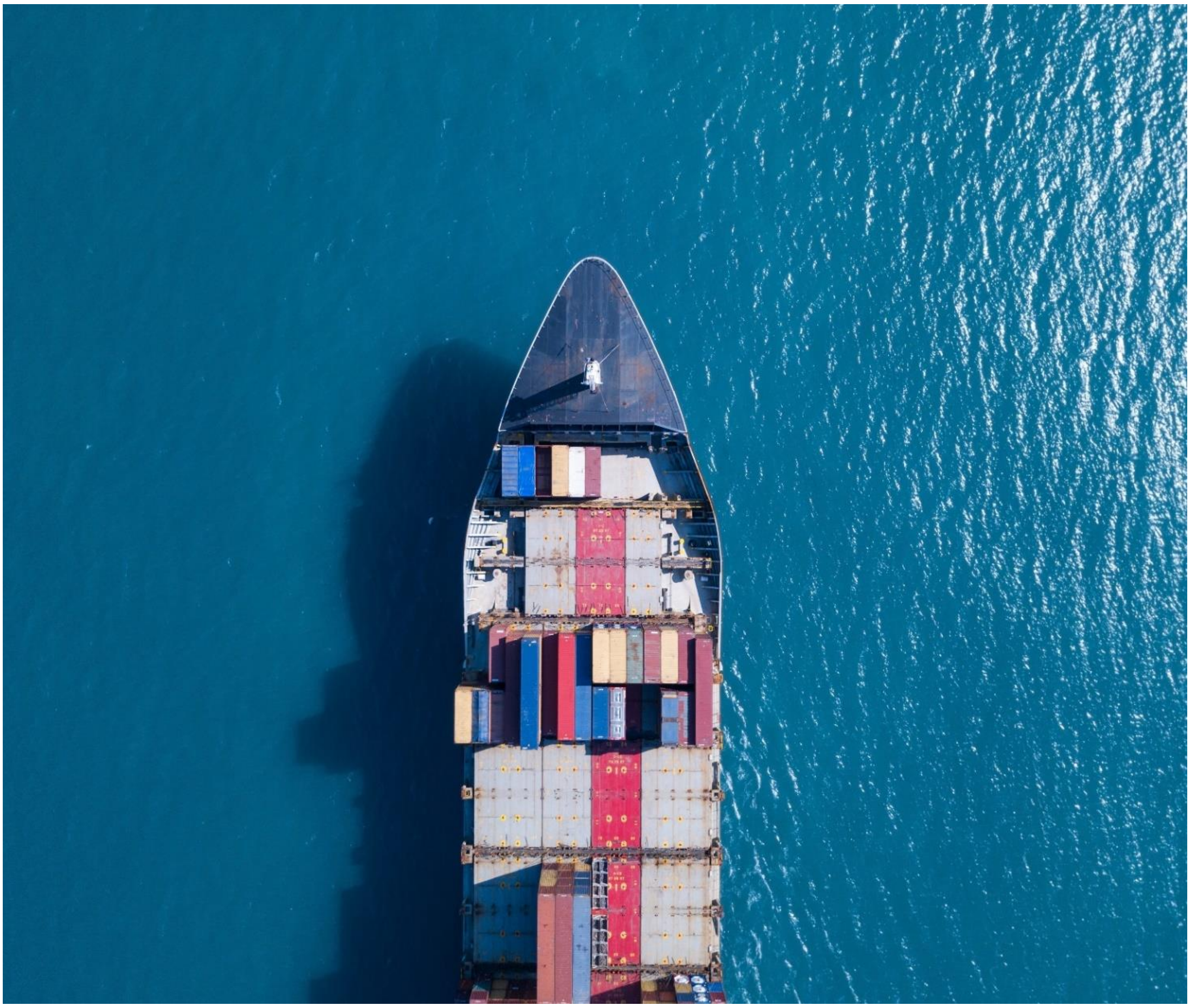
Innovation needs for decarbonization of shipping

Extended summary, November 2021



About this analysis

This analysis on the innovation needs for the decarbonization of shipping has been conducted on behalf of the Danish Maritime Authority and will be used to guide the work of the international Zero-Emission Shipping Mission under the auspices of Mission Innovation. The Shipping Mission is co-led by Denmark, the United States, Norway, Global Maritime Forum and the Maersk Mc-Kinney Møller Center for Zero Carbon Shipping.

The aim of the analysis is to uncover and structure the innovations needed across the value chain in order to achieve commercially viable zero-emission shipping. These innovation needs are also referred to as innovation gaps in the following text.

Innovation is key to the transition to zero-emission fuels in international shipping

Today, international shipping accounts for 3 percent of the global emission of greenhouse gases (GHG). With global trade expected to grow further in the 21st century, the shipping industry will have an increasing need for energy and continue to increase its emission of GHG, if steps to decarbonize international shipping by the use of zero-emission fuels are not taken.

Decarbonization is a particular challenge for the shipping industry. The industry is truly global, relying on the supply and availability of fuels in every major port. Hence, the decarbonization of the industry must encompass the full value chain of shipping, including production, transportation, bunkering and the use of zero-emission fuels. It is a particular challenge for international shipping to decarbonize through, for instance, electrification, due to the long distances and heavy loads transported.

