MARITIME TECHNOLOGIES FORUM

LEADING THE MARITIME WORLD FORWARD

# UPDATED FUELS EVALUATION THROUGH THE MTF FRAMEWORK FOR ASSESSING DECARBONIZATION TECHNOLOGIES AND ALTERNATIVE ENERGY CARRIERS

## Executive Summary

The '2023 IMO Strategy on Reduction of GHG Emissions from Ships' sets out the International Maritime Organization's (IMO) ambitions for decreasing carbon emissions to be net zero (or near) by 2050. The relative importance of alternative fuels will grow to achieve the necessary decarbonization. At the same time, there is still uncertainty in the industry as to which alternative fuel option will support a future-proof asset and operation. There is also a widely available view that the future maritime fuel mix might not be dominated by a single fuel as it is today, but rather will see several fuels in use.

In 2022, MTF published an initial evaluation of four fuels (Fossil MGO, Fossil LNG, Bio-Methanol & Green Ammonia) and has extended that work with the present report by adding four additional fuels (Fossil MGO+CCS, Liquefied Bio Methane, Green Synthetic Methanol & Liquefied Blue Hydrogen), carefully chosen to complement the previously selected fuels and enabling multiple comparisons across fuel groups, fossil vs low carbon/carbon neutral and bio vs synthetic fuels. The MTF Framework has also been recently updated to account for the lessons learned in the first application, and, as such, all eight fuels are assessed against the updated criteria.

When compared to the baseline fuel, fossil MGO, all alternative fuels show lower GHG emission intensities[1] although values for biofuels and hydrogen-based synthetic fuels depend on details in production pathways. When looking at the number of barriers to adoption, biofuels and green synthetic methanol were found to have fewer than green ammonia or liquefied (blue) hydrogen.

Table 1. Summary of GHG Emission Intensity and Number of Barriers to Adoption

| Item | Fossil MGO | Fossil LNG | Fossil MGO+ CCS | Liquefied Blue Hydrogen | Liquefied Bio-Methane | Green Synthetic Methanol | Green Ammonia | Bio Methanol |
|---|---|---|---|---|---|---|---|---|
| GHG emission intensity ($gCO_2eq$/MJ) | 90.6 | 84.9 | 49.5 | 37 | 31.5 | 28.5 | 27.5 | 14 |
| Number of barriers to adoption | 2 | 2 | 18 | 24 | 1 | 5 | 17 | 4 |

Five main observations emerged, which include high priority suggestions for the industry.

1. **Well-to-Wake GHG emission performance is critical in the long term.** The use of biofuels and hydrogen-based solutions will provide lower lifecycle emissions (potentially zero or near zero when using sustainable energy sources).
2. **Safety needs careful management for some hydrogen-based synthetic fuels.** There is a moderate amount of data available for using ammonia and hydrogen as fuel. Most of this data is from other industries, or the carriage of fuel on liquified gas carriers. Additional research and studies are needed to further reduce or fully mitigate the associated risks addressing bunkering and onboard handling for these alternative solutions as fuels.
3. **The need for additional training related to handling of more hazardous alternative fuels is reconfirmed.** Training, safety awareness and management practices need to develop to similar levels seen onshore for these hazardous fuels.
4. **Technology for many fuel options is available with high maturity.** In terms of technology readiness, all solutions considered as demonstrated, or proven, in a relevant environment (TRL 6 or above). Use of ammonia and CCS still needs to be proven to reach a sufficient TRL for commercial uptake. Retrofits are generally possible with varying engineering complexity.
5. **Supply Chain Resilience is not known for biofuels and hydrogen-based synthetic fuels.** Supply chain resilience has been evaluated as low on confidence for all the biofuels and hydrogen-based fuels considered, and currently as not feasible for green ammonia. This is accounting for the current limited fuel availability.

## Introduction

The Maritime Technologies Forum (MTF) is a group of flag States and classification societies which aims to bridge the gap between technological progress and regulatory process. This report provides recommendations to industry stakeholders toward safe adoption of alternative fuels onboard ships in line with MTF's purpose.

The MTF has recently updated its Framework for Assessing Decarbonization Technologies and Alternative Energy Carriers. Using this, an expanded evaluation of eight fuel solutions has been undertaken as a collaborative exercise within MTF that assesses the feasibility of proposed alternative energy carriers expected to drive the decarbonization of the maritime industry.

The present report is based on the updated framework and extends the evaluation of future alternative fuels performed in the previous report with four additional fuels, as listed in Table 3. The second set of fuels were selected to complement the first set in building fuel groups. With these choices, multiple comparisons are becoming possible: fossil vs low carbon or carbon neutral fuels, pairwise comparison within each group, bio vs synthetic fuels, as well as adding carbon capture options for fuel production and onboard.

Table 2: Fuels Selected for Evaluation [with Fuel Pathway Codes from the LCA Guidelines]

| Group | Round 1 | | Round 2 | |
|---|---|---|---|---|
| | Fuel Selected | Draft IMO Fuel Code [1] | Fuel Selected | Draft IMO Fuel Code [1] |
| Diesel | Fossil MGO | MDO/MGO(VLSFO)_f_SR_gm | Fossil MGO+CCS | MDO/MGO(VLSFO)_f_r_CP_gm* |
| Methane | Fossil LNG | LNG_f_SLP_gm | Liquefied Bio Methane | LNG_b_AD_gm |
| Methanol | Bio-Methanol | MeOH_b_G_MS_gm | Green Synthetic Methanol | MeOH_f$CO_2$_rH2_MS_gm* |
| Hydrogen/ Ammonia | Green Ammonia | $NH_3$_r$N_2$_rH2_HB_gm | Liquefied Blue Hydrogen | $H_2$_f_SMR_CCS_gm* |

* Closest code available

The MTF Framework provides a holistic view of the elements that should be considered in such an analysis and this report represents the second application to a select group of fuels, including fossil fuels as an existing baseline. This report highlights risks associated with certain fuels and technologies, as well as existing knowledge and data gaps. This report:

- Starts with a comprehensive approach to evaluate a selection of different fuels
- Investigates on-board as well as onshore sustainability and safety aspects
- Builds on existing literature and identifies what is readily available
- Leverages MTF members' strengths, primarily around regulatory and rule development

This report is intended for broad use among maritime industry stakeholders, including ship owners, charterers, shipyards, equipment suppliers, flag states, classification societies, intergovernmental organizations and sustainability certification bodies.

