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Overview of the Development of Low/Zero-Emission Marine Fuels and Implications for China

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Executive Summary

The severe flooding and record-high heat waves that China and other parts of the world experienced this summer reflects a global trend of increasingly frequent episodes of extreme weather driven by climate change. Earth's average temperature is already up by 1.1°C and on track for a 2.4°C temperature increase by the end of the century. To avoid the potentially irreversible threat posed by global warming, the 2021 Glasgow Climate Pact reaffirms the goal of Paris Agreement to limit the average global temperature increase to 1.5°C above pre-industrial levels. The Pact called for reducing carbon dioxide (CO_2) emissions by 45% from 2010 to 2030, reaching net-zero around mid-century, and substantially reducing other greenhouse gases (GHGs).

Joining the world's efforts to combat climate change, China elevated co-control of air pollution and climate change impacts to the top of its policy agenda. Peaking carbon emissions by 2030 and striving to achieve carbon neutrality by 2060, while continuing efforts to combat pollution, have become an overarching goal of China's economic, development and environmental plans.

International shipping, currently not covered by the Paris Agreement, is the world's sixth largest CO_2 emitter if it was treated as a nation. Shipping also saw a surge in methane emissions—a potent GHG—that have increased 150% from 2012 to 2018. While the International Maritime Organization (IMO) has committed to cutting annual GHGs emissions from international shipping by at least 50% compare with 2008 by 2050, its targets are criticized for falling far short of the Paris Agreement 1.5 °C goal.

To fill the gap, many state and non-state actors have taken actions to boost the development and deployment of, and spur market demand for, low/zero-emission marine fuels and propulsion technologies. Most notable actions include major cargo owners calling for the offering of climate-friendly maritime freight services, and more and more ship financiers and insurance providers starting to track and evaluate their portfolios against decarbonization criteria.

As a major maritime nation, China could play an important role to support the shipping sector's transition to zero-emission. To inform policy makers in devising actions that support such transition, this paper reviews the latest development of alternative marine fuel solutions, and offers policy recommendations that could catalyze the uptake of these new fuel solutions while achieving the nation's own climate neutrality, air quality and development goals.

As of to date, ammonia, hydrogen, methanol, natural gas and electricity are alternative energy carriers that are getting the most traction in shipping. If produced using renewable resources, these energy carriers can be low/zero-emission solutions, as shown in Table ES1. They are at different stage of development and each has its own advantages and challenges for use as a marine fuel.

While it remains uncertain which of these solutions will dominate in the future, research and demonstration projects launched to date suggested that battery electric propulsion and hydrogen-fuel cell systems are technically feasible and scalable zero-emission technologies for river and short-distance coastal vessels. Using electricity or hydrogen directly for propulsion avoids the energy losses that will incur for producing more complicated e-fuels, such as e-ammonia, e-methanol and e-methane, hence is a more energy efficient use of renewable energy sources for shipping. For deep-sea shipping, renewable-derived methanol and ammonia have emerged as the two most promising near zero-GHG fuels in this decade, as they have higher energy density and can be relatively easy to transport and store onboard. In the longer-term, hydrogen appears to be a favorable zero-emission solution having the least potential threat to the environment in case of leakage. A prerequisite is having hydrogen refilling infrastructure strategically built along busy shipping lanes, preferably at locations that have easy access to cheap renewable energy sources.

But a successful transition to GHG-free shipping requires not just zero-emission fuels, but also zero-emission vessels and fuel bunkering infrastructure. For global shipping to reach zero-emissions by the middle of the century, the sector would inevitably require large number of zero-emission new build ships as well as a massive retrofitting of existing vessels for zero-emission fuels in the 2030s. China is one of the very few countries in the world that has a leading shipbuilding sector, a high potential for generating renewable energy and is an important shipping hub with many of the world's largest ports. These factors place China in an advantageous position to propel the shipping sector's energy transition through:

- developing emissions-free vessels and their key components (e.g., fuel cells, batteries and alternative fuel engines),
- ramping up research and development of technologies for producing low/zero-emission marine fuels (e.g., electrolyzers), and expanding fuel production capacity, and
- establishing port infrastructure for supplying low/zero-emission fuels.

The growing global demand for low/zero-emission shipping services therefore presents a valuable opportunity for China's shipbuilding, shipping and port industries. For China to be able to grasp this opportunity, policies should be put in place to spur the development and deployment of zero-emission fuels and propulsion technologies, validate their technical and commercial feasibility, and expedite the adoption of regulations and protocols to ensure safe use of these new fuels. Those policies could include:

1. Adopting GHG and energy efficiency regulations for the domestic shipping fleet, including:
   - Adding GHG-related requirements to marine engine emission standards to ensure that control of air pollutants and GHGs are considered during engine design
   - Setting energy efficiency requirements for new and in-use vessels to lower the cost barrier to transit to alternative fuels
   - Setting GHG intensity standards for shipping fuels based on well-to-wake emissions to drive the production and uptake of truly low/zero-emission fuels

2. Supporting pilot port regions to scale up demonstration projects for vessels powered by low/zero-GHG emission fuels, including:
   - Increasing funding to scale up demonstration projects
   - Providing funding to support development of core technologies for producing and supplying low/zero-carbon fuels
   - Setting long-term, zero-emission target for selected segment of domestic vessels
   - Participating in bilateral or multilateral green shipping corridor programs

3. Ensuring that shipping be an integral part of China's actions to transition to a carbon-neutral economy, thereby enabling the shipping sector to tap into new supplies of renewable energy and renewable hydrogen.

As the global shipping industry goes through an inevitable energy transition to zero-emission, supporting China's shipbuilding, shipping and port industries to build the competency on producing, using and supplying zero-emission fuels and technologies is imperative for their remaining globally competitive. Doing so not only could ensure China maintains its position as a strong maritime nation, it also enables China's shipping sector to have easy access to low/zero-emission fuels and technologies that are essential for addressing climate change and combating air pollution at home and abroad.

Table ES1. Climate and Environmental Performances, Cost, Advantages and Challenges of Using Alternative Energy Carriers

Energy Carrier	Well-to-Wake (WTW) GHG Emissions Compared to MGO[a]		Tank-to-Wake (TTW) Air Emissions Compared with Conventional Fuel			Renewable-Derived e-Fuel Cost Ratio, Relative to MGO Price[h]		Technical, Safety and Fuel Supply Considerations	
	Fossil-based Fuel[a]	Renewable-derived e-Fuel[b]	PM	NO_x	SO_x	2030	2050	Advantages	Challenges
Liquid Ammonia	140%	6%	0[d]	Likely more than conventional fuel; NO_x emissions control needed	0[d]	3.2	2.7	• Low flammability risk • Easy to store and transport • Renewable e-ammonia less costly to produce than other renewable e-fuels • Traded globally as a commodity	• Highly toxic • Possible N_2O emission and ammonia slip • Engine development at design stage • Poor combustion characteristics • Lack of fuel infrastructure • Safety regulations not yet adopted • Corrosiveness to certain materials
Liquid Hydrogen	166%	0%	0[d]	Vary by engine design	0[d]	3.7	2.7	• Low toxicity • Low risk to the environment if leaked	• Costly to store and transport • Explosion risk • Lack of fuel infrastructure • First pure hydrogen engine recently launched, limited operation experiences
Methanol	101%	1%	Fewer than con-ventional fuel[e]	~35%[f] to 100%[g]	0[d]	4.5	3.3	• Engines commercially available • Easy to store and transport • If leaked less hazardous to the environment than conventional fuel • Can use existing fuel infrastructure with minor modifications • Retrofitting in-use engines to run on methanol far less costly than other alternative fuels • Interim safety guidelines adopted at IMO • Traded globally as a commodity	• More storage space needed than conventional fuel • High explosion risk • Toxic, but less so than ammonia • Renewable e-methanol more costly to produce than other renewable e-fuels • Corrosiveness to certain materials

Liquefied Natural Gas (LNG)	83– 103% [c]	2 – 12% [c]	0 [d]	~75% to 100% [g] (Diesel cycle) ~10% (Otto cycle)	0 [d]	4.0	2.9	• Low toxicity • Engines commercially available • Fuel infrastructure exists in a few large sea ports • Safety regulations adopted at IMO	• High flammability risk • Methane slip and upstream methane leakage can significantly offset CO_2 reduction benefits • Renewable e-methane more costly than renewable e-ammonia • Scalability of bio-methane is questionable • High storage and transport cost
Lithium-ion Battery	Depends on GHG intensity of electricity		0	0	0	n.a.		• WTW emissions will fall with rising share of renewable electricity in many countries • Mature technology • Much quieter and scentless than internal combustion engines	• Very low energy intensity; limited range and battery capacity are major constraints for fully electric vessels • Lack of recharging infrastructure

Source: GHG emissions - Lindstad et al. (2020), Lindstad et al. (2021), Pavlenko et al. (2020) and Martin (2021); air emissions - Zhou et al. (2020), Anderson et al. (2015), Lewis (2021), Fridell et al. (2021), RINA (2020), Maritime Knowledge Center et al. (2018), Ellis (2020); costs - Ash et al. (2020); other considerations - Kass et al. (2021); Alfa Laval et al. (2020).

MGO=marine gas oil, PM=particulate matter, NO_x=nitrogen oxide, SO_x=sulfur oxides, N_2O=nitrous oxide.

Notes:

a. WTW emissions from ammonia, hydrogen and methanol derived from natural gas. For LNG, includes emissions from fuel production and combustion.
b. Assume best-case scenario where all e-fuels are produced using renewable electricity, and carbon for e-methanol and e-methane production is obtained through direct air capture.
c. Lower and upper bound data represent emissions from Diesel cycle and Otto cycle engines respectively.
d. Not including air emissions from the use of pilot fuel, which are proportional to the amount of pilot fuel used.
e. Engine out PM emissions vary depending on the engine combustion technology used (Maritime Knowledge Center et al., 2018; Fridell et al., 2021).
f. NO_x emissions without adopting NO_x control measures to maximize efficiency (Ellis, 2020); NO_x emissions lower than that of conventional fuel due to the colder methanol flame (RINA, 2020).
g. By adopting NO_x control technologies, combustion can be optimized to maximize energy efficiency and PM control, in which case NO_x emissions are similar to the levels of conventional fuels. NO_x control technologies include selective catalytic reduction, exhaust gas recirculation; for methanol engines, adding water to the combustion process can also be used. Lower bound data represent emissions without using NO_x control technologies.
h. The cost ratio is defined as the levelized cost of producing e-fuels relative to the price of MGO sold in Rotterdam as of November 24, 2020 (https://shipandbunker.com/prices).

1. Urgent Need for Global Climate Actions

The Glasgow Climate Pact was adopted by 197 nations in 2021 to avoid the potentially irreversible threat posed by climate change to human societies and the planet. Temperature goals set by the Paris Agreement were reaffirmed, along with a commitment to pursue efforts to limit the average global temperature increase to 1.5°C above pre-industrial levels. The Glasgow Climate Pact recognizes that achieving these goals will require reducing carbon dioxide (CO_2) emissions by 45% as of 2030 compared to the 2010 level and to net-zero around mid-century, as well as deep reductions in other greenhouse gases (GHGs) (UNFCCC, 2021). With Earth's average temperature already up by 1.1°C and on track for a 2.4°C temperature increase by the end of the century, extreme weather is wreaking havoc around the world. More ambitious actions are critically needed now to deliver additional emissions cuts within this decade and beyond (Climate Action Tracker, 2021).

International shipping, not currently included in the Paris Agreement's national commitments, generated more than 900 million tons of CO_2 in 2018. This exceeds emissions from most countries, except for the countries ranked as the top five creators of carbon emissions in the world. Global shipping also emits methane, which saw a sharp 150% rise from 2012 to 2018 due to increased use of ships powered by liquefied natural gas (LNG), which includes LNG carriers, and a significant increase of diesel/LNG dual-fuel machinery (Faber et al., 2020). Methane, a powerful short-lived greenhouse gas (GHG), accounts for about a quarter of the heat trapped in the atmosphere since the pre-industrial era and has become a key target of global climate efforts (Figure 1) (IPCC, 2021).

