hydrogen-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Onboard fuel storage and safety	Onboard fuel storage	7.0	2.0	Although, some concerns were expressed that technological and safety aspect for cargo vessels is not proven at TRL 7. In terms of onboard hydrogen fuel storage, the technological readiness score is TRL 7. Onboard storage of hydrogen is currently possible, but it is an emerging and not a mature technology. The commercial readiness is CRI 2.	Further developments of safety aspects of operating on hydrogen, including demonstration of 100% leak-free pipe installation products for safe hydrogen distribution (tank to consumers).	4.5
					Further research and development of detection, censors etc. Fast detection and communication methods.	4.3
					Technical demonstration of prototypes of advanced LH2 tanks whose shape and insulation properties are optimized for marine applications. All the LH2 tank technology was developed for land-based uses, not marine. More flexibility in the shape of LH2 tanks (not just cylinders) would help.	4.3
					Commercialization measure: Clear rules for using hydrogen in vessel installations, covering requirements for maintenance and emergency procedures and safety considerations for crew and passengers.	4.7
					Commercialization measure: Research and development into the impacts of the large volume of space that hydrogen would require, due to its volumetric H2 density 7.5 kg-H2/500L.	4.8
	Cooling for onboard storage of hydrogen fuel	4.0	1.0	Hydrogen is not used greatly in the maritime sector. However, some feedback suggested that hydrogen has been cooled and used as fuel for decades and is used in some niche industries, like space. In terms of cooling for onboard storage of hydrogen fuel, we have allocated a technology readiness score of TRL 4, given the level of readiness and high amounts of energy needed. The commercial readiness of the cooling is CRI 1.	Demonstrate safe handling and storage, including. boil of gas i.e. when fuel heats up and needs to be released.	5.0
					Research on how to optimize the compression and storage of hydrogen at low temperatures and high pressures, including research on how low temperatures can make steel structures and cylinders brittle.	3.7

Table 11: Assessments and measures related to crew safety and management for hydrogen-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance scores
Crews	Crew safety and management	N/A	1.0	Regarding crew safety and management, we consider the commercial readiness to be CRI 1. The necessary training and standards have yet to be developed to ensure safe management of hydrogen as a fuel. However, of course, knowledge is available on the transport of ammonia as a commodity, which should support efficient development of standards.	Commercialization measure: Establishment of educational programs for the safety training of crews.	4.3

Table 12: Assessments and measures related to emissions from hydrogen-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance scores
Emissions	Technologies to minimize emissions	7.0	1.0	In terms of preventing emissions from the use of hydrogen as a fuel, we have allocated a technological readiness score of TRL 7. NOx and particle emissions can be eliminated when using hydrogen fuel cells. Green hydrogen has zero carbon emissions. Given the lack of ships that use hydrogen as a fuel, we have given a score of CRI 1.	Research into how to reduce NOx with hydrogen engines.	4.5
					Commercialization measure: Regulation, tests and demonstrations are needed on safety measures to prevent slips, e.g. ventilation, remote control stop off valves and location of piping in separated spaces.	5.0

4.2 Green ammonia

Green ammonia is a newly proposed fuel for the maritime sector. It is currently transported as a commodity, so there is existing experience in port handling and onboard storage (but not as a fuel). Ammonia can across the value chain be viewed as a fuel that can be ready within a timeframe of 3-4 years, based upon the consolidated assessments cf. table 13. The main technological requirements are in terms of vessel operations and proving the operational behavior. This is showcased in table 13, which illustrates the average TRL score across the value chain.

The feedback from the Delphi panels highlights the need for further commercialization across the full value chain, if ammonia is to be a viable alternative fuel for the maritime sector. Further innovation is welcomed to ensure green ammonia at a fair cost e.g. technological development of electrolyzers for green hydrogen could reduce capital and operational costs of ammonia production. Efficiency of nitrogen capture is also an area for innovation. Innovation of green hydrogen production methods would also be beneficial for production of other e-fuels and HVO diesel.

Box: Characteristics of green ammonia fuel

Ammonia is a compound of nitrogen and hydrogen produced through an electrolysis process. Ammonia can be used in liquid form as a green, zero carbon fuel, however with lower energy density than traditional fuels. A key aspect is the production of competitive and consistent green hydrogen through electrolysis, which is a highly energy intensive process. Ammonia is already an established commercial product and green ammonia production is under development on an industrial scale in several world locations.

The current level of green production of ammonia fuel is limited, as reflected by the consolidated assessments in table 13. Further demonstration projects are needed to strengthen the market knowledge on the operational behavior.

Ammonia gas is highly corrosive to certain metals and compounds, as well as toxic, and is therefore associated with major safety dilemmas. Ammonia can cause burns, lung damage and, in worst case, be deadly. Serious concerns were raised by the panelists across the value chain about the toxicity and safety around ammonia. However, it is moderated by the current transportation of ammonia as a commodity. Further development of the required technological safety mechanisms and legal frameworks are to be developed. These issues are reflected in the assessments across the value chain. These are mostly reflected in the assessments of the commercial readiness, cf. table 13.

The chemical composition of ammonia includes hydrogen atoms – i.e. ‘once cracked’, ammonia can be an efficient fuel source. Compared to hydrogen, ammonia storage is more practical, due to its energy density and liquefaction temperature. Ammonia liquid can be stored at room temperature (unlike hydrogen).

The consolidated assessments for bunkering of ammonia fuel indicates a high technological readiness, cf. table 13, but the obstacles and issues regarding safety and toxicity need to be addressed. Likewise, there is the gap that bunkering of ammonia fuel has not been proven on a commercially sustained basis. The fact that ammonia currently is being used as a commodity in agriculture and industry means that as demand from other sectors grows, green ammonia will be transported via ports. There are already global supply chains for the handling of ammonia as a commodity, which to some extent can be inferred to the supply of ammonia fuel.

When assessing the operations of vessels powered by ammonia there are both technological and commercial gaps to be filled, as indicated by the consolidated scores in table 13. The propulsion systems that use ammonia require further development. This is the case for both fuel cells and engines systems. Furthermore, there needs to be developed systems to handle the nitrous oxide emissions. The scores reflect that there is a general need for demonstration projects to strengthen the knowledge of the operational behavior of ammonia across the value chain and guide further development, cf. table 13.

Table 13: Average TRL and CRI scores of technologies for ammonia by value chain part

	Fuel production		Bunkering		Vessel operations		Average	
	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*
Ammonia	8.2	2.8	8.0	2.0	5.7	1.3	7.0	1.9

In the following parts we summarize the results of the assessments for ammonia for each part of the value chain and the corresponding sub parts.

4.2.1 Fuel production

Key requirements of green ammonia fuel production

Feedstock requirements

The production of ammonia fuel requires two main feedstock components.

I. Hydrogen separated from water via electrolysis, and nitrogen obtained from air using a separation process.
II. Renewable energy

Fuel production

Using renewable energy, green ammonia is produced via the Haber-Bosh process. In simple terms, the process entails the reaction of hydrogen and nitrogen at high temperatures and pressures with the aid of a catalyst to produce ammonia, NH_3.

Green ammonia production is a well-known technology. For instance, Norway produced green ammonia until the 1990's using hydropower (until the arrival of gas). Also, other sites have provided green ammonia at industrial scale. So, there is some prior experience. Therefore, green ammonia production can benefit from established technologies such as the Haber-Bosch process. However, new methods are needed for electrolysis. Air separation may not be needed, as new electrolysis methods can produce the gases needed for ammonia. Green ammonia production facilities are planned or are at an early stage of scale up. However, they have not yet reached full technological or commercial readiness, thus green ammonia is not available with competitive prices and industrial scale to the maritime sector.

Projects to further the development of the needed infrastructure and facilities to produce green ammonia are planned or already being demonstrated, cf. box 4.

Box 4: Selected examples of demonstration and production projects

- **Alfa Laval, Hafnia, Haldor Topsoe, Vestas, and Siemens Gamesa** has published a joint report on ammonia as marine fuel. “Ammonfuel - an industrial view of ammonia as marine fuel”
- **Vestas** (Denmark) is developing a 10 MW power green ammonia site in West Jutland.
- **Chile:** Aker and Mainstream have signed a letter of intent in 2021 to develop a green ammonia production site.
- **Norway:** Yara and Nel will launch “next generation” alkaline 5MW electrolyzer at an ammonia production site in 2022.
- **UAE:** Helios industry will develop an 800MW green ammonia production site at Khalifa Industrial Zone Abu Dhabi (KIZAD).

Examples of green electrolysis for ammonia include:

- **Thyssenkrupp** will supply a 20MW alkaline electrolysis plant for green ammonia and hydrogen production by 2023. thyssenkrupp to supply 20MW electrolysis plant to CF Industries for green hydrogen for green ammonia production – Green Car Congress
- **Haldor Topsoe** is developing a facility using solid oxide electrolyzer cells (SOEC) to be ready by 2024. Haldor Topsoe and Aquamarine enter into a Memorandum of Understanding with the purpose of building a green ammonia facility based on SOEC electrolysis
- Examples of projects that seek to optimize electricity use for electrolysis include ABB’s work on high powered rectifiers for electrolysis. ABB and Hydrogen Optimized to explore development of large-scale green hydrogen production systems
- There is indication that air separation is not required using new electrolysis methods. Green ammonia: Opportunity knocks | Argus Media
- Produce Green Hydrogen with The AEM Electrolyzer | Enapter

Technological assessment and gap

The feedback from the Delphi panelists indicated that ammonia production is a technologically ready process, indicated by high scores e.g., air separation technologies (TRL 9.0), Alkaline electrolysis needed to obtain hydrogen (TRL 9.0), and Haber-Bosch process to combine nitrogen and hydrogen (TRL 9.0). Hence, there is not a major technological gap concerning efficiency of ammonia production, but further innovation is welcomed e.g. technological development of electrolyzers for green hydrogen could reduce capital and operational costs of ammonia production.

Commercial assessment and gap

With respect to green ammonia production specifically, i.e. using renewable energy, there remains a major commercial readiness gap. There are green ammonia production prototypes undergoing testing and demonstration, which are considered TRL 7.0 and CRI 2.0. Regarding the production and usage of green ammonia, commercialization measures were seen as key, considering the importance scores.

Table 14: Assessments and measures related to feedstock for fuel production of Ammonia

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Feedstcok	Technologies to optimize electricity use for electrolysis e.g. high-powered rectifiers	8.0	2.0	Technologies to optimize electricity use for electrolysis e.g., high powered rectifiers, are at TRL 8 and CRI 2. There are some trials ongoing that appear to suggest that innovation is needed in this area.	No measure was provided, but the Delphi agreed that rectifiers were at TRL 8, suggesting some room for improvement.	
	System prototypes for green electrolysis methods	7.0	2.0	System prototypes for green electrolysis methods are currently being tested in operational environments and are considered as TRL 7. We consider green electrolysis to be at the commercial trial stage or CRI 2.	No measure was provided, but the Delphi agreed that rectifiers were at TRL 7, suggesting some room for improvement.	
	Technologies to separate nitrogen from air	9.0	5.0	Technologies to separate nitrogen from air are well established and do not need much innovation for green ammonia production. They are currently subject to commercial trials, indicating a high commercial readiness It was stressed that nitrogen is produced widely for sale today. Although, currently we have not been able to identify that this is done extensively using renewable energy.	No measure was provided, but the Delphi panel agreed that TRL 9 and CRI 5 were correct.	
	PEM water electrolysis methods	8.0	3.0	Enapter announced mass production of AEM water electrolyzers starting end of 2022, with 120,000 modules per year. 440 units provide a containerized 1 MW electrolysis system. PEM water electrolysis also has been demonstrated by several companies on a commercial scale (Siemens, Nel etc.).	Further development of the processes used to combine atmospheric N2 and H2 from seawater, with focus on increasing efficiency and reducing costs.	3.4
					Further innovation into alternatives to PEM electrolyzers, with a focus on reducing costs.	4.3
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Electrolyzers: Further development and testing of SOEC electrolyzers to improve the stability and durability.	3.9
					Air separation: Further development and testing of ammonia synthesis with regards to the needs for compression and separation, with the purpose of increasing the energy efficiency.	3.4
					Air separation: Development of cryogenic separation or pressure swing absorption to reduce inefficiencies for both processes in the production of nitrogen.	3.0

Table 15: Assessments and measures related to fuel production and facilities for ammonia fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel production and facilities	Haber-Bosch process	9.0	2.0	The Haber-Bosch process is a mature technology. However, green ammonia production facilities are at an initial stage of commercial scale up, therefore when considered in this context the commercial readiness of the Haber-Bosch process needs further development to ensure global availability.	Development of alternatives to the Haber-Bosch process, that could bring production costs down.	3.7
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Commercialization measure: Demonstrate the viability of technologies needed for the electrification of the ammonia process.	4.4
					Commercialization measure: Demonstration across the value chain is needed to ensure the viability of ammonia as a marine fuel.	4.2
					Commercialization measure: Development of international standards for safe fuel production, handling and downstream operations.	4.7
					Investment finance for scale up of green ammonia sites.	4.4
					Engagement and involvement of stakeholders, notably seafarers and port communities to address safety concerns.	4.8

4.2.2 Bunkering

Key requirements for green maritime fuel bunkering, storage and transport

Ammonia is a commercially demanded chemical, which currently is being transported to and bunkered in ports as a commodity. Therefore, safe and proven technologies already exist, for example, pressurized or cooled cylinders to transport and store liquid ammonia. However, given that ammonia is not bunkered as a fuel, there remains technological and safety gaps concerning transferring ammonia to the fuel storage system of a cargo ship, among other things. Bunkering ammonia fuel could take place at the same time as moving cargo. Bunkering of ammonia as a commodity currently takes place in dedicated ports that have tested safety approaches to allow both processes to take place simultaneously. Bunkering of ammonia fuel is possible via truck, tank or ship.

There are serious health and environmental requirements, which need to be met in order to make ammonia a commercially viable fuel. This is due to ammonia being a toxic substance and hazardous to both people and water quality. Especially the storage of ammonia is subject to tight safety restrictions, for example, residential properties must be at a safe distance from the sites. Public concerns and international and national regulations need to be considered to ensure effective take up. Spillage in the sea is a major risk and will result in irreversible damage. The risks may be too great for some countries to allow ammonia fuel carriers to dock. The panel highlighted the need to focus on these risks for the crew, public and the environment.

Projects to further the development of the needed infrastructure and bunkering for ammonia as a fuel is planned or already being demonstrated, cf. box 5.

Box 5: Selected examples of the readiness of the technologies

- Brown ammonia is already a transported commodity that is stored at ports. Green Ammonia | Sustainable fuels | DFDS (INT)

There are plans to launch ammonia fuel bunkering:

- **Singapore:** In 2021, Maersk and Yara will undertake a feasibility study for a ship-to-ship bunkering base in 2021. Maritime industry leaders to explore ammonia as marine fuel in Singapore (maersk.com)
- **Japan:** In 2021, Itochu, Itochu Enex, and Ube Industries announced the launching of production and bunkering operations. ITOCHU Announces Supply of Marine Ammonia Fuel in Japan and Joint Development of Supply Sites | Press Releases | ITOCHU Corporation
- **Japan:** NYK Line is working on a project to develop a floating bunkering system for ammonia fuel.
- Joint R&D Starts for Use of Ammonia in Marine Transportation to Reduce GHG Emissions | NYK Line
- **Japan:** NYK LINE has started the Ammonia-fueled Tugboat project, which includes the development of an ammonia-fueled engine, containment system, and demonstration of bunkering system (truck to ship). Joint R&D Starts for Practical Application of Ammonia-fueled Tugboat | NYK Line

Technological assessment and gap

Technological assessment and gap: the feedback from the Delphi panelists indicated that transporting ammonia as a commodity is technologically well-known, as indicated by high scores (**TRL 9**). The experience of transporting ammonia as a commodity can be used for ammonia bunkering systems, but there are some significant safety problems to overcome, which require both technological and commercial development, the latter in terms of developing the regulatory framework and assessing the safety implications further (**TRL 7**). The panel highlighted that there is a need for further demonstration of bunkering while loading cargo, as well as safe piping and control systems.

Commercial assessment and gap

Some of the main barriers for the scale up of ammonia bunkering concern commercialization aspects. A key issue is gaining the approval of ports to bunker ammonia (especially ones that do not bunker ammonia as a commodity), which would be assisted if relevant rules and standards for bunkering were in place.

Table 16: Assessments and measures related to fuel transport of ammonia fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel transport	Systems for storing and transporting ammonia	9.0	3.0	The systems needed to transport and store ammonia are at TRL 9, given their existing extensive use in the trade of ammonia as a commodity. This experience can be used for storing ammonia to be used as a fuel. The commercial readiness to store and transport ammonia as a fuel is CRI 3, given the need to further scale up the infrastructure to meet future fuel demands.	Further development and testing of ammonia transfer in different types of tanks e.g. from Type-A or B to Type-C tank (Semi-refrigerated or fully refrigerated to pressurized tank).	4.0
					Supply tanks and fuel system piping needs to be doubled, with introduction of sensors to detect leaks before they enter into the engine space.	4.2

Table 17: Assessments and measures related to port and bunkering storage and supply facilities for ammonia fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Port and bunkering storage and supply facilities	Commercial ammonia bunkering	7.0	1.0	Given the safety concerns, there is an engineering challenge related to safety and commercial testing of bunkering ammonia fuel. Therefore, the current stage of development is TRL 7. Currently, there are plans to test commercial ammonia bunkering, but these have not been launched yet. Therefore, bunkering of ammonia fuel remains a hypothetical proposition and is at CR 1.	Demonstration of more proven concepts for bunkering vessels with ammonia to ship-to-ship fueling while loading/unloading cargo.	4.2
					Remote control systems to control the shut off valves in case of leaks when transferring fuel.	3.8
					Demonstration of the port infrastructure and supply chain i.e. green logistics and expertise to support green ammonia fuel supply from ports.	4.3
					Innovation and testing are needed in order to cope with the increased frequency at which ships have to bunker, due to limitations on fuel efficiency.	3.8
					Commercialization measure: Development and testing of international safety frameworks for bunkering ammonia.	4.7
					Commercialization measure: Promoting scale up – global availability of ammonia bunkering infrastructure is needed to ensure global uptake.	4.0
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Commercialization measure: Assessment of barriers to social acceptance of ammonia with regard to safety concerns.	4.0

4.2.3 Vessel operations

Key requirements for onboard fuel storage, safety and emissions of green ammonia

In terms of onboard ammonia fuel storage, the toxic and corrosive properties of the fuel will need to be accounted for. Pressurized tanks can be used for storage, but ammonia will require much more storage space, given its lower energy density compared to current and traditional marine fuels. Key safety issues for the storage of ammonia include the need to prevent ammonia slip, installation of ammonia detectors, ventilation, pressure relief system (or the fuel can be cooled), remotely operated isolation valves, route piping at a sufficient distance from the side shell, locating piping in separate unmanned spaces, master gas valves to protect the engine, gas combustion unit, airlock for access in the storage tank and two pumps/tanks but one storage space. Solutions for storing ammonia as a fuel require significant development to address the safety concerns.

Regarding crew safety and management, crews will need to be trained in handling ammonia safely as a fuel. It is likely that new regulations and standards will need to be introduced to ensure safe onboard management.

The issue for ammonia is a need to address the higher concentration of NOx emissions. These need to be controlled either by after-treatment or by optimizing the combustion process. NOx can be dealt with using selective catalyst reduction. N_20 emissions needs to be controlled by catalysts.

Key requirements for ship design, propulsion and retrofitting of green ammonia

The naval architecture for ships fueled by ammonia requires design, engineering and safety adaptations given the need to carry a higher volume of fuel, account for the risks associated with ammonia, and ensure sufficient cargo space. Moreover, there is a question around whether the initial vessels that use ammonia fuels would be limited to carriers that carry ammonia as a commodity. There may be further design challenges around ensuring that ships that carry other types of cargo can use ammonia as a fuel.

For propulsion, new ammonia engines or ammonia fuel cells are needed. A green pilot fuel or ignition promoter are also needed to meet the targets. Currently no such solution is available to the market. Ammonia has poor ignition and very slow flame propagation speed compared to other fuels. This must be subject to further investigation. For instance, dimethyl ether could be mixed into ammonia for ignition. Given the high autoignition temperature, the dual-fuel approach in a diesel turbocharged multicylinder engine can potentially overcome this issue. The octane rating of ammonia is much higher compared to gasoline, making it preferable to run at a higher compression ratio. Auxiliary engines may require innovation, as there seems to be less reported developments in this area.

The possibilities for using solid oxide fuel cells should also be considered. While the technology does exist, cost and durability of solid oxide fuel cells are a major issue. They have a lower TRL than engines, but they present some benefits, for example aftertreatment and, when compared to medium- and high-speed engines, lower fuel consumption and hence reduced operational costs. That said, for large vessels using a slow speed diesel (SSD) today - assuming SSDs can achieve a comparable efficiency using ammonia to what today's diesel-fired engines burn - the efficiency of a SSD and a solid oxide fuel cell is comparable. So, given the higher expected capital investment of a solid oxide fuel cell, it seems likely that SSD engines will remain the preferred solution. In sum, there is a limited track record of using ammonia as a fuel and no current commercial availability of ammonia fuels cells or engines.

Retrofitting requires commercial availability of green hydrogen engines or fuels cells that can be installed into the existing ship fleet. Technical solutions and installation services will need to be made available. Green pilot fuels for retrofitting are also needed. However, no such solutions or services currently exist on the market. The panel stated that all MAN ME-C engines can be retrofitted to include the use of ammonia fuel.

Projects to further the development of the needed technological and commercial availability are being developed over the coming years, cf. box 6.

Box 6: Selected examples of demonstration and production projects

There are plans to develop ammonia carrying vessels

- **New Times Shipbuilding Co** is building a SuezMax tanker in China that follows the ABS Ammonia Ready Level 1 Requirements. ABS-Classed Suezmax is World's First Ammonia Ready Vessel - American Bureau of Shipping (cision.com)
- **Lloyds Register** announced compliance assessment projects for a 23,000 TEU Ultra-Large Container Ship (ULCS) and 180,000-ton bulk carrier both with two stroke ammonia engines.
- Lloyd's Register awards Approval in Principle to ammonia-fuelled 23,000 TEU ultra-large container ship - (fathom.world)
- **ABS** announced an Approval in Principle carrier of 2,700 TEU capacity with a two-stroke ammonia engine. Maritime Sector is Set to Become 'Ammonia-Ready' - Ammonia Energy Association

There are plans to develop green ammonia engines, but it is not clear if these will use green pilot fuels. Green ammonia auxiliary engines do not seem to be in the pipeline yet.

- **Wärtsilä with Knutsen OAS Shipping AS, Repsol and Sustainable Energy Catapult Centre** are planning to test ammonia in a marine four-stroke engine, under the Norwegian Research Council through the DEMO 2000 program. Wärtsilä has already performed some initial tests of ammonia in dual-fuel and spark-ignited gas engines, which will be followed by field tests in collaboration with ship owners from 2022. Wärtsilä, Repsol, and Knutsen to test ammonia four-stroke engine - Ammonia Energy Association
- **MAN Energy solutions:** MAN has announced that it will conduct first R&D engine tests on ammonia in full size in 2022 and demonstration of a full engine test including emission aftertreatment to the market in 2023 or 2024 with availability of production engines from 2025.

There are planned solutions for retrofitting

- **MAN Energy Solutions** has indicated that it will launch a green ammonia retrofit engine solution for existing ships by 2025. The Motorship | MAN ES unveils 2025 ammonia retrofit target
- **Viking Energy,** a Norwegian supply ship, used by Equinor for offshore operations, will be retrofitted with ammonia fuel cells and will be ready in 2024. The world's first high-temperature ammonia-powered fuel cell for shipping (fraunhofer.de)
- **Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (DK)** is currently undertaking research on ammonia safety. Industry leaders collaborate to develop guidance on the safe use of Ammonia as a shipping fuel

Technological assessment and gap

The feedback from the panel indicated some uncertainty about the feasibility of ammonia vessel operations. While there is experience in transporting ammonia as a commodity, there is little knowledge of how ammonia can be used safely as a fuel. On-board fuel safety technologies are not yet developed/used widely, as indicated by the assessments agreed upon by the panel (TRL 7.0 and CRI 2.0). The panel states that there needs to be focus on the management of emissions, especially nitrous oxide (N_20) a GHG (TRL 5.0 for N_20). Existing selective reductive catalysts are effective for NOx removal (TRL 9.0). There are three main gaps, which have been identified by the panel 1) lack of knowledge on operational behavior 2) need for new failsafe safety technologies 3) development of appropriate emission control systems.

There is consensus around the ship design being close to technologically ready, as some vessel designs have been approved (TRL 8.0). There are challenges with both fuel cells (TRL 5.0 and CRI 1.0) and engines using green pilot fuels (TRL 5.0 and CRI 1.0), these are not seen as being ready for the market. The main technological uncertainties are around the optimal way to burn ammonia efficiently in auxiliary engines (TRL 4.0). As for retrofitting, the technological readiness is low, but there are signs of improvement with some MAN retrofit engines under development (TRL 5.0 and CRI 1.0).

Commercial assessment and gap

Commercial assessment and gap: The panel indicated that the low commercial availability constitutes a barrier for the further development of ammonia as a fuel. The safety standards and protocols around the safe use of ammonia are yet to be defined (CRI 1.0).

Commercial assessment and gap: Commercial scaling needs to overcome some key barriers. It is interesting that the panel for vessels also stressed the issue of gaining the social acceptance of ammonia (like the bunkering panel). Again, developing safety standards are seen as key to helping the industry learn the necessary protocols, and the issue of examining the impact of additional fuel space on cargo costs was mentioned again.

Table 18: Assessments and measures related to ship design of ammonia-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Ship design and building	Ship design and building	8.0	2.0	In terms of ship design and building, currently green ammonia-fueled ships are planned for manufacturing and commercial distribution. It seems that some designs have been approved in principle by third parties. Therefore, the commercial readiness is CRI 2. Yet, there are engineering challenges in ensuring vessel safety for commercial use, but likely a limited innovation challenge. There may be challenges in ensuring ammonia can be used as a fuel for ships that do not carry ammonia as a commodity. Therefore, technological readiness is TRL 8.	Full-scale demonstration of ammonia engine safety and emissions.	4.8
					Further research and testing of how to keep lowering costs, e.g. in terms of redundant systems, double piping, sensors etc.	4.5
					Full-scale demonstration of normal commercial operation.	4.8
					Commercialization measure: Research into what impacts the bigger storage tanks for fuel onboard the vessels will have on the space for cargo.	3.8

Table 19: Assessments and measures related to retrofitting of ammonia-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Retrofitting	Retrofitting	5.0	1.0	Considering the feedback that there is a possibility of retrofitting the MAN ME C engine, we have allocated a score of TRL 5 and CRI 1. There seems to be possibilities to retrofit engines to use ammonia, but seemingly there is some way to go before we see developments on the market.	Further innovation and testing are required in terms of investigating the possibilities of applying the special coating/lining to convert the current HFO tanks to Ammonia storage tanks.	4.0

Table 20: Assessments and measures related to propulsion of ammonia-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Propulsion	Engines using green pilot fuels	5.0	1.0	Regarding propulsion, there are plans to launch ammonia engines and fuel cells. The fundamental question is how to burn ammonia efficiently in an internal combustion engine for the main and auxiliary engines. That it is possible in small engine tests. How to do it in an optimal way for the industry is still a somewhat open question.	Clarification of maintenance requirements for ammonia engines.	4.6
					Development and testing of a final engine concept in an operational environment.	4.8
	Ammonia fuel cells	5.0	1.0		R&D on how ammonia affects the duration of fuel cell performance and durability.	3.3
	Ammonia auxiliary engines	4.0	1.0		No measure was provided but the Delphi agreed that there is a need for both technological and commercial development.	

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
	Not directly linked to the technology assessments, but were recommended as supporting measures				Development of engines that can run on multiple fuels e.g., ammonia, hydrogen and diesel.	4.3
					Demonstration of burning ammonia in internal combustion engines.	4.8

Table 21: Assessments and measures related onboard fuel storage and safety for ammonia-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Onboard fuel storage and safety	Onboard ammonia fuel storage	7.0	2.0	In terms of onboard ammonia fuel storage, the technological readiness score is TRL7. On the one hand, safe carriage of ammonia as a commodity already operates on a commercial scale. Yet, with regard to ammonia fuel use, there needs to be consideration of the supply tank and fuel supply system. This does not require major innovation but rather commercial development testing. Considering that vessels using ammonia as a fuel are planned and under development (as indicated in an early part of the survey), the commercial readiness is CRI 2.	Demonstration of on-board safety and failsafe solutions to reduce risks related to ammonia fuel.	4.8
					Development of fuel system piping to include sensors for detection of leaks before entering the engine space.	5.0
					Commercialization measure: Define the barriers to social acceptance.	3.5
					Commercialization measure: Establishment of international regulation for the use of ammonia fuel.	4.8

Table 22: Assessments and measures related to crew safety and management for ammonia-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Crews	Crew safety and management	N/A	3.0	The necessary training and standards have yet to be developed to ensure safe management of ammonia as a fuel. However, of course, knowledge is available on the transport of ammonia as a commodity, which should support efficient development of standards.	Commercialization measure: Development of safety design standards, safeguards, operational guidelines and training of personnel (e.g. for specific engine types such as solid oxide fuel cells (SOFC)).	5.0
					Commercialization measure: Investment in standards for crew safety and training.	4.5

Table 23: Assessments and measures related to emissions from ammonia-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Emissions	Technologies to control NOx emissions	9.0	2.0	There is a low innovation need related to removal of NOx. A selective catalyst reduction can be used. The technological readiness is TRL 9. Vessels using green ammonia fuel are in production but not yet launched, CRI 2.	No measure was provided, but the Delphi agreed that there is a need for commercial development.	
	Technologies for controlling N20 emissions	5.0	N/A	The technological readiness of methods to control N20 is TRL 5. N20 catalysts are at an early stage of development and are associated with some uncertainty. So, further ammonia combustion strategies should be tested. Lean burn testing has resulted in the detection of N20 emissions. Further research is needed to see if lean burn can work.	Further testing of lean burn technologies to address N20 emissions.	4.5
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Research and testing into how to reduce emissions from ammonia production and fuel use, including NOx, NH3 slip, and N2O technologies to manage on-board toxicity.	4.8
					R&D on the extent of the pollutants produced by fuel cells and ICs.	4.25

4.3 E-Methanol

The assessments indicate that e-methanol to a large extent is technologically ready. The same goes for the commercial readiness, although in relation to the competitiveness there are still significant improvements to be made in terms of commercial scale up, cf. table 24. This is mainly due to lower technological readiness for the propulsion of methanol-powered vessels. The primary technological advancement seems to be in terms of furthering the development of e-methanol fuel cells and further demonstration projects in operational settings.

A potential cost issue is the future competition with the aviation sector for this fuel. Another concern raised by the panel was the uncertainty around the price of e-methanol derived from carbon capture. There is a need for technological development for these technologies and systems in order to make e-methanol more commercially viable.

One of the issues in terms of the sustainability for e-methanol is that it uses carbon as an input. This can be obtained from waste CO2 from industrial sites or carbon capture from air (CO2 will however be lower) – however, as industry decarbonizes, this source will diminish and could become more expensive. This source of CO2 is not part of the natural carbon cycle, unlike biomass (although perhaps could be subject to carbon accounting methods). Secondly, the technologies needed for carbon capture to be a viable and cost-effective solution are at a relatively low technological readiness level, hence, there is a need for further development.

Box: Characteristics of e-methanol fuel

Methanol consists of hydrogen, oxygen and carbon atoms. It also naturally occurs in many living organisms and can therefore also be produced as a green fuel from renewable sources, i.e. from plants. Methanol is easily biodegradable and liquid at room temperature, but is also a hazardous chemical, highly flammable and toxic. Methanol is already being used for different purposes and experience therefore already exists. Methanol can also be transformed into DME.

The bunkering of e-methanol has a high technological readiness, cf. table 24. One significant advantage is that e-methanol is a liquid at room temperature, which means that it can be handled safely with existing technology (and production could be at a distance from ports). Experience with existing maritime liquid fuels can inform the approach to bunkering. Methanol is currently stored as a commodity at over 100 ports globally. This should, all things being equal, help to reduce the operational costs of bunkering e-methanol.

The fuel is toxic if ingested or absorbed through the skin. There are, however, less safety risks and protocols to be addressed when dealing with e-methanol, in comparison to hydrogen and ammonia. This is reflected in both a higher technological and higher commercial readiness, as stated in table 24.

In terms of propulsion, there is an e-methanol compatible engine on the market currently. The low consolidated readiness for vessel operations, is due to the inclusion of assessments and corresponding measures for other propulsion systems, i.e. fuel cells, which are less developed. The existing MAN LPG engines can be used for e-methanol. Auxiliary engines, however, have not been approved.

E-methanol releases CO_2 when burned, although in much lower amounts than diesel. Another benefit is lower emissions of both Sulphur and NOx.

Table 24: Average TRL and CRI scores of technologies for e-methanol by value chain part

	Fuel production		Bunkering		Vessel operations		Average	
	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*
E-methanol	9.0	2.0	9.0	2.5	7.1	2.0	7.6	2.1

In the following parts we summarize the results of the assessments for e-methanol for each part of the value chain and the corresponding sub parts.

4.3.1 Fuel production

Key requirements for e-methanol fuel production

Feed stock

The production of e-methanol fuel requires three main feedstock components.

I. Renewable electricity
II. Carbon dioxide (e.g. gathered via a carbon capture method from CO_2 emission sources).
III. Hydrogen, using electrolysis

Fuel production

It seems that some e-methanol sites are up and running, and companies like Thyssenkrupp manufacture infrastructure for e-methanol processing. Haldor Topsoe and Johnson Matthey also have technology for licensing in the area of green methanol. Haldor Topsoe started internal testing of CO_2 + H_2 for e-methanol synthesis 30 years ago and is a basis for Liquid Wind, cf. box 8.

Carbon capture technology was mentioned by an e-methanol producer as requiring further development. The feedback from the panel was subject to disagreements in terms of the technological readiness for producing e-methanol.

Projects to further the development of the needed infrastructure and facilities to produce e-methanol is planned or already being demonstrated, cf. box 8.

Box 8: Selected examples of demonstration and production projects

Justifications for the TRL and CRI scores

- Innovation Outlook: Renewable Methanol (irena.org)
- Saturday read: More than just a pipe dream – pv magazine Australia (pv-magazine-australia.com)
- Energy efficiency and economic assessment of imported energy carriers based on renewable electricity", Sustainable Energy Fuels, 4:2256 (2020). Energy efficiency and economic assessment of imported energy carriers based on renewable electricity - Sustainable Energy & Fuels (RSC Publishing)
- **Liquid Wind** (Sweden) has plans to produce e-methanol. eMethanol — Liquid Wind - eMPowering our Future.
- **CRI** (Iceland): produces e-methanol by combining renewable hydrogen and CO2 from a geothermal power plant. CRI - Carbon Recycling International
- **Accelor Mitatal** plans to build a 140 million EUR green methanol site in Belgium. Major green-methanol complex to be built in Belgium - Chemical Engineering | Page 1 (chemengonline.com)
- **Power to X** method of green methanol production. Green Methanol | Power-to-X | thyssenkrupp (thyssenkrupp-industrial-solutions.com)
- There is a planned commercial scale carbon capture test plant in Norway that aims to provide e-methanol. Commercial-scale ETL Plant Under Development in Norway — CRI - Carbon Recycling International
- E-methanol – the future fuel? (wallenius-sol.com)
- Methanol for a more sustainable future (topsoe.com)

Technological assessment and gap
The main technological gaps relate to the energy usage for electrolysis and carbon capture, even though both technologies are mature, as indicated by the assessments and the feedback from the Delphi panels. The main innovation need is lower production costs.

Commercial assessment and gap
Demonstration to illustrate the business case for using this fuel was suggested. Based on the feedback from the panel, an accounting method for the carbon emissions is needed. This is both from the carbon used as feedstock and, later on, also as emissions from burning e-methanol.

Table 25: Assessments and measures related to feedstock for fuel production of e-methanol fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Feedstock	Production of green hydrogen	9.0	2.0		Further developments and innovations into electrolysis for the production of hydrogen for e-methanol, with the aim of reducing costs.	4.8
	Carbon capture	7.0	2.0	Carbon capture technology has been noted as expensive and requiring further development TRL 7.	Further research, innovation for efficient carbon capture.	4.7
					Commercialization measures: Carbon sourcing at scale and methodology for LCA accounting.	5.0

Table 26: Assessments and measures related to fuel production and facilities for e-methanol fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel production and facilities	E-methanol processing (e.g. gas purification and compression, methanol synthesis, distillation).	9.0	2.0	The processing of methanol is at TRL 9 considering that such technologies are in use. Commercial readiness as commercial trials of E methanol production are underway but require further commercial scale up.	Demonstration of methanol synthesis from CO2/H2 with fluctuating energy input.	3.3
					Demonstrations of the complete production system using renewable electricity.	4.4
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Commercialization measures: Emission certificates.	3.8
					Commercialization measures: Investment to secure scaling of production. Sufficient amount of methanol must be available for marine purpose.	5.0
					Commercialization measures: Defining the business case for renewable methanol and the question of where the carbon shall come from in a fully decarbonized future.	5.0
					Commercialization measures: Establishment of regulations and standards to handle toxicity.	3.9

4.3.2 Bunkering

Key requirements for green maritime fuel bunkering, storage and transport

Methanol is stored and transported as a commodity currently. Methanol can use the same storage and transportation infrastructure as LPG (liquified petroleum gas), such as pressurized cylinders, pipes, pumps etc.

It has been possible to identity one methanol ship-to-ship bunkering demonstration, upon the time of writing this report. A vessel, all things being equal, also needs to bunker more often with methanol than with the traditional fuels because of lower energy density. An alternative is for a vessel to have much larger tanks on board. The bunkering methods constitute a main determinant for both the technological and commercial readiness.

Projects to further the development of the needed technological and commercial readiness are being developed over the coming years, cf. box 9.

Box 9: Selected examples of demonstration and production projects

- **NYK Group** has operated one methanol-fueled methanol/product tanker (MR class) and two methanol-fueled vessels are on order at Hyundai Mimpo Dockyards in Korea.
- The relative ease of storing, transporting and bunkering methanol is stressed in Innovation Outlook: Renewable Methanol (irena.org)
- **Stena Germanica (SE)**: developed a new technology for methanol bunkering. METANOL – FRAMTIDENS BRÄNSLE - Stena line
- **A collaboration of Port of Rotterdam, Vopak, NYK and TankMatch** recently launched the first barge-to-ship methanol bunkering operation in the world. First Barge-to-Ship Methanol Bunkering at Port of Rotterdam (gcaptain.com)
- **Green Methanol Cooperation (DE)**: Uniper, Liberty Pier Maritime Projects and SDC have recently formed an open collaboration to develop the infrastructure and logistics framework needed to supply methanol in Europe and establish the relevant shipping requirements.

Technological assessment and gap

Only minor modifications to existing infrastructure are needed, which bear a modest cost. While transferring and handling methanol as a commodity traditionally has taken place from land to ship, there are some demonstration projects of barge-to-ship methods for bunkering methanol as a fuel, e.g., at the Port of Rotterdam.

Commercial assessment and gap

The main issues concerned providing guidelines for bunkering and demonstrating the good supply of the fuel.

Methanol has significant potential, since bunkering of methanol is similar to marine fuels, such as heavy fuel oil, meaning that similar infrastructure can be used, which is an advantage due to the lower extra costs compared to other new fuel types.

Table 27: Assessments and measures related to fuel transport of e-methanol fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel transport	Systems needed to transport and store methanol as a fuel	9.0	3.0	The systems needed to transport and store methanol are at TRL 9, given their existing extensive use in the trade of methanol as a commodity. Systems used for LPG can be used to store and transport methanol. Therefore, the innovation requirement is very low. The commercial readiness to store and transport methanol as a fuel is CRI 3, given the need to scale up the existing infrastructure to meet future methanol fuel demands.	Further research and development is needed into corrosion of methanol tanks on board vessels that are powered by methanol and not only transporting it as cargo. Research and development is also needed on how to construct the supporting corrugation transverse and longitudinal bulkheads and external stiffener system, which are to minimize the free edge so as to ensure the corrosion preventive performance by zinc silicate coating.	4.5

Table 28: Assessments and measures related to port and bunkering storage and supply facilities for ammonia fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Port and bunkering storage and supply facilities	Bunkering e-methanol fuel	9.0	2.0	There has been tests of methanol bunkering via ship-to-ship. Other feedback points to benefits of methanol being able to use large parts of existing infrastructure for bunkering. The commercial availability of methanol bunkering infrastructure (e.g., by ship, truck and tank) is CRI 2. Existing solutions for methanol bunkering have been tested commercially, these do not require further innovation, although engineering activities are required to ensure scale up.	Demonstration projects of bunkering methanol fuel, both in ports and from ship-to-ship.	4.0
					Demonstration of existing bunkering infrastructure to promote cost efficiencies.	4.0
					Commercialization measure: Development of bunkering guidelines for ship-to-ship bunkering.	4.0
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Commercialization measure: Demonstrate that sufficient methanol fuel can be supplied to ports	4.7

4.3.3 Vessel operations

Key requirements for onboard fuel storage, safety and emissions of e-methanol

In terms of onboard e-methanol fuel storage, the key safety issues that need to be addressed are the same as for other gaseous fuels, e.g. detectors, tubing, distances etc.

Regarding crew safety and management, crews will need to be trained to handle e-methanol safely as a fuel. It is likely that new or revised regulations and standards will need to be introduced to ensure safe onboard management. Carrying methanol as a fuel requires some further commercial testing to ensure full safety e.g. to ensure safety around the supply tank and fuel supply system.

Using e-methanol as a marine fuel there should be a significant reduction in terms of the sulfur, particle, and nitrogen oxide emissions compared to diesel engine emissions. Furthermore, zero-emission is possible if produced from renewable energy sources and the pilot fuel is zero-emission. The total emissions are also dependent on the pilot fuel of choice, since e-methanol requires a pilot fuel.

Key requirements for ship design, propulsion and retrofitting of e-methanol

The naval architecture for ships designed to use methanol would not require a major redesign compared to current vessel designs. The energy density of methanol is half that of diesel, so therefore bigger tanks are needed as ships have to carry more fuel.

For propulsion by e-methanol, it will require that e-methanol burning engines use a green pilot fuel and auxiliary engines for the entire ship to be zero-emission. Fuel cells could also be developed in the future.

When dealing with retrofits, it is possible for existing vessels to be retrofitted with new methanol engines. Old engines can also be modified. As a low flashpoint fuel, there are fuel system design requirements such as double-walled piping to the engine. However, this has not been explored thoroughly.

Projects to further the development of the needed technological and commercial availability are being developed over the coming years, cf. box 10.

Box 10: Selected examples of demonstration and production projects

- Safety issues around using methanol fuel have been researched by the America Bureau of Shipping. Sustainability-Methanol-as-Marine-Fuel.pdf (safety4sea.com)
- The MAN B&W LGIM engine that used methanol offers good emission reduction potential. The engine is the methanol-burning version of ITS dual-fuel solution for liquid injection of fuels, the ME-LGI engine. It does not use a green pilot fuel however. Methanol (man-es.com).
- Recently, methanol converted by Stena Germanica has reduced harmful emissions. FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf

Building of ships that use methanol as a fuel is underway.

- **A.P. Møller – Mærsk** (Denmark) recently announced its first carbon-neutral vessel that will run on methanol. Maersk will launch the world's first carbon neutral container ship by 2023 (stateofgreen.com)
- Mærsk announced further that by Q1 2024 they will launch 8 large ocean-going vessels which can operate on carbon neutral methanol. A.P. Moller - Maersk accelerates fleet decarbonisation with 8 large ocean-going vessels to operate on carbon neutral methanol | Maersk
- **Proman Stena Bulk** expects delivery of a methanol-fueled 49,900dwt vessel in early 2022. Stena Bulk bolsters ECO MR fleet with additional newbuilding charters | Cyprus Shipping News
- **Waterfront Shipping Company** has announced eight new methanol-fueled dual-fuel ships to be built at Hyundai Mipo Dockyard and delivered between 2021 and 2023 in partnership with Marinvest, NYK, Meiji Shipping, KSS Line and Mitsui O.S.K. Lines. Waterfront Shipping orders 8 methanol dual-fuel ships from Hyundai Mipo Dockyard - Offshore Energy (offshore-energy.biz)
- **The MAN B&W LGIM** engine is the methanol-burning version of a dual-fuel solution for liquid injection of fuels, the ME-LGI engine.
  Methanol (man-es.com)

- Existing Stena Line ferry engines were modified to a dual fuel system that includes methanol, in cooperation with Wärtsilä
  ETIP-B-SABS 2 (etipbioenergy.eu)
- Methanol fuel cells are being tested at Alfa Laval Denmark. A carbon-neutral methanol fuel cell system is taking shape at the Alfa Laval Test & Training Centre | Hellenic Shipping News Worldwide

Technological assessment and gap

Storage systems were seen to be ready, given that current approaches can be largely used (TRL 8.0 and CRI 2.0). However, there were some concerns about the corrosive effects of methanol. Also, the impact of storing more fuel due to the lower energy density was mentioned as a key issue.

Emissions from methanol contain reduced levels of sulfur, particles, NOx and lower CO_2 emissions over the entire fuel lifecycle and can be zero-emission. There are current systems available that reduce emissions, such as those used by the MAN B&W LGIM. (TRL 9.0 and CRI 2.0). However, there are concerns that methanol should be considered as a transition fuel unless it is produced from renewables.

Ships designed to use methanol do not require a major redesign. The space for the additional fuel needs to be taken into account and several companies are now using, or have ordered, methanol-powered vessels (Maersk, Stena). Some methanol carriers also use methanol as a fuel. (TRL 9.0 and CRI 2.0).

Regarding propulsion, there is an engine on the market i.e. the MAN LPG engine (TRL 9.0 and CRI 2.0). However, the auxiliary engines are not yet approved (TRL 5.0) and green pilot/ignition fuel still needs development (TRL 5.0)

Methanol fuel cells are under development (TRL 5.0). These are being tested by e.g. Alfa Laval in Denmark.

Commercial assessment and gap

ABS has published guidance on methanol as marine fuel[3], that addresses some of the challenges in design and operation of methanol-fueled vessels. Yet a more specific safety standard was requested. (CRI 2.0)

[3] Please see Sustainability Whitepaper: Methanol as Marine Fuel (ABS.com)

Table 29: Assessments and measures related to ship design of e-methanol-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Ship design and building	Ship design and building	9.0	2.0	In terms of ship design and building, there is ongoing construction of ships that use methanol as a fuel source. The technology readiness level is TRL 9. There is not a widespread commercial availability of methanol-based ships on the market. The commercial readiness score is CRI 2.	The effect of larger stowage tanks must be analyzed. Will this result in less cargo and thereby a lower energy efficiency (energy per cargo unit)?	4.0
					Commercialization measure: Development of safety standards to be commercialized via IMO, which are to include design specifications.	4.75
					Commercialization measure: Development of standards for carbon tracing and well-to-wake life cycle analysis.	4.67

Table 30: Assessments and measures related to retrofitting of e-methanol-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Retrofitting	Retrofitting existing vessels with new methanol engines The availability of services to retrofit the existing ships with methanol engines	9.0	2.0		No measure was provided, but the Delphi agreed that the technologies need for retrofitting are mature.	
	Modifying traditional engines to use methanol as primary fuel source	5.0	N/A	The mean and mode of the scores received suggested that no modifications are needed. However, one panelist indicated a higher score as retrofits of MAN engines to Dual fuel (including methanol) are a standard service. Another indicated that auxiliary engines on gasoline type engines (Otto) will easily be modified to Methanol. Any further clarifications are welcomed.	No measure was provided, but the Delphi agreed that the technologies need for retrofitting are mature.	

Table 31: Assessments and measures related to propulsion of e-methanol-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Propulsion	The design of methanol engines	9.0	2.0	The main engine is on the market i.e. the MAN LPG engine. However, the auxiliary engines are not yet approved. Further innovation is needed for the fuel cells.	Further development of more engine sizes and types to be commercially available.	4.8
					Demonstrations of dual fuel and/or dedicated methanol engines.	4.0
	The design of green pilot/ignition fuel used by methanol engines	5.0	N/A	The panel indicated that the engines currently available and under development probably do not use green pilot fuel.	Research into the opportunities of ignition without pilot fuel.	4.7
	Methanol fuel cells	5.0	N/A		Further testing and demonstration of solid oxide fuel cells (SOFC).	4.3
					Further testing and demonstration of low-temperature fuel cell systems.	4.3
					Demonstration of the durability MW-scale SOFCs in operational marine environment in terms of their ruggedness.	4.7
	Methanol auxiliary engines	5.0	N/A	Missing the approval of the auxiliary engines.	Auxiliary engines approval.	4.3

Table 32: Assessments and measures related onboard fuel storage and safety for e-methanol-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Onboard fuel storage and safety	Onboard storage of methanol	8.0	2.0	However, some felt the TRL score should be increased to 9, as methanol can be stored onboard already and methanol carrying tankers also have methanol engines. Please provide further feedback. Also, as methanol is a liquid, the safety concerns are lower. In terms of onboard methanol fuel storage, we suggest a technology readiness score of TRL 8. The availability of storage of methanol fuel is low, the commercial readiness score is CRI 2.	Demonstrate safe handling and storage of methanol.	5.0
					Further research and testing of how to prevent chloride contamination when dealing with methanol as a fuel.	4.5
					Commercialization measure: New regulations for safe handling of Methanol as a fuel.	4.5

Table 33: Assessments and measures related to crew safety and management for e-methanol-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Crews	Crew safety and management	N/A	2.0	The commercial readiness score is CRI 2. There needs to be further development of standards and training specific to methanol use, although there has been some initial work done by ABS.	Commercialization measure: Further developments/ standards on safety awareness/approaches regarding the handling of methanol.	4.8

Table 34: Assessments and measures related to emissions from e-methanol-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Emissions	Technologies to minimize emissions	9.0	2.0	The market availability of the technologies to prevent unwanted emissions is not widespread, therefore the commercial readiness score of CRI 2.	Further research and testing in how to prevent chloride contamination when dealing with methanol as a fuel.	4.5

4.4 Biofuels

The focus is on 2nd generation biofuels. They are collectively technologically ready and are primarily subject to a lack of commercial scale up, cf. table 35. A key issue is the uncertainty around the sustainable supply of biomass, given the level of foreseen demand between industries. There are also constraints around the extent of the land and ocean that can be used to produce biomass, and in securing the supply of waste food etc. Therefore, scalability is an issue, and this has led to reduced confidence in moving over to this fuel source. Other problems include the amount of energy needed for biofuel production, which needs to come from a renewable source to ensure green credentials. However, both assessed biofuels (biodiesel and biogas) constitute a high technological readiness and a corresponding high commercial readiness, cf. table 35.

Biofuels are already produced and used as a maritime fuel to a limited extent. However, more groundbreaking innovation is needed to address supply issues and reduce CO_2 emissions. The technological readiness in terms of fuel production is high, cf. table 35.

Box: Characteristics of biodiesel

Biodiesels are non-petroleum alkylate esters (e.g. FAME) that can be used as alternative fuels for existing diesel engines. This means that the innovation requirement for the use of such fuels is low. Biodiesel can be developed using biomass feedstocks such as waste fats, oils, and greases (FOGs) or energy crops. Such feedstocks are subject to intense demand by several industries. Biodiesels can significantly reduce GHG emissions but are not CO_2 free. The production of energy crops offsets CO_2 emissions. HVO drop-in biodiesel uses energy crops as feedstock and is produced in biorefineries. Drop-in fuels do not need to be blended with diesel. HVO fuels are processed using hydrogen to make hydrocarbons that are similar to diesel. However, they produce a low level of CO_2 when burned. Therefore, emissions should be addressed in a life cycle perspective.

Box: Characteristics of biogas

Biogas is a sustainable source of methane fuel. It is produced from an anaerobic digestion process using food and similar waste as feedstock. Biogas has no Sulphur or NOx emissions, but should be assessed from a life cycle perspective. Biogas also does emit a small amount of CO_2.

There were disagreements in the feedback from the panel as to whether biofuels only can be seen as offering a partial solution to reducing carbon emissions for the maritime sector. When burned, biofuels produce CO_2, but these can be considered as part of the natural carbon cycle. Some of the panelists thought that biofuels should only be treated as a transition fuel and must be viewed in a life cycle perspective.

The bunkering of biofuels is seen as technologically ready, cf. table 35. Large parts of the current bunkering infrastructure for diesel and LNG can be used for the transportation and bunkering of biofuels.

In terms of safe handling and use of biofuels it is possible to rely on the current frameworks and processes. Furthermore, there has already been guides published by regulatory bodies on the safe use of biodiesel.

Table 35: Average TRL and CRI scores of technologies for biodiesel and biogas by value chain part

	Fuel production		Bunkering		Vessel operations		Average	
	TRL (1-9)	CRI (1-6)	TRL (1-9)	CRI (1-6)	TRL (1-9)	CRI (1-6)	TRL (1-9)	CRI (1-6)
Biodiesel	9.0	2.0	9.0	3.0	9.0	3.8	9.0	2.9
Biogas	9.0	2.0	9.0	3.0	9	2.8	9.0	2.8

In the following parts we summarize the results of the assessments for biofuels for each part of the value chain and the corresponding sub parts.

4.4.1 Fuel production

Key requirements for biodiesel production

Feed stock

The feedstock needed depends on the specific pathway. In some cases, the source includes e.g. waste fats, oils, and greases (FOGs), in others, energy crops are required. The feedstock requirement is a major constraint considering the level of competition for such inputs, and the land constraints. Moreover, indirect land change effects may undermine meeting GHG targets, but are less relevant for 2nd and 3rd generation biofuels. An energy source is needed to heat the feedstock. This could be biomass or renewable electricity.

The feedback from the panel stressed that it is not unlikely that the level of demand for fuel in the maritime sector outweighs what could be feasibly produced from bio sources. Prices would become too high and availability cannot be guaranteed. However, biodiesel is widely produced and used in road transport globally, although its use in shipping remains limited.

Fuel production

Biodiesel can be produced from various production methods, among others:

I. Fatty acid methyl ester (FAME) biodiesel produced from waste fats, oils, and greases (FOGs)
II. Hydrotreated renewable diesel produced from waste FOGS
III. Fischer-Tropsch (FT) diesel produced from lignocellulosic biomass

Hydrotreated Vegetable Oil (HVO) or drop-in fuels can be used without blending with diesel. Production facilities for biodiesel are well established. Biodiesels can be produced on a stand-alone basis, or they can be co-processed in existing petroleum refineries. Petroleum refineries are likely locations for biodiesel production. Due to public sector funding, there is a complex range of facilities already established covering the different approaches to producing biodiesel.

Projects to further the development of the needed infrastructure and facilities to produce biodiesel are planned or already being demonstrated, cf. box 11.

Box 11: Selected examples of demonstration and production projects

In 2021, the production of biodiesel in Europe reached more than 12.5 billion of litres per year following year on year increases. Energies | Free Full-Text | Small-Scale Biodiesel Production Plants—An Overview (mdpi.com)
However, there is uncertainty around ensuring sustainable supply of biomass. Supplying biodiesels on an industry-wide scale is a major barrier to commercial take up across industries. The potential of liquid biodiesels in reducing ship emissions (theicct.org)
biodiesels_for_low_carbon_shipping_0.pdf (lindholmen.se)
Examples of sites producing biodiesel:

- Rotterdam has 5 biodiesel production sites. Biodiesels Alternative Energy | Port of Rotterdam

- **Avril** with plants in France, Germany, Italy, Austria, Belgium has a total production of 1,800,000 tonnes. Pioneer in biodiesels | Avril (groupeavril.com)
- **Infinita** with plants in Spain has a total production capacity of 900,000 tonnes. http://www.infinitarenovables.es
- **Pertorp Sweden** is a FAME producer. Perstorp säljer dotterbolaget Bioproducts till svensk investerare | Bioenergitidningen
- **Neste** has HVO plants in Finland and the Netherlands with a production capacity of 2,600,000 tonnes. Neste MY Förnybar Diesel™ | Neste

Technological assessment and gap

Production is limited considering the energy needs of the maritime sector and there are doubts expressed by the panel around the scalability as a maritime fuel. For this reason, there were calls to develop alternative drop-in fuels to HVO to access more sustainable feedstocks, and to find ways to reduce their CO2 emissions in a life cycle perspective. However, 'drop-in biofuels' derived from Hydrotreated Vegetable Oil (HVO) are seen as very high-quality, as they can be used without blending with diesel and without causing any damage to the engines (theoretically). HVO is also referred to as "renewable diesel fuels". These are produced in biorefineries using hydrogen to create hydrocarbons that are similar to diesel. Drop-in biofuel is in production and gaining popularity, but only to a small extent in the maritime sector, TRL 9.0 and CRI 2.0.

Commercial assessment and gap

Commercial volumes of conventional drop-in biofuels are produced through the oleochemical pathway. However, the cost sustainability, and availability of the feedstocks are significant challenges.

Key requirements for biogas (bio-LNG) production

Feed stock

The production of biogas requires organic matter and an oxygen-free tank.

Fuel production

Biogas (bio-LNG) is produced via an anaerobic digestion (AD) process, which breaks down organic matter (such as food or animal waste) in an oxygen-free tank to produce methane-rich biogas. This makes it a renewable fuel – which means it produces far fewer carbon emissions and pollutants.

Biogas production is well established and profitable, but the gas is often used locally for heat and electricity. Local production facilities should be made to make it efficient to use it for fuel.

Projects to further the development of the needed infrastructure and facilities to produce bio-LNG are planned or already being demonstrated, cf. box 12.

Box 12: Selected examples of demonstration and production projects

- LBG as a maritime fuel | Gasum
- Wärtsilä Biogas Solutions (wartsila.com)

Technological assessment and gap

Production is fairly limited considering the energy needs of the maritime sector and there are doubts expressed by the panel around the scalability as a maritime fuel.

Commercial assessment and gap

The panel stressed that the industry would be better placed with quality standards and carbon accounting methods. Cost competitiveness was also highlighted as an issue.

Table 36: Assessments and measures related to the feedstock of biodiesel and biogas

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Feedstock	The approach used to access biomass for biodiesel	9.0	2.0	The technological readiness level of the approach used to access biomass for biodiesel is TRL 9, considering that there are established systems to gather feedstock for biodiesel. However, the commercial readiness is CRI 2, considering that further scale up would be needed to meet maritime fuel demand, along with the associated uncertainty around the sustainability of the supply of biomass.	Further research and testing into a shift from edible feeds to non-edible feeds to produce biodiesel.	3.4
					The competition with food production is an issue which needs to be considered. The feedstock should be broader, e.g. not be based on pure rape seed oil.	4.4
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Innovation is needed in decreasing the carbon footprint of the existing bio-based feedstocks.	3.1
					Innovation and demonstration with the aims of maturing and upscaling of FT lignocellulosic waste pre-treatment and production facilities.	3.6
					Commercialization measure: Carbon accounting clarity and regulation must be established.	4.0
					Commercialization measure: Further research into clarifications regarding life-cycle-analysis and well-to-wake assessments.	3.8
					Commercialization measure: Standard specifications for the general requirements for biofuels and especially biodiesel needs to be developed and published as soon as possible.	5.0

Table 37: Assessments and measures related to fuel production and facilities for biodiesel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel production and facilities	Production of "drop-in" biodiesel	9.0	2.0	The technological readiness level of producing 'drop-in' biodiesel is TRL 9, given that such fuel is produced for the maritime sector currently. However, the commercial readiness is CRI 2, considering that further scale up would be needed to meet maritime fuel demand. Issues around production costs will need to be addressed in particular for HVO. There is likely to be competition for biodiesel between different industries.	Tests/demonstrations focused on Fischer Tropsch diesel produced from lignocellulosic biomass, which are at a lower CRI, but could potentially unlock much larger supplies.	3.1
					Innovations are needed in order to ensure reduced CO2 emissions from the production of biodiesel, which currently is highly energy intensive.	3.8
					Commercialization measure: Innovation and demonstrations are needed to improve the performance and the cost competitiveness of drop-in biofuels.	4.5

Table 38: Assessments and measures related to fuel production and facilities for bio-LNG

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel production and facilities	Production of bio-LNG	9.0	2.0	Bio-LNG is already produced by several companies, but the level of production is small compared to the demand.	Further development and tests of separation/pre-treatment technologies for biological wastes to improve quality prior to gasification.	3.9

4.4.2 Bunkering

Key requirements for green maritime fuel bunkering, storage and transport for biodiesel

Biodiesel fuels, including drop-in-fuels and blended fuels, can use the same transport and storage systems as traditional diesel fuel. To prevent pollution of pure diesel fuels, blended fuel cannot be stored or transported simultaneously with traditional diesel and requires its own infrastructure.

Biodiesel is currently bunkered as fuel. However, the existing supply chain will need to be expanded to ensure good supply to the maritime sector.

Projects to further the development of the needed technological and commercial readiness are being developed over the coming years, cf. box 12.

Box 13: Selected examples of demonstration and production projects

- **GoodFuels** is a bunkering company based in Rotterdam that delivers bio-derived hydrocarbons that can be used as a direct replacement (100%) in the existing fleet. GoodFuels | Better world | Home : GoodFuels
- **Oldendorff**'s eco-kamsarmaxes dry bulk carrier has been tested for bunkering at Singapore using a biodiesel blend. Oldendorff Carriers
- **Skaw** and **Gothenburg** announced in 2021 plans to provide lorry-based bunkering of biodiesel blend. Biodiesel bunkering available for ships in Danish Straits - SAFETY4SEA

Biodiesel fuels, including drop-in-fuels and blended fuels, can use the same transport and storage systems as traditional diesel fuel. E.g. there is already bunkering of biofuels at the Port of Amsterdam.

Technological assessment and gap

Overall, there is a limited innovation gap concerning bunkering technology

Commercial assessment and gap

The concerns raised by the panel with biodiesel are that the maritime sector will not consider them as sustainable alternatives and therefore investing in bunkering infrastructure may not make sense. Demonstration at appropriate scales and safety standards were seen as necessary.

Key requirements for green maritime fuel bunkering, storage and transport for biogas

Bunkering biogas (bio-LNG) is currently underway with several commercial stage projects. The transport and storage do not require much innovation, as the technologies already exist for Liquified Natural Gas, a comparable fuel type.

Transport equipment is expensive, and the logistics are complicated, due to boil-off gasses, among other things.

Projects to further the development of the needed technological and commercial readiness are being developed over the coming years, cf. box 14.

Box 14: Selected examples of demonstration and production projects

- Liquefied Biogas Supply Secured for Gothenburg Bunkers | NGV Global
- LNG as marine fuel - DNV
- Total Biogas Push is 'Important Step' Towards Bio-LNG Bunkers - Ship & Bunker (shipandbunker.com)

Technological assessment and gap

Overall, there is a limited innovation gap concerning bunkering technology, although possible methane slips were a concern (bio-LNG).

Commercial assessment and gap

The concerns raised by the panel with bio-LNG is that the maritime sector will not consider them as sustainable alternatives and therefore investing in bunkering infrastructure may not make sense. Demonstration at appropriate scales and safety standards were seen as necessary.

There were doubts expressed by the panel that biofuels could progress beyond CRI3. This is due to the limited availability of the feedstock. There was less of a concern with the technologies.

Table 39: Assessments and measures related to bunkering of biodiesel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel transport	Systems for transporting and storing bio-diesel	9.0	3.0	The systems needed to transport and store biodiesel are at TRL 9, given that existing systems can be used for this purpose. The commercial readiness to store and transport biodiesel as a fuel is CRI 3, given the need to scale up the existing infrastructure to meet future biodiesel fuel demands.	Commercialization measure: Further demonstration and proof of concepts of the global usability of biofuels is required in order to ensure that it is more than a niche market.	4.2

Table 40: Assessments and measures related to port and bunkering storage and supply facilities for biodiesel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Port and bunkering storage and supply facilities	Bunkering biodiesel as a fuel	9.0	3.0	The technological readiness to bunker biodiesel as a fuel is at TRL 9, given that the same approach would be followed as for traditional bunkering fuels. The commercial availability of biodiesel bunkering infrastructure (e.g., by ship, truck and tank) is CRI 3. Existing solutions for biodiesel bunkering have been tested commercially, these do not require further innovation, although engineering activities are required to ensure scale up.	Commercialization measure: Establishment of standards for the safety of biodiesels regardless of the feedstock.	4.2
					Commercialization measure: Demonstrate volume availability in one lot (500-2000 ton/bunkering) for ocean going vessel if decarbonization is achieved by using this fuel only.	4.7

Table 41: Assessments and measures related to bunkering of bio-LNG

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance scores
Fuel transport	Storage and transport of bio-LNG	9.0	3.0	Bio-LNG is already stored and transported by several companies.	Commercialization measure: Ensuring global availability.	4.8
					Innovation and testing of the abilities to handle methane slips are to be conducted, in order for LNG to be seen as a credible fuel for the future and not to just a temporary option.	4.5

Table 42: Assessments and measures related to Port and bunkering storage and supply facilities for io-LNG

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Port and bunkering storage and supply facilities	Bunkering bio-LNG as a fuel	9.0	3.0	Bio-LNG is already bunkered in ports. The scores are therefore TRL 9 and CRI 3.	Further demonstration and proof of concepts on the ability to store bio-LNG safely, and eliminate the risks of leakages.	3.3

Table 43: Measures related to bunkering of biofuels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Commercialization measure: Further demonstration and proof of concepts of the global usability of bio-fuels is required in order to ensure that it is more than a niche market.	4.2
					Commercialization measure: Development of an in-ternational certification system to prove the green credentials of biofuels, i.e. verification to production site to on board the vessel.	5.0

4.4.3 Vessel operations

Key requirements for onboard fuel storage, safety and emissions of biofuels

In terms of onboard biofuel storage, the storage systems are similar or the same as those already in use. Temperature control of biodiesels is very important to maintain correct viscosity levels. This is crucial to improve flow characteristics, reduce clogging, optimize the fuel injection, atomization and combustion within engine cylinders. Biodiesel storage temperatures should be kept at 10-15° C above the cloud point, and hot spots should be cooled. The temperature required may vary depending on the type of biodiesel and feedstock. Many fuel storage tanks are already fitted with heating devices which would be adequate for heating biodiesels.

Regarding crew safety and management, the safety aspect is similar to existing fuels. Biodiesel has a higher flashpoint and therefore may be considered 'safer'. The technological challenges with respect to maintenance are likely to be greater.

The type of biodiesel used impacts heavily on the type of emissions. NOx emissions can be managed in the same way as for traditional diesel engines. The emissions are not CO2 free when burning, but the production of energy crops offsets the CO_2 produced. Second generation biodiesels are a limited resource and are competing with food production. The panels raised concerns about the sustainability of biofuels.

Key requirements for ship design, propulsion and retrofitting of biofuels

The naval architecture for ships fueled by biodiesel does not need to undergo dramatic changes regarding the current methods. The innovation requirement for shipbuilding is low. The main barrier is related to commercial scale up.

For propulsion, existing engines can use drop-in fuels without conversion. There are technological challenges such as microbial growth, oxygen degradation, poor flow properties, corrosion, and degradation of rubber seals[4]. As a fuel, LBG (Liquid BioGas) is used interchangeably with LNG[5], as they both consist mainly of methane (CH_4). This means that the two gases can be mixed and that separate propulsion technologies are not needed. The issue of methane slip should however be dealt with. The panel raises concerns with regard to the hygroscopic nature of biodiesel leading to embedded water in the fuel. This could implicate lower efficiency for propulsion with biodiesel.

When dealing with retrofits, HVO could be used without issues in existing marine gas oil-powered main and auxiliary engines. The panel stressed that while the reality is that retrofitting is possible, it rarely occurs.

Projects to further the development of the needed technological and commercial readiness are being developed over the coming years, cf. box 15.

[4] Please see Using biodiesel in marine diesel engines: new fuels, new challenges (dnv.com)

[5] Please see Cleaner maritime transport | Gasum

Box 15: Selected examples of demonstration and production projects

- Sustainability Whitepaper: Biofuels as Marine Fuel (ABS.com)
- GHG Emission Study on the Use of LNG as Marine Fuel - Sphera
- The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping (worldbank.org)
- A chemical tanker was tested in 2021 using drop-in fuel from Rotterdam to Houston. Stolt Tankers tests marine biodiesel at Rotterdam (argusmedia.com)
- Cost of conversion may be lower for biodiesels compared to other alternative fuels due to the nature of drop-in biodiesels.Biodiesels as Marine Fuel (eagle.org)

Examples pointing to positive developments for propulsion:

- Depth RoRo carrier Patara was bunkered with 100% drop-in G Bio-Fuel Oil at Vlissingen. Volkswagen Group Logistics selects GoodFuels BFO for low-carbon shipping | Bioenergy International

Examples of projects related to use of biogas in fuels

- Multi-fuel vessels - Wallenius Marine
- Finnish firms testing liquefied biogas as shipping fuel | Bioenergy Insight Magazine (bioenergy-news.com)
- Nordic firms begin testing bio-LNG as shipping fuel (argusmedia.com)

Technological assessment and gap

Emissions and issues with engine maintenance were seen as the key problems.

Commercial assessment and gap

The panel questioned whether the demand for biofuels in general is sufficient to label them as a sustainable alternative for maritime purposes in the long run. The concerns were centered around uncertainties for supply and actual CO_2-reductions. Further demonstrations and proof of concept are needed.

Table 44: Assessments and measures related to ship design of biofuel-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Ship design and building	Ship building and design	9.0	2.0	In terms of ship design and building, the innovation requirement is low. The main barrier is related to commercial scale up. The technology readiness score is TRL 9. Due to the main barriers being commercial, the commercial readiness score is CRI 2.	Research and testing are to be done in order to determine the durability of the internal components of IC engines.	4.3
					Research and testing on the potential problems with maintenance must be considered - there are problems with engines running on biofuels.	5.0
					Further research and testing of engines with the capabilities of being interoperable i.e. so that can use biofuels, alongside hydrogen and ammonia.	3.3
					Testing and assessments are to be made for the implications which the bigger fuel tanks will have, due to the lower LHV of biodiesel compared to marine diesel.	4.0
					Commercialization measure: Long duration tests to be performed. Not only one voyage with biofuel onboard, but continuous operation must be demonstrated.	4.3

Table 45: Assessments and measures related to retrofitting of biofuel-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Retrofitting	Retrofitting	9.0	5.0	For retrofitting, the scores of TRL 9 and CRI 5, considering that existing engines can use drop-in fuels.	No measure was provided, but the Delphi agreed that the technology is mature, and the availability of retrofitting services is present.	

Table 46: Assessments and measures related to propulsion for biodiesel-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Propulsion	Biodiesel engines	9.0	3.0	In terms of propulsion, the technology readiness score is TRL 9, given that existing engines can be used. Given the commercial availability of biodiesel on the market currently, the commercial readiness level is CRI 3.	Hygroscopic nature of biodiesel leading to embedded water in the fuel requires further investigation to improve performance.	4.3
					Research and testing of the durability of the seals in engines when running biodiesel through an IC engine.	4.0

Table 47: Assessments and measures related to propulsion for bio-LNG-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Propulsion	Propulsion by using existing LNG engines	9.0	3.0	In terms of propulsion, existing LNG engines can be used for biogas (bio-LNG). The scores are therefore TRL 9 and CRI 3.	No measure was provided, but the Delphi agreed that the technology is mature, but still needs commercial scaling.	

Table 48: Assessments and measures related onboard fuel storage and safety for biofuel-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Onboard fuel storage and safety	Fuel storage and safety	9.0	3.0	In terms of fuel storage and safety, the innovation requirement is low. There may be a need to engineer new solutions that optimize storage of biodiesel. The score is TRL 9. There is biodiesel on the market, but it is not widespread. The commercial readiness score is CRI 3.	No measure was provided, but the Delphi agreed that the technologies needed to ensure safe storage of biofuels are mature and to some extent commercially available.	

Table 49: Assessments and measures related to crew safety and management for biodiesel vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Crews	Crew safety and management	N/A	3.0	With regards to crew safety and management, there has been guides published by regulatory bodies on the safe use of biodiesel. The commercial readiness score is CRI 3.	No measure was provided, but the Delphi agreed that the needed safety training to some extent is available.	

Table 50: Assessments and measures related to emissions from biodiesel powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Emissions	Technologies to eliminate biodiesel emissions	9.0	3.0	For emissions the technology readiness score is TRL 9. There are available technologies for eliminating unwanted biodiesel emissions, but they are not widespread. The commercial readiness score is CRI 3.	Research and testing of how to handle the emissions are needed. This involves further research on e.g., new exhaust cleaning technologies or engine tuning.	4.0

Table 51: Assessments and measures related to emissions from bio-LNG powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Emissions	Technologies to eliminate bio-LNG emissions	9.0	3.0		Further innovation to cope with the very high methane emissions from certain types of biofuel engines (e.g. DF LNG/BNG engines).	4.5
					Innovation for the prevention of methane slip in ICE and FCs.	4.5
					Commercialization measure: Establishment of regulations and standards for methane emissions.	5.0

Table 52: General measures regarding vessel operations of biofuels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Research and testing of the fuel and engine stability are needed in order to cope with changing properties of the feedstock for the production of the fuel.	4.0
					Commercialization measure: Proof of concept and demonstration for the large scale and sustainable use of biofuels.	4.0
					Commercialization measure: Proving the availability of sufficient feedstock to ensure that biofuels is a suitable fuel.	4.3
					Commercialization measure: Demonstrations on full scale in different operational environments.	4.3
					Commercialization measure: Regulation needs to be introduced to count carbon use.	3.8
					Commercialization measure: Enforcement of rules and penalties for fake or mixed fuel use.	4.6
					Commercialization measure: The different types of biofuels need to be certified and approved by the engine producers in order to ensure the transition. An example provided is the loss of engine guarantee if a vessel is using HVO on a traditional diesel engine.	4.3

4.5 Dimetyhl ether (DME)

Dimethyl ether (DME) is a synthetically produced alternative to diesel although it has half the energy density – it is a gas in ambient conditions, but can be handled as a liquid if lightly pressurized. DME can be produced in several ways, including directly from biomass or indirectly from methanol via an additional processing step. There is significant uncertainty around the viability of DME as a fuel currently, but the potential upside is present. The consolidated assessments indicate a low readiness in terms of producing DME, cf. table 53. The feedback from the panel indicated disagreement in terms of the potential and actual demand. On the other hand, some panelists did argue for great possibilities. This indicates that there is a need for further investigation into the potential of DME. The panel argued for further investigation into the production of DME using renewable energy, green hydrogen and carbon capture methods – like e-methanol. There are however potential inefficiencies for this, as DME potentially is more energy intensive to produce than is the case for e-methanol. This illustrates the need for maturing the technologies to produce DME, as indicated in table 53.

There is a general concern about the uncertainty and lack of knowledge on the operational behavior of DME. The main problem with DME is that it is '*unknown'* to the maritime sector – our industry respondents were not supportive, largely because there is limited knowledge about its use and performance (although it is a relatively common industry energy source in China). However, some academic panelists were strongly in favor of investigating the potential of DME further. This is illustrated by the consolidated assessments in table 53.

A general observation from the three panels is a lack of specific knowledge on DME as a marine fuel. That being said, some panelists did pose detailed information about the current state of play for DME. The assessments and measures should therefore be interpreted with this in mind.

Box: Characteristics of DME

Green DME can be produced from biomass and renewable energy using two alternate methods: gasification or pyrolysis. DME is a compound of methanol molecules and is a gas under normal conditions. Because of its lack of carbon-to-carbon bonds, using DME as an alternative to diesel can virtually eliminate particulate emissions and potentially negate the need for costly diesel particulate filters. However, DME has half the energy density of diesel fuel, requiring a fuel tank twice as large as that needed for diesel.

The bunkering of DME is subject to a high technological readiness, cf. table 53, due to the fact that DME can be transported and bunkered by the current infrastructure, with minor adjustments, like traditional marine fuels. Especially LPG infrastructure is suitable for the use of DME.

The safety aspects of DME are substantially lower than is the case for ammonia and hydrogen. DME is non-toxic, and does not require a fundamentally new regulatory framework. However, due to the low technological and commercial readiness of DME, there is no formulated framework with regards to the required safety protocols. Any accidental spill of DME would evaporate before it could damage an ecosystem.

DME has low particulate, sulphur, NOx and CO_2 emissions compared to traditional fuel. The emissions are below current regulatory frameworks.

Existing propulsion systems can be used for DME. LPG/gas injection engines are compatible with DME use. There are currently trials ongoing for DME engine systems. But, there is still room for technological improvements, cf. table 53.

Table 53: Average TRL and CRI scores of technologies for DME by value chain part

	Fuel production		Bunkering		Vessel operations		Average	
	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*	TRL *(1-9)*	CRI *(1-6)*
DME	5.8	1.8	8.5	1.5	7.4	1.5	7.1	1.6

In the following parts we summarize the results of the assessments of DME for each part of the value chain and the corresponding sub parts.

4.5.1 Fuel production

Key requirements for production of DME

Feedstock

The production from DME can be done from two pathways:

I. Using biomass combined with electricity from renewable energy sources
II. Using carbon capture combined with electricity from renewable energy sources

Fuel production

There are two main production pathways using biomass:

I. Using biomass e.g. (energy crops) that uses a gasification process to generate a syngas stream to be fed to a one-step or two-steps DME synthesis process. A water gas shift reactor is used for this process.
II. The other pathway uses organic trash, manure or sewage as biomass for an anaerobic digestion and pyrolysis system to generate the CO2 and H2 stream. Pyrolysis occurs in a methanol/DME reactor.

There are two main pathways using carbon capture:

I. Carbon capture from gas effluents of power plants, industry etc.
II. Carbon capture from direct air capture (DAC).

The feedback from the panel indicated that using biomass as feedstock for the production of DME as a main pathway is not an optimal strategy. A pathway using H_2 and CO_2 would be preferred, e.g. co-electrolysis of CO2 and water to produce a mixture of H_2, methanol, possibly DME. This pathway could also supplement the biomass pathway or substitute it in the future.

Projects to further the development of the needed infrastructure and facilities to produce DME are planned or already being demonstrated, cf. box 16.

Box 16: Examples of e-methanol sites at the planning or development stage

- The **bioliq®** pilot plant at the Karlsruhe Institute of Technology (KIT) is running successfully along the complete process chain to produce green DME and methanol using gasification methods.
  Gasoline from the bioliq® process: Production, characterization and performance - ScienceDirect
  KIT - KIT - Media - Press Releases - Archive Press Releases - bioliq®: Complete Process Chain Is Running
- **Volvo**, Sweden, is involved in the BioDME project that is developing a test facility to produce DME on a commercial scale for the automotive industry.
- The Canadian company, **DME Basics** has plans to produce and supply DME using the existing propane infrastructure for automotive and maritime industries. DME Basics — ChemBioPower

Several universities are undertaking early stage research on DME fuel production including DTU:

- Researchers investigate new green fuel for ships - DTU Mechanical Engineering (rain-erosion.dk)

- Nexterra's Gasification Technology | Technology | Nexterra - The Next Generation of Industrial Gasification Systems

Technological assessment and gap

The panel stressed the importance of identifying the optimal feedstock and production methods. Therefore, further research, innovation and demonstration are needed.

Commercial assessment and gap

The feedback suggested limited support for DME generally. This could be a plausible explanation for the low importance scores. Further proof of concept and demonstration was requested by the panel.

Table 54: Assessments and measures related to feedstock for fuel production of DME

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Feedstock	Carbon capture from direct air capture (DAC)	4.0	1.0		Fundamental research is to be done for the production of DME from air.	2.8
Feedstock	Not directly linked to the technology assessments, but were recommended as supporting measures.				Further research and testing for the feedstock to produce DME.	3.0

Table 55: Assessments and measures related to fuel production and facilities for DME

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel production and facilities	Gasification for producing green DME from biomass	7.0	2.0		Demonstration of large-scale gasification of biomass/waste and producing a clean syngas is still needed.	3.0
Fuel production and facilities	Pyrolysis for producing green DME from biomass	5.0	2.0		No measure was provided, but the Delphi agreed that the production of DME from pyrolysis is at TRL 5 and CRI 2, indicating room for improvement in both technological and commercial areas.	
Fuel production and facilities	Production of DME from carbon capture using gas effluents	7.0	2.0		Further research into the production of DME from concentrated gas streams.	2.8
Fuel production and facilities	Not directly linked to the technology assessments, but were recommended as supporting measures.				Further assessments of the optimal production method need to be selected in order to proceed with scalability.	3.3
					Further research into the production of DME from green hydrogen (water electrolysis).	3.4
					Research and innovation are needed in order to make DME production more energy efficient to ensure that it can be a sustainable alternative to non-renewable energy sources.	3.0
					Commercialization measure: Development of common standard for carbon tracing and well-to-wake life cycle analyses.	4.4
					Commercialization measure: Development of international regulation on DME production (safety, quality).	3.7
					Commercialization measure: Demonstration of large-scale production facilities.	3.7

4.5.2 Bunkering

Key requirements for green maritime fuel transport, storage and bunkering

Although not used currently as a maritime fuel, DME could use existing storage and transport solutions used for liquefied petroleum gas (LPG), such as road, rail and pipeline systems. Possibly, pipelines are preferred for long distances, given the cost of transportation.

DME is currently bunkered as a commercial commodity, but not as a fuel. As a fuel, DME could use the same bunkering infrastructure solutions as used for LPG e.g., cylinders, stores, pipes etc.

DME requires pressure tanks or cooling - but a low pressure or cooling compared to hydrogen or biogas. A 20 feet tank container approved for transport of DME weighs 3.5 metric tons more than one for methanol. Existing LPG distribution equipment can be used for DME, if polymers that are in contact with DME are changed to compatible types. There are few DME compatible polymers, and they are quite expensive. Storage underground could be a possibility. This is however only a hypothetical possibility.

Projects to further the development of the needed technological and commercial readiness are being developed over the coming years, cf. box 17.

Box 17: Selected examples of demonstration and production projects

Bunkering DME is not yet a commercial practice. However, similar fuels are bunkered currently. For example, bunkering of LPG is well established and includes major bunkering hubs such as Rotterdam, Antwerp, Hong Kong, Singapore, Fujairah and Houston etc.LPG-Bunkering-2019.pdf (wlpga.org)

Technological assessment and gap

The lack of need for innovation, but also lack of knowledge, on DME meant that few measures were proposed apart from demonstration.

Commercial assessment and gap

Demonstration of supply chain capabilities were suggested to illustrate that DME can match demand, if used as a fuel.

Table 56: Assessments and measures related to transport of DME fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Fuel transport	Systems for transporting and storing DME	9.0	2.0	The technological readiness of the systems needed to transport and store DME are at TRL 9, given that existing systems can be used for this purpose. The commercial readiness to store and transport DME as a fuel is CRI 2, given that it is sold as a commodity currently and the existing approach would require scale up.	Demonstration of full-scale transportation of DME is needed.	4.0

Table 57: Assessments and measures related to port and bunkering storage and supply facilities for DME fuel

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Port and bunkering storage and supply facilities	Bunkering of DME as a fuel	8.0	1.0	The technological readiness to bunker DME as a fuel is at TRL 8, given that the same approach would be used as for traditional bunkering fuels, meaning that the innovation requirement is very low. There is no commercial availability of DME bunkering infrastructure (e.g., by ship, truck and tank) there the score allocated is CRI 1. Commercial testing of DME bunkering has yet to take place.	Further research, testing and demonstration for DME bunkering infrastructure.	4.0

4.5.3 Vessel operations

Key requirements for onboard fuel storage, safety and emissions of DME

In terms of onboard DME fuel storage, it will require storage of the gaseous fuel in pressurized or cooled tanks, like the case is for LPG. Of course, this presents safety issues that must comply with (potential new) regulation. The technological focus should be on ensuring safe carriage of gaseous DME fuels.

Regarding crew safety and management, there are significant safety issues in carrying gaseous fuels. Crews will need to be trained in handling DME as a fuel.

In terms of emissions when using DME as the engine fuel, it eliminates all particulate matter and sulfur emissions and reduces NOx and CO_2 emissions to a level significantly below any current thresholds. Any DME spill would evaporate before it could penetrate and damage an ecosystem.

DME engines do not require a particulate filter or a selective catalytic reduction (SCR) system, so engines could be made that are slightly cheaper and less complicated than standard diesel engines.

Key requirements for ship design, propulsion and retrofitting of DME

The naval architecture for ships fueled by DME would not require a major redesign compared to current vessel designs. The space needed to carry the fuel will need to be considered (i.e. using pressurized cylinders), but it does not require a major reorganization of a traditional ship build.

For propulsion, DME can be used in compression ignition engines. DME can be used as an ignition promoter or a pilot flame for two-stroke engines. DME engines are on the market in the form of MAN LGI engines - these can use DME. There is a commercial requirement around market scale-up. The existing MAN LGI engines use diesel as a pilot fuel. This allows for flexibility if other fuels are not available. The pilot could be switched off for a DME engine.

However, auxiliary engines may require innovation. These are behind the two-stroke main engines. The technological requirement is lower for DME, due to the lack of a pilot flame. 4-stroke engines need to employ a different ignition strategy.

When dealing with retrofits, it is possible to modify existing engines to use DME, but this has not been explored thoroughly at the time of this study. The innovation requirement is likely to be low for DME retrofitting, considering that LPG retrofits have been introduced on the market.

It would be fairly easy to develop a DME engine. However, methanol fuel is cheaper to produce, therefore, the business case for using DME is missing. Yet, some academics stated that demonstration is needed to reveal its potential.

Projects to further the development of the needed technological and commercial readiness are being developed over the coming years, cf. box 18.

Box 18: Selected examples of demonstration and production projects

Examples pointing to positive development for fuel storage and safety:

- LPG has already entered the shipping industry. LPG To Be Used as Marine Fuel in The Shipping Industry (mfame.guru)

Examples pointing to positive developments for eliminating emissions from the use of DME:

- Comparison between different fuels show that DME has environmental emission advantages compared to other fuels.
  Emission Control Using Dimethyl Ether in Marine Applications (azocleantech.com)

Examples pointing to positive developments for shipbuilding:

- **Minnaminippon**'s oil and chemical tanker, the Lindanger, uses MAN's ME LGI engine. Methanol is the fuel used in this case, but this engine can alternatively use DME and other fuels. Successful results with MAN D&T's Methanol Dual Fuel Two-Stroke ME-LGI Engines | VEUS-Shipping.com

Examples pointing to positive developments for propulsion and retrofitting:

- **MAN's ME LGI** ship engine can be used using several fuels, including methanol and DME, among others. The pilot fuel used is diesel and is required for ignition of the alternative fuel e.g. DME. No large commercial ships are fueled with DME currently. 1510-0216-02ppr_ME-LGI Engine.indd (mandieselturbo.com)

  Successful results with MAN D&T's Methanol Dual Fuel Two-Stroke ME-LGI Engines | VEUS-Shipping.com
- Test conversions of auxiliary diesel engines to use DME and methanol fuel have been conducted successfully. SPIRETH – Methanol as marine fuel | SSPA
- **Wartsila** has established a commercial solution for LPG retrofits.
  Retrofit highlights use of LPG as a marine fuel (wartsila.com)
- LPG retrofit considered as sensible investment. Riviera - News Content Hub - 'Sensible investment': why LPG retrofits might work for your fleet (rivieramm.com)

Technological assessment and gap

Despite high TRL scores, demonstration was suggested along with development of auxiliary engines. Furthermore, emissions and safety warranted demonstration, due to the lack of knowledge about DME.

Commercial assessment and gap

Proving the business case to address doubts with DME, rules for vessel design etc. Regulation and training were called for around safety and quality.

Table 58: Assessments and measures related to ship design of DME-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Ship design and building	Ship design and building	9.0	1.0	In terms of ship design and building, Current ships do not use DME. However, there are emerging possibilities for using DME as a maritime fuel. Yet, there may be an issue with ensuring that cargo ships that do not carry chemicals can also use DME e.g. due to the fuel space needed. The technology readiness score is TRL 9. Due to the lack of current ships that use DME, the commercial readiness score is CRI 1.	Demonstration in operationel environment.	4.5
					Clear and applicable rule sets for retrofit and new vessel design.	4.3

Table 58: Assessments and measures related to retrofitting of DME-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Retrofitting	Retrofitting	7.0	2.0	For retrofitting, the innovation requirement is likely to be l ow for DME retrofitting considering that LPG retrofits have been introduced on the market and that there are some initial positive test results for conversions. MAN also offers on the market an engine that can use DME. The challenge is commercial scale up. The technology readiness level is TRL 7 for the retrofitting. The availability of services for retrofitting is not widespread, the commercial readiness score is CRI 2.	Research and development into retrofitting to overcome the challenges of materials compatibility with DME.	4.0
	Modifications of current engines to run on DME	5.0	N/A		No measure was provided, but the Delphi agreed that there is a need for technological development.	

Table 58: Assessments and measures related to propulsion of DME-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Propulsion	Design of DME engines	7.0	2.0	The design of DME engines is at TRL 7, as some solutions are available e.g. MAN LGI engines. There are commercial trials on the use of DME engines on the market, the commercial readiness level is CRI 2.	Demonstration of propulsion systems fueled by DME engines.	5.0
					Proof of concept of the business case for DME engines in order to ensure and establish demand.	5.0
	Design of DME ignition/pilot fuel solutions	6.0	N/A		No measure was provided, but the Delphi agreed that there is a need for technological development.	

	Technology, process, system	TRL (1-9)	CRI (1-6)	Justification, description	Measures	Importance score (1-5)
	DME auxiliary engines	7.0	5.0	DME might not have been demonstrated in 4-stroke aux engines but lots of smaller compression ignition engines are running on gas and that should not be difficult to transfer to DME operation on marine aux engines. The technology exists already even if there are no DME engines developed as yet.	Demonstration on auxiliary engines in operational environments.	4.7
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Demonstration ships operating off dedicated or dual fuel DME supply, including storage.	4.0
					Demonstrations of the use of DME in diesel engines with gas injections.	4.7

Table 59: Assessments and measures related onboard fuel storage and safety for DME-powered vessels

	Technology, process, system	TRL (1-9)	CRI (1-6)	Justification, description	Measures	Importance score (1-5)
Onboard fuel storage and safety	Fuel storage and safety	9.0	2.0	In terms of fuel storage and safety, there is a limited innovation need for the introduction of DME fuel storage systems considering that solutions have already been found for comparable fuels. The technology readiness level is TRL 9. The commercial availability of DME is not widespread. The commercial readiness score is CRI 2.	Demonstrations of the handling and storage of DME.	4.8
	Not directly linked to the technology assessments, but were recommended as supporting measures.				Commercialization measures: Establishment of clear safety and quality regulation.	3.8
					Commercialization measures: Mapping all risk and safety issues.	4.5

Table 60: Assessments and measures related to crew safety and management for DME-powered vessels

	Technology, process, system	TRL (1-9)	CRI (1-6)	Justification, description	Measures	Importance score (1-5)
Crews	Crew safety and management	N/A	1.0	With regards to crew safety and management, ensuring safe storage and management is a requirement although not a major innovation dilemma. The commercial readiness score is CRI 1.	Commercialization measures: Development of educational programs for the training of personal on use.	4.5

Table 61: Assessments and measures related to emissions from DME-powered vessels

	Technology, process, system	TRL *(1-9)*	CRI *(1-6)*	Justification, description	Measures	Importance score *(1-5)*
Emissions	Technologies to minimize emissions	9.0	N/A	For emissions, there are significant existing benefits of using DME to meet emission targets that do not require major technological innovations. Better efficiencies could be found but not a major innovation needed. The technology readiness score is TRL 9. The availability of technologies to eliminate unwanted emissions from the use of DME is not widely available. The commercial readiness score is CRI 2.	Testing and demonstrations of NOx emissions from DME engines.	4.3

Annex A: Methodology

In the following sections we present the overall methodology used in the study. Firstly, we elaborate on the Delphi approach and how this has benefited the study. Secondly, we explain the objective and process of the two Delphi rounds separately. Thirdly, we elaborate on the two indices used to assess the technological and commercial readiness throughout the study.

In order to identify the innovation gaps in the technologies and the needed innovation, the value chain has been broken down in its subparts, cf. figure 1A. For each part the technology required has been identified and assessed based on the identified gaps. Innovations needed to close or remedy the gaps has finally been identified. The project team from Oxford Research and Maritime DTU, including researchers from DTU with expertise in mechanical engineering, energy conversion and general expertise with application for the maritime sector, were involved throughout the project. Initially, and before conducting the two Delphi rounds, identifications of the needed technological requirements for each of the six fuels were made by the project team. Following the identification initial technological and commercial readiness assessments were made. These assessments were based on desk research, which included publicly available reports, news articles and academic literature. These assessments were used as material for the first Delphi round. In figure 1B an illustrative presentation of the entire process is showcased.

Figure 1A: Overview of the assessed value chain parts

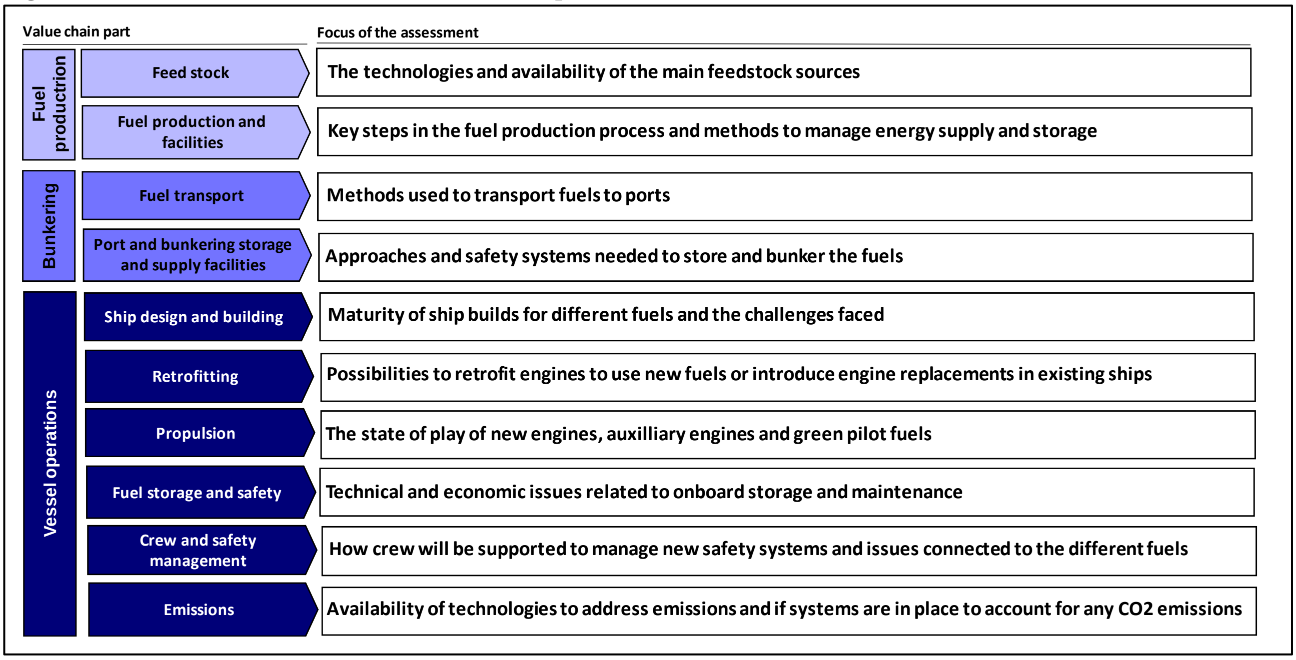
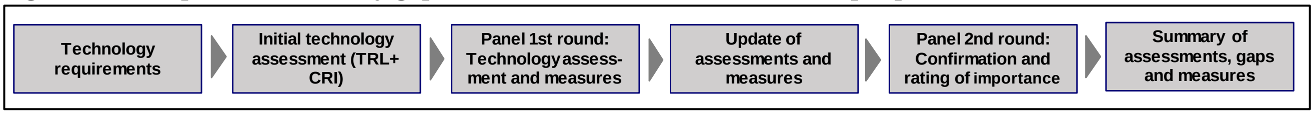


Figure 1B: The process to identify gaps and measures has involved two Delphi panel rounds



The Delphi approach

The Delphi method is used in order to get experts to qualify the findings of the study, with the aim of reaching a set of conclusions on the needed innovation and commercialization measures.

The Delphi method is an approach that seeks the input of a group of experts to specific issues with the purpose of obtaining consensus. The method entails a group of participants that reply to questionnaires. After each round, survey answers are collected and revised based on accumulated feedback. In subsequent rounds, Delphi participants are asked to re-evaluate and modify initial statements, leading to a final list of statements that reflect the level of agreement between participants. In the box below, further detailing about the background of the Delphi method can be found.

For this study, three Delphi panels were established – one panel for each part of the value chain. The process involved two rounds. The objective and purpose were the same across the three Delphi panels – the difference being the part of the value chain they were asked to cover and corresponding material and assessments. The panelists involved in the three panels were each selected based upon their knowledge of and involvement with the specific part of the value chain. The panelists were recruited from a combination of desk research and the global network amongst the full value chain which DTU Maritime possesses. The panelists consisted of a mix between people from the maritime industry and academia. A full list of the participating experts in the three panels can be seen in Annex B.

Box: Background about the Delphi method

The Delphi method can be described as: "[…]. a group facilitation technique that seeks to obtain consensus on the opinions of 'experts' through a series of structured questionnaires (commonly referred to as rounds). The questionnaires are completed anonymously by these experts' (commonly referred to as the panelists, participants or respondents)". The Delphi method is thus a multistage process that combines opinions so that they form a group consensus.

The method entails a group of participants that reply to questionnaires. After each round, survey answers are collected and revised based on accumulated feedback. In subsequent rounds, Delphi participants are asked to re-evaluate and modify initial statements, leading to a final list of statements that reflect the level of agreement between participants.

The Delphi was developed by Rand in the 1950's, to forecast the impact of technology on warfare. The Delphi method can however be used to illuminate any subject field where the purpose is to forecast future solutions, from an expert perspective. Besides technology, some areas where the Delphi method has been used include diverse settings such as the healthcare sector, strategic planning, education, and cyber security.

Process and content of the 1st round

The main objective of the first Delphi round was two-fold. Firstly, the panelists were asked to what extent they agreed with our initial assessments of the technological and commercial readiness. Each panel was only asked to assess and qualify the assessments related to their expertise, e.g., the panelists in the panel for vessel operations were not asked to assess technologies related to fuel production. If the panelists disagreed with our assessments, they were asked to provide feedback as to why they disagreed and what they thought was a correct assessment.

Secondly, the panelists were asked to list measures that are needed in order to achieve a higher technological and/or commercial readiness for the given technology or entire value chain. These questions took the form of open text boxes, so the panelists were not limited in their feedback. The panelists were not limited to only name measures related to their own part of the value chain, e.g., a panelist from the panel on fuel production could name an innovation measure which focused upon bunkering.

Following the responses received from the first round, the project team updated and corrected the initial assessments in line with the received responses from the three panels. In terms of the innovation and commercialization measures, the project team categorized and processed them in order for them to be compatible with the Delphi-format. They constituted the main objective for the second round.

Process and content of the 2nd round
Following the updated assessments of the technological and commercial readiness, the panelists were not explicitly asked to re-evaluate these updated assessments in the second round. As part of the background material for each of the included fuels, the assessments and comments about the corrections following the first round were listed. An open textbox for additional comments was available if the panelists had any supplementary inputs. No major corrections were made following these inputs.

The main objective for the second round was for the panelists to assess the importance of the innovation and commercialization measures received in the first round. The panelists were, for the measures related to the given part of the value chain, asked to assess the importance of each measure on a scale of 1-5. With 1 being the lowest level of importance and 5 being the highest. The sheer amount of measures each panel was asked to assess did not allow for the possibility of the panelists to rank the importance. Albeit, no panelists did rank all listed measures as being of the utmost importance.

TRL and CRI

Two indices have been used to assess the technological and commercial readiness of the technologies across the three parts of the value chain. The Technology Readiness level (**TRL**) approach has been used to assess the technological readiness. To assess the commercial readiness, the Commercial Readiness Index (**CRI**) has been used. The two can both be used separately and combined. The combination allows for a better understanding of what is required for the actual uptake and commercial use of the technologies to happen. Put simply, the TRL is mainly used to assess and cover R&D and demonstration of a technology, whereas the CRI extends to cover deployment on a commercial scale – both in terms of a supportive/subsidized and a competitive way. The combination of the two indices in the study, allows for a focus upon the issues and needs for deployment and improvement of the commercial readiness of green fuels for the maritime sector.

As is clear from the scores in table 1, the technological readiness is not enough for securing a commercial uptake, because you may have a high TRL level and a low CRI level. Moreover, as will become clear, further technological development and innovations may be needed even though the technological readiness is at a high level. The reason is that a high TRL scores does not necessarily imply that a technology is sufficiently efficient and competitive in the marketplace. The illustration that a high technological level is not enough to secure a commercial uptake demonstrated in the figure below.

Technology Readiness Level (TRL)
The TRL scale spans from 1-9. A score of 1 indicating that only the basic principles of a given technology/system have been observed. A TRL score of 9 indicates that a technology/system has been proven in an operational environment. The TRL scale is a globally accepted benchmarking tool for assessing technologies across various sectors. Since the introduction of the scale in the 1970's there have been various editions and revisions to the scale. The most common scale being used today is the nine-point scale, which is used in this study. Originally, the TRL was invented by NASA in order to assess technological readiness and needs for further development of the components and systems needed for operations in space.

Commercial Readiness Level (CRI)
The CRI scale spans from 1-6. A score of 1 indicating that the technology/system is only a hypothetical commercial proposition. A score of 6 indicates that the technology/system can be classified as a bankable asset.

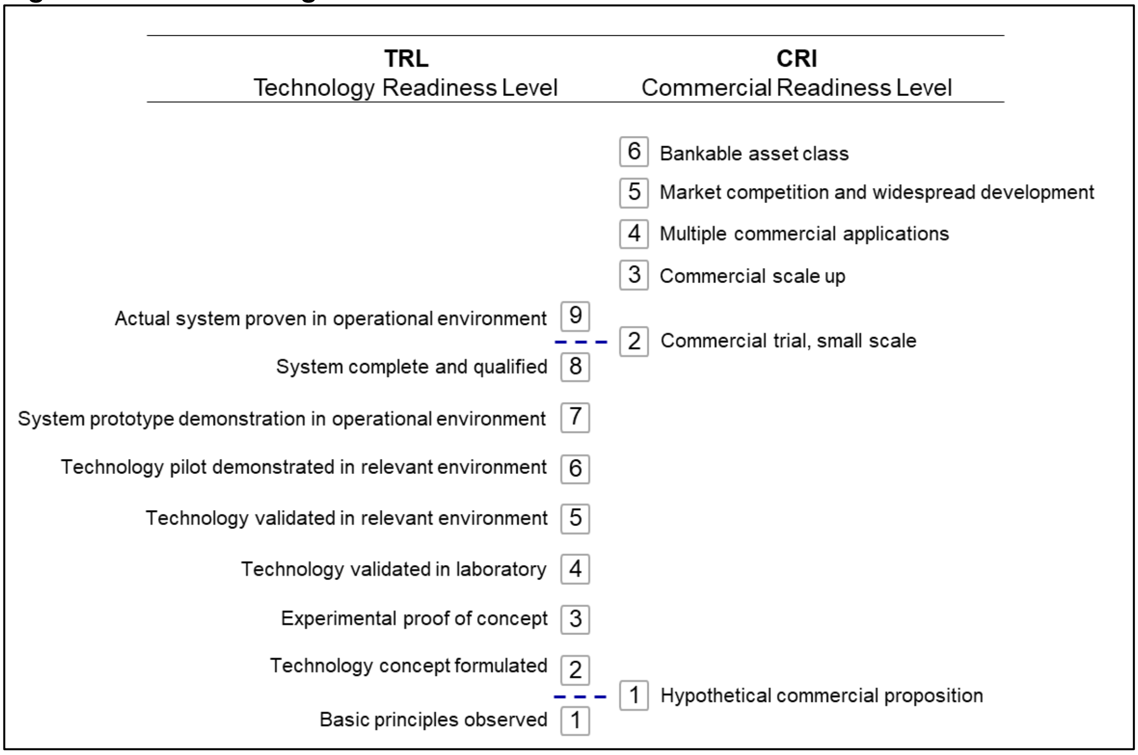
The CRI is developed to be used in combination with the TRL, as it is not possible to assess the commercial uncertainty through the TRL. The Australian Renewable Energy Agency (ARENA) developed the index due to a need for an assessment tool for the process from being technologically ready to becoming a bankable asset. ARENA argues that while most of the risks associated with innovation are eliminated through the increase in technological readiness, as covered by the 9 TRL levels, when dealing with renewable energy and in general when entering a well-established market, there are a variety of commercial risks which need to be overcome in order to compete on the market.

Throughout the study the sources listed in the box below have been used to provide information on the TRL and CRI.

Box: Sources and background material

ARENA (2014) Presentation of and guidelines for use of the Commercial Readiness Index; ARENA (2019), Technology Readiness Level; De Jager, David (2017). Commercial Readiness Index Assessment – Using the method as a tool in renewable energy policy design (RE-CRI); IEA RETD TCP (2017), Commercial Readiness Index Assessment – Using the method as a tool in renewable energy policy design (RE-CRI), IEA Renewable Energy Technology Deployment Technology Collaboration Programme (IEA RETD TCP), Utrecht, 2017; Mankins, John. 1995. “Technology readiness levels – a white paper”

Figure: The interlinkage between the two indices



5. Annex B: Delphi panelists

Participants in the Delphi panel for fuel production

Name	Position	Organization	Country	Participation	
				1st round	2nd round
Randy Cortright	Research advisor, chemistry	NREL	United States	✓	
James Corbett	Environmental director, Europe	World Shipping Council	United States	✓	✓
Tristan Smith	Lecturer	University College London	United Kingdom	✓	
Pat A Han	R&D Director	Haldor Topsoe	Denmark	✓	
Dolph Gielen	Director for Innovation and Technology	Irena	Germany	✓	✓
Anker Degn Jensen	Professor	DTU KT	Denmark	✓	
Rene Bañares-Alcántara	Professor	University of Oxford	United Kingdom	✓	✓
Dan Rutherford	Program Director for aviation and maritime	ICCT	United States/Japan	✓	✓
Torben Nørgaard	Head of Energy & Fuels	Zero Carbon Shipping	Denmark	✓	✓
Dirk Henkensmeier	Professor	Korea Institute for Science and Technology	Korea	✓	✓
KangKi Lee	Senior Vice President	LG Chem Research Park	Korea	✓	✓

Participants in the Delphi panel for bunkering

Name	Position	Organization	Country	Participation	
				1st round	2nd round
Jasmine Siu Lee Lam	Associated Professor	NTU	Singapore	✓	✓
Yosuke Kuroki	LNG & NH3 Bunkering Business development	Sumitomo	Japan	✓	✓
Kjartan Ross	Chief Commercial Officer	Port of Aalborg	Denmark	✓	✓
Anne Zachariassen	Technical Operating Officer	Århus Havn	Denmark	✓	✓
Henrik Sornn-Friese	Associated Professor	CBS	Denmark	✓	
Sif Lundsvig	Project manager	DFDS	Denmark	✓	✓
Ankie Janssen	Head of Program Alternative Fuels	Port of Rotterdam	Holland	✓	✓
Jun Kato	Manager of Shipplan Team	NYK	Japan	✓	✓

Participants in the Delphi panel for vessel operations

Name	Position	Organization	Country	Participation	
				1st round	2nd round
Theodore R. Krause	Theme Leader for Catalysis and Energy Conversion	Chemical Sciences and Engineering Division at Argonne National Laboratory	United States	✓	
Lennie Klebanoff	Principal Member of the Technical Staff	Sandia National Laboratory, Klebanoff	United States	✓	
Edward Schwartz	Vice President, of Sales of Marine Systems	ABB Marine	United States	✓	
Marie Lützen	Associate Professor	SDU	Denmark	✓	✓
Jytte Ravn Jyrkinewsky	Chief Engineering Officer	OMT – Odense Maritime Technology	Denmark	✓	✓
Stefan Mayer	Head of Engine Process Research	MAN Energy Solutions	Denmark	✓	
Claus Winter Graugaard	Head of Onboard Vessel Solutions	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping	Denmark	✓	
Jesper Schramm	Professor	DTU MEK	Denmark	✓	✓
Per Skaaning Mølris	Vice President, Head of Operational Performance & Energy Efficiency	TORM	Denmark	✓	
Sverre P. Vange	Head of Digital Solutions and Analytics	J. Lauritzen A/S	Denmark	✓	✓
Patrick Derry	Engineer	Ghana Maritime Authority	Ghana	✓	✓
Henrik Røjel	Head of fuel efficiency	Norden	Denmark	✓	

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