Both policy measures and further innovations are some of the tools that are needed to decarbonize international shipping. Regulation that requires or incentivizes the use of green fuels will be needed, as they can ensure broad uptake of the fuels. Innovation is required to address some of the core issues that constitute obstacles to the applicability and uptake of green fuels. Firstly, green fuels are less price competitive and energy intensive compared to fossil fuels, meaning the introduction of green fuels will likely increase the cost of shipping. This will have clear 'knock-on' effects for the industry, related sectors, and consumers. Innovation can improve the efficiency and scalability of green fuel technologies and thereby improve their price competitiveness. Additionally, the complex technical issues around the production, bunkering and use of green, zero-emission fuels must also be addressed through innovation. For instance, the hazardous properties of some of the green fuels present risks and challenges to their safe transport and storage and will require new technologies and systems. Also, the lack of standards of both the properties and handling of the fuels may necessitate further innovations and international standards that can help set the direction for the technologies and approaches that need to be adopted.

As summarized in this document and detailed further in a technical annex report, 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.

The four main conclusions of the study

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 generally 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 need to be addressed. There is thus 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, but for now, the 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 addressing the gaps that affect all fuel types and supporting 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'[1] 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 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 for approaches that address safety management and fuel quality concerns. This gap points to the need for supporting measures, in particular the development of new international standards, together with the revision of existing ones, that can 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 green fuels, generating a clearer framework for innovation.

c. **Scaling and supply**: There is a lack of supply of both renewable energy and the 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. Experts also 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 through 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 and sustainability of the fuel value chains.

d. Concerning **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 for 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 regards to biomass fuels, further innovation is needed to e.g. 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.

[1] 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.

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

f. Concerning **vessel designs and fuel storage systems**, adaptions to enable the safe carriage of larger quantities of alternative fuels with lower energy density is needed. And new propulsion and emission control approaches will be necessary 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.

About the study: A Delphi survey methodology has been used to develop and verify conclusions

The results and conclusions of this analysis have been arrived at by using a Delphi methodology, cf. box 1 below. Three international expert panels composed of academics and industry members from Europe, the Americas and Asia each covered parts of the value chain of international shipping and verified the readiness and gaps of the relevant technologies. Furthermore, the panels identified the needed innovation. In total, 275 innovation and commercialization proposals were provided via the Delphi process. The focus of the Delphi process was specifically on six green fuels. Three electricity-based fuels: green hydrogen, green ammonia and e-methanol, and three biofuels: drop-in-diesel (HVO), biogas and Dimethyl ether (DME). We consider green fuels as those which can be produced and used without emitting $C0_2$ or those that are produced from biomass and thus release $C0_2$ in the context of the natural carbon cycle.

In the following four sections each of the main conclusions of the study are elaborated further. In the technical annex report the detailed results from the Delphi process are reported.

Box 1: Delphi procedure has been used to assess technologies and develop innovation

To support the study, three expert panels were established with a total of 31 members from academia and industry in Europe, Asia and Americas. Each panel covered one part of the value chain (fuel production, bunkering infrastructure and vessel operations) and assessed the readiness and innovations needed regarding the technologies of six selected green fuels; three electricity-based fuels: green hydrogen, green ammonia and e-methanol, and three biofuels: drop-in diesel, biogas and Dimethyl ether (DME).

A two-step Delphi process was facilitated with each of the three panels. In the first Delphi round an assessment of the readiness of individual technologies was conducted and proposals for innovations and other measures were suggested by the panel members. For the second Delphi round the assessment, innovations and measures were consolidated and updated. The assessments, innovations and measures were confirmed, and the importance of the innovations and measures rated.

Based on the Delphi process Oxford Research and Maritime DTU summarized the findings in this document and technical report.

Altogether, 131 assessments of individual technologies were made and updated. In total, 275 proposals for innovation and other measures were received and reviewed.

1. The readiness of fuel technologies

Based on the input from the Delphi panels it is concluded that the needed technologies across the value chain are to demonstrateda large extent technologically ready to support the transition towards zero-emission shipping. The expert assessments show that the technologies are moderately to highly ready.

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

In table 1 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 has been used to assess the technologies, cf. box 2.

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

Table 1: Technology readiness measured by average TRL-score and commercial readiness measured by average CRI-score of technologies, by value chain part and fuel type

	Fuel production		Bunkering infrastructure		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)***
Green 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	7.9	2.4	8.2	2.2	7.1	1.9		

Box 2: Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) approaches

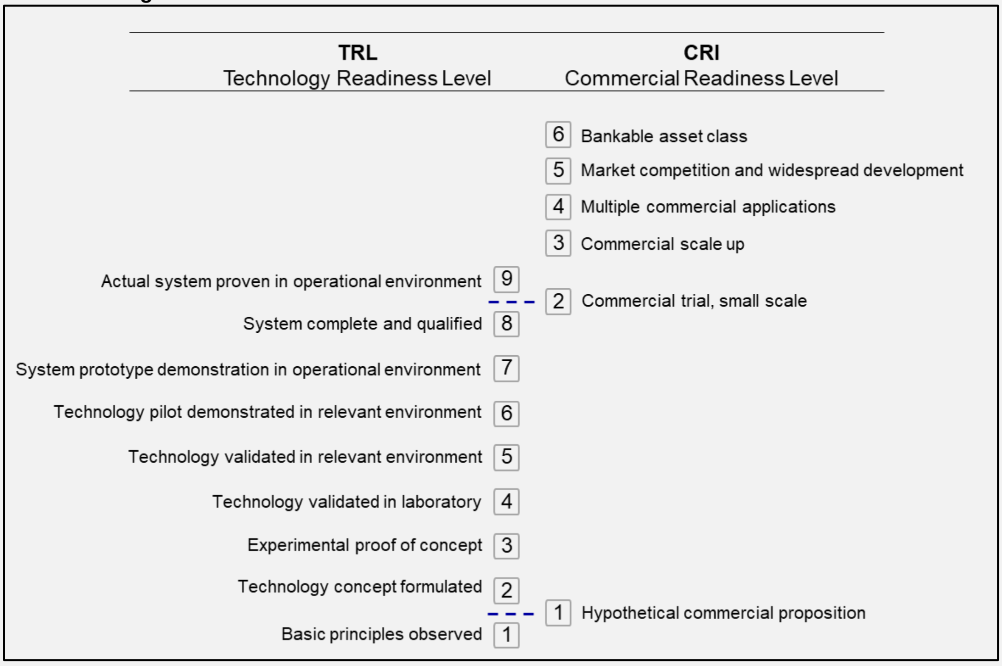
Two indices have been used to assess the technological and commercial readiness of the technologies across the three parts of the value chain. The Technology Readiness level (**TRL**) approach has been used to assess the technological readiness. To assess the commercial readiness, the Commercial Readiness 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.

As is clear from the scores in table 1, the technological readiness is not enough for securing a commercial uptake, as there may be a high TRL level but 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 for this is that high TRL scores do not necessarily imply that a technology is sufficiently efficient and competitive in the marketplace. That a high technological level is not enough to secure a commercial uptake is illustrated 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 its introduction 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.

Commercial Readiness Index (CRI)
The Commercial Readiness Index (CRI) provides a commercialization readiness scale from 1 to 6. A score of 1 indicates 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 designed to be used in combination with the TRL, as it is not possible to assess the commercial uncertainty through the TRL.

The interlinkage between the two indices



Sources: 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"

Technologies for fuel production
In relation to fuel production, the assessments of the technologies related to each individual fuel confirmed by the Delphi panels show 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 green hydrogen, green ammonia, and e-methanol (TRL 7.0) have entered operational demonstrations, and biodiesel and biogas (TRL 9.0) are already sold commercially, although they are not used widely by the maritime sector for several reasons, including the relative cost to fossil based marine fuel and uncertainty around efficiency and ongoing engine maintenance, among others. Another possible fuel, DME (TRL 7.0), is not used at all by the maritime industry, and there are some doubts about its feasibility, though some academics consider that it has potential. 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. With respect to biofuels, further innovation is needed to address the limited availability of biomass feedstock, for instance, by diversifying possible sources.

posMoreover, the average Commercial Readiness Index score for fuel production (CRI score 2.4) indicates that significant gaps remain. This is especially true with regards to the current scale of the present 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 and scaling of renewable energy. This is both an innovation issue and a commercialization issue.

Technologies for bunkering infrastructure
The possibilities around bunkering, again, are 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 to those for marine fossil fuel, albeit with relatively minor modifications. While not unfeasible, bunkering systems for green hydrogen and green ammonia (TRL 7.0), however, are not yet ready and demand further development. Yet, 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), though these are dual fuel solutions that also allow the use of fossil fuels. It should be noted that operators currently 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.

Green ammonia engines (TRL 8.0) and green hydrogen fuels cells (TRL 7.0), on the other hand, are lagging and have yet to be fully developed, although they 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 being at the mid-point on the TRL scale. While improvements could be made, the technologies needed to control emissions from e-methanol and biofuel are relatively strong (TRL 9), although solutions to address nitrous oxide emissions from green ammonia (TRL 5.0) are needed.

However, the commercial use of vessels designed for green fuels is low (CRI 1.9). Nevertheless, some promising activities are underway, for example, e-methanol and biofuel ships are being tested in commercial settings, and green ammonia and green hydrogen vessels, in particular chemical carriers, are undergoing demonstration. This will provide the needed information for fine-tuning the technologies and help display the possibilities of using these vessels.

Yet, to support uptake, improving vessel designs to enable more efficient performance and 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 can be 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. A summary of the main technological gaps is 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, the Delphi panelists still 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 the cost of green fuels is reduced.

2. Six alternative fuel pathways, but no clear solution at this stage

As mentioned, the scope of the research was on zero carbon fuels. The fuels in question either do not emit CO_2 or their emissions can be considered as part of the natural carbon cycle.

We find that at this stage there is no clear, competitive alternative to marine fossil fuels among the six fuels assessed. All green fuels have limitations and challenges. Therefore, there is no single way forward for the decarbonization of international shipping. Ultimately, it could very well be the case in the future that several green fuels are adopted by different parts of the maritime sector, and all thus needing further development to explore their potential. Hence, for the foreseeable future it is important to favor a technology neutral approach.

The fuels reviewed in this study comprise two core pathways, each with their own benefits and challenges. One pathway comprises *electricity-based fuels* i.e., green hydrogen, green ammonia and e-methanol. Using renewable energy, these are all manufactured using green hydrogen as a base component. The other pathway concerns *second generation biofuels* such as drop-in bio-diesel, biogas and Dimethyl ether (DME). They are all produced in biorefineries using biomass like energy crops or food waste.

As illustrated in table 2 with examples, all fuels have limitations. These limitations constitute some of the issues that need to be addressed mainly through innovations, but also by means of other supportive initiatives.

Table 2: All fuels have limitations, and more innovation is needed

Type	Fuel	Risk to users	Feedstock	Storage	Emissions
Electricity based fuels	**Green hydrogen**	**Very high**, highly flammable	Demand can only be met with a major roll out of electricity producing facilities. Solar and wind fluctuations need to be managed.	High storage volume needed and low temperature	NO_X and other particle emissions (internal combustion engines) Does not emit $C0_2$
	Green ammonia	**Very high**, corrosive and toxic substance		High volume	N_20 and NOx emissions Does not emit $C0_2$
	E-methanol	**High**, toxic, corrosive and poisonous		Liquid at room temperature, although more storage is needed due to lower energy density	Lower CO_2 and low emissions of sulphur, particulates and NOx. Requires a form of GHG accounting to be considered as carbon neutral as the $C0_2$ feedstock is from an industrial source.
Biobased fuels	**Biodiesel**	**Moderate**	Issues around consistent supply of biomaterials at the appropriate scale	Can use existing storage, though it has a lower energy density	Reduced CO_2 emissions, but sequestered via new crops etc.
	Biogas	**High**, highly flammable		Can use existing LNG storage, however it has a lower energy density than LNG	Reduced CO_2 emissions, however sequestered via new crops etc.
	DME	**High**, highly flammable		Low energy content, requiring more storage, but better than others	Reduces NOx and CO_2 emissions to below guideline amounts. CO_2 emissions from DME produced from biomass can be considered as part of the natural carbon cycle.

From an emissions perspective, electricity-based fuels seem advantageous, considering that green hydrogen and green ammonia do not emit CO_2. However, e-methanol uses waste CO_2 as a feedstock input and thus emits CO_2, although in much lower volumes compared to marine fossil fuels. This means that it offers good transition potential, but further thinking is needed, if it is to play a role as part of a zero-carbon future, perhaps by using GHG accounting methods. Moreover, new technologies are needed to address GHG emissions from burning green ammonia fuel, namely nitrous oxide.

However, while green hydrogen has clear potential for other sectors, its low energy density means that there are practical challenges in adopting this fuel for the maritime sector, especially in international shipping with long distances. Green hydrogen needs to be stored cryogenically, requiring significant energy inputs and onboard storage space, substantially reducing the amount of cargo that may be carried. While green ammonia offers a better alternative concerning its energy density, it is both toxic and corrosive, thus posing a significant threat to human and environmental health. Furthermore, when burned, green ammonia emits nitrous oxide, so the development of a solution for controlling this successfully is needed.

Considering the expected demand from different sectors, compared to electricity-based fuels, there is some uncertainty around the sustainable supply of feedstock i.e., biomass, to produce biofuels. Therefore, while biofuels can play a role, it needs to be discovered to what extent, and in what way, for the maritime industry.

At the same time, biofuels emit CO_2, which reduces their appeal. However, the impact of these emissions can be considered as part of a GHG life cycle perspective. Moreover, existing systems for biofuel production, bunkering and vessel operations are ready and already used commercially, reducing the technological barriers to transition. While offering some clear emissions benefits, the known performance of DME is limited though, and the industry has yet to 'get-to-grips' with the idea of transitioning to this fuel.

Unavoidably, these limitations add to the complexity around the most suitable fuel(s) to propose as the viable way forward. A technology neutral innovation approach is therefore needed to further explore and develop these options. However, in the short to medium term, some signaling is required to steer the industry towards a narrower choice of fuel option(s) to clarify the way forward.

3. Cross-cutting gaps, innovations and measures

The experts' assessment of the technologies across the value chain for each of the six fuels has 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, 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 the updating of existing international standards or the implementation of new ones that can underpin and steer further innovation. For example, standards specifying the need for technologies or procedures that ensure safe bunkering and usage, along with quality certification demonstrating the green credentials of the fuels.

- **Scaling and supply:** Lack of supply of feedstock, namely the 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 lower the price of renewable energy further. 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. Therefore, the measures addressing the cross-cutting gaps are not exclusively requiring innovations. 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. This is particularly the case over long durations in a real-life commercial setting with other technologies, and regards 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 and operational and maintenance costs, considering also the cost impact of the displacement of cargo space due to additional fuel storage.

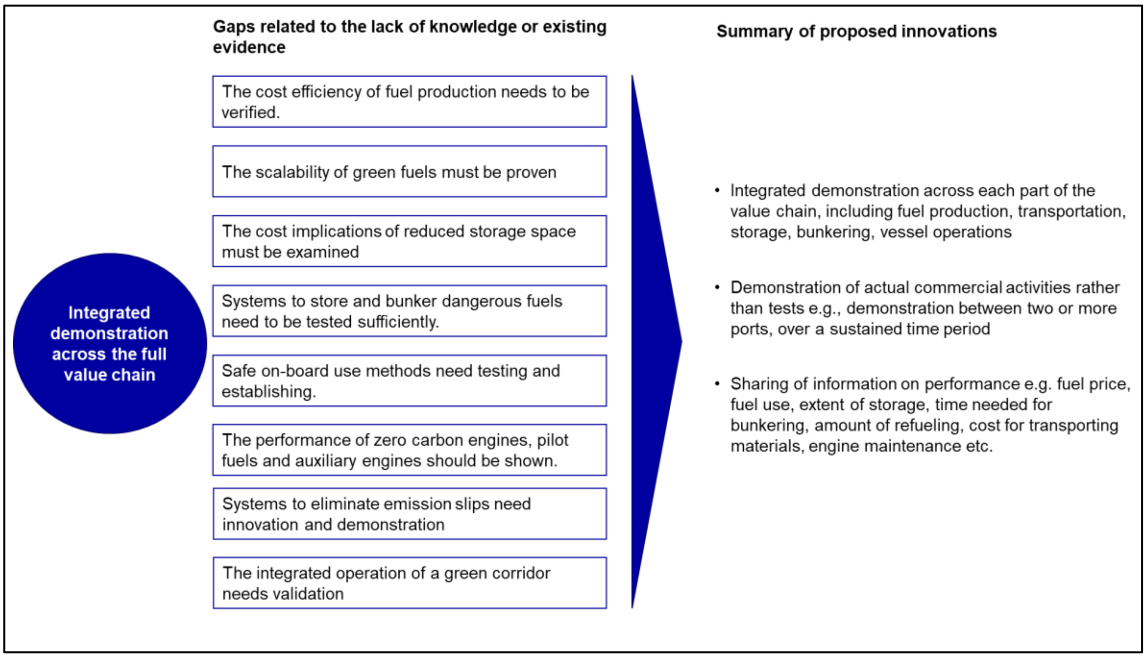
Demonstration on real ships can contribute to the needed information and transparency, while at the same time supporting further innovation, such as fine-tuning of the technologies to enhance their performance and applicability, as well as learning how these technologies work alongside other existing 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 between 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 technical challenges. The idea is that the organisations providing the value chain 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 measures: 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 standards or revisions to existing ones offer potential in addressing these gaps.

These gaps call for other types of measures beyond 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 technical requirements can be defined specifically 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.

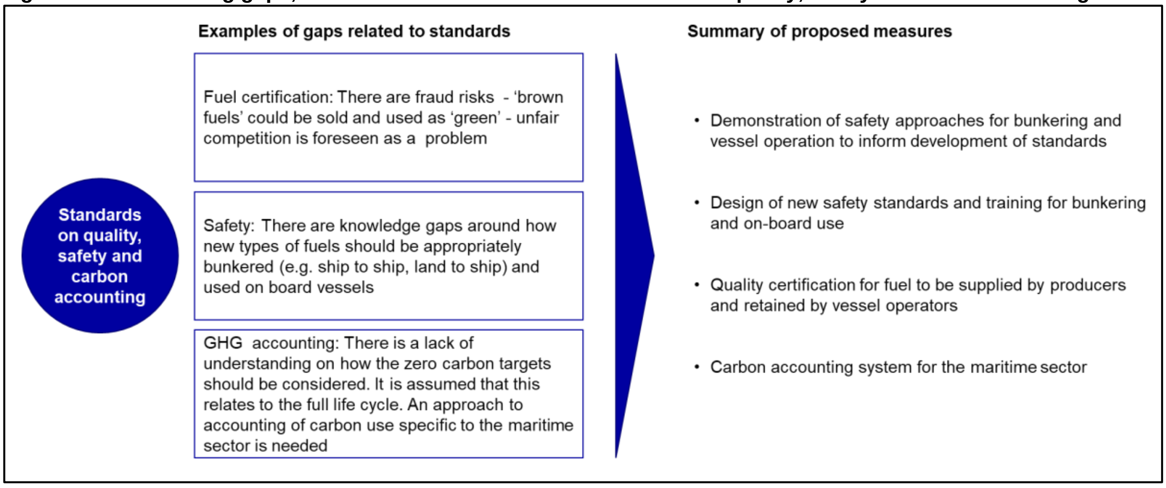
New international standards and revisions to existing ones, to better cover new fuels and other zero-emission technologies, can be defined and implemented to address these gaps. But, ultimately these would need to be supported and enforced under existing or new regulation, and supported by penalties 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 to 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, in order both to reduce the possibility of fraud and enable 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 these gaps of concern 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 gap, innovations and measures: Innovation is needed to secure higher efficiency as well as scaling of renewable energy supply for green fuel production and also biomass supply

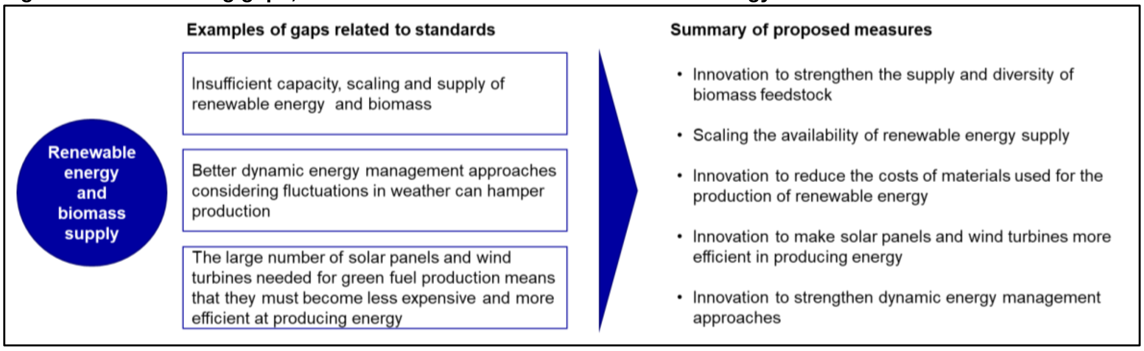
Innovation is needed to strengthen the supply of essential feedstock, namely renewable energy and biomass.

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 aimed at lowering 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 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 innovations

While cross-cutting innovations and measures are needed to address broad gaps common to all, or groups of, fuels and facilitate innovation, fuel specific innovations and commercialization measures are also warranted. Typically, these have the general aim of improving the cost efficiency, performance as well as sustainability of the fuel value chains. The number of proposed innovation and commercialization measures by panel members indicate the importance of innovation to address these gaps, cf. table 3.

Table 3: Proposed innovation and commercialization needs by focus and value chain part

	Innovation	Commercialization measures	Total
Fuel production	64	50	114
Bunkering	36	10	46
Vessel operations	69	46	115
Total	169	106	275

Of the 275 innovations and measures that were proposed by panel members, 169 were related to innovation needs, while 106 were related to commercialization issues. The numerical distribution of the proposals between the value chain parts indicates that a majority of the innovation needs are related to fuel production and vessel operations, while the innovation issues are less pronounced among the proposals related to bunkering issues. In the following, the core innovation issues and measures are summarized for each of the three value chain parts. As the focus of the study was on innovation, only selected commercialization measures are mentioned briefly at the end of each section. Please find the full assessment in the technical annex Report.

Innovations for fuel production

The input from the Delphi panel highlighted that a series of specific innovations are needed to address challenges around production of alternative fuels.

Thematically, these innovation needs address similar and related problems concerning the cost, efficiency and availability of the materials, processes and feedstock used to produce the green fuels. In doing so, the intended results are to strengthen their price competitiveness vis-a-vis marine fossil fuels, improve the consistent supply of the fuels, and ease the scale-up of production.

Specifically, the gaps concern the high costs and energy intensiveness of current electrolysis technologies, as well as other technologies.

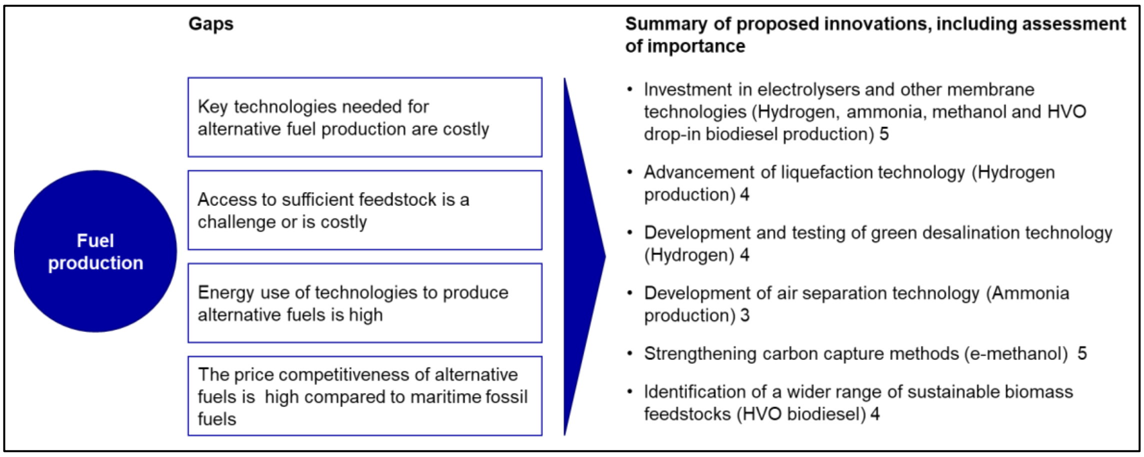
With respect to green hydrogen, green ammonia, methanol and drop-in-diesel (HVO), a core concern is that current alkaline electrolysis methods for green hydrogen production are a costly investment and require too much energy to run, impacting both capital and operational expenditure. Electrolysis is needed to produce green hydrogen from water, to be used as a standalone fuel or as an input for other fuels. Innovation in this area could explore alternative approaches, such as Solid Oxide Electrolysis Cells (SOEC) and other methods that are likely to improve efficiencies.

Similarly, the Delphi panel indicated that other key technologies and processes necessary to produce electricity-based fuels need to be more energy efficient to lower operational costs. This, among others, includes green desalination needed for 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, such as drop-in-diesel and biogas, further innovation is needed to 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.

The gaps and proposed innovations for fuel production are summarized in figure 6. The average score of importance of each of the innovations on a scale from 1 to 5 is indicated. These scores indicated the priority that these innovations could have.

Figure 6: Overview of key innovations for fuel production and their score of importance



In terms of commercialization measures suggested for fuel production, the general idea is that they would address gaps around the current scale and availability of fuels. Suggestions included, better exploitation of green investment channels and identification of sites, including conversion of ports into energy producing hubs.

Innovations for storage, transport and bunkering

The Delphi panelists also specified the innovation needs for supporting the storage, transport and bunkering of alternative fuels.

The innovations suggested aim to address several key gaps, including the need to transport the fuels to ports efficiently and at scale, while guaranteeing the safe and efficient bunkering of the fuels. It was notable that safe storage at ports was not considered a major issue, since all alternative fuels are stored as commodities already.

Regarding the efficient transportation of the fuels, fuel pipeline infrastructure could assist in carrying liquid or gas fuels from production sites at the scale needed. Alternatively, green truck networks could be deployed, assisted by renewable refueling or recharging sites at ports. In this area, the innovation challenges were not considered as significant, but still necessary to ensure zero carbon goals are met.

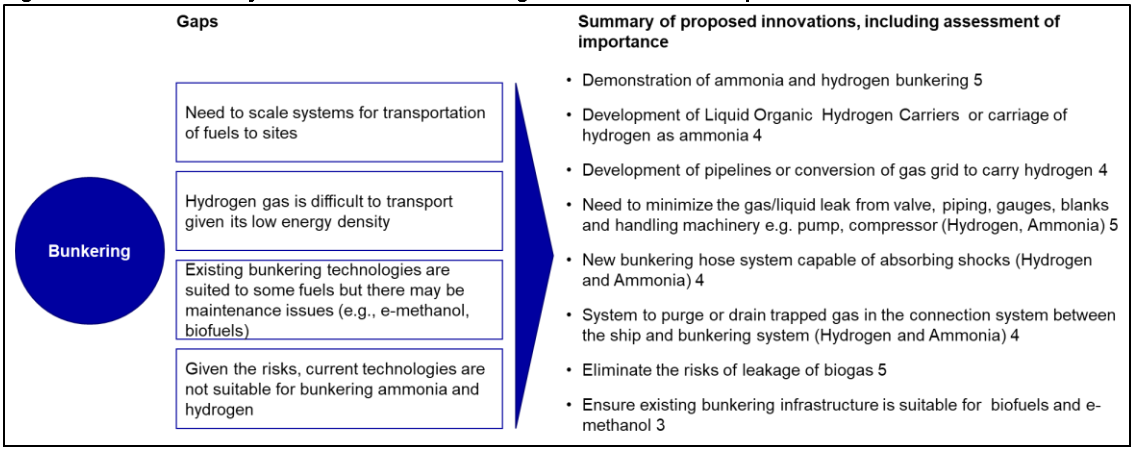
More specifically, innovation would be beneficial in addressing the difficulties in transporting green hydrogen in large volumes efficiently. For instance, green hydrogen could be carried in the form of Liquid Organic Green Hydrogen Carriers (LOHC), which could be stored in conventional storage systems and converted to green hydrogen in ports or used by designated fuel cells, requiring some technological advances.

It should be stressed that for biofuels and e-methanol, bunkering needs are similar to existing marine fuels, and while some innovations are needed to ensure safety and good maintenance, these were not considered as major technological gaps. For example, this includes ensuring that biogas can be stored safely without leakage and allowing for good maintenance of bunkering infrastructure using alternative fuels to conventional marine fuels.

Yet, given the risks and the lack of knowledge, the bunkering of green ammonia and green hydrogen requires new safety solutions. Suggested innovations included new hose systems that can absorb shocks from waves/tide/wind, sensors to detect leaks, controls for safety valves, double piping systems, and systems to purge or drain trapped gaseous LH2 fuel etc. Moreover, demonstration of differing bunkering methods (ship to ship, shore to ship, refrigerated to pressurized tanks etc.) were also called for in order to provide insights to ports regarding the possible approaches and how they perform.

The experts' gaps and proposed innovations for bunkering are summarized in figure 7. The average score of importance of each of the innovations are in the high end, indicating the priority that these innovations must have.

Figure 7: Overview of key innovations for bunkering and their score of importance



In terms of commercialization measures for bunkering, key issues included the safety issues and related concerns, especially with dangerous fuels such as green ammonia and green hydrogen. Therefore, it was suggested that local planning rules need to be assessed to learn if ports can store such fuels at significant scales. Also, it was recommended that community engagement actions should be launched together with ports, seafarers and local communities, to communicate how the fuels can be managed safely and address concerns.

Innovations for ship design, storage, propulsion and emissions

Similarly, the need for greater safety, efficiency and performance were at the heart of the innovations proposed for ship design, storage and propulsion. Moreover, finding new ways of controlling harmful emissions was also called upon.

Vessel design

As it currently stands, designs for vessels using green hydrogen and green ammonia have been approved, and trials are underway for cargo ships that use other types of alternative fuels such as biodiesel and methanol. Yet, to ensure similar levels of performance and maintenance of operating distances, it was felt by the panelists that further considerations could be made on how the total vessel design could be optimized to account for the use of alternative lower density fuels that require more storage.

Storage

Similarly, further research and innovation could be conducted on how to optimize fuel storage systems, through cylinder designs adapted to the on-board space available. In addition, the storage of green hydrogen poses challenges in that high pressures and low temperatures can make metal brittle and fatigued.

It was considered that some alternative fuels can use existing fuel distribution and storage technologies such as e-methanol, biodiesel, biogas and DME. While the innovation needs are lower, these fuels pose some maintenance and handling challenges. For example, methanol can cause corrosion and become contaminated with chloride.

Propulsion

With regards to propulsion, further advances are needed with respect to green ammonia and green hydrogen fuels. Green hydrogen fuel cells and green ammonia combustion engines are expected to enter the market in the coming years, but still require some advances in terms of performance, safety and demonstration before being sufficiently ready for the market. Development of methanol fuel cells were also suggested to find greater efficiencies than those offered by existing engine technologies.

Development of innovations for safety needed for operating on green hydrogen and green ammonia were deemed essential, including demonstration of a 100% leak-free pipe product for safe fuel distribution censors, shut down systems, and safe handling of boil-off gases that occur when the fuels are heated.

Common gaps across all alternative fuels include commercially available green pilot fuels and zero-emission auxiliary engines – these are regarded as being at the mid-point on the TRL scale. A further push is required so that the entire vessel propulsion systems can meet zero carbon targets.

There are commercially available engine solutions for e-methanol, biofuels, and DME – but there is uncertainty concerning their ongoing performance, along with the steps needed to ensure good maintenance. For example, when running on biodiesel, engine stability may be affected due to changing properties of the feedstock, along with the durability of engine seals and the risk of water becoming embedded in the fuel system etc.

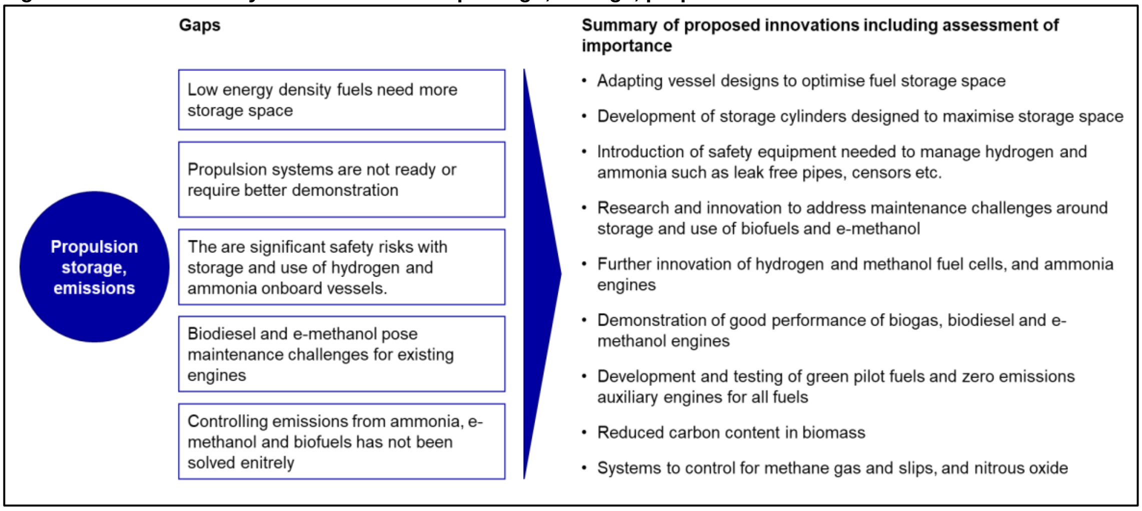
Moreover, cost effective retrofitting services and solutions are needed to support the conversion of existing vessels to green fuel usage.

Emissions

Further innovations to control emissions are needed to ensure GHG emission-free transition to other fuels. For instance, nitrous oxide emissions from green ammonia fuel were seen as a key challenge. One solution was to further explore the use of lean burn technologies. Green ammonia and methane from biogas slips were also seen as a challenge that needs to be addressed.

Concerning biodiesel, innovation to reduce the carbon content of biomass was seen as a possible way to reduce CO_2 emissions, along with exhaust cleaning technologies to ensure good maintenance.

Figure 8: Overview of key innovations for ship design, storage, propulsion and emissions



Finally, regarding possible commercialization measures for ship design, storage propulsion and emissions, suggestions included those already mentioned in the section on cross-cutting measures. Namely, standards for on board safety, fuel quality and GHG accounting, and crew training on safe use of new fuels.