MARITIME TECHNOLOGIES FORUM

LEADING THE MARITIME WORLD FORWARD

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

Introduction

Purpose of this report

The Fuels Evaluation through the MTF Framework for Assessing Decarbonization Technologies and Alternative Energy Carriers (MTF Framework) is a collaborative exercise that assesses the feasibility of proposed alternative fuels expected to drive the decarbonization of the maritime industry. The MTF Framework provides a holistic view of the elements that should be considered in such an analysis and this report represents the first application to a select group of fuels, including fossil fuels to provide 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.

MTF Framework

The MTF Framework was published in November 2021 against the backdrop of the United Nations Paris Agreement, the IMO's commitment to 'phase out' GHG emissions from the sector in its 2018 Initial Strategy, and an urgency to reduce the impacts of climate change. It offers a holistic approach for assessing the relative suitability of technologies and energy carriers to be used in the maritime sector. It serves to help the industry choose technologies and/or energy carriers that are suitable for long term use in the marine environment and in line with the United Nations Sustainable Development Goals.

The MTF Framework can be accessed here by visiting https://www.maritimetechnologiesforum.com/documents/MTF-concept-paper.pdf.

Executive summary

Four fuels were selected for assessment, fossil marine gas oil (MGO), fossil liquefied natural gas (LNG), bio-methanol and green ammonia, and three main takeaways emerged which include critical action items and high priority suggestions for the industry:

Sustainability and Environmental Criteria

1. Bio-methanol and green ammonia perform better with regards to GHG emissions and ecological impact during production when compared to fossil MGO and fossil LNG. In addition, bio-methanol performs better among the four fuels in terms of ecological impact as it pertains to storage and distribution. In terms of resilience to disruption, MGO has established value chains, but in contrast, ammonia does not meet this criterion today due to lack of an established value chain.

Economic Feasibility Criteria

2. The study found that there is insufficient data on production and availability of green ammonia and bio-methanol, and in both cases, the corresponding criteria are not met. While regulations can incentivize the uptake of alternative fuels, currently bio-methanol and green ammonia fuels must overcome a number of challenges to achieve economic feasibility. This suggests the need for prioritizing more research and pilot projects to gain practical experience and scale.

People Criteria

3. The introduction of alternative fuels leads to a paradigm shift in shipboard operations compared to the established operations involving fossil fuels, including the baseline fuel considered in this report, fossil MGO. This suggests the need for further development of skills and competencies and the establishment of training modules with corresponding certification to build a scalable, global workforce capable of safe handling of the more hazardous fuels. The latter exists for LNG and methanol but needs further development. For ammonia there is a lack of training in place due to insufficient experience and data.

Methodology

The fuels evaluation against the MTF framework criteria was done through a series of workshops. Different fuels were evaluated and distilled down to three emerging fuels and one baseline case. Fossil MGO was selected to be the baseline case. The three fuels identified as emerging fuels for this report were fossil LNG, bio-methanol and green ammonia.

While evaluating these four fuels, feedback was sought from all MTF members. After the members provided their individual input, a concluding workshop was conducted to aggregate the results.

The evaluation was performed using all 45 sub-criteria laid out in the framework and categorized into eight high-level criteria. For each sub-criterion, data availability and the level of meeting the criterion was assessed using the options shown in the table below.

OPINIONS	OPTIONS	DESCRIPTION
Data availability: Data availability is needed to understand if there is enough information available and whether it exists in a structured manner.	Available and organized	Available and organized means data exists in a structured manner which is easily evaluated against the criteria.
	Available, needs processing	Available, needs processing means data exists but not in a structured manner, and efforts are needed to compile and assess against the criteria.
	Assessment not needed	Assessment not needed is used for the base case when the criteria itself is based on current performance and future fuels and technology needs to be at least as good or better than incumbent solutions.
	Insufficient data	Insufficient data means that no or limited data is available for evaluation against the criteria. A likely assessment has been provided, but it cannot be confirmed at this stage.
Meets criterion: The criterion here refers to whether the fuel meets the framework criteria.	Meets criterion	Meets criterion means the fuel fully meets or is expected to meet the framework criteria.
	Meets criterion – can be improved	Meets criterion – can be improved means the fuel either meets or is expected to meet the framework criteria but can be upgraded further.
	Fail	Fail means the fuel either requires significant developments to achieve the criteria in the future or is not expected to meet the framework criteria.

Assumptions

When no information was readily available, the MTF members made reasonable assumptions to complete the exercise. The opinions and options were the best judgement of the members based on their expertise. The options available listed in the table above were determined through a collaborative effort. Then members were encouraged to make their choices on available options.

Disclaimer

The results here are a collaborative effort between all of the 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.

Conclusions

With fossil MGO as the base case, we compared the other three emerging fuels through the framework. The results aggregated on the high-level criteria are presented below as heatmaps and conclusions.

Additional detailed heatmaps presenting the results of assessing sub-criteria are contained in the appendix which also describes the method of translating qualitative assessments into numbers for the purpose of aggregation. High-level criteria priorities shown in the heatmaps below were also used to weight assessment results, i.e., assessment scores for criteria with lower priority were scaled down. The application of priorities was considered in the context of decarbonization, but it is not meant to facilitate comparisons across categories of both fuels and technologies.

The color-coding of the heatmaps in this report assigns green if criteria are fully met or data is fully available and red if criteria are failed upon or data is not available.

Heatmap – summarizing level of meeting assessment criteria

Avg of meeting criteria	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Sustainability & Environmental	0.96	0.79	0.68	1.11	0.86
Safety	1.00	2.00	1.88	1.50	1.38
Technology Status	0.63	1.25	1.25	1.00	0.63
Security	0.75	1.50	1.50	1.38	0.75
Economic Feasibility	0.91	1.81	0.91	0.75	0.66
Regulatory	0.75	1.50	1.31	0.38	0.19
People	0.75	1.00	0.75	0.75	0.50
Engineering	0.68	1.36	1.25	0.68	0.68
aggregate		1.40	1.19	0.94	0.70

(range from 0 to 2, with higher values indicating higher level of meeting criteria)

The criteria category, Sustainability and Environment, are met to a greater extent by the low carbon fuels, bio-methanol and green ammonia. The current small scale production and projects as well as gaps in related regulations and standards lead bio-methanol and green ammonia to lower scores compared to more established fuels.

Heatmap – summarizing level of data availability

Avg of data availability	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Sustainability & Environmental	0.96	1.36	0.96	1.00	0.57
Safety	1.00	2.00	1.00	0.88	0.38
Technology Status	0.63	1.25	1.25	0.63	0.63
Security	0.75	1.50	0.75	0.75	0.50
Economic Feasibility	0.91	1.81	1.16	0.59	0.84
Regulatory	0.75	1.50	0.75	0.75	0.19
People	0.75	1.25	0.75	0.75	0.50
Engineering	0.68	1.25	1.36	0.50	0.21
aggregate		1.49	1.00	0.73	0.48

(range from 0 to 2, with higher values indicating higher level of data availability)

Availability of data to assess the criteria of the MTF Framework is lower for alternative fuels compared to fossil MGO and is lowest for green ammonia. This indicates a need for more research and development as well as pilots to close the knowledge gaps.

CRITERIA	DOES THE FUEL MEET ASSESSMENT CRITERIA?	IS THERE SUFFICIENT DATA AVAILABLE?
Sustainability & Environmental	Bio-methanol and green ammonia perform better with regards to GHG emissions and ecological impact during production when compared to fossil MGO and fossil LNG. In addition, bio-methanol performs better among the four fuels in terms of ecological impact as it pertains to storage and distribution. In terms of resilience to disruption, MGO has established value chains, but in contrast, ammonia does not meet the criterion due to lack of an established value chain and insufficient data	Data availability for Sustainability and Environmental is low for all alternative fuels but can be further organized.
Safety	Additional enhancements are required in the case of bio-methanol and green ammonia to meet safety aspirations while noting that the former performs better than the latter.	Data for safety is fully available for Fossil MGO. It is mostly available for Fossil LNG and bio-methanol but is lacking for green ammonia.
Technology Status	Fossil MGO and fossil LNG are readily available. Bio-methanol and green ammonia are on the cusp of readiness with impending improvements, however technology development is further along for bio-methanol than green ammonia.	Data is available and organized for fossil MGO and fossil LNG. Data is available but processing is required for bio-methanol and green ammonia.
Security	Although there are some challenges identified, we except that Security will not significantly impact the assessment output in the context of this study.	Data for the security of fuels is generally available for all alternate fuels.
Economic Feasibility	The study found that there is insufficient data on production and availability of green ammonia and bio-methanol, and in both cases, the corresponding criteria are not met. While regulations can incentivize the uptake of alternative fuels, currently bio-methanol and green ammonia fuels must overcome a number of challenges to achieve economic feasibility This suggests the need for prioritizing more research and pilot projects to gain practical experience.	Data for economic feasibility is highest for fossil MGO. Green ammonia economic feasibility data is lowest. The other two options fall somewhere in between.
Regulatory	Regulations are robust for fossil MGO and fossil LNG. Regulations are currently lacking for bio-methanol and green ammonia. There is scope for improvement with emerging regulations for methanol and ammonia.	Data for regulatory aspects is lowest for green ammonia and highest for fossil MGO. Data for the other two alternate fuels at a regulatory level is available but needs processing.
People	The introduction of alternative fuels leads to a paradigm shift in shipboard operations compared to the established operations involving fossil fuels, including the baseline fuel considered in this report, fossil MGO. This suggests the need for further development of skills and competencies and the establishment of training modules with corresponding certification to build a scalable, global workforce. The latter exists for LNG and methanol but needs further development. For ammonia there is no training in place due to insufficient experience and data.	The workforce has the greatest experience in fossil MGO and also green ammonia from land- based applications. Fossil LNG and bio-methanol data is intermediary.
Engineering	Engineering design is robust for fossil MGO and fossil LNG. With few designs for bio-methanol and green ammonia, the engineering expertise is lower.	Engineering support and data exists widely for fossil MGO and fossil LNG. Data is lacking for the other two alternative fuels.

Future Work

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

1. The study identifies several sub-criteria for which data is not sufficiently available and failure to meet the assessment suggest the need for further research and development to enhance industry knowledge and support future decision making.
2. Additional fuels such as hydrogen and other biofuels including their production pathways as well as technologies such as onboard carbon capture and storage should be added to the heatmap to have a more complete basis for decision making.
3. One of the key risks of all alternate fuels is scalability. Though this is addressed through availability within the current MTF framework, this section could be expanded to integrate aspects of scaling.
4. The first full application of the MTF Framework showed the need to review the framework in terms of association of sub-criteria, definition of measurement methodologies and thresholds.
5. Fundamental technical challenges could also be identified and expanded within the framework.

APPENDIX 1 – Detailed Results

Results of the assessment for all sub-criteria are shown in the following heatmaps per high-level criterion for each of the four fuels evaluated. The level of meeting the criteria and the level of data availability is presented in separate diagrams. Priorities of sub-criteria have been used to scale the results. The translation of qualitative assessment results into the numbers displayed in the diagrams is shown in the table below.

PRIORITY	NUMERICAL VALUE
High	1
Medium	0.75
Low	0.5

ASSESSMENT	DATA AVAILABILITY	NUMERICAL VALUE
Meets criterion	Available and organized	2
Meets criterion – can be improved	Available, needs processing	1
Fail	Insufficient	0

Level of meeting sub-criteria within Sustainability and Environment

Sustainability and Environment - meets criterion?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Greenhouse gas emission	1.00	0.00	0.00	1.00	1.00
Ecological and social impact (externalities) in production scenarios	1.00	0.00	0.00	1.00	1.00
Ecological and social impact (externalities) in storage and distribution scenarios	1.00	1.00	1.00	2.00	1.00
Ecological and social impact (externalities) in bunkering scenarios	1.00	1.00	1.00	1.00	1.00
Ecological and social impact (externalities) in onboard use scenarios	1.00	1.00	1.00	1.00	1.00
Recyclability and disposal	1.00	1.00	1.00	1.00	1.00
Resilience to shocks and disruptions (in market, ecological, etc; not physical)	0.75	1.50	0.75	0.75	0.00

Level of data availability within Sustainability and Environment

Sustainability and Environment - data available?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Greenhouse gas emission	1.00	2.00	1.00	2.00	1.00
Ecological and social impact (externalities) in production scenarios	1.00	1.00	1.00	1.00	1.00
Ecological and social impact (externalities) in storage and distribution scenarios	1.00	1.00	1.00	1.00	1.00
Ecological and social impact (externalities) in bunkering scenarios	1.00	1.00	1.00	1.00	0.00
Ecological and social impact (externalities) in onboard use scenarios	1.00	1.00	1.00	1.00	0.00
Recyclability and disposal	1.00	2.00	1.00	1.00	1.00
Resilience to shocks and disruptions (in market, ecological, etc; not physical)	0.75	1.50	0.75	0.00	0.00

The detailed heatmaps for Sustainability and Environment show that Fossil MGO and Fossil LNG fail to meet the sub-criteria on GHG emissions and ecological and social impact in production and that this assessment is backed with sufficient data quality. In contrast, green ammonia fails to meet the criterion on resilience to shocks but low data availability indicates a possible future improvement.

Level of meeting sub-criteria within Safety

Safety - meets criterion?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Safety during production	1.00	2.00	2.00	2.00	2.00
Safety during land distribution	1.00	2.00	2.00	2.00	2.00
Safety during land storage	1.00	2.00	2.00	2.00	2.00
Safety during bunkering	1.00	2.00	2.00	1.00	1.00
Safety during onboard storage	1.00	2.00	2.00	2.00	1.00
Safety during onboard usage	1.00	2.00	2.00	1.00	1.00
Aggregated safety considerations	1.00	2.00	1.00	1.00	1.00
Safety during disposal	1.00	2.00	2.00	1.00	1.00

Level of data availability within Safety

Safety - data available?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Safety during production	1.00	2.00	1.00	1.00	1.00
Safety during land distribution	1.00	2.00	1.00	1.00	1.00
Safety during land storage	1.00	2.00	1.00	1.00	1.00
Safety during bunkering	1.00	2.00	1.00	1.00	0.00
Safety during onboard storage	1.00	2.00	1.00	1.00	0.00
Safety during onboard usage	1.00	2.00	1.00	1.00	0.00
Aggregated safety considerations	1.00	2.00	1.00	0.00	0.00
Safety during disposal	1.00	2.00	1.00	1.00	0.00

Bio-methanol and green ammonia are evaluated similarly regarding certain safety aspects however, there is differentiation in the level of safety between methanol and ammonia, which more detailed assessments can illustrate better. So, while both fuels are evaluated with the option "Meets criterion - can be improved" they perform on different ends of that option.

Furthermore, data availability related to green ammonia on safety during bunkering, onboard storage and use, aggregated safety considerations and disposal is expected to improve with more research and experience through demonstration projects and pilots.

Level of meeting sub-criteria within Security

Security - meets criterion?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Security during production	0.75	1.50	1.50	1.50	0.75
Security during land storage	0.75	1.50	1.50	1.50	0.75
Security during land distribution	0.75	1.50	1.50	1.50	0.75
Security during bunkering	0.75	1.50	1.50	1.50	0.75
Security during onboard usage	0.75	1.50	1.50	0.75	0.75
Security during disposal	0.75	1.50	1.50	1.50	0.75

Level of data availability within Security

Security - data available?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Security during production	0.75	1.50	0.75	0.75	0.75
Security during land storage	0.75	1.50	0.75	0.75	0.75
Security during land distribution	0.75	1.50	0.75	0.75	0.75
Security during bunkering	0.75	1.50	0.75	0.75	0.00
Security during onboard usage	0.75	1.50	0.75	0.75	0.00
Security during disposal	0.75	1.50	0.75	0.75	0.75

Green ammonia trails in meeting the sub-criteria related to security due to possible malicious actions which are considered easier-to-perform than for other fuels due to the toxicity of ammonia.

Level of meeting sub-criteria within Economic feasibility

Economic feasibility - meets criterion?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Cost of storage (on land)	1.00	2.00	1.00	1.00	1.00
Cost of storage (onboard)	1.00	2.00	1.00	1.00	1.00
Cost of production	1.00	2.00	1.00	0.00	0.00
Cost of distribution	1.00	2.00	1.00	1.00	1.00
Technical complexity of distribution	0.75	1.50	0.75	1.50	0.75
Complexity of retrofitting	0.50	1.00	0.50	0.50	0.50
Impact on ship operation	1.00	2.00	1.00	1.00	1.00
Availability (quantity)	1.00	2.00	1.00	0.00	0.00

Level of data availability within Economic feasibility

Economic feasibility - data available?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
Cost of storage (on land)	1.00	2.00	2.00	1.00	2.00
Cost of storage (onboard)	1.00	2.00	1.00	1.00	2.00
Cost of production	1.00	2.00	1.00	0.00	0.00
Cost of distribution	1.00	2.00	2.00	1.00	2.00
Technical complexity of distribution	0.75	1.50	0.75	0.75	0.75
Complexity of retrofitting	0.50	1.00	0.50	0.00	0.00
Impact on ship operation	1.00	2.00	1.00	1.00	0.00
Availability (quantity)	1.00	2.00	1.00	0.00	0.00

Low data availability for assessing economic feasibility criteria for bio-methanol and green ammonia, and to a certain extent also for fossil LNG, indicates an urgent need for more research and development and real-life pilots delivering more reliable economic estimates, in particular addressing cost of production and fuel availability.

It is noted that the level of meeting sub-criteria "complexity of retrofitting" and "impact on ship operation" for fossil MGO was labeled as "no assessment needed." For the purpose of translating the qualitative assessment to numerical values, this assessment was translated into "meeting criterion."

Level of meeting sub-criteria within Regulatory and People

Regulatory and People - meets criterion?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
R: Complexity of resulting regulation (onboard focus)	0.75	1.50	1.50	0.75	0.00
R: Regulatory compatibility between nations	0.75	1.50	1.50	0.00	0.00
R; Regulator interfaces (internal to singular nations)	0.75	1.50	1.50	0.00	0.00
R: Complexity of production, storage and distribution regulations (on land)	0.75	1.50	0.75	0.75	0.75
P: Skill base and competency within production, distribution and storage industry	0.75	1.50	0.75	0.75	0.75
P: Certification and training within maritime industry	0.75	1.50	0.75	0.75	0.00
P: Social acceptance	0.75	0.00	0.75	0.75	0.75

Note that the combination of high-level criteria Regulatory and People has been done only with the aim to deliver a more compact visualization in this section.

Level of data availability within Regulatory and People

Regulatory and People - data available?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
R: Complexity of resulting regulation (onboard focus)	0.75	1.50	0.75	0.75	0.00
R: Regulatory compatibility between nations	0.75	1.50	0.75	0.75	0.00
R; Regulator interfaces (internal to singular nations)	0.75	1.50	0.75	0.75	0.00
R: Complexity of production, storage and distribution regulations (on land)	0.75	1.50	0.75	0.75	0.75
P: Skill base and competency within production, distribution and storage industry	0.75	1.50	0.75	0.75	1.50
P: Certification and training within maritime industry	0.75	1.50	0.75	0.75	0.00
P: Social acceptance	0.75	0.75	0.75	0.75	0.00

It is easy to observe that novel low-carbon fuels such as bio-methanol and green ammonia cannot meet the sub-criteria under the Regulatory category since relevant regulations are not in yet in place, which is expected to change with the ongoing developments at IMO. Similarly, training and certification of crew onboard ships using ammonia is also not yet available.

Level of meeting sub-criteria within Technology and Engineering

Technology and Engineering - meets criterion?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
T: Current technology readiness	0.50	1.00	1.00	0.50	0.50
T: Potential trajectory of technology readiness	0.75	1.50	1.50	1.50	0.75
E: Engineering complexity (production, installation, decommissioning)	0.50	1.00	1.00	0.50	0.50
E: Availability	0.75	1.50	1.50	0.75	0.75
E: Reliability	0.75	1.50	1.50	0.75	0.75
E: Maintainability	0.50	1.00	1.00	0.50	0.50
E: Logistics / supportability	0.75	1.50	0.75	0.75	0.75
E: Interoperability	0.75	1.50	1.50	0.75	0.75
E: Quality standards	0.75	1.50	1.50	0.75	0.75

Note that the combination of high-level criteria Technology and Engineering has been done only with the aim to deliver a more compact visualization in this section.

Level of data availability within Technology and Engineering

Technology and Engineering - data available?	Priority	Fossil MGO	Fossil LNG	Bio-methanol	Green Ammonia
T: Current technology readiness	0.50	1.00	1.00	0.50	0.50
T: Potential trajectory of technology readiness	0.75	1.50	1.50	0.75	0.75
E: Engineering complexity (production, installation, decommissioning)	0.50	1.00	1.00	0.50	0.00
E: Availability	0.75	1.50	1.50	0.75	0.00
E: Reliability	0.75	1.50	1.50	0.00	0.00
E: Maintainability	0.50	1.00	1.00	0.00	0.00
E: Logistics / supportability	0.75	0.75	1.50	0.75	0.75
E: Interoperability	0.75	1.50	1.50	0.75	0.75
E: Quality standards	0.75	1.50	1.50	0.75	0.00

Low data availability for green ammonia and bio-methanol reduces the levels of meeting sub-criteria for Technology and Engineering. Again, demonstration projects and pilots will improve this situation.

The following pages present the detailed assessment results in tabular form as reference.

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
1	Sustainability & Environmental	Greenhouse gas emission	Well-to-wake greenhouse gas emissions from the production, storage & distribution, use and disposal of the technology and/or energy carrier.	HIGHER	Available and organized	Fail	Available, needs processing	FAIL	Available and organized	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved
2	Sustainability & Environmental	Ecological and social impact (externalities) in production scenarios	This is the ecological and social impact (externalities) arising as a result of production scenarios.	HIGHER	Available, needs processing	Fail	Available, needs processing	FAIL	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved
3	Sustainability & Environmental	Ecological and social impact (externalities) in storage & distribution scenarios	This is the ecological and social impact (externalities) arising as a result of production scenarios.	HIGHER	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved
4	Sustainability & Environmental	Ecological and social impact (externalities) in bunkering scenarios	This is the ecological and social impact (externalities) arising as a result of bunkering scenarios, considering shore-to-ship and ship-to-ship bunkering.	HIGHER	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
5	Sustainability & Environmental	Ecological and social impact (externalities) in onboard use scenarios	This is the ecological and social impact (externalities) arising as a result of onboard use scenarios.	HIGHER	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
6	Sustainability & Environmental	Recyclability and disposal	This is the recyclability and waste aspects, within production scenario, when in service (via operation and maintenance), and also when it comes to end of life, relating to the energy carrier or technology. Includes all impacts from disposal at end of system life.	HIGHER	Available and organized	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved
7	Sustainability & Environmental	Resilience to shocks and disruptions (in market, ecological, etc; not physical)	This relates to resilience within the system (including within its supply chain and value chain) in relation to shocks and disruptions which can happen in the market, ecologically, etc.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved	Insufficient data	Fail
8	Safety	Safety during production	This considers the level of safety, achieved and achievable, during production.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion
9	Safety	Safety during land distribution	This considers the level of safety, achieved and achievable, during land distribution.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion
10	Safety	Safety during land storage	This considers the level of safety, achieved and achievable, during land storage.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
11	Safety	Safety during bunkering	This considers the level of safety, achieved and achievable, during bunkering, including all modes of bunkering.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
12	Safety	Safety during onboard storage	This considers the level of safety, achieved and achievable, during onboard storage (on the vessel).	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Insufficient data	Meets criterion - can be improved
13	Safety	Safety during onboard usage	This considers the level of safety, achieved and achievable, during onboard use (on the vessel). This includes during all onboard-use scenarios (underway, at anchor, in port, dry dock, etc), and includes operation and maintenance.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
14	Safety	Aggregated safety consid-derations	The level of safety may be affected by the environment outside the vessel itself. This considers the level of safety achieved and achievable when you go beyond one singular vessel, such as when you look at multiple vessels in the same location (e.g. port, anchorage, etc). This criterion is more relevant to energy carriers, and less so to technology. Facets such as how energy carriers are stored and transported in the aggregated quantities they need to be in are relevant in the overall safety consideration.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
15	Safety	Safety during disposal	This considers the level of safety, achieved and achievable, during disposal.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
16	Technology Status	Current technology readiness	This is the technology readiness level at the time of assessment.	LOWER	Available and organized	Meets criterion	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved
17	Technology Status	Potential trajectory of technology readiness	This is the expected change of technology readiness level over time. This contributes to the assessment by providing information on the level of technology availability.	MEDIUM	Available and organized	Meets criterion	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
18	Security	Security during production	This considers the level of security required and achievable during production.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved
19	Security	Security during land storage	This considers the level of security required and achievable during land storage.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved
20	Security	Security during land distribution	This considers the level of security required and achievable during land distribution.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved
21	Security	Security during bunkering	This considers the level of security required and achievable during bunkering, including all modes of bunkering.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Insufficient data	Meets criterion - can be improved
22	Security	Security during onboard usage	This considers the level of security required and achievable during onboard usage. This includes during all onboard use scenarios (underway, at anchor, in port, dry dock, etc) and includes operation and maintenance.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
23	Security	Security during disposal	This considers the level of security required and achievable during disposal.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved
24	Economic Feasibility	Cost of storage (on land)	This relates to the cost of storage on land.	HIGHER	Available and organized	Meets criterion	Available and organized	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available and organized	Meets criterion - can be improved

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
25	Economic Feasibility	Cost of storage (onboard)	This relates to the cost of storage onboard.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available and organized	Meets criterion - can be improved
26	Economic Feasibility	Cost of production	This relates to the cost of production.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Fail	Insufficient data	Fail
27	Economic Feasibility	Cost of distribution	This relates to the cost of distribution.	HIGHER	Available and organized	Meets criterion	Available and organized	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available and organized	Meets criterion - can be improved
28	Economic Feasibility	Technical complexity of distribution	This is how technically complex it will be to achieve distribution in the quantities required.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved
29	Economic Feasibility	Complexity of retrofitting	This is the complexity of applying this in retrofit scenarios.	LOWER	Assessment not needed	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
30	Economic Feasibility	Impact on ship operation	This is the impact of the technology, or energy carrier, on ship operations. This will differ with different ship types and uses. Below a certain threshold it will not be viable to progress a technology / energy carrier because the negative impact will be too high.	HIGHER	Assessment not needed	Meets criterion	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
31	Economic Feasibility	Availability (quantity)	This is the availability, in terms of quantity. Depending on the technology or energy carrier, availability could be limited due to availability of an element within it. Cost to scale up availability would be included.	HIGHER	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Fail	Insufficient data	Fail
32	Regulatory	Complexity of resulting regulation (onboard focus)	This is complexity of the regulatory aspects relating to onboard; the implementation of it, plus potential cost of changes.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Fail
33	Regulatory	Regulatory compatibility between nations	This is the level of compatibility between multiple nations when it comes to regulation.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Fail	Insufficient data	Fail
34	Regulatory	Regulator interfaces (internal to singular nations)	This is the look of the complexity of the landscape with regard to regulatory interfaces between where jurisdictions meet (jurisdictions internal to one nation, rather than compatibility/ complexity of regulation between nations). For example, where the ship to shore regulatory interface exists.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion	Available, needs processing	Fail	Insufficient data	Fail

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
35	Regulatory	Complexity of production, storage and distribution regulations (on land)	This is complexity of the implementation of the regulations relating to production, storage and distribution. This includes consideration of the cost associated with that complexity.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved
36	People	Skill base and competency within production, distribution and storage industry	This is the level of change that would be required, regarding the skill base and competency within production, distribution and storage industry, in order to accept the new technology or energy carrier into service.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available and organized	Meets criterion - can be improved
37	People	Certification & Training within Maritime industry	This is to the level of change that would be required, regarding the certification and training for maritime industry personnel, in order to accept the new technology or energy carrier into service.	MEDIUM	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Insufficient data	Fail
38	People	Social acceptance	This concerns the social acceptance of the technology or energy carrier in question. It also includes whether it is aligned with other sectors in drive to decarbonization, or if it is misaligned.	MEDIUM	Available, needs processing	Fail	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
39	Engineering	Engineering complexity (production, installation, decom-missioning)	This is the engineering complexity relating to bringing the technology or energy carrier into service.	LOWER	Available and organized	Meets criterion	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
40	Engineering	Availability	Availability is the measure of an item/ system's readiness for use. It is a function of the reliability and maintainability attributes of the system/item, and the level and effectiveness of the support arrangements in place. Preventative maintenance may be considered as part of the availability calculation.	MEDIUM	Available and organized	Meets criterion	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
41	Engineering	Reliability	Reliability relates to an item/system working to its full capability (design capability) when it's required to.	MEDIUM	Available and organized	Meets criterion	Available and organized	Meets criterion	Insufficient data	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved
42	Engineering	Maintain-ability	Maintainability relates to the difficulty of repairing things once they have a problem. Therefore, it does not include preventative maintenance, but does incorporate the notion of corrective maintenance.	LOWER	Available and organized	Meets criterion	Available and organized	Meets criterion	Insufficient data	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
43	Engineering	Logistics / support-ability	This looks at the aspects required in order to support the item, including their complexity. For example, how simple is it to get support (parts, labor, etc) in different worldwide locations, as well as constraints around that (cost, time, complexity, etc). This is affects the supply chain, across all required locations and how complex that is and what is required to achieve it. This relates more to the support supply chain, rather than the initial production of the item. It can also include aspects such as consideration to connections for data for maintenance, diagnostics, calibration, etc.	MEDIUM	Available, needs processing	Meets criterion	Available and organized	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved
44	Engineering	Inter-operability	This concerns the interoperability surrounding the technology or energy carrier. For example, shore power connection compatibility. Also, can you buy the same fuel in all countries, etc?	MEDIUM	Available and organized	Meets criterion	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Available, needs processing	Meets criterion - can be improved

	Criteria (high level)	Sub criteria	Explanation / Additional notes	Priority (mandatory, high, medium, low)	Fossil MGO		Fossil LNG		Bio-methanol		Green Ammonia	
					Fossil MGO - Assessment - Data availability	Fossil MGO - Assessment - Meets criterion?	Fossil LNG - Assessment - Data availability	Fossil LNG - Assessment - Meets criterion?	Bio-Methanol - Assessment - Data availability	Bio-methanol - Assessment - Meets criterion?	Green Ammonia - Assessment - Data availability	Green Ammonia - Assessment - Meets criterion?
45	Engineering	Quality standards	This concerns safety aspects as a result of quality, as well as compatibility (internationally) as a result of quality, etc. This can apply for technologies and also energy carriers.	MEDIUM	Available and organized	Meets criterion	Available and organized	Meets criterion	Available, needs processing	Meets criterion - can be improved	Insufficient data	Meets criterion - can be improved

Appendix 2 – MTF Framework Criteria

Sustainability & Environmental	• Greenhouse gas emission • Ecological and social impact (externalities) in production scenarios • Ecological and social impact (externalities) in storage & distribution scenarios • Ecological and social impact (externalities) in bunkering scenarios • Ecological and social impact (externalities) in onboard use scenarios • Recyclability and disposal • Resilience to shocks and disruptions (in market, ecological, etc; not physical)
Safety	• Safety during production • Safety during land distribution • Safety during land storage • Safety during bunkering • Safety during onboard storage • Safety during onboard usage • Aggregated safety considerations • Safety during disposal
Technology Status	• Current technology readiness • Potential trajectory of technology readiness
Security	• Security during production • Security during land storage • Security during land distribution • Security during bunkering • Security during onboard usage • Security during disposal
Economic Feasibility	• Cost of storage (on land) • Cost of storage (onboard) • Cost of production • Cost of distribution • Technical complexity of distribution • Complexity of retrofitting • Impact on ship operation • Availability (quantity)
Regulatory	• Complexity of resulting regulation (onboard focus) • Regulatory compatibility between nations • Regulator interfaces (internal to singular nations) • Complexity of production, storage and distribution regulations (on land)
People	• Skill base and competency within production, distribution and storage industry • Certification & Training within Maritime industry • Social acceptance
Engineering	• Engineering complexity (production, installation, decomissioning) • Availability • Reliability • Maintainability • Logistics / supportability • Interoperability • Quality standards

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