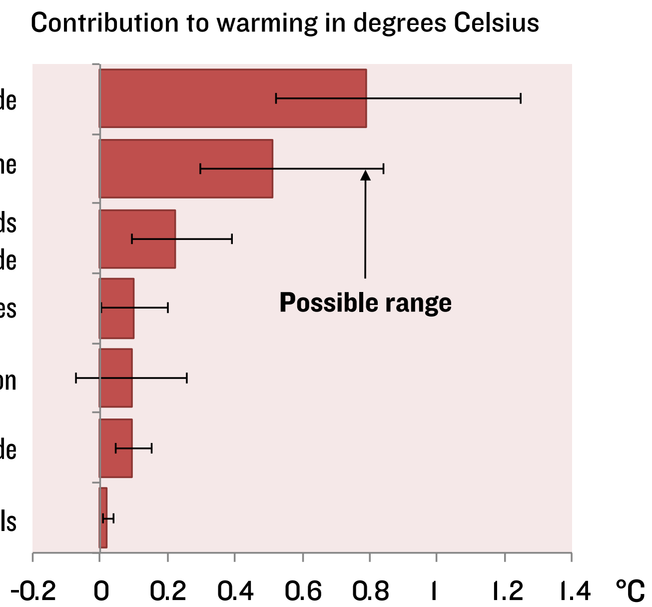
In China, striving to peak carbon emissions by 2030 and endeavoring to achieve carbon neutrality by 2060 has become the nation's unswerving direction for development.[1] At the same time, the nation needs to further the efforts to protect its ecology and environment and continuing the fight against pollution.[2] Therefore the country's construction of an ecological civilization has entered a vital phase: With carbon emissions reduction being the key strategic direction, authorities are undertaking efforts to advance coordinated reduction in carbon emissions and air pollution,

1 See more info on China government website: http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm.

2 See more info on China government website: http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm.

and promote eco-friendly economic and social development in all aspects, to realize substantial ecological and environmental improvements.[3] Research, development and deployment of low/zero-emission marine fuels is an important step for expediting the shipping sector's transition to zero-emissions, in order to address the global climate emergency while meeting the country's need for constructing an ecological civilization.

Figure 1. Major Climate Pollutants' Contribution to Global Warming



Data source: IPCC (2021)

Figures are for contributions to 2010-2019 warming relative to 1850-1900.

3 See more info on China government website: http://www.gov.cn/xinwen/2021-05/01/content_5604364.htm.

2. IMO's Initial GHG Strategy

To put the brake on GHG emissions from shipping, member states of the International Maritime Organization (IMO) adopted an initial strategy in April 2018 to reduce total GHGs from international shipping, with the goal to reach the targets of the Paris Agreement. IMO's initial strategy[4] set out the following levels of ambition:

- ***New ships:*** Spur a decline in carbon intensity (measured by CO_2 emissions per transport work) by strengthening the requirements of the Energy Efficiency Design Index (EEDI).
- ***Existing ships:*** Improve the carbon intensity of shipping by reducing CO_2 emissions per transport work[5] by at least 40% as of 2030 and pursuing efforts towards a 70% reduction by 2050, compared to 2008.
- ***Entire vessel fleet:*** Bring GHG emissions from shipping to a peak as soon as possible and then reduce the total annual GHG emissions by at least 50% as of 2050 compared to 2008 while pursuing efforts towards phasing them out on an emissions-reduction pathway in line with the Paris Agreement temperature goal.

Since adopting the initial strategy, IMO has started deliberating a list of candidate short-, mid- and long-term measures that aim to promote port-side and ship-side efficiency improvements in the near-term, and support uptake of alternative low/zero-emission fuels[6] and innovative emission reduction mechanisms in the mid- and long-term (Figure 2).

4 See more details from the IMO website: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

5 Carbon intensity reduction targets are estimated as an average across international shipping.

6 Hereafter "low/zero-emission fuels" refers to fuels that have low or zero well-to-wake GHG emissions.

Figure 2. IMO Actions for Addressing Climate Change

2018-2023	2023-2030	2030 and beyond
Near-term measures	Mid-term measures	Long-term measures
New vessel efficiency requirement: Energy Efficiency Design Index **(EEDI)**	***Alternative Low-and Zero-Carbon Fuels:*** Implementation program for accelerating uptake of alternativefuels	***Development and Provisions of Zero-Carbon and Fossil-Free Fuels***
In-service vessel efficiency requirements: Technical efficiency measures- Energy Efficiency Existing Ship Index **(EEXI)**	Further operational and efficiency measures	Adoption of new and innovative emission reduction measure(s)
Operational efficiency requirement- Carbon IntensityIndicator**(CII)**	Market-based measures	
Measures to address methane and VOCs		
Technical cooperation		
National Action Plans		
Revised GHG strategy 2023	Revised GHG strategy 2028	Revised GHG strategy 2033

Adapted from Oftedal (2020).

In 2019, the IMO agreed to strengthen the stringency and move up the implementation date for the Energy Efficiency Design Index (EEDI), which set energy efficiency standards for new builds, of a variety of ship, including gas carriers, general cargo, LNG carriers and container ships. In 2021, two additional near-term measures were adopted: a technical requirement based on a new Energy Efficiency Existing Index (EEXI) and an operational requirement based on a Carbon Intensity Indicator (CII). EEXI rates the energy efficiency performance against a baseline for every existing ship, and is measured based on a ship's design parameters. CII scores each ship on its carbon intensity, derived from actual annual fuel consumption, distance traveled and capacity, and tracks improvement over time.[7]

7 The EEXI measures CO_2 emissions per unit of transport work (measured in gCO_2 per ton-mile), considering a ship's design parameters in a manner comparable to what the EEDI does for new ships. EEXI is based on three factors: the power of the main engine, the reference speed of the ship, and the fuel oil consumption from the test-bed. To drive improvement of the global fleet's energy efficiency, the IMO sets a maximum threshold level that a ship's EEXI must fall below. Taking effect in January 2023, this requirement applies retroactively to all vessels of 400 gross tonnage and above. CII regulates the operational, or real-life CO_2 emissions from ships, and is based on a ship's annual fuel consumption and distance travelled. Starting January 1, 2023, all ships above 5,000 gross tonnage will have to report their annual fuel consumption each year. A rating from A to E will be given to a ship based on its yearly CII. For more information about EEXI and CII: https://www.napa.fi/the-basics-of-eexi-from-2023-all-existing-ships-must-meet-new-energy-efficiency-standards/, https://www.dnv.com/maritime/insights/topics/eexi/answers-to-frequent-questions.html and https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/answers-to-frequent-questions.html.

While the EEXI and CII are important tools for driving energy efficiency improvement of in-service vessels, some IMO member states, shipping companies, and environmental groups have voiced concerns that the modest targets set for these two indexes[8] would not suffice to induce enough efficiency improvements to reach IMO's 2030 target. Setting a lenient target may risk placing more burden on the mid- and long-term measures, like alternative fuel deployment, to achieve IMO goals for 2050 and beyond (Safety4Sea, 2021; Valeur, 2021; Smith et al., 2021).

Even if the in-service vessel requirements were set in line with the IMO 2030 target, there is growing skepticism over IMO's current level of ambition. An increasing number of countries, along with the United Nations and key shipping stakeholders have noted that the current IMO GHG-reduction targets for 2050 fall far short of net-zero CO_2 emissions, which scientists warned are necessary for the world to avoid catastrophic climate impacts (Harvey, 2021). The UN Secretary-General, 12 nations, and over 230 industry leaders and organizations representing the entire maritime value chain have called on the IMO to raise its target to full decarbonization by 2050 (Abnett et al., 2021; Global Maritime Forum, 2021).

Given that new vessels ordered today would likely still be in operation by 2050, it is imperative to accelerate development and deployment of low/zero-emission fuels and propulsion technologies well before 2030 to place international shipping on the path to align with the Paris Agreement's 1.5°C target.

As one of the world's leading maritime nations, China could be an important force that propels the development and uptake of low/zero-emission maritime solutions. In the past decade, the country has played a critical role in accelerating the uptake of renewable electricity and electric vehicles in China and around the world, through scaling up production of photovoltaic panel and batteries and bringing down costs. In a similar way, China could support its ship builders, port equipment makers and potential fuel providers to build up expertise throughout the low/zero-emission shipping value chain, and enable the global shipping industry to transition to zero emissions by the middle of this century.

To inform China's policy makers in devising actions to promote low/zero-emission shipping, this paper provides an overview of the most commonly discussed alternative marine fuel solutions, explores opportunities and challenges for deploying these fuels in China, and examines possible policies for stimulating the development and uptake of these marine fuel solutions.

8 About 70% of post-EEDI ships are expected to be compliant with the EEXI requirements as is (Bureau Veritas, 2021), and analysis suggested that the less than 2% annual improvement of the CII set for 2019 to 2026 is significantly lower than reductions needed to align with the IMO target for 2050 (Comer, 2021a).

3. Overview of Alternative Fuel Solutions

Global shipping is almost entirely powered by fossil fuel. Heavy fuel oil (HFO), very low sulfur fuel oil (VLSFO), and marine gas oil (MGO) together account for over 96% of fuel consumed by all international, domestic and fishery vessels, and liquefied natural gas (LNG) for about 3% (Faber et al., 2021). A range of alternative fuels and energy carriers that could reduce the GHG emissions from shipping are being studied and tested by the industry. Characteristics of the most promising alternative fuels and energy carriers are listed in Table 1 alongside conventional fuels. Air emissions from combustion and spill characteristics of these promising fuels are listed in Table 2. GHG emissions data listed in Table 1 are well-to-wake (WTW) emissions, which account for all climate pollutants emitted upstream well-to-tank (WTT) and downstream tank-to-wake (TTW). Upstream emissions include emissions from fuel extraction, processing, storage, distribution and bunkering.

Table 1 shows that alternative fuels /energy carriers that are made using renewable electricity and renewably generated feedstock (renewable e-fuels, more discussion in Section 3.2) can have very low or close to zero WTW GHG emissions. Based on studies conducted in Europe, Figure 3 compares the current and projected furture costs of these renewable e-fuels with the current price of conventional fuels.

This section summarizes the characteristics of alternative fuels that have gained the most traction, followed by a discussion on the latest developments of synthetic fuels (electrofuels and biofuels) that are created to be compatible with existing fuel infrastructure and vessels.

Table 1. Characteristics of Conventional and Alternative Maritime Fuels

Energy Carrier	Gravimetric Energy Density, LHV (MJ/kg)	Volumetric Energy Density (GJ/m^3)	Storage Pressure (bar)	Storage Temp (°C)	Well-to-Wake (WTW) GHG Emissions (gCO_2e/MJ)		WTW GHG Emissions Compared to MGO[a]		Compatible With	
					Fossil-based Fuel[b]	Renewable-derived Electrofuel (e-Fuel)[c]	Fossil-based Fuel[b]	Renewable-derived e-Fuel[c]	Combustion Engine	Fuel Cell
VLSFO	41	38.7	1	20	92.1	--	101%	--	√	×
MGO	43	36.6	1	20	90.8	1.3	100%	1%	√	√ [e]
Liquid Ammonia	18.6	12.7	1 or 10	-34 or 20	126.7	5.3	140%	6%	√	√ [e]
Liquid Hydrogen	120	8.5	1	-253	150.8	0	166%	0%	√	√
Methanol	19.9	15.8	1	20	92	0.9	101%	1%	√	√ [e]
Liquefied Natural Gas (LNG)	50	23.4	1	-162	75.2 – 94	1.7 – 11.1	83 – 103%[d]	2 – 12%[d]	√	√ [e]
Lithium-ion Battery	0.9	2.4	n.a.	n.a.	Depends on GHG intensity of electricity				n.a.	n.a.

Source: Fuel characteristics - ABS (2019), Alfa Laval et al. (2020), de Vries (2019), and Manthiram (2017); GHG emissions - Lindstad et al. (2020), Lindstad et al. (2021), Pavlenko et al. (2020) and Martin (2021).

LHV=low heating value, n.a.=not applicable.

Notes:

a. Include upstream emissions, emissions from combustion and methane slip, and cover CO_2, methane, nitrous oxide (N_2O), all assessed on a one-hundred-year time horizon (GWP 100). Assume that hydrogen is used in fuel cells, all other fuels are combusted in internal combustion engines.

b. For ammonia, hydrogen and methanol, estimates represent WTW emissions of fuels derived from natural gas; for MGO and LNG, WTW emissions include emissions from fuel production and from combustion of these two types of conventional fuel.

c. Assume all e-fuels are produced using 100% renewable energy, which represents the best-case scenario. For renewable MGO, WTW emissions are based on data of renewable e-diesel.

d. Lower bound estimate represents emissions from high-pressure Diesel cycle engine, higher bound estimate represents low-pressure Otto cycle engine.

e. High-temperature fuel cells, such as solid oxide and molten carbonate, can run on LNG, MGO, ammonia and methanol without an external transformer. Direct methanol fuel cell is designed to run on pure methanol. More information about the different types of fuel cell can be found at: https://www.energy.gov/eere/fuelcells/types-fuel-cells.

Table 2. Air Emissions from Combustion and Spill Characteristics of Ammonia, Hydrogen, Methanol, and Methane

Energy Carrier	Tank-to-Wake Air Emissions Compared with Conventional Fuel			Spill Characteristics of Large and Sudden Releases of Fuel					
	Particulate (PM)	Nitrogen Oxides (NO_x)	Sulfur Oxides (SO_x)	Toxicity	Dissipation and Degradation Rate	Flammable/ Explosion Risk	Air Displacement and Suffocation of Crews	Ecological Impacts	Spill Cleanup
Ammonia	0 [a]	Likely more than conventional fuel, NO_x emissions control needed	0 [a]	Very high	Fast	Low	High	No long-term impacts; marine life near the spill zone may be burned or poisoned	Will dissipate before cleanup can begin
Hydrogen	0 [a]	Vary by the mixture of fuel to air and other engine design [b]	0 [a]	Low		Very high	Possible	No long-term impacts; marine life at the water surface in the spill zone may suffocate or become chilled	
Methanol	Fewer than conventional fuel [c]	~35% [d] to 100% [e]	0 [a]	High, but limited to spill zone		High	Low	No long term impacts; aquatic life in contact with spill may be poisoned	
LNG	0 [a]	~75% to 100% [e] (Diesel cycle) ~10% (Otto cycle)	0 [a]	Low		High	Possible	Marine life at the water surface in the spill zone may suffocate or become chilled	

Source: Kass et al. (2021); Zhou et al. (2020); Anderson et al. (2015); Alfa Laval et al. (2020); Lewis (2021); Fridell et al. (2021); RINA (2020); Maritime Knowledge Center et al. (2018); Ellis (2020).