Work at IMO is progressing towards a future Marine Fuel Life Cycle GHG Analysis and an initial list of 101 fuel pathways have been identified in a recent report[2]. The Nordic Roadmap project[3] has provided a life cycle assessment of potential zero-carbon fuels in the Nordic context, addressing well-to-wake GHG emissions as well as other environmental impacts. The Sustainable Shipping Initiative[4] has outlined sustainability issues, principles and criteria developed according to different feedstocks and primary energy sources for zero and low carbon marine fuels. A study[5] by Ricardo and DNV reported on the readiness and availability of low- and zero-carbon ship technology and marine fuels The Lloyd's Register zero-carbon fuel monitor[6] recently showed an average increase in readiness across all fuels and supply chain stages from three perspectives: technology (TRL), investment (IRL) and community (CRL).

## Methodology

The fuels evaluation against the updated MTF framework criteria was done through a series of workshops. While evaluating these fuels, feedback was sought from all MTF members individually, prior to a workshop that was conducted to aggregate results for each subcategory.

The evaluation was performed using all 33 sub-criteria laid out in the MTF Framework which are categorized into eight high-level criteria: GHG emission, technology, environmental sustainability, safety, economic viability, regulatory maturity, skills availability and engineering.

The categories of environmental sustainability, safety, economic viability, regulatory maturity and skills availability are further divided into the same four parts of the supply chain: production, storage and distribution; bunkering; onboard storage and use; and disposal.

For each sub-criterion, data/evidence availability (i.e. confidence) and the feasibility of the solution to meet criteria were assessed using the grading options shown in Table 4. The exceptions are the GHG emission intensity provided as a numerical value in grams $CO_2$ eq per MJ of energy, and the technology readiness level provided as a numerical value between 1 and 9.

It is the intention of MTF to quote GHG emission intensity values, well-to-wake (WtW), from the default values of the relevant pathway in the IMO Guidelines on Life Cycle GHG Intensity of Marine Fuels (LCA Guidelines). At the time of preparing this report, default GHG intensity values are not yet defined for all of the fuels considered. In the interim, default values are taken from the FuelEU Maritime Regulations for fossil MGO (baseline) and Grey LNG, with the Ricardo and DNV study[4] used for all other fuel solutions represented as a median value from the range reported.

Table 3: Description of grading options

| Dimension | Grading (Key to Results) | Description |
|---|---|---|
| Feasibility Assessment | High (Dark Blue) | The solution fully meets the criterion. |
| | Medium (Mid blue) | The solution meets the criterion but can be upgraded further. |
| | Low (Light Blue) | The solution requires significant developments to achieve the criterion, but is expected to be able to meet it in the future |
| | Not Feasible (White) | The solution does not meet the criterion and is not expected to be able to meet it in the future. |
| Confidence Level | High (●●●) | The data availability is high and there is robust evidence for the assessment. |
| | Medium (●●) | There is data available and there is medium evidence for the assessment. |
| | Low (●) | The data availability is low and there is limited evidence for the assessment. |
| | Insufficient data (no data) | Insufficient data means that no or limited data is available for evaluation against the criterion. |

## Assumptions and Limitations

When no information was readily available, the MTF members made reasonable assumptions to complete the exercise. The opinions and options represent the best judgement of the members based on their experience and expertise. This evaluation considers a broad range of aspects relating to each fuel and it is worth noting that the MTF members predominantly have expertise in engineering and regulation.

The options available and fuels considered were predetermined through a collaborative effort. Members were encouraged to make their choices using the available options. Although for some sub criteria the options are arguably less applicable than others, and the number of them limit the granularity of the scoring, they were chosen to allow the evaluation to proceed in a timely manner.

## Disclaimer

The results here are a collaborative effort between participating MTF members. Each organization within the forum may have an independent opinion different from the results presented in this report. This report does not preclude MTF members from having their own independent opinion or conclusion.

## Summary of Results

With fossil MGO as the base case, the group compared existing and new/emerging fuels through the MTF Framework. The results for all eight fuels are summarized below with detailed results for each fuel presented in Appendix A.

The GHG emission intensity value is the primary criterion when considering the objective is to reach IMO's decarbonization targets. Whilst single values are presented in Table 4, these represent a median value from published values in in Appendix 1[4]. For Fossil MGO + CCS we assume a 30% fuel penalty and a 90% CO2 capture rate. Further evaluation of the fuels considers that it must be produced according to this GHG emission intensity.

In reviewing the results there are obvious and well-known trends identified. In terms of technology readiness, all solutions considered are demonstrated, or proven, in a relevant environment (TRL 6 or above) so it can be concluded that this is not a barrier to adoption for any of the solutions.

The level of confidence reduces with new and emerging fuels where the operational experience is limited or non-existent. This indicates a need for more research and development, as well as pilots, to close the knowledge gaps. Secondly, the feasibility of hydrogen-based synthetic fuels needs to be improved, particularly in terms of cost in establishing robust infrastructure for production, storage and distribution. A key factor for any of the alternative fuels considered is the availability of fuel and scalability of production and distribution to meet demand, considering that the marine industry will be competing against demand from other industries.

There are 3 instances where a solution has been marked as 'not feasible – cannot be improved':

1. **Fossil MGO** – 'social acceptance' as doing nothing is not acceptable for the industry or wider society. Noting that the sustainability of production, storage and distribution is also 'not feasible – can be improved' for all fossil fuels.
2. **Grey LNG** – 'social acceptance' as above.
3. **Liquified Blue Hydrogen** – complexity of retrofitting, as greater storage volumes would be required with limited space, complete fuel supply system replacement.

Although it is believed that the low carbon fuels such as green ammonia can meet the sustainability goals, the current small-scale production (and projects) as well as gaps in related regulations and standards lead these to have a 'not feasible – can be improved' grading when compared to more established fuels.

Safety is a key area that also requires improvement across new / emerging fuels in terms of hazards associated with bunkering and onboard use, recognizing that for fuels like ammonia and hydrogen more needs to be done on a risk assessment level to address consequence effects and to justify their use. This also links to training, especially for seafarers, where a greater understanding of the major hazard potential is needed similar to other process industries.

This is further illustrated by the low confidence and feasibility grading on the skills availability for onboard criterion considering both green ammonia and liquefied blue hydrogen. One item discussed during the assessment was whether training should be graded low for everything that does not have a 'model course' provided by IMO and graded high for everything that does. In the end, it was decided to take a view that although ammonia and hydrogen, for example, do not have model courses, there can be a lot of cross pollination from the training of the carriage of ammonia as a cargo and use of LNG as a fuel for example.

Summary Results Figure Legend:

| | | | |
|---|---|---|---|
| | Very Feasible | ••• | High Confidence |
| | Feasible – Can Be Further Improved | •• | Medium Confidence |
| | Not Feasible – Can Be Improved | • | Low Confidence |
| | Not Feasible – Cannot Be Improved | | Insufficient Data |

Table 4: Summary of Results Against the MTF Framework

| Category | Criterion | Fossil MGO | Grey LNG | Fossil MGO+CCS | Liquefied Bio-Methane | BioMethanol | Green Synthetic Methanol | Green Ammonia | Liquefied Blue Hydrogen |
|---|---|---|---|---|---|---|---|---|---|
| Greenhouse Gas Emission (GHG) | Greenhouse Gas emission intensity ($gCO_2eq/MJ$) | 90.6 | 84.9 | 49.5 | 31.5 | 14 | 28.5 | 27.5 | 37 |
| Technology | Current technology readiness level | **TRL 9** | **TRL 9** | **TRL 6** | **TRL 9** | **TRL 8** | **TRL 7** | **TRL 6** | **TRL 7** |
| | Expected technology readiness level in five years | **TRL 9** | **TRL 9** | **TRL 8** | **TRL 9** | **TRL 9** | **TRL 8** | **TRL 8** | **TRL 8** |
| | Social acceptance | ●● | ●● | ● | ●● | ●● | ●● | ● | ● |
| | Supply chain resilience | ●●● | ●● | ●●● | ● | ● | ● | ● | ● |
| | Security against malicious actions | ●●● | ●● | ●●● | ●● | ●● | ●● | ●● | ●● |
| Environmental Sustainability | Sustainability of production, storage and distribution | ●●● | ●● | ●● | ●● | ●● | ●● | ●● | ●● |
| | Sustainability of bunkering | ●●● | ●● | ●●● | ●●● | ●● | ●● | ● | ● |
| | Sustainability of onboard storage and use | ●●● | ●● | ●● | ●● | ●● | ●● | ● | ● |
| | Recyclability and sustainability of disposal | ●●● | ●● | ● | ●●● | ●● | ●● | ●● | ● |
| Safety | Safety during production, storage and distribution | ●●● | ●● | ●●● | ●● | ●● | ●● | ●● | ● |
| | Safety during bunkering | ●●● | ●● | ●●● | ●● | ●● | ●● | | ● |
| | Safety during onboard storage and use | ●●● | ●● | ●● | ●● | ●● | ●● | | ● |
| | Safety during disposal | ●●● | ●● | ● | ●● | ●● | ●● | ●● | ●● |
| Economic Viability | Cost of production, storage and distribution | ●●● | ●●● | ●●● | ●●● | ●● | ● | ● | ●● |
| | Cost of bunkering | ●●● | ●●● | ●●● | ●● | ●● | ●● | ●● | ●● |
| | Cost of onboard storage and use | ●●● | ●● | ● | ●● | ●● | ●● | ●● | ● |
| | Cost of disposal | ●●● | ●● | ● | ●● | ●● | ●● | ●● | ●● |

| Category | Criterion | Fossil MGO | Grey LNG | Fossil MGO+CCS | Liquefied Bio-Methane | BioMethanol | Green Synthetic Methanol | Green Ammonia | Liquefied Blue Hydrogen |
|---|---|---|---|---|---|---|---|---|---|
| Regulatory maturity | Maturity of regulations related to production, storage and distribution | ●●● | ●● | ●●● | ●● | ●● | ●● | ●● | ● |
| | Maturity of regulations related to bunkering | ●●● | ●● | ●●● | ●● | ●● | ●● | ●● | ● |
| | Maturity of regulations related to onboard storage and use | ●●● | ●● | ●● | ●● | ●● | ●● | ●● | ● |
| | Maturity of regulations related to disposal | ●●● | ●● | ●● | ●● | ●● | ●● | ● | ● |
| Skills availability | Skill base and competency for production, storage and distribution | ●●● | ●● | ● | ●● | ●● | ●● | ●●● | ● |
| | Skill base and competency for bunkering | ●●● | ●● | ●●● | ●● | ●● | ●● | ●● | ● |
| | Skill base and competency onboard storage and use | ●●● | ●● | ● | ●● | ●● | ●● | ● | ● |
| | Skill base and competency for disposal | ●●● | ●● | ● | ●● | ●● | ●● | ●● | ●● |
| Engineering | Engineering complexity (production, installation, decommissioning) | ●●● | ●●● | ● | ●●● | ●● | ●● | | ● |
| | Complexity of retrofitting | ●●● | ●● | ● | ●● | | ● | | ● |
| | Availability | ●●● | ●●● | ● | ●●● | ●● | ●● | | ● |
| | Reliability | ●●● | ●●● | ● | ●●● | | ● | | ● |
| | Maintainability | ●●● | ●●● | ● | ●●● | | ● | | ● |
| | Logistics/supportability | ●●● | ●●● | ● | ●●● | ●● | ●● | ●● | ● |
| | Quality standards | ●●● | ●●● | ● | ●●● | ●● | ●● | | ● |

Table 5 shows a summary of the feasibility barriers which include any fuel that is graded as "not feasible".

Table 5: Summary of feasibility barriers

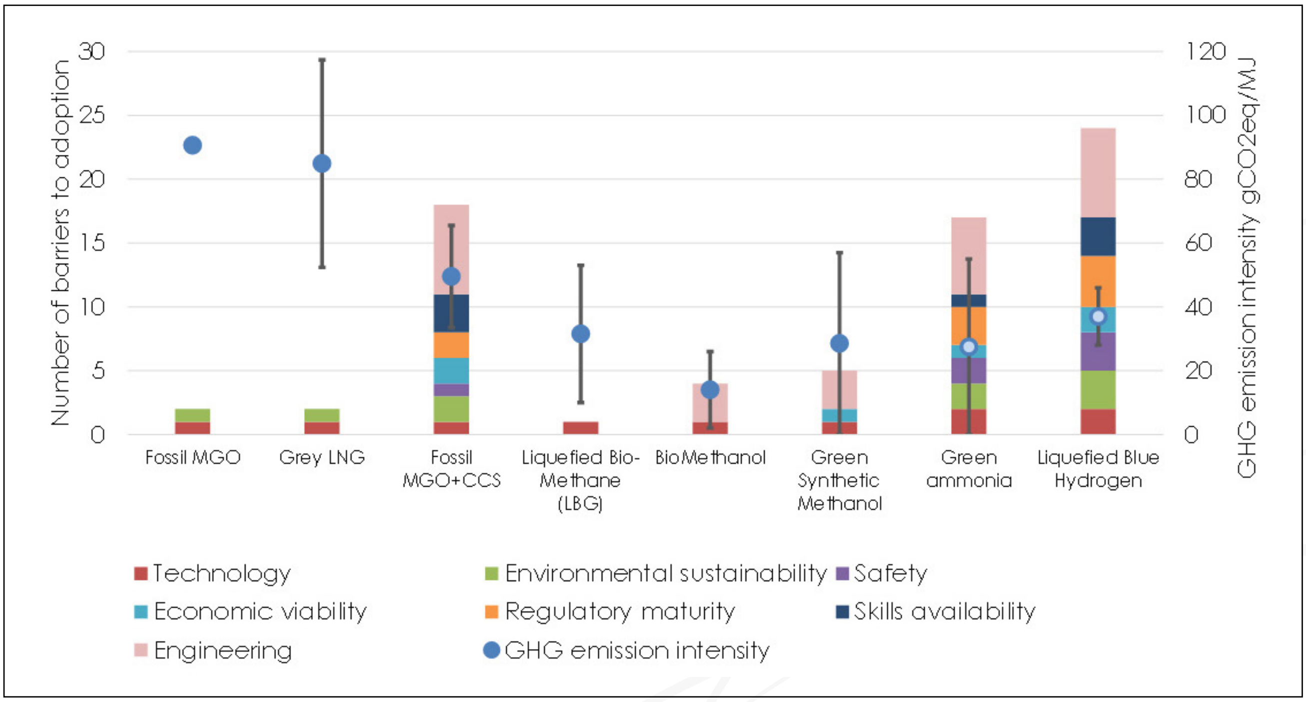
| Category | Criterion | Feasibility barriers |
|---|---|---|
| Technology | Social acceptance | Fossil MGO and Fossil LNG will not be able to sufficiently reduce GHG emissions and may not be accepted in the future. |
| | Supply chain resilience | A Green Ammonia supply chain may have low resilience due to vulnerability when scaling up a new solution |
| Environmental Sustainability | Sustainability of production, storage and distribution | Fossil MGO, Fossil LNG and Fossil MGO+CCS still relies on extraction of fossil fuels |
| | Recyclability and sustainability of disposal | Fossil MGO + CCS needs a disposal and storage infrastructure that prevent the release of $CO_2$ |
| Economic Viability | Cost of production, storage and distribution | Green Synthetic Methanol, Green Ammonia, Liquefied Blue Hydrogen all have large production costs |
| | Cost of onboard storage and use | Fossil MGO + CCS comes with a large fuel penalty and storage costs |
| | Cost of disposal | Fossil MGO + CCS: the $CO_2$ must be disposed of and permanently stored or utilised |
| Regulatory Maturity | Maturity of regulations related to production, storage and distribution | Liquefied Blue Hydrogen needs detailed regulations on production, distribution and storage. |
| | Maturity of regulations related to onboard storage and use | Fossil MGO + CCS lacks incentives for use in many regulations, and together with Green Ammonia also lacks safety standards. |
| | Maturity of regulations related to disposal | Fossil MGO + CCS has limited regulations and standard related to disposal and storage. |
| Skills Availability | Skill base and competency onboard storage and use | Green Ammonia, Liquefied (Blue) Hydrogen lacks skilled seafarers |
| Engineering | Complexity of retrofitting | Liquefied (Blue) Hydrogen is likely not possible to retrofit |

Figure 1 shows the number of barriers to adoption for each fuel as a bar chart with the GHG emission intensity (median) values plotted, including the possible range of intensity values indicated as an error bar. A barrier is defined on the basis that either the feasibility is graded as one of the 'not feasible' options or has low/no confidence due to insufficient data or evidence.

On review of Table 5 and Figure 1, the methanol fuel options are shown to have the least barriers to adoption, similar to existing fossil fuels, which is largely due to the use of existing infrastructure for production, storage and distribution. The barriers shown for technology and engineering are based on the low confidence scorings, as further evidence and use of methanol on large-scale projects is required. A barrier for the adoption of CCS and ammonia is the lack of regulations. For CCS there is lack of incentives for the uptake, regulations for safe handling onboard and for disposal. For ammonia and onboard CCS, the main issue is the lack of safety standards.

When considering the number of barriers to adoption, caution should be exercised as some barriers may be simpler to address or require less resources than others. The number of fuel solutions reaching TRL9, actual systems/fuels used in an operational environment, will also influence this current viewpoint.

Figure 1 Comparison of Fuels: Barriers and GHG emission intensity values




## Conclusions and Future Work

### Conclusions

The evaluation of fuels against the MTF Framework supports the idea that the future of international shipping will be a fuel mix depending on many factors such as ship type, function, operating environment and available fuel source / infrastructure. The following high-level observations are derived from the 'Summary of Results' across all eight solutions.

**Observation # 1: Well-to-Wake GHG emission performance is critical in the long term**
The GHG emission intensity value is the primary criterion when considering the objective is to reach IMO's decarbonization targets. The use of biofuels and hydrogen-based solutions will provide lower lifecycle emissions (potentially zero or near zero when using sustainable energy sources).

**Observation # 2: Safety needs careful management for some hydrogen-based synthetic fuels**
Given the lower flashpoint and toxicity of some of these fuels results in the need for detailed safety studies/risk assessment and using these findings to demonstrate equivalent level of safety to fuel oil.

There is a moderate amount of data available for using liquefied bio-methane, bio-methanol, green ammonia and hydrogen. Most of this data is from other industries, or the carriage of fuel on liquified gas carriers, with much of the safety philosophy and protection being utilized from these applications. Until more knowledge is acquired, additional research and studies are needed to further reduce or fully mitigate the associated risks addressing the increased handling and interactions when using alternative solutions as fuels.

Safety during bunkering for methanol, ammonia and hydrogen also needs to be improved.

**Observation #3: The need for additional training related to handling of more hazardous alternative fuels is reconfirmed.**
This safety observation also links to training and the need for safety awareness and management practices to develop to similar levels seen onshore for these hazardous fuels. In terms of training, it has been observed that cross pollination from existing training courses, such as the carriage of ammonia as a cargo and use of LNG as a fuel, is possible.

**Observation # 4: Technology for many fuel options is available with high maturity**
Fossil fuels are well established solutions. In terms of technology readiness, all solutions considered as demonstrated, or proven, in a relevant environment (TRL 6 or above) so it can be concluded that this alone is not a barrier to adoption. The current technology readiness, and expected growth in readiness levels, is high for all evaluated fuels except green ammonia and Fossil MGO & CCS. Use of ammonia and CCS still needs to be proven to reach a sufficient TRL for commercial uptake. Retrofits are generally considered feasible with varying engineering complexity.

**Observation # 5: Supply Chain Resilience is not known for biofuels and hydrogen-based synthetic fuels**
Supply chain resilience has been evaluated as low on confidence for all the biofuels and hydrogen-based fuels considered, and currently as not feasible for green ammonia. This is accounting for the current limited fuel availability and competing demands with other industries. This is a well-known issue within the industry, with much discussion on ensuring a clear supply demand, and should be communicated to policy makers and fuel producers.

### Future Work

Based on the discussions during the assessment, areas of future focus emerged:

1. The study identifies several criteria for which data is not sufficiently available, such as for green ammonia and bioMethanol as shown in Table 4, and failure to meet the assessment suggests the need for further research and development to enhance industry knowledge and support future decision making.
2. Additional fuel and power options may be added to the fuel evaluation to have a more complete basis for decision making. It is noted that hybrid power options may be used with alternative fuels, thus a detailed analysis of the same would be required eventually. The industry may adopt this framework for any variant of fuels and other fuels not part of this evaluation.

## References

[1] MEPC 80/7/4, Final report of the Correspondence Group on Marine Fuel Life Cycle GHG Analysis, 28 April 2023

[2] IMO MEPC 79/7/12, Interim report of the Correspondence Group on Marine Fuel Life Cycle GHG Analysis, 07 October 2022

[3] Life Cycle Assessment of Marine Fuels in the Nordic Region – Task 1C, Nordic Roadmap Publication No.1-C/1/2023. Available at https://futurefuelsnordic.com/life-cycle-assesment-of-selected-fuels/

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[5] Study on the readiness and availability of low- and zero-carbon ship technology and marine fuels, Ricardo and DNV, April 2023. Published in MEPC 80/INF.10 and available at https://www.imo.org/en/OurWork/Environment/Pages/Future-Fuels-And-Technology.aspx

[6] Zero Carbon Fuel Monitor, The Lloyd's Register Maritime Decarbonisation Hub, July 2022 update [Published Zero-Carbon Fuel Monitor (lr.org)]

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# Appendix 1 – Detailed Results by Fuel

**Solution:** Fossil MGO [Fuel Pathway Code: MDO/MGO(VLSFO)_f_SR_gm]

**Description:** Standard crude oil refinery process using grid mix electricity.

**Evaluation:** Not surprisingly, a mature fuel choice of fossil MGO is largely graded as 'very feasible' across the criteria, except for social and environmental sustainability.

| | |
|---|---|
| | Very Feasible |
| | Feasible – Can Be Further Improved |
| | Not Feasible – Can Be Improved |
| | Not Feasible – Cannot Be Improved |

| | |
|---|---|
| ●●● | High Confidence |
| ●● | Medium Confidence |
| ● | Low Confidence |
| | Insufficient Data |

| | | Well-to-wake: Production, storage and distribution | Bunkering | Onboard Storage and use | Disposal |
|---|---|---|---|---|---|
| Greenhouse gas emission intensity | | **90.6 gCO2eq/MJ** | | | |
| Technology | Current technology readiness level | **TRL 9** | | | |
| | Potential trajectory of technology readiness | **TRL 9** | | | |
| | Social acceptance | ●● | | | |
| | Supply chain resilience | ●●● | | | |
| | Security against malicious actions | ●●● | | | |
| Sustainability & Environmental | | ●●● | ●●● | ●●● | ●●● |
| Safety | | ●●● | ●●● | ●●● | ●●● |
| Economic Feasibility | | ●●● | ●●● | ●●● | ●●● |
| Regulatory | | ●●● | ●●● | ●●● | ●●● |
| People | | ●●● | ●●● | ●●● | ●●● |
| Engineering | Engineering complexity (production, installation, decommissioning) | | | ●●● | |
| | Complexity of retrofitting | | | ●●● | |
| | Availability | | | ●●● | |
| | Reliability | | | ●●● | |
| | Maintainability | | | ●●● | |
| | Logistics/supportability | | | ●●● | |
| | Quality standards | | | ●●● | |

**Solution:** Grey LNG [Fuel Pathway Code: LNG_f_SLP_gm]

**Description:** Standard LNG production, including liquefaction, and using grid mix electricity.

**Evaluation:** No significant barriers, but mostly medium and high confidence across the board. Sustainability, safety, regulatory, skills availability have medium confidence. Not many LNG vessels have reached end-of-life to understand disposal aspects.

| | |
|---|---|
| | Very Feasible |
| | Feasible – Can Be Further Improved |
| | Not Feasible – Can Be Improved |
| | Not Feasible – Cannot Be Improved |

| | |
|---|---|
| ●●● | High Confidence |
| ●● | Medium Confidence |
| ● | Low Confidence |
| | Insufficient Data |

| | | Well-to-wake | | | |
|---|---|---|---|---|---|
| | | Production, storage and distribution | Bunkering | Onboard Storage and use | Disposal |
| Greenhouse gas emission intensity | | 84.9 gCO2eq/MJ (range 76-91 gCO2eq/MJ) | | | |
| Technology | Current technology readiness level | TRL 9 | | | |
| | Potential trajectory of technology readiness | TRL 9 | | | |
| | Social acceptance | ●● | | | |
| | Supply chain resilience | ●● | | | |
| | Security against malicious actions | ●● | | | |
| Sustainability & Environmental | | ●● | ●● | ●● | ●● |
| Safety | | ●● | ●● | ●● | ●● |
| Economic Feasibility | | ●●● | ●●● | ●● | ●● |
| Regulatory | | ●● | ●● | ●● | ●● |
| People | | ●● | ●● | ●● | ●● |
| Engineering | Engineering complexity (production, installation, decommissioning) | | | ●●● | |
| | Complexity of retrofitting | | | ●● | |
| | Availability | | | ●●● | |
| | Reliability | | | ●●● | |
| | Maintainability | | | ●●● | |
| | Logistics/supportability | | | ●●● | |
| | Quality standards | | | ●●● | |

**Solution:** Fossil MGO & CCS [Fuel Pathway Code: MDO/MGO(VLSFO)_f_r_CP_gm]

**Description:** Fossil and recycled carbon co-processing in refinery using grid mix electricity. Scope includes both the fuel and manufacture, installation etc. of carbon capture units, as well as the disposal and subsequent permanent storage or utilization of the $CO_2$. The assessment assumes a 50% to 90% capture rate (coming to a 70% average) and a 20% to 40% increase in energy usage (coming to a 30% average).

**Evaluation:** The limiting factor for the use of CCS is the regulatory maturity for both onboard storage and use, and disposal. Further, the confidence levels are graded low for many of the sub-criteria when considering onboard and disposal, however, it is recognized that the technology is relatively mature (particularly on land). It is anticipated that the TRL will move from 6 to 7 shortly with full scale pilot projects being undertaken.

| | |
|---|---|
| | Very Feasible |
| | Feasible – Can Be Further Improved |
| | Not Feasible – Can Be Improved |
| | Not Feasible – Cannot Be Improved |

| | |
|---|---|
| ●●● | High Confidence |
| ●● | Medium Confidence |
| ● | Low Confidence |
| | Insufficient Data |

| | | Well-to-wake | | | |
|---|---|---|---|---|---|
| | | Production, storage and distribution | Bunkering | Onboard Storage and use | Disposal |
| Greenhouse gas emission intensity | | **49.5 gCO2eq/MJ (range 31.9-64.4 gCO2eq/MJ)** | | | |
| Technology | Current technology readiness level | **TRL 6** | | | |
| | Potential trajectory of technology readiness | **TRL 8** | | | |
| | Social acceptance | ● | | | |
| | Supply chain resilience | ●●● | | | |
| | Security against malicious actions | ●●● | | | |
| Sustainability & Environmental | | ●● | ●●● | ●● | ● |
| Safety | | ●●● | ●●● | ●● | ● |
| Economic Feasibility | | ●●● | ●●● | ● | ● |
| Regulatory | | ●●● | ●●● | ●● | ●● |
| People | | ● | ●●● | ● | ● |
| Engineering | Engineering complexity (production, installation, decommissioning) | | | ● | |
| | Complexity of retrofitting | | | ● | |
| | Availability | | | ● | |
| | Reliability | | | ● | |
| | Maintainability | | | ● | |
| | Logistics/supportability | | | ● | |
| | Quality standards | | | ● | |

**Solution:** Liquified Bio-methane (LBG)[Fuel Pathway Code: LNG_b_AD_gm]

**Description:** Assumed to be based on organic waste and comply with sustainability criteria (e.g. RED, IMO LCA).

**Evaluation:** Bio-methane would reduce the GHG emissions throughout the supply chain and onboard the vessel when compared to LNG. In terms of technology and engineering, the use of bio-methane is very feasible, with a high level of confidence, based on the industry experience with using LNG. Its feasibility is further supported by the use of existing LNG distribution, storage and bunkering facilities. Where confidence has been graded low is in relation to supply chain resilience, accounting for the current limited fuel availability and competing demands with other industries.

| | |
|---|---|
| | Very Feasible |
| | Feasible – Can Be Further Improved |
| | Not Feasible – Can Be Improved |
| | Not Feasible – Cannot Be Improved |

| | |
|---|---|
| ●●● | High Confidence |
| ●● | Medium Confidence |
| ● | Low Confidence |
| | Insufficient Data |

| | | Well-to-wake | | | |
|---|---|---|---|---|---|
| | | Production, storage and distribution | Bunkering | Onboard Storage and use | Disposal |
| Greenhouse gas emission intensity | | **31.5 gCO2eq/MJ (range 10-53 gCO2eq/MJ)** | | | |
| Technology | Current technology readiness level | **TRL 9** | | | |
| | Potential trajectory of technology readiness | **TRL 9** | | | |
| | Social acceptance | ●● | | | |
| | Supply chain resilience | ● | | | |
| | Security against malicious actions | ●● | | | |
| Sustainability & Environmental | | ●● | ●●● | ●● | ●●● |
| Safety | | ●● | ●● | ●● | ●● |
| Economic Feasibility | | ●●● | ●● | ●● | ●● |
| Regulatory | | ●● | ●● | ●● | ●● |
| People | | ●● | ●● | ●● | ●● |
| Engineering | Engineering complexity (production, installation, decommissioning) | | | ●●● | |
| | Complexity of retrofitting | | | ●● | |
| | Availability | | | ●●● | |
| | Reliability | | | ●●● | |
| | Maintainability | | | ●●● | |
| | Logistics/supportability | | | ●●● | |
| | Quality standards | | | ●●● | |

**Solution:** BioMethanol [Fuel Pathway Code: MeOH_b_G_MS_gm]

**Description:** Assumed to be based on waste and comply with sustainability criteria (e.g. RED, IMO LCA).

**Evaluation:** Biomethanol would reduce the GHG emissions throughout the supply chain and onboard the vessel when compared to fossil MGO. In terms of technology and engineering, the use of bio-methanol is feasible, with a medium level of confidence, or some cases lacking data, based on the limited industry experience with using methanol. Where confidence has been graded low is in relation to supply chain resilience, accounting for the current limited fuel availability and competing demands with other industries.

| | |
|---|---|
| | Very Feasible |
| | Feasible – Can Be Further Improved |
| | Not Feasible – Can Be Improved |
| | Not Feasible – Cannot Be Improved |

| | |
|---|---|
| ●●● | High Confidence |
| ●● | Medium Confidence |
| ● | Low Confidence |
| | Insufficient Data |

| | | Well-to-wake | | | |
|---|---|---|---|---|---|
| | | Production, storage and distribution | Bunkering | Onboard Storage and use | Disposal |
| Greenhouse gas emission intensity | | **14 gCO2eq/MJ (range 2-26 gCO2eq/MJ)** | | | |
| Technology | Current technology readiness level | **TRL 8** | | | |
| | Potential trajectory of technology readiness | **TRL 9** | | | |
| | Social acceptance | ●● | | | |
| | Supply chain resilience | ● | | | |
| | Security against malicious actions | ●● | | | |
| Sustainability & Environmental | | ●● | ●● | ●● | ●● |
| Safety | | ●● | ●● | ●● | ●● |
| Economic Feasibility | | ●● | ●● | ●● | ●● |
| Regulatory | | ●● | ●● | ●● | ●● |
| People | | ●● | ●● | ●● | ●● |
| Engineering | Engineering complexity (production, installation, decommissioning) | | | ●● | |
| | Complexity of retrofitting | | | | |
| | Availability | | | ●● | |
| | Reliability | | | | |
| | Maintainability | | | | |
| | Logistics/supportability | | | ●● | |
| | Quality standards | | | ●● | |

**Solution:** Green Synthetic Methanol [Fuel Pathway Code: MeOH_fCO2_rH2_MS_gm]

**Description:** Scope was limited to renewable electricity resources and excluded nuclear.

**Evaluation:** Unsurprisingly, green synthetic methanol gradings are very similar to biomethanol except for economic viability, specifically cost of production, storage and distribution. Synthetics can be done but doing so at scale needs improvement, and supply chain resilience is an issue.

| | |
|---|---|
| | Very Feasible |
| | Feasible – Can Be Further Improved |
| | Not Feasible – Can Be Improved |
| | Not Feasible – Cannot Be Improved |

| | |
|---|---|
| ●●● | High Confidence |
| ●● | Medium Confidence |
| ● | Low Confidence |
| | Insufficient Data |

| | | Well-to-wake | | | |
|---|---|---|---|---|---|
| | | Production, storage and distribution | Bunkering | Onboard Storage and use | Disposal |
| Greenhouse gas emission intensity | | **28.5 gCO2eq/MJ (range 0-57 gCO2eq/MJ)** | | | |
| Technology | Current technology readiness level | **TRL 7** | | | |
| | Potential trajectory of technology readiness | **TRL 8** | | | |
| | Social acceptance | ●● | | | |
| | Supply chain resilience | ● | | | |
| | Security against malicious actions | ●● | | | |
| Sustainability & Environmental | | ●● | ●● | ●● | ●● |
| Safety | | ●● | ●● | ●● | ●● |
| Economic Feasibility | | ● | ●● | ●● | ●● |
| Regulatory | | ●● | ●● | ●● | ●● |
| People | | ●● | ●● | ●● | ●● |
| Engineering | Engineering complexity (production, installation, decommissioning) | | | ●● | |
| | Complexity of retrofitting | | | ● | |
| | Availability | | | ●● | |
| | Reliability | | | ● | |
| | Maintainability | | | ● | |
| | Logistics/supportability | | | ●● | |
| | Quality standards | | | ●● | |

**Solution:** Green Ammonia [Fuel Pathway Code: NH3_rN2_rH2_HB_gm]

**Description:** Feedstock is produced from renewable electricity using the Haber Bosch synthesis process.

**Evaluation:** Green ammonia is a key solution for achieving near-zero GHG emissions (WtW). There is limited marine experience with using ammonia as fuel and machinery technology is under development (e.g. engine), which is what drives the confidence levels to be low or insufficient on many of the criteria. While much experience can be taken from onshore industries and the carriage of ammonia in liquified gas carriers there remains challenges around safety and managing the risks associated with the toxicity.

| | |
|---|---|
| | Very Feasible |
| | Feasible – Can Be Further Improved |
| | Not Feasible – Can Be Improved |
| | Not Feasible – Cannot Be Improved |

| | |
|---|---|
| ••• | High Confidence |
| •• | Medium Confidence |
| • | Low Confidence |
| | Insufficient Data |

| | | Well-to-wake | | | |
|---|---|---|---|---|---|
| | | Production, storage and distribution | Bunkering | Onboard Storage and use | Disposal |
| Greenhouse gas emission intensity | | **27.5 gCO2eq/MJ (range 0-55 gCO2eq/MJ)** | | | |
| Technology | Current technology readiness level | **TRL 6** | | | |
| | Potential trajectory of technology readiness | **TRL 8** | | | |
| | Social acceptance | • | | | |
| | Supply chain resilience | • | | | |
| | Security against malicious actions | •• | | | |
| Sustainability & Environmental | | •• | • | • | •• |
| Safety | | •• | | | •• |
| Economic Feasibility | | • | •• | •• | •• |
| Regulatory | | •• | •• | •• | • |
| People | | ••• | •• | • | •• |
| Engineering | Engineering complexity (production, installation, decommissioning) | | | | |
| | Complexity of retrofitting | | | | |
| | Availability | | | | |
| | Reliability | | | | |
| | Maintainability | | | | |
| | Logistics/supportability | | | •• | |
| | Quality standards | | | | |

**Solution:** Liquified Bio-methane (LBG)[Fuel Pathway Code: LNG_b_AD_gm]

**Description:** Assumed to be based on organic waste and comply with sustainability criteria (e.g. RED, IMO LCA).

**Evaluation:** Bio-methane would reduce the GHG emissions throughout the supply chain and onboard the vessel when compared to LNG. In terms of technology and engineering, the use of bio-methane is very feasible, with a high level of confidence, based on the industry experience with using LNG. Its feasibility is further supported by the use of existing LNG distribution, storage and bunkering facilities. Where confidence has been graded low is in relation to supply chain resilience, accounting for the current limited fuel availability and competing demands with other industries.

| | |
|---|---|
| | Very Feasible |
| | Feasible – Can Be Further Improved |
| | Not Feasible – Can Be Improved |
| | Not Feasible – Cannot Be Improved |

| | |
|---|---|
| ••• | High Confidence |
| •• | Medium Confidence |
| • | Low Confidence |
| | Insufficient Data |

| | | Well-to-wake | | | |
|---|---|---|---|---|---|
| | | Production, storage and distribution | Bunkering | Onboard Storage and use | Disposal |
| Greenhouse gas emission intensity | | **37 gCO2eq/MJ (range 28-46 gCO2eq/MJ)** | | | |
| Technology | Current technology readiness level | **TRL 7** | | | |
| | Potential trajectory of technology readiness | **TRL 8** | | | |
| | Social acceptance | • | | | |
| | Supply chain resilience | • | | | |
| | Security against malicious actions | •• | | | |
| Sustainability & Environmental | | •• | • | • | • |
| Safety | | • | • | • | •• |
| Economic Feasibility | | •• | •• | • | •• |
| Regulatory | | • | • | • | • |
| People | | • | • | • | •• |
| Engineering | Engineering complexity (production, installation, decommissioning) | | | • | |
| | Complexity of retrofitting | | | • | |
| | Availability | | | • | |
| | Reliability | | | • | |
| | Maintainability | | | • | |
| | Logistics/supportability | | | • | |
| | Quality standards | | | • | |

## Appendix 2 – MTF Framework Criteria

| | |
|---|---|
| Greenhouse Gas Emission (GHG) | • Greenhouse gas emission intensity |
| Technology | • Current technology readiness level<br>• Expected technology readiness in 5 years<br>• Social acceptance<br>• Supply chain resilience<br>• Security against malicious actions |
| Environmental Sustainability | • Sustainability of production, storage and distribution<br>• Sustainability of bunkering<br>• Sustainability of onboard storage and use<br>• Recyclability and sustainability of disposal |
| Safety | • Safety during production, storage and distribution<br>• Safety during bunkering<br>• Safety during onboard storage and use<br>• Safety during disposal |
| Economic Viability | • Cost of production, storage and distribution<br>• Cost of bunkering<br>• Cost of onboard storage and use<br>• Cost of disposal |
| Regulatory Maturity | • Maturity of regulations related to production, storage and distribution<br>• Maturity of regulations related to bunkering<br>• Maturity of regulations related to onboard storage and use<br>• Maturity of regulations related to disposal |
| Skills Availability | • Skill base and competency within production, storage and distribution<br>• Skill base and competency for bunkering<br>• Skill base and competency onboard storage and use<br>• Skill base and competency for disposal |
| Engineering | • Engineering complexity (production, installation, decommissioning)<br>• Complexity of retrofitting<br>• Availability<br>• Reliability<br>• Maintainability<br>• Logistics/supportability<br>• Quality standards |

MARITIME TECHNOLOGIES FORUM

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