Notes:

a. Pilot fuel is required, resulting in a small amount of PM and SOx emissions proportional to the amount of pilot fuel used. Emissions from pilot fuels not included here.

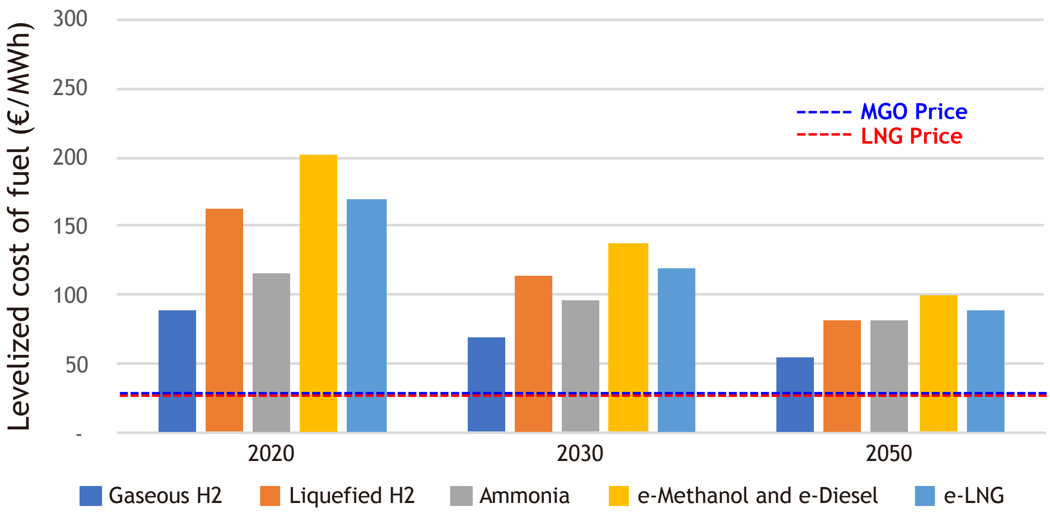
b. The current combustion technology of hydrogen is not yet mature, and NO_x emissions vary by the mechanisms used for controlling peak combustion temperature, such as fuel-to-air ratio and engine design (e.g., premixing fuel and air). More discussion can be found in Lewis (2021).

c. Engine out PM emissions vary depending on the engine combustion technology used (Maritime Knowledge Center et al., 2018; Fridell et al., 2021).

d. Without adopting NO_x control measures for maximizing efficiency (Ellis, 2020); NO_x emissions lower than that of conventional fuel due to the colder methanol flame (RINA, 2020).

e. If NO_x control measures are used, engine combustion can be optimized to maximize energy efficiency and PM reduction, in which case NO_x emissions are similar to the levels of conventional fuels. NO_x control measures include selective catalytic reduction, exhaust gas recirculation; for methanol engines, adding water to the combustion process can also be used. Lower bound data represent emissions without using NO_x control technologies.

Figure 3. Levelized Cost of Renewable Hydrogen, Ammonia, e-Methanol, e-Diesel and e-LNG with Prices of MGO and LNG in Europe



Extracted from Ash et al. (2020).

For comparison, blue and red dotted lines are added to show prices of MGO and LNG (€30 and €27/MWh, respectively). These are prices as of November 24, 2020 in Rotterdam, the latest available 2020 data from Ship&Bunker (https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam)

Assume that all e-fuels are created using renewable electricity, and carbon for SHCF production is obtained through direct air capture with costs declining from €222/tCO_2 in 2020, to €105/tCO_2 in 2030 and €54/tCO_2 in 2050.

3.1 Alternative Marine Fuels

3.1.1 Hydrogen-based Fuels: Hydrogen and Ammonia

3.1.1.1 Background

Both hydrogen and ammonia are recognized as promising carbon-free energy carriers for maritime applications as they contain zero carbon. When run on fuel cells they produce only water vapor. If used in combustion engines, hydrogen produces only nitrogen dioxide (NO_2) and nitrous oxide (N_2O). Burning ammonia in combustion engines generates N_2O and NO_2, and releases unburned ammonia. Also, as pilot fuel is needed to overcome ammonia's poor combustion characteristics,[9] the air pollution characteristics of the pilot fuel will need to be considered in proportion to the quantity used (Duynslaegher, 2011).

9 Pilot fuel is needed for ammonia-fueled combustion engines due to ammonia's poor combustion characteristics. Characteristics that make ammonia less than ideal as a combustion fuel include high auto-ignition temperature, low flame speed, narrow flammability limits and high heat of vaporization (Alfa Laval et al., 2020). It should be noted that most alternative fuels, such as LNG and methanol, also require the use of pilot fuel to initiate combustion.

Managing byproducts from combustion is particularly important for ammonia because it is toxic, a precursor to secondary $PM_{2.5}$ pollution, and harmful to land and water, especially in causing eutrophication and soil acidification (Wang et al., 2015; Shen et al., 2016). The release of unburned ammonia needs to be strictly controlled. In addition, NO_2 is a precursor of ozone and harmful to human health, and N_2O is a powerful greenhouse gas (GHG) that is 300 times more potent than CO_2. Existing after-treatment systems, such as selective catalytic reduction (SCR), combined with enhanced fuel injection strategies, seem to be promising technology for controlling NO_2, N_2O, and unburned ammonia emissions (Dimitriou and Javaid, 2020). Research is underway to evaluate and demonstrate the effectiveness of commercially available after-treatment systems.

Because of ammonia's high toxicity to humans and marine life, high solubility in water, and adverse air quality and environmental impacts (Table 2), the use of ammonia as fuel should be regulated for safety, and special ship design requirements and safety protocols should be adopted to avoid ammonia leakage and control potential spills. Classification societies[10], together with engine manufacturers, are leading efforts to design fuel storage and handling systems as well as developing safety and emissions abatement measures.[11]

3.1.1.2 Status of deployment

Widespread deployment of hydrogen and ammonia as marine fuels hinges on whether compatible ship propulsion systems are market ready, and if there can be a secure supply with safe transport and handling of these fuels.

Relative to hydrogen, ammonia is considered the preferred option for long-distance maritime applications as it has higher energy density and can be easily compressed and stored as liquid in either atmospheric tanks (1 bar at -34 °C), or in pressurized tanks (10 bar at 20 °C) (Table 1) (de Vries, 2019). In addition, ammonia is a commodity already traded globally, mainly for producing fertilizer. Around the world, nearly 40 ports export ammonia and nearly 90 ports import ammonia, including Nanjing and Zhanjiang in China. Hence, some of the infrastructure needed for supplying ammonia as a marine fuel, such as distribution networks to ports and storage tanks already exist (Alfa Laval et al., 2020).

10 Classification Societies are non-governmental organizations that set and maintain technical standards for the construction and operation of vessels to address maritime safety and environmental protection. They ensure continuing compliance with these standards by surveying ships and structure during the process of construction and commissioning and conducting regular surveys in service.

11 See for example: Guide for Ammonia Fueled Vessels issued by the American Bureau of Shipping (https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/325_guide_ammonia_fueled_vessels/ammonia-fueled-vessels-sept21.pdf), Ammonia as a Marine Fuel Safety Handbook issued by DNV (https://grontskipsfartsprogram.no/wp-content/uploads/2021/01/Ammonia-as-a-Marine-Fuel-Safety-Handbook.pdf).

Hydrogen, on the other hand, is believed to be more operationally viable for smaller scale ships in the near-term due to its low volumetric energy density and high onboard storage costs. Compared to other alternative fuels, hydrogen fuel is expensive to store onboard and presents a difficult trade-off with smaller storage tanks that need to be refilled frequently, or larger tanks that come with higher capital and operational costs. This trade-off renders hydrogen less competitive than other alternative fuels, particularly in the near-term when refueling infrastructure is not yet widely established.

A study that examines a representative long-distance route—container shipping between the US west coast and China—shows that almost all container voyages serving the US west coast-China corridor could be powered by hydrogen with only minor changes to onboard fuel storage capacity, such as sacrificing 5% of cargo space, or operation, such as adding one refueling stop (Mao et al., 2020). A follow-up study illustrates that liquid hydrogen fuel cells paired with wind-assisted propulsion could serve as a substitute for conventional fuels for three bulk carriers in China, North America, and Northern Europe with a range of sizes, with only one carrier needing to replace a small percentage of cargo space with storage for hydrogen fuel (Comer et al., 2022). These studies demonstrate that hydrogen fuel cells could feasibly power larger vessels that serve coastal and deep-sea routes. With strategic planning of bunkering sites along major shipping lanes to enable more frequent bunkering, hydrogen could become a cost-competitive fuel solution for coastal and deep-sea shipping.

The use of hydrogen or ammonia as marine fuel is still in the infant stage. While there is currently no ammonia-fueled vessel in operation, the development of propulsion systems and vessel design is progressing rapidly. Wärtsilä, one of the major marine engine manufacturers, announced that it has successfully conducted full-scale engine tests for a marine engine concept using a fuel with up to 70% ammonia, and announced that it will have a prototype for pure ammonia ready by 2023 (Wärtsilä, 2021). The two main two-stroke engine manufacturers—MAN Energy Solutions and WinGD (a subsidiary of China State Shipbuilding Corporation)—plan to have ammonia-fueled engines available by 2024 and 2025 respectively, and MAN also aims to offer a retrofit package for rebuilding in-service vessels by 2025 (Bahtić, 2021; Lindstrand, n.d.).

Responding to increasing demand from customers and financiers for zero-emission shipping services, more ship owners are placing orders for ammonia-fueled or ammonia-ready ships. The world's first vessel that can operate partially on ammonia is slated to launch as early as late 2023 (Maritime Executive, 2021). A Belgium-based tanker company, Euronav NV, is also building two new ammonia-ready tanker vessels that will be ready for delivery in 2023 and 2024.[12] Major shipbuilders

12 See news report: https://www.greencarcongress.com/2021/07/20210707-euronav.html

in South Korea, China, and Japan are racing to meet the demand with new designs of ammonia-fueled vessels that are approved in principle from classification societies, including designs for ultra-large container ships, very large crude carriers, very large gas carriers, ammonia-bunkering vessels, and bulk carriers, as well as a deep-sea tanker due for commercialization by 2024 (Table 3).[13] To secure a competitive edge in the ammonia-fueled vessel segment, South Korean shipbuilders Samsung Heavy Industries and Daewoo Shipbuilding & Marine Engineering have set a goal to commercialize ammonia-fueled propulsion systems by 2024 and 2025 respectively.[14]

Table 3. Ammonia-Fueled Vessels Designed or Being Built by Asian Shipbuilders[15]

Design for Ammonia-fueled Vessels Approved in Principle				
Shipbuilder / Ship Designer	Country	Approved Design Concept for...	Classification Society	Approval Date
Shanghai Merchant Ship Design & Research Institute (SDARI)	China	Bulk carrier (180,000 DWT)	LR	Dec 2019
Dalian Shipbuilding Industries		Ultra-large container ship (23,000 TEU)	LR	Dec 2019
Jiangnan Shipyard		Very large gas carrier	LR	Oct 2020
Jiangnan Shipyard		Liquid gas carrier	LR	Mar 2021
SDARI		Wind-assisted container vessel (2,500 TEU)	Bureau Veritas	May 2021
Shanghai Waigaoqiao Shipbuilding		Bulk carrier	ABS	Aug 2021
COSCO shipping and Marine Design and Research Institute (MARIC)		Very large crude carrier (VLCC)	CCS and ABS	Nov 2021

13 See news reports for examples: https://www.ammoniaenergy.org/articles/ammonia-fueled-ships-entering-the-design-phase/; http://news.sohu.com/a/500112987_624484; https://en.yna.co.kr/view/AEN20200924003200320

14 See news reports: http://www.ajudaily.com/view/20210525131541139; https://www.kedglobal.com/newsView/ked202108190015

15 See news reports: https://www.ammoniaenergy.org/articles/ammonia-fueled-ships-entering-the-design-phase/; https://www.xindemarinenews.com/topic/yazaishuiguanli/24507.html; http://www.eworldship.com/html/2021/classification_society_0313/168947.html; https://www.163.com/dy/article/GA7IOSGG05521RL7.html; http://www.cansi.org.cn/cms/document/16594.html; https://www.offshore-energy.biz/aip-for-samsungs-ammonia-fuelled-tanker-design/; https://www.offshore-energy.biz/samsung-heavy-gets-aip-for-basic-design-of-ammonia-fuel-ready-ship/ https://www.lr.org/en/latest-news/lr-awards-aip-to-ammonia-fuelled-23000-teu-ultra-large-container-ship/ https://www.offshore-energy.biz/hyundai-mipo-dockyard-wins-lr-approval-for-ammonia-powered-ship/; https://pulsenews.co.kr/view.php?sc=30800028&year=2021&no=852515; https://www.maritime-executive.com/article/k-line-is-developing-an-ammonia-powered-car-carrier https://splash247.com/iino-kaiun-orders-ammonia-carrier-at-hyundai-mipo-for-mitsui-charter/ https://splash247.com/euronav-doubles-down-on-ammonia-fitted-tankers/ https://safety4sea.com/hoegh-autoliners-to-receive-four-more-multi-fuel-and-zero-carbon-ready-vessels/; https://www.maritime-executive.com/article/construction-begins-on-world-s-first-ammonia-ready-tanker.

Hyundai Mipo Dockyard (HMD)*	South Korea	Tanker	LR	Jul 2020
Samsung Heavy Industries (SHI)		Tanker	LR	Oct 2020
Daewoo Shipbuilding & Marine Engineering		Ultra-large container ship (23,000 TEU)	LR	Oct 2020
Korean Register (KR), KMS EMEC and Navig8		Ammonia bunkering vessel (8,000 m^3)	KR	Mar 2021
SHI		VLCC	DNV	Aug 2021
Korea Shipbuilding and Offshore Engineering (KSOE), Hyundai Heavy Industries (HHI) and HMD		Ammonia carrier/bunkering vessel (38,000 m^3)	KR	Dec 2021
KSOE, HHI and HMD		Ammonia carrier (60,000 m^3)	KR	Dec 2021
Shin Kurushima Dockyard and K Line	Japan	Car carrier	ClassNK	Dec 2021

Dual-Fueled Ammonia-ready Vessels On Order				
Shipyard	**Country**	**Vessel Type (size; vessels ordered)**	**Ship Owner**	**Delivery Date**
China Merchant Heavy Industries	China	Car carrier (9,100 CEU; 8)	Höegh Autoliners	2024-2026
New Times Shipbuilding		Suezmax tanker (1)	Avin International	Not announced
HMD	South Korea	Ammonia carrier (23,000 m^3, 1)	Iino Kaiun	2023
Hyundai Heavy Industries		Suezmax tankers (3)	Euronav	2023-2024
Hyundai Samho		Very large crude carrier (1)		

LR=Lloyd's Register, ABS=American Bureau of Shipping, CCS=China Classification Society, KR=Korean Register of Shipping, DWT=dead weight tonnage, TEU=twenty-foot equivalent unit, CEU=car equivalent unit.

* A shipbuilding unit of Korea Shipbuilding & Offshore Engineering Co., which is a subsidiary of Hyundai Heavy Industries Group.

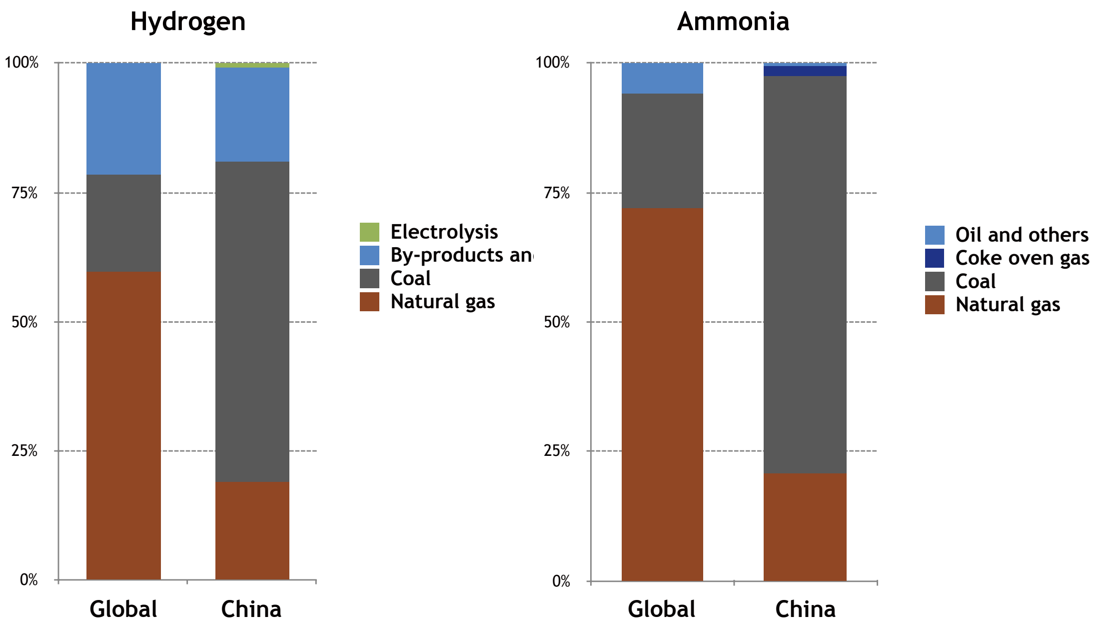
Progress developing hydrogen-fueled vessels is also happening rapidly. More than 10 hydrogen fuel-cell powered vessels have been tested on the sea or are being built for delivery before 2025 in Europe, the US, and Asia (including China), covering a wide range of segments (RoPax, offshore service vessels, cargo ships, cruise ships, tugs, ferries, and tourist boats).[16] Fuel cell makers in South Korea and Japan (including Hyundai Motor, Toyota, and Toshiba), whose governments are investing

16 These include two cruise ships (Xianhu No.1 and Lihu) in China and a cruise ship in Norway, a ferry (SeaChange) in California, two cargo ships to commence operation in Norway and France, a tug powered by methanol-fuel cell in Europe, and a tour boat in Japan. Sources: http://www.qibebt.cas.cn/xwzx/kydt/202101/t20210126_5877430.html; https://baijiahao.baidu.com/s?id=1700830362705871797&wfr=spider&for=pc; https://www.seetao.com/details/85599.html ; https://meethydrogen.com/resource/hydrogen-fuel-cell-cruise-ship-for-norways-fjords; https://www.businesswire.com/news/home/20210818005674/en/5032461/SWITCH-Maritime-and-All-American-Marine-Announce-the-Launch-and-Operational-Trials-of-the-Sea-Change-the-World%E2%80%99s-First-Commercial-Vessel-Powered-100-by-Hydrogen-Fuel-Cell; https://flagships.eu/2021/04/07/worlds-first-hydrogen-cargo-vessel-set-for-paris-debut/; https://www.cnbc.com/2021/06/24/statkraft-lined-up-to-provide-green-hydrogen-for-zero-emission-ship.html; https://www.svitzer.com/press-and-media/news-and-releases/2021/11/08/maersk-svitzer-to-develop-carbon-neutral-methanol-fuel-cell-tug; https://www.maritime-executive.com/article/nyk-leads-project-to-develop-hydrogen-powered-ferry.

heavily in building a hydrogen economy, are developing hydrogen-fuel cell propulsion systems for marine application, with plans to introduce commercial models asearly as 2023.[17]

To enable the rapid uptake of hydrogen- and ammonia-fueled vessels and ensure these vessels deliver substantial climate benefits, an essential prerequisite is to secure the supply, safe storage, transport and bunkering of low/zero-emission hydrogen-based fuels. At present ammonia and hydrogen are produced mainly using natural gas and coal. In China, over 60% of hydrogen production is derived from coal and 19% from natural gas, and more than three-quarters of ammonia output is derived from coal and one-fifth from natural gas (Figure 4). Coal-derived hydrogen and ammonia result in higher well-to-wake CO_2 emissions than directly burning conventional marine fuel.[18] Hence for China, hydrogen-based fuel produced from renewable electricity or resources must become more widely available for hydrogen- or ammonia-powered vessels to realize GHG reduction benefits.

Figure 4. Sources of Hydrogen and Ammonia Production



Data source: IEA (2021b); EV100 (2021); Giddey (2020); Tu (2020).

17 See news reports: https://www.ship-technology.com/news/hyundai-motor-signs-pact-for-hydrogen-fuel-cell-propulsion-systems/; https://www.offshore-energy.biz/samsung-heavy-bloom-energy-push-forward-with-developing-fuel-cells-for-ships/; https://www.electrive.com/2021/02/02/corvus-to-develop-fuel-cell-system-for-ships/; https://www.maritime-executive.com/article/first-high-pressure-hydrogen-fueling-demonstrated-in-japan.

18 CO_2 emissions from the production of ammonia and hydrogen from coal are 240g CO_2e/MJ and 166g CO_2e/MJ respectively (Brightling, 2018; ABS, 2021), which are much higher than the well-to-wake GHG emissions of MGO of 90.8 gCO_2e/MJ for two-stroke marine diesel engines (see Table 1).

An encouraging trend is that global capacity for producing hydrogen from water using renewable energy (hereafter called renewable hydrogen) is expected to grow steadily. An increasing number of countries are embracing renewable hydrogen as a key pillar to replace the use of coal or natural gas for generating electricity, powering transport, and producing steel, cement, fertilizer and other high-carbon intensity products. Nations that have strategies for developing low/zero-emission hydrogen (renewable hydrogen and fossil-derived hydrogen with carbon capture and storage [CCS]) have increased from three as of 2019 to 17 as of 2021 (IEA, 2021b).

Some of these countries have tapped into the growing renewable hydrogen production capacity to serve the maritime sector. For instance, Norway granted government funding to companies with plans to establish between two and four hydrogen hubs along the coast to supply green hydrogen to the maritime sector (Ocean Hyway Cluster, 2021). Maersk and DFDS (a Danish ferry and logistic company) are investing in the development of an ammonia plant in Denmark that will synthesize electro-ammonia using hydrogen produced from offshore wind power.[19]

Parallel efforts are underway to develop a global logistics chain for supplying green ammonia and green hydrogen at major ports. Several industry consortia are currently working on establishing a logistics chain to transport and supply green ammonia to ships in the Baltic and Norway (Ship & Bunker, 2021; Mandel, 2021). Companies in Australia, Singapore, Japan, and the UK, with government support, are looking into building the import/export and supply infrastructure for hydrogen and ammonia for use on ships and at ports, while also establishing safety protocols and requirements for using green hydrogen and ammonia.[20]

3.1.2 Methanol

3.1.2.1 Background

Methanol has been promoted as a clean marine fuel. With no sulfur and a lower heat value than conventional fuel, it produces zero SO_x, and fewer particulate and NO_x emissions (Table 2). It was piloted for use on road transport in California in the 1980s and 1990s and in five Chinese provinces

19 See news report at: https://www.maritime-executive.com/article/dfds-maersk-commit-to-launch-of-europe-s-largest-green-ammonia-plant.

20 See Maritime Singapore Decarbonisation Blueprint: Working Towards 2050 issued by Maritime and Port Authority of Singapore (https://www.mpa.gov.sg/web/portal/home/maritime-singapore/green-efforts/decarbonisation) and news report at: https://www.miragenews.com/australia-partners-with-singapore-on-hydrogen-575583/; https://www.fuelsandlubes.com/singapore-explores-hydrogen-low-carbon-alternative/; https://www.itochu.co.jp/en/news/press/2020/200612.html; https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/111521-h2-green-to-develop-hydrogen-and-ammonia-hub-in-shoreham-uk-to-decarbonize-port

since 2012, for addressing air pollution and energy security concerns.[21]

Methanol has drawn increasing interest from the shipping sector as a more readily applicable low GHG solution for a number of reasons:

1) Methanol is easy to store and transport, and its supply chain can be set up using existing infrastructure with minor modifications: Methanol is in liquid form at ambient temperature and pressure, making it much easier and cheaper to transport and store onboard than gaseous or cryogenic fuels such as liquid hydrogen or liquefied natural gas. As methanol and diesel are similar in physical properties, existing conventional fuel transportation and storage infrastructure could be retrofitted with minor modifications to supply methanol as bunker fuel. In addition, chemical and other industries have been shipping methanol around the world for decades. With methanol currently available at more than 100 ports worldwide, infrastructure is in place to transport and supply it as a marine fuel (ETC, 2020a).

2) Methanol dual-fueled engines are commercially available: Dual fuel methanol-powered engines are already being used to power 11 chemical tankers, a Ropax ferry, and a pilot boat (Wärtsilä, 2020; Offshore Energy, 2020; Ellis, 2020).

3) International guidelines are available to guide the safe use of methanol as a marine fuel: IMO approved the Interim Guidelines for the Safety of Ships Using Methyl and Ethyl Alcohols as Fuel in 2020 (ShipInsight, 2020). These guidelines, which are already added to IMO's International Code of Safety for Ships using Gases and other Low-flashpoint Fuels (IGF code), provides criteria for arranging, installing, controlling, and monitoring the machinery, equipment, and systems for vessels that use methyl or ethyl alcohol as fuel. The amended IGF code enables shipping companies to consider methanol when planning for new building projects or to convert in-use vessels.

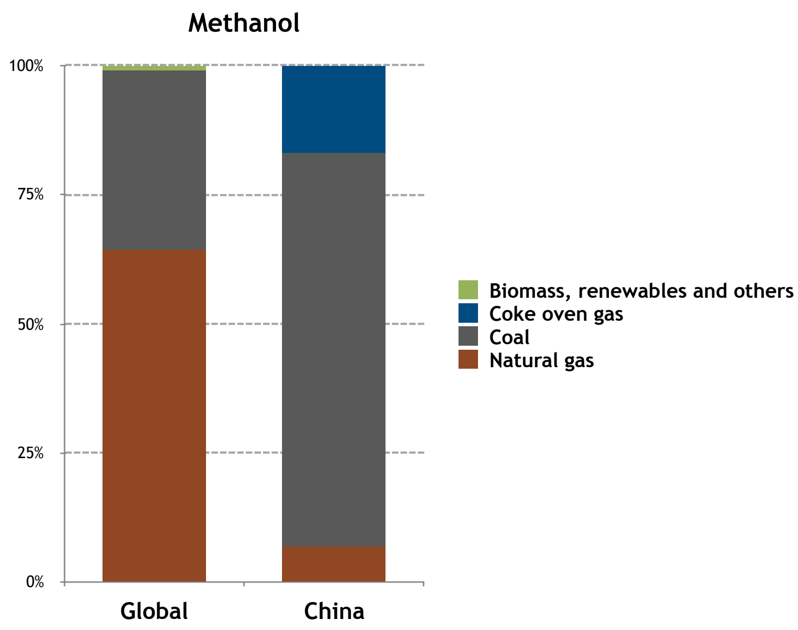
4) Methanol poses less threat to human health and the marine environment than conventional fuel and ammonia: Methanol is toxic but less so than ammonia. It is also less hazardous to the environment than diesel or heavy fuel oil, as it is miscible in water and would biodegrade rapidly in the event of a spill (Table 2).

21 To control vehicular air pollution, California launched a demonstration program in the 1980s and 1990s to promote the use of methanol on passenger vehicles, with methanol refueling stations built in over 100 locations at its peak, but without success. In China, pilot projects for testing the use of methanol on light and heavy-duty vehicles have been launched in five provinces/municipalities since 2012: Shanxi, Shaanxi, Shanghai, Guizhou, and Gasu (Joyce, n.d.; Zhao, 2019). The pilots were considered a success, and eight ministries have jointly issued a guidance document supporting expanded use of methanol on vehicles, initially in the pilot provinces (OFweek, 2019).

With regard to air pollution, studies have shown that adding water into methanol during combustion can help the engine to reach IMO Tier III-NO_x levels without the use of more expensive SCR or exhaust gas recirculation systems (RINA, 2020). This renders methanol a relatively less costly marine fuel option for controlling both air pollutants in the near term than ammonia, which requires the use of SCR systems for NO_x and N_2O control.

At present, the biggest hurdle with adopting methanol as a low-emission marine fuel is not making it operational on ships but sourcing low/zero-emission methanol. Like hydrogen and ammonia, most methanol is currently produced using natural gas and coal (Figure 5). In China, methanol is mainly produced from coal, which accounts for over 75% of the supply, while only 7% comes from natural gas (Tu, 2020). Natural gas-derived methanol has slightly higher GHG emissions than distillate fuel on a well-to-wake basis. Emissions from coal-derived methanol are even higher. Even if combined with carbon capture and storage (CCS), natural gas-derived methanol is only slightly better than distillate fuel with respect to well-to-wake GHG emissions (Martin, 2021). In order for methanol-fueled ships to deliver meaningful climate benefits, there must be a steady supply of low/zero-emission methanol.

Figure 5. Sources of Methanol Production



Data source: Dolan (2020); Tu (2020).

Deep reductions in lifecycle GHGs could be achieved with methanol derived from sustainable biomass feedstock (cellulosic bio-methanol) (more discussion in Sec. 3.2.2.). However, it is questionable whether bio-methanol is scalable as the production of cellulosic bio-methanol is constrained by the limited supply of sustainably harvested biomass feedstock, which is also keenly demanded by other hard-to-abate sectors like aviation.

Alternatively, methanol can be created from chemically synthesizing hydrogen and carbon (more discussion in Sec. 3.2.1.). This type of fuel, known as e-methanol, generates close to zero emissions if it is produced using renewable hydrogen and renewably generated carbon, such as carbon captured from air or sustainable biogenic sources. While hydrogen can be generated via electrolysis, a large volume of renewably produced carbon or CO_2 is difficult and expensive to secure. In addition, e-methanol is costly (see Figure 3). Currently e-methanol costs about twice as much as fossil-based methanol (Wittels, 2021). Moreover low-carbon e-methanol is always going to be more expensive to produce than equivalent hydrogen and ammonia fuels (e.g., hydrogen and ammonia produced using the same electricity source), because it has an additional carbon molecule (Ash et al., 2020).

3.1.2.2 Status of deployment

Despite the challenges in sourcing low-emission methanol, shipping companies are increasingly looking into methanol as the next step for zero-emission transition as methanol-powered ships can be deployed in the very near term given that methanol propulsion technology is mature and IMO guidelines have been approved to ensure the safe use of methanol on ships.

In addition to the methanol-fueled vessels already in operation, more than 40 methanol dual-fuel newbuild vessels will be launched in the 2022-2024 timeframe. Maersk, the world's largest container shipping company, has ordered a methanol dual-fuel container feeder vessel for delivery in 2023, and twelve 16,000 TEU methanol dual-fuel container ships, with plans to enter service beginning in 2024. Tanker shipping company Proman Stena Bulk will have six new methanol dual-fuel tankers in operation from 2022-2023. Methanex, the world's largest methanol producer and supplier, will have eight methanol dual-fuel chemical tankers in operation by 2023, in additional to its eleven methanol dual-fuel tankers that are already in service. A Singapore-based container carrier, X-Press Feeders, recently placed an order for sixteen 1,176 TEU newbuild container ships that can run on methanol and regular fuel (Table 4).[22]

Retrofit solutions that enable in-service vessels to run on methanol are also being developed. The Swedish ship owning group Stena and Swiss-based methanol producer Proman are jointly developing a methanol retrofit and supply solution for in-service oceangoing vessels (Ajdin, 2021). A consortium of maritime engineering companies, technical universities and a sustainable biofuel

22 See news report from: https://splash247.com/x-press-feeders-signs-for-16-methanol-powered-newbuilds/.

producer in Denmark are also developing a methanol fuel system that can adapt to today's marine diesel engines (F&L Asia, 2021).

Table 4. Methanol-Fueled Vessels Being Built by Asian Shipbuilders[23]

Methanol Dual-fueled Vessels On Order *				
Shipyard	**Country**	**Vessel Type (size; vessels ordered)**	**Ship Owner**	**Delivery Date**
Guangzhou Shipyard International (GSI)	China	Tanker (49,900 DWT; 3)	Proman Stena Bulk	2022-2023
GSI		Tanker (49,900 DWT; 3)	Proman	2022-2023
New Dayang Shipbuilding		Container ship (1,170 TEU; 8)	X-Press Feeders	2023-2024
Ningbo Xinle Shipbuilding Group		Container ship (1,170 TEU; 8)	X-Press Feeders	2023-2024
Dalian Shipbuilding Industries		Container ship (7,100 TEU; 2)	Danaos	2024
Taizhou Sanfu Ship Engineering		Container ship (1,300 TEU; 2)	MPC Container Ships	2024
Dalian Shipbuilding Industries		Container ship (15,000 TEU; 6)	CMA CGM	2025
Hyundai Mipo Dockyard (HMD) *	South Korea	Chemical carrier (49,999 DWT; 8)	Waterfront Shipping Company **	2021-2023
HMD		Container ship (2,100 TEU; 1)	Maersk	Mid-2023
Hyundai Heavy Industries		Container ships (16,000 TEU; 12)	Maersk	2024-2025
Daehan Shipbuilding		Container ship (7,200 TEU; 2)	Danaos	2024

DWT=dead weight tonnage, TEU=twenty-foot equivalent unit.

* A shipbuilding unit of Korea Shipbuilding & Offshore Engineering Co., which is a subsidiary of Hyundai Heavy Industries Group.

** A subsidiary of Methanex, a large producer and supplier of methanol.

23 See news reports: https://www.offshore-energy.biz/proman-stena-bulk-1st-methanol-powered-tanker-launched-in-china/; https://splash247.com/x-press-feeders-signs-for-16-methanol-powered-newbuilds/; https://www.maersk.com/news/articles/2021/07/01/container-fueled-by-carbon-neutral-methanol; https://www.maersk.com/news/articles/2021/08/24/maersk-accelerates-fleet-decarbonisation; https://www.offshore-energy.biz/danaos-orders-four-more-methanol-ready-containerships/; https://lloydslist.maritimeintelligence.informa.com/LL1141124/CMA-CGM-orders-six-methanol-fuelled-box-ships; https://splash247.com/mpc-container-ships-orders-methanol-powered-boxship-duo-for-norwegian-charter/.

3.1.3 Natural Gas (Methane)

Natural gas, usually composed of 85-90% methane,[24] is becoming increasingly popular as an alternative shipping fuel. Unlike in power generation, where switching from coal to gas generation could deliver considerable CO_2 emission reductions (Gould and McGlade, 2017), the CO_2 reduction benefits from substituting marine fuel oil with natural gas are much smaller. The climate change advantages of gas are further diminished or negated if there is a slight release of methane, a potent greenhouse gas, from combustion, upstream extraction, production, and transmission processes. More discussion on the debatable climate benefits of natural gas can be found in Sec. 4.

On air quality, there is a broad consensus on the benefits of LNG in reducing sulfur and particulate pollution, as LNG produces no sulfur and fewer particulate emissions during combustion (see Table 2) (Anderson et al., 2015; Lindstad et al., 2020). However, the NO_x emissions level depends on the peak combustion temperature and varies with the engine type. Not counting LNG carriers, currently most of the LNG-fueled engines are dual-fueled and predominately use the low-pressure Otto cycle or high-pressure Diesel cycle engine technology (thereafter referred to as the Otto cycle and Diesel cycle engine, respectively).[25] Otto cycle engines operating on LNG can achieve IMO Tier III NO_x requirements without exhaust after-treatment, such as using the SCR system, but Diesel cycle engines need to use after-treatment systems to reach Tier III levels.

Before the surge in global gas prices in 2021, LNG had been generally less expensive than distillate fuel with maximum sulfur content of 0.1% (which complies with IMO Emission Control Area [ECA] requirements for SO_x), and was even cheaper than HFO in some regions from 2016 onwards (DNV, n.d.-a). LNG was therefore seen as a cost-competitive and technologically mature solution for fulfilling ECA requirements. With stricter ECA requirements taking effect in North America and Europe, and Asian countries adopting increasingly more stringent sulfur standards for marine fuels, the number of LNG-powered vessels of all kinds has been steadily increasing, especially in ferry, off-shore, tanker, and container segments (Pavlenko et al., 2020; DNV, n.d.-b). At the end of September 2021, there were 704 ships capable of burning LNG (including LNG carriers), representing 0.7% of the global vessel fleet, though a much bigger share of new ship orders—28% in

24 Refers to composition of commercial natural gas, see Britannica, n.d. Composition and properties of natural gas. In Britannica online. https://www.britannica.com/science/natural-gas/Composition-and-properties-of-natural-gas (accessed December 22, 2021).

25 LNG carriers use boil-off methane gas as fuel, and commonly use steam turbines for propulsion, hence are excluded from the above discussion. The two most commonly used combustion technologies for LNG engines are low-pressure lean-burn Otto cycle engines and high-pressure Diesel cycle engines (Jääskeläinen, 2020). While Otto cycle engines could reach IMO Tier III standards without the use of an after-treatment system, NO_x emissions from Diesel cycle engines are only 25% below emissions of conventional engines, and cannot meet Tier III requirements unless after-treatment systems are used (Andersen et al., 2015).

gross tonnage terms—are LNG capable.[26]

LNG is also embraced by many as a transition solution for shipping decarbonization, as it can result in about 25% lower CO_2 emissions than conventional fuels, when considering only CO_2 emissions from fuel combustion (tank-to-wake emissions) (Lindstad et al., 2020).[27] However, methane leaks occur when natural gas is extracted, processed, transmitted, and distributed, and unburned methane is released from engines (methane slip). Methane is a potent GHG: pound-for-pound it has 84 times the heat-trapping power of CO_2 in the first 20 years after it is released, and 30 times over a 100-year horizon.[28] So while substituting conventional marine fuels with methane reduces CO_2 emissions at the point of use, these climate benefits could be more than offset by methane slip and leakage.

A case in point is Otto cycle engines. When running on LNG, their well-to-wake GHG emissions are higher than diesel engines burning MGO by as much as 20% for two-stroke engines and 48% for four-stroke engines over a 20-year horizon (GWP20) (see Figure 6). Even if warming effects in a 100-year horizon (GWP100) are considered, LNG still emits more GHG emissions than conventional fuels for four-stroke Otto cycle engines, and only 4% less GHGs for two-stroke engines. Diesel cycle engines perform better, with well-to-wake GHG emissions lower than conventional engines for both two- and four-stroke engines—9% and 15% of reduction for GWP20 and GWP100 respectively (Lindstad et al., 2020; Pavlenko et al., 2020).

At present the more leaky Otto cycle engines are more economical to purchase and operate than Diesel cycle engines, so more of them are sold—as of 2019 most of the LNG-fueled vessels in service or on order use Otto cycle engines (Pavlenko et al., 2020; Lindstad et al., 2020). In fact, at present there is no commercially available four-stroke LNG-powered marine engine that use the Diesel cycle technology.

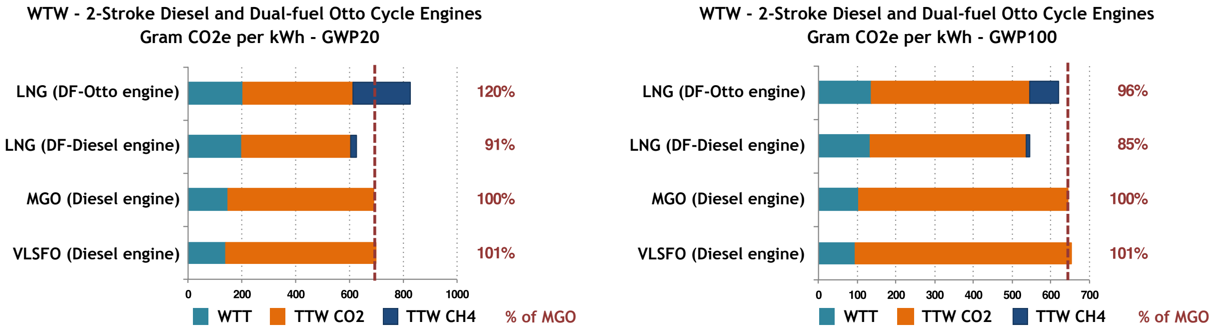
26 According to Clarksons data, see Chambers (2021).

27 The lower CO2 emissions of LNG from fuel combustion are mainly due to the higher hydrogen-to-carbon ratio of methane compared to HFO and MGO.

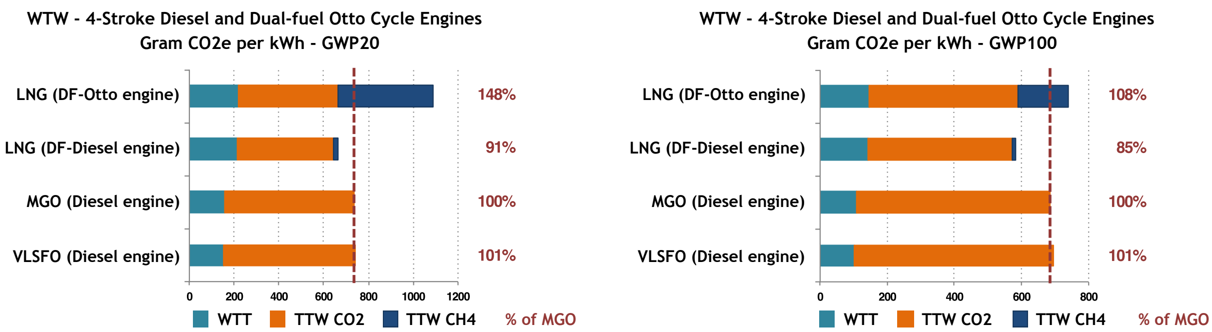
28 One of the metrics used for measuring the impacts of greenhouse gases is global warming potential (GWP), which presents how much energy a tonne of the greenhouse gas will absorb over a period of time, relative to the emissions of a tonne of CO_2. GWP 20 represents the climate impacts of a GHG in the short-term, within a 20-year time horizon, whereas GWP 100 represents the long-term impacts within a 100-year time horizon.

Figure 6. Well-to-Wake CO_2 Equivalent (CO_2e) Emissions of Diesel and Dual-Fueled Engines

i) Two-stroke Engines: Heat-trapping Power in the First 20 Years (left) and 100 Years (right)



ii) Four-stroke Engines: Heat-trapping Power in the First 20 Years (left) and 100 Years (right)



Reproduced based on Lindstad et al. (2020)

WTW=well-to-wake, WTT=well-to-tank, TTW=tank-to-wake, DF=dual fuel, MGO=marine gas oil, VLSFO=very low sulfur fuel oil, LNG=liquefied natural gas, and GWP=global warming potential.

Notes:

1. Low-pressure Otto cycle engines typically have much higher methane slip than high-pressure Diesel cycle engines.
2. GWP, presented in CO_2e, represents the ability of a tonne of GHG in absorbing heat relatively to a tonne of CO_2 within a given time horizon. GWP20 presents climate impacts within a 20-year short-term time horizon, and GWP100 shows climate impacts over a 100-year long-term horizon.
3. At present there is no commercial four-stroke LNG-powered engine that uses Diesel cycle technology.

Active research is underway on methane slip control. For instance, WinGD's updated Otto cycle engine includes a technology option that the company claims could reduce methane slip by up to 50% compared to the previous model (gCaptain, 2021). However, marine engine methane emissions are not yet regulated by international standards. Without regulations that reward the most climate-friendly engine solutions, market demands alone will be unlikely to drive the uptake of the less leaky engine technologies, which means even the modest climate benefits from switching to natural gas cannot be guaranteed.

The uncertain climate benefits of LNG have led the World Bank and leading ship owners, such as Maersk and Euronav, to call for pulling back further investment in LNG-fueled vessels and bunkering infrastructure to reduce risks of stranded assets and avoid locking us into the associated GHG emissions that make the transition to zero-emission solution more difficult (Englert et al., 2021; Adamopoulos, 2021).

3.1.4 Electricity

3.1.4.1 Background

The number of hybrid and fully electric vessels has been steadily increasing in the past decade, mainly driven by government efforts to reduce air and climate pollution from shipping.[29] Running vessels on electric batteries bring a host of environmental benefits. Not only do they have zero tailpipe emissions, they are much quieter and odorless compared to ships running on conventional fuels. In addition, electric motors are less complex than internal combustion engines, which makes them less costly to service and maintain.

However, high initial capital investments for electric vessels would be a challenge, as well as investments to create the necessary shore connection and charging infrastructure. Also, because of the low volumetric energy density of batteries (Table 1), limited range and capacity are major constraints of fully electric vessels at present. For these reasons, all-electric vessels are currently confined to inland and short-sea operations.

The lifecycle air and climate benefits of e-vessels depend mainly on the GHG intensity of the electricity being used. While most of the electric vessels deployed to date use grid electricity which means the air and climate performance depends on the generation-mix of local power generation, some electric vessel pilot projects have made efforts to ensure the use of carbon-free electricity. For instance, the fully electric ferry Ellen is truly zero-emission as it is charged from the local grid on Ærø, where the electricity is entirely powered by wind (Cerny, 2021). Looking at the broader picture, as more and more nations, including China, commit to becoming carbon neutral by mid-century, the share of renewable electricity will inevitably grow which in turn will lead to a gradual reduction in the lifecycle air and climate pollution of electric vessels.

29 Almost all electric vessels now in operation are powered by batteries, though there are demonstration projects using supercapacitors. See examples of demonstration projects in China and France: https://www.ship-technology.com/news/china-test-homegrown-electric-cargo-ship/, https://min.news/en/economy/1c562966b6ff8ddd4a1d1cbfa3dc5f9d.html, https://www.nidec-industrial.com/document/supercapacitor-energy-storage-system-electric-ferry-case-study/.

3.1.4.2 State of deployment

As of 2021, 337 fully electric and hybrid vessels were already in operation around the world, and 199 were under construction. Of these 536 vessels with battery-electric propulsion, fully-electric and plug-in electric vessels each accounted for 24% (130 units), and hybrid-electric accounted for about half (248 units) (DNV and Maritime Battery Forum, n.d.). Car and passenger ferries, with set routes and relatively shorter journeys, accounted for the largest number of hybrid and fully electric vessels that were deployed or under construction, with 43% of the world's total, followed by offshore supply ships, with 12% of the global total (DNV, n.d.-b).

With battery technology quickly evolving and costs coming down, electric vessels with large battery capacity are coming to the market, enabling electric propulsion to serve longer voyages or more energy demanding services. For instance, the world's largest fully electric ferry in operation, Bastø Electric, uses batteries with a capacity of 4.3 MWh and has room for 600 passengers and 200 cars or 24 trucks. Its battery size and passenger and car capacity are respectively four times and almost double that of the world's first fully electric car ferry, Ampere, launched in 2015 (Siewers, 2021). In China, over 50 fully electric vessels are already in operation or being constructed. The world's largest electric river cruise ship, Yangtze River Three Gorges 1, with 7.5 MWh of battery capacity (close to twice the capacity of Bastø) entered service in March 2022 to serve popular Yangtze River tourist routes (Doll, 2022).

3.2 Carbon-based Synthetic Fuels: Synthetic Hydrocarbon Fuels and Biofuels

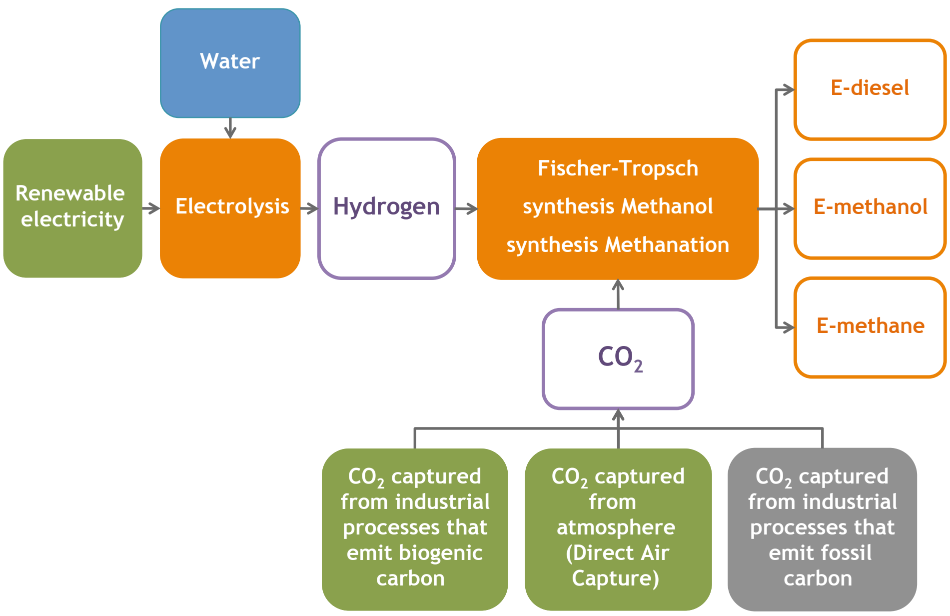
Producing fuels synthetically via chemical conversion processes using defossilized CO_2 sources, such as direct capture of carbon from air, or biological sources, offers a way to manufacture fuels that are energy dense, can be easily stored, are compatible with existing engine and fuel infrastructure, and can be burned cleanly with less air pollutants compared to fossil fuels. This section discusses two types of carbon-based synthetic fuels—synthetic hydrocarbon fuel and advanced biofuel (also known as second-generation biofuel)—that are looking increasingly attractive as pressure grows to accelerate the transition away from fossil fuels.

3.2.1 Synthetic Hydrocarbon Fuels

3.1.2.1 Background

Electrofuel (also called e-fuel, power-to-x) is one form of synthetic fuel that converts electricity into hydrogen through the electrolysis of water. The hydrogen produced can be used directly as a final energy carrier (hydrogen fuel, as discussed in Sec. 3.1.1.), or can be combined with other molecules to produce other forms of e-fuel through chemical synthesis. For instance, synthetic hydrocarbon fuel (SHCF) can be manufactured by reacting hydrogen with captured carbon. The most commonly discussed SHCFs for marine application are e-diesel, e-methanol, and e-methane (Figure 7). Ammonia is another form of e-fuel created by combining hydrogen and nitrogen separated from air, as discussed in Sec. 3.1.1.

Figure 7. Potential Pathways for Producing Carbon-based E-fuels



Note: Examples of industrial processes that emit biogenic carbon include waste treatment and pulp and paper, and examples of sources of fossil carbon include coal- and gas-fired power plants.

SHCFs are made to have comparable composition and energy to conventional fuels, and can readily serve as a substitute for fossil fuels in existing fuel infrastructure and vessel engines with minimal, if any, modifications. The potential of using renewable electricity to produce the hydrogen feedstock and power the fuel synthesis process presents SHCFs as a possible climate-friendly fuel solution. But SHCFs emit CO_2 at the point of use. To make them nearly carbon-free requires using sustainably sourced carbon feedstock. One possible source is capturing CO_2 from air (Direct Air Capture, DAC) which is expensive. Another source is from sustainably produced biomass feedstock which is very limited and as a result, is unlikely scalable (see discussion in Sec. 3.2.2).

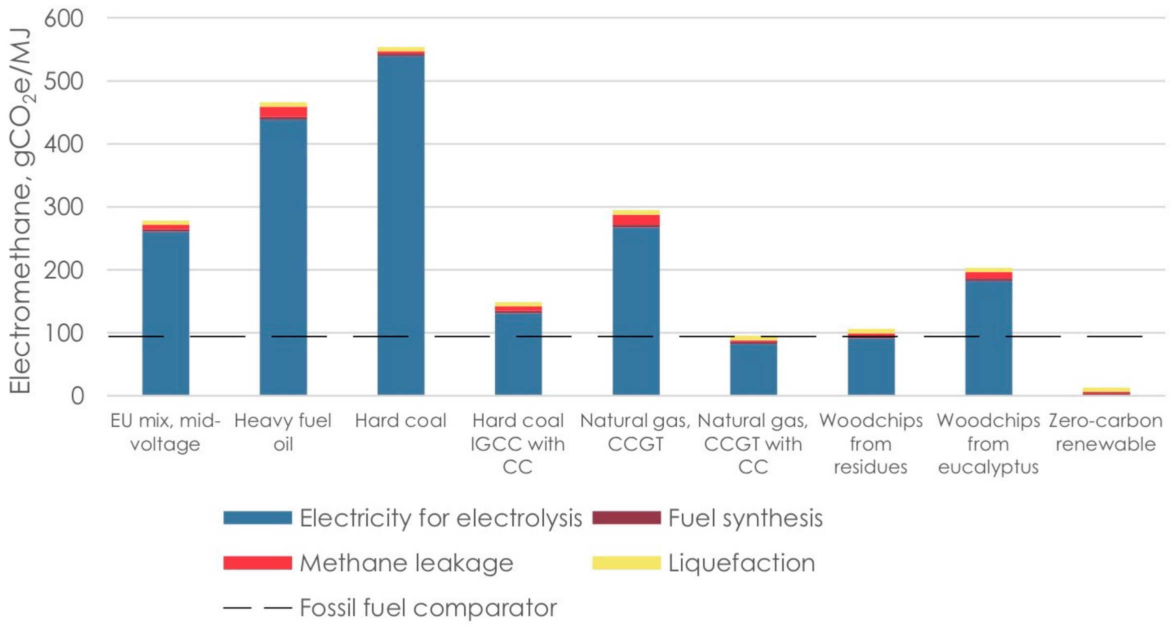
While compatibility is a huge advantage, SHCFs take a lot of electricity to produce due to the many processes involved, leading to significant conversion losses. Low-carbon SHCFs made from renewable hydrogen and sustainable carbon sources (e.g., DAC) are also currently more costly to produce than renewable hydrogen and renewable ammonia, which avoid the need for CO_2 capture. At present, the levelized cost for producing SHCFs is more than five times the price of conventional fuels[30] (Figure 3).

The well-to-wake GHG intensity of SHCFs is predominantly driven by the GHG intensity of the electricity used for electrolysis. If zero-carbon renewable electricity is used, the carbon intensity of SHCFs can be close to zero. If produced using non-renewable electricity (e.g., coal-, oil- or natural gas-fired power plants), the well-to-wake GHG intensity of SHFCs is estimated to be several times higher than that of fossil fuels (see for example Figure 8, extracted from Malins [2018], for a comparison of GHG intensity of e-methane produced using different electricity sources). For e-methane, distribution and use of the fuel would entail some degree of methane leakage upstream and during combustion, which would reduce the climate benefits if not controlled effectively (Malins, 2018).

Because of conversion losses, it is always more costly to use SHCFs than directly using electricity. The need for sustainably produced carbon feedstock also suggests that producing SHCFs would likely be more costly than producing renewable hydrogen and renewable ammonia, as illustrated in Figure 3. Taking a system-wide energy efficiency perspective, the direct use of renewable energy should be preferred, wherever electrification is possible (Agora Verkehrswende et al., 2018; Malins, 2018). In the context of shipping, SHCFs should be considered only as a supplementary solution to electrification and hydrogen-based e-fuels, and would be best adopted only for vessels not suitable or too costly for electrification or using hydrogen-based e-fuels. Such vessels would likely be in-service vessels that serve long-distance and non-fixed routes, in regions that lack local grid capacity, or where hydrogen-based e-fuels will not be available in the near- and medium-term.

30 Due to the spike of fossil fuel prices triggered by the war in Ukraine, the author used prices of MGO and LNG in November 2020 for a more equitable comparison.

Figure 8. GHG Intensity of e-Methane Using Various Electricity Sources



Extracted from Malins (2018).

Analysis of GHG intensity of e-methane for road transport using EU data; GHG intensity should be slightly higher for ships.

IGCC=integrated coal gasification combined cycle, CC=carbon capture, and CCGT=combine cycle gas turbine.

3.2.1.2 Air pollution impacts

SHCFs are sulfur-free, as combustion produces no SO_2 and fewer particulate emissions than conventional fuels, but they produce NO_x emissions at a similar level to conventional fuels. Emissions control devices (such as SCR and exhaust gas recirculation systems) are needed to ensure NO_x emissions standards can be attained (Royal Society, 2019).

3.2.1.3 Status of deployment

SHCFs have not yet been commercially deployed. In the past two years, a number of pilot projects have been launched to demonstrate viability for use in the maritime sector. In September 2021, a container feeder vessel made the world's first trial voyage from Brunsbuttel, Germany near Hamburg, to St. Petersburg, Russia using e-methane produced from wind powered-derived hydrogen and CO_2 captured from a biogas plant (Bundesregierung, 2021).

A few ports and shipping lines are now working with fuel providers to speed up the development of SHCFs. For instance, a business consortium that includes the Port of Antwerp is building an e-methanol demonstration plant where the e-fuel will be made using renewably generated hydrogen and CO_2 captured from a carbon capture and utilization (CCU) plant, with production expected to start in 2022 (Port of Antwerp, 2020).

Maersk has been actively working with fuel producers to secure a supply of low/zero-emission methanol to power its fleet of methanol-powered container ships. The efforts to date include signing a deal with Reintegrate, a producer of e-methanol made from renewably generated hydrogen and biogenic carbon, to supply low/zero-emission methanol to Maersk's first methanol dual-fuel vessel to be launched in 2023 (Maersk, 2021). Prometheus Fuels, a start-up with a direct air capture-technology, has also received investment from Maersk for the production of carbon-neutral e-methanol (Port Technology, 2021). Recently, Maersk formed a strategic partnership with six companies to scale green methanol production, with the intent to source at least 730,000 tonnes per year by the end of 2025. Three of Maersk's strategic partners, all located in Europe, will be supplying e-methanol (one of them supplying both e-methanol and biomethanol). The other three partners will supply biomethanol (Maersk, 2022).

3.2.2 Biofuels

3.2.2.1 Background

Biofuels are fuels that are produced from biomass, including plants, agricultural waste, waste oils, and algae.

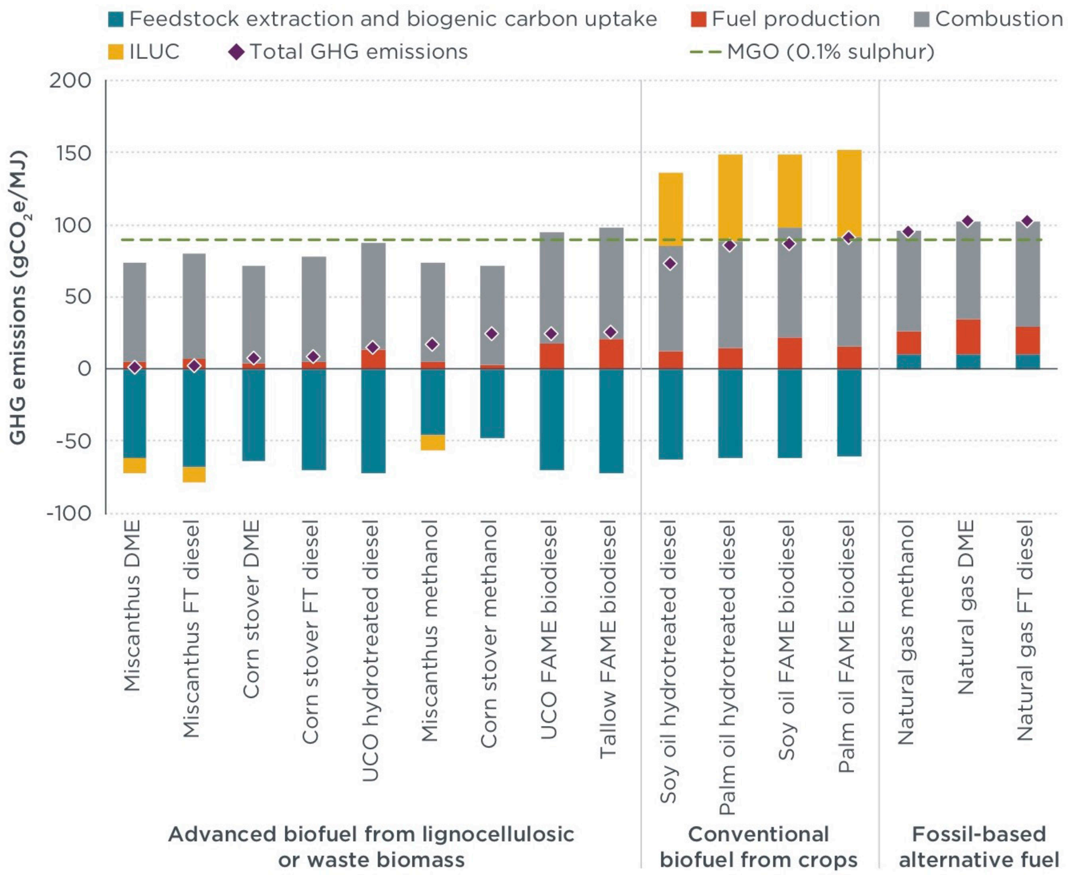
First-generation biofuels (also known as conventional biofuel) produced from sugary, starchy, or oily food crops such as corn or grapeseeds have achieved commercial-scale production and been widely used for on-road transport across the world. However, the use of food crops as feedstock raises serious environmental and sustainability concerns due to competition with food production and direct impacts on water availability in regions with scarce water resources (Yeh et al., 2011). In addition, a growing body of literature has found that the increased production of first-generation biofuels spurred agricultural land expansion at a global scale for feedstock production, resulting in additional GHG emissions (known as indirect land-use change effects) (Valin et al., 2015). These concerns led governments, including the EU, to scale back incentives to stimulate the production of first-generation biofuels (ABS, 2019).

Second-generation biofuels, also known as advanced biofuels, are produced from non-food feedstock, such as energy crops (e.g., switchgrass), agricultural and forestry residues (e.g., corn stalks and twigs), and wastes (e.g., used cooking oil and municipal solid waste). In the US, commercial production began in the early 2010s driven by on-road transport renewable fuel mandates, but the scale of production fell far short of expectation due to high production costs (Rapier, 2018). Third-generation biofuels use algae as feedstock, but there is no commercial production in place.

Biofuels emit much lower particulate and sulfur emissions than conventional fuels, but have NO_x emissions similar to HFO, and slightly higher than MGO (Gilbert et al, 2018; MAN Energy Solutions, 2022). The GHG emissions of a given biofuel depend chiefly on the type of feedstock, the fuel production process, and whether additional biofuel demand would cause changes to land use. Both second- and third-generation biofuels pose much less indirect land use change risks than first-generation biofuels.

Studies found that biofuels made from sustainably sourced feedstocks, such as second-generation biofuels made from wastes or residues, can achieve 70% to near 100% well-to-wake GHG emission reductions relative to MGO, while GHG emissions from first-generation biofuels are close to that of MGO after accounting for indirect land-use change effects (see the purple dots on Figure 9 showing the GHG intensity of a variety of biofuels and fossil-based alternative fuels) (Zhou et al., 2020; Searle, 2019).

Figure 9. Lifecycle GHG Emissions of Advanced Biofuels, Conventional Biofuels and Fossil-based Alternative Fuels



Extracted from Zhou et al. (2020).

DME=dimethyl ether, FT=Fischer-Tropsch, UCO=used cooking oil, FAME=fatty acid methyl ester, ILUC=indirect land use change.

3.2.2.2 Status of deployment

Second-generation biofuels derived from waste have been trialed by a number of shipping companies in the past few years, including CMA CGM, Maersk, Eastern Pacific Shipping and Stena Bulk.[31] Biofuels are included as one part of the shipping decarbonization strategy of some shipping lines including Maersk and Stena Bulk (Prevljak, 2021; Kennedy, 2021). As mentioned earlier, Maersk has inked a strategic partnership with six companies to supply methanol by 2025. Four of these six companies, including two based in China, plan to supply biomethanol (Maersk, 2022).

Despite growing interest, there are grave concerns regarding the scalability of biofuels given that the amount of feedstock that could be sustainably sourced is limited. Questions remain whether the production of sustainably produced biofuels could be sufficiently scaled up to fully meet future demand from the marine sector, particularly in the face of competition from other hard-to-abate sectors like aviation and plastic (ETC, 2020b).

In China, the development of second-generation biofuels has been limited mainly due to logistic challenges in finding reliable supplies of feedstock at low costs, and the higher costs of building and operating cellulosic plants compared to first-generation biofuel plants (USDA, 2020). The Carbon Peaking Action Plan Before 2030 released by the State Council in October 2021 named advanced biofuels as one of the strategies for decarbonizing the transport sector, but it is expected that advanced biofuels will likely be developed for serving the aviation sector which has more limited decarbonization options (State Council, 2021; Biogenic Energy Observer, 2021).

31 See press reports on the biofuel trials for examples: https://www.maritime-executive.com/article/ikea-cma-cgm-and-goodshipping-test-biofuels; https://www.joc.com/maritime-news/maersk-trials-biofuel-drive-decarbonize_20190620.html; https://www.marinelink.com/news/eastern-pacific-shipping-trial-biofuels-482566; https://biofuels-news.com/news/company-embarks-on-bulk-carrier-biofuel-trial-in-quest-for-carbon-neutral-shipping/.

3.3 Summary: Comparison of Alternative Marine Fuels

Based on the above discussion, Table 5 summarizes the GHG and air emission levels, and production costs of alternative marine fuels that have gained most traction, alongside with advantages and challenges of using these fuels as a marine fuel.

Table 5. Climate and Environmental Performances, Costs, Advantages and Challenges of Using Alternative Maritime Energy Carriers

Energy Carrier	WTW GHG Emissions Compared to MGOa		TTW Air Emissions Compared with Conventional Fuel			Renewable-Derived e-Fuel Cost Ratio, Relative to MGO Price [h]		Technical, Safety and Fuel Supply Considerations	
	Fossil-based Fuel [a]	Renewable-derived e-Fuel [b]	PM	NO_x	SO_x	2030	2050	Advantages	Challenges
Liquid Ammonia	140%	6%	0 [d]	Likely more than conventional fuel; NO_x emissions control needed	0 [d]	3.2	2.7	• Low flammability risk • Easy to store and transport • Renewable e-ammonia less costly to produce than other renewable e-fuels • Traded globally as a commodity	• Highly toxic • Possible N_2O emission and ammonia slip • Engine development at design stage • Poor combustion characteristics • Lack of fuel infrastructure • Safety regulations not yet adopted • Corrosiveness to certain materials
Liquid Hydrogen	166%	0%	0 [d]	Vary by engine design	0 [d]	3.7	2.7	• Low toxicity • Low risk to the environment if leaked	• Costly to store and transport • Explosion risk • Lack of fuel infrastructure • First pure hydrogen engine recently launched, limited operation experiences

Methanol	101%	1%	Fewer than conventional fuel [e]	~35% [f] to 100% [g]	0 [d]	4.5	3.3	• Engines commercially available • Easy to store and transport • If leaked less hazardous to the environment than conventional fuel • Can use existing fuel infrastructure with minor modifications • Retrofitting existing engines to run on methanol far less costly than other alternative fuels • Interim safety guidelines adopted at IMO • Traded globally as a commodity	• More storage space needed than conventional fuel • High explosion risk • Toxic, but less so than ammonia • Renewable e-methanol more costly to produce than other renewable e-fuels • Corrosiveness to certain materials
LNG	83 – 103% [c]	2 – 12% [c]	0 [d]	~75% to 100% [g] (Diesel cycle) ~10% (Otto cycle)	0 [d]	4.0	2.9	• Low toxicity • Engines commercially available • Fuel infrastructure exists in a few large sea ports • Safety regulations adopted at IMO	• High flammability risk • Methane slip and upstream methane leakage can significantly offset CO_2 reduction benefits • Renewable e-methane more costly than renewable e-ammonia • Scalability of bio-methane is questionable • High storage and transport cost
Lithium-ion Battery	Depends on GHG intensity of electricity		0	0	0	n.a.		• WTW emissions will fall with rising share of renewable electricity in many countries • Mature technology • Much quieter and scentless than internal combustion engines	• Very low energy intensity; limited range and battery capacity are major constraints for fully electric vessels • Lack of recharging infrastructure

Source: GHG emissions - Lindstad et al. (2020), Lindstad et al. (2021), Pavlenko et al. (2020) and Martin (2021); air emissions - Zhou et al. (2020), Anderson et al. (2015), Lewis (2021), Fridell et al. (2021), RINA (2020), Maritime Knowledge Center et al. (2018), Ellis (2020); costs - Ash et al. (2020); other considerations - Kass et al. (2021); Alfa Laval et al. (2020).

WTW=well-to-wake, TTW=tank-to-wake, MGO=marine gas oil, PM=particulate matter, NO_x=nitrogen oxide, SOx=sulfur oxides, N_2O=nitrous oxide.

Notes:

a . WTW emissions from ammonia, hydrogen and methanol derived from natural gas. For LNG, includes emissions from fuel production and combustion.

b. Assume best-case scenario where all e-fuels are produced using renewable electricity, and carbon for e-methanol and e-methane production is obtained through direct air capture.

c. Lower and upper bound data represent emissions from Diesel cycle and Otto cycle engines respectively.

d. Not including air emissions from the use of pilot fuel, which are proportional to the amount of pilot fuel used.

e. Engine out PM emissions vary depending on the engine combustion technology used (Maritime Knowledge Center et al., 2018; Fridell et al., 2021).

f. NO_x emissions without adopting NO_x control measures to maximize efficiency (Ellis, 2020); NO_x emissions lower than that of conventional fuel due to the colder methanol flame (RINA, 2020).

g. By adopting NO_x control technologies, combustion can be optimized to maximize energy efficiency and PM control, in which case NO_x emissions are similar to the levels of conventional fuels. NO_x control technologies include selective catalytic reduction, exhaust gas recirculation; for methanol engines, adding water to the combustion process can also be used. Lower bound data represent emissions without using NO_x control technologies.

h. The cost ratio is defined as the levelized cost of producing e-fuels relative to the price of MGO sold in Rotterdam as of November 24, 2020 (https://shipandbunker.com/prices).

4. Implications for China

4.1 Pathways for developing and applying low/zero-emission shipping fuels to decarbonize shipping is becoming clear

The latest Intergovernmental Panel on Climate Change (IPCC) Working Group I report: Climate Change 2021: The Physical Science Basis delivered a stark warning that limiting global warming to 1.5°C, compared to pre-industrial levels, cannot be possible without at least net-zero CO_2 emissions globally by 2050 and concurrent deep reductions in emissions of non-CO_2 GHGs (IPCC, 2021). With shipping being the backbone of global trade, and emitting 3% of global emissions, it would be impossible to fully decarbonize the global economy by 2050 without the shipping industry doing the same.

Recognizing that IMO's initial climate strategies have fallen far short of alignment with the 1.5°C goal (Comer, 2021b; Smith et al., 2021), many nations and industry leaders have already stepped up and announced a series of actions and commitments that support shipping's transition to zero-emissions in line with the Paris Agreement (see Box 1).

Box 1. Actions and Commitments Announced to Support the Shipping Industry's Zero-Emission Transition by 2050[32]

(1) Fourteen countries launched the Declaration on Zero-Emission Shipping by 2050, in which they pledged to work at the IMO to double its climate ambition to zero emissions by 2050.

(2) Fifty-five developing country members of the Climate Vulnerable Forum called for accelerated IMO efforts to establish a mandatory GHG levy on international shipping to ensure IMO's measures fully align with a 1.5°C reduction pathway.

(3) Twenty-two nations pledged to establish clean sailing routes (Clydebank Declaration) between ports in their nations to demonstrate that shipping decarbonization is possible.

(4) Leading maritime freight customers, including Amazon, Unilever and Ikea, joined the Cargo Owners for Zero Emission Vessels (CoZEV) initiative, committing to only purchase ocean freight services powered by zero-carbon fuels by 2040.

(5) Cargo owners joining the First Movers Coalition initiative committed to shipping 10% of their cargo using zero-emission fuels by 2030, and ship owners and charterers partaking in this initiative committed to make 5% of their fuel use zero-emission by 2030.

(6) Six of the world's leading marine insurers launched the Poseidon Principles for Marine Insurance initiative to provide a framework to quantitatively assess and disclose the climate alignment of marine insurers' underwriting portfolios.

These announcements show a growing consensus among governments and the private sector on the urgent need for climate action, and their willingness to collaborate to create regulatory certainty and market demand and provide green finance and insurance protection to incentivize deployment of the climate-friendly fuels and propulsion technologies discussed in Sec. 3.

32 See news reports at https://www.reuters.com/business/sustainable-business/denmark-us-12-other-nations-back-tougher-climate-goal-shipping-2021-11-01/; https://www.seatrade-maritime.com/regulation/ics-sets-out-plan-deliver-net-zero-shipping-2050; https://www.offshore-energy.biz/intertanko-backs-shippings-net-zero-emissions-path-by-2050/; https://thecvf.org/our-voice/statements/dhaka-glasgow-declaration-of-the-cvf/; https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors; https://www.aspeninstitute.org/news/press-release/first-movers-coalition-2030-commitments/; https://www.aspeninstitute.org/news/press-release/first-movers-coalition-2030-commitments/; https://www.poseidonprinciples.org/insurance/; https://www.globalmaritimeforum.org/news/cop26-will-summits-ambitions-for-shipping-translate-to-progress-at-imo

As shipping companies and major maritime nations consider investing in future fuel and propulsion solutions, impressive progress has been made in developing low/zero-emission propulsion technologies that show promise as solutions.

For inland waterway and short-distance coastal shipping, battery-electric propulsion has emerged as the most promising of the emission-free technologies. For coastal vessels that are not serving fixed routes or require power and capacity beyond what batteries alone can offer, the hydrogen-fuel cell is a promising propulsion solution that can potentially create zero air and GHG emissions. With strong government support, most notably in Norway, Japan, and South Korea, electric propulsion and marine fuel cell maritime systems are developing quickly. Commercial fuel cell propulsion models are expected to be ready by 2023.[33]

For deep sea shipping, ammonia and methanol have emerged as the most promising GHG-free fuel solutions over the next decade given their higher energy density, and relative ease of storage and handling (not requiring cryogenic storage). With methanol-powered engines already on the market and a set of interim guidelines adopted by the IMO to ensure safe use of methanol as a marine fuel, shipowners have ordered a new fleet of methanol-powered vessels to be operational by around 2024. On ammonia, all of the world's major marine engine manufacturers are actively developing ammonia-fueled engines with the first prototype ready by 2023. At least ten new ammonia-ready vessels will be launched between 2023 and 2025. In the longer-term, feasibility studies have shown that hydrogen-fueled ships could also be a solution for deep-sea shipping if bunkering infrastructure along heavily trafficked routes can be strategically planned and developed.

4.2 Pilot projects and research undertaken by shipbuilders and engine makers in China have laid the foundation for developing low/zero-emission solutions

Given that more and more shipping customers and charterers are demanding zero-emissions freight services and a growing number of countries are pushing forward with shipping decarbonization, it is in the interest of China, as a major maritime and shipbuilding nation, to be part of that transition.

33 See Norway's Action Plan for Green Shipping (https://www.regjeringen.no/en/dokumenter/the-governments-action-plan-for-green-shipping/id2660877/), South Korea's 2030 Green Ship-K Initiative (https://www.maritime-executive.com/article/south-korea-to-invest-870-million-developing-eco-friendly-shipping), Japan's Roadmap To Zero Emission from International Shipping (https://www.mlit.go.jp/en/maritime/GHG_roadmap_en.html) and announcement by Japan's Yanmar Power Technology (https://www.maritime-executive.com/article/first-high-pressure-hydrogen-fueling-demonstrated-in-japan).

The good news is, national and local governments, and the shipbuilding industry and equipment manufacturers in China have already initiated a number of pilot projects to test the viability of low/zero-emission marine solutions and are starting to build the capacity to deliver these solutions.

For inland and coastal shipping, there were over 50 pure electric vessels in operation or on order in China by the summer of 2020, mainly operating along the Yangtze River and Pearl River. In 2021, three hydrogen-fuel cell demonstration vessels were sea-trialed in the cities of Dalian in Liaoning province and Foshan in Guangdong province.[34] The China Classification Society has also granted type approval to two sets of marine fuel cell systems (70kW and 50-80kW), with one set going to be tested on a purpose-built 2,100 DWT (dead weight tonne) bulk carrier.[35]

Chinese shipbuilders and engine makers are also making strides in developing propulsion systems and vessels that could be powered by methanol or ammonia (Tables 3 and 4). The latest development is the new Global Test Center established by China Shipbuilding Power Engineering Institute and engine maker WinGD, which will conduct research on advanced fuel propulsion, including ammonia and methanol. Separately, the China Classification Society is partnering with Maersk to undertake research on carbon-neutral technologies and standards.[36]

These research and development efforts are critical for testing and evaluating new solutions and paving the way for wider deployment of these solutions in China and abroad. In the coming five years, the Ministry of Transport plans to actively explore the use of hydrogen, ammonia, methanol, and hybrid electric propulsion for powering ships.[37] The Medium- and Long-term Plan for the Development of China's Hydrogen Energy Industry, released in March 2022, also calls for actively exploring the use of hydrogen fuel cells for maritime applications in the next five years.[38] These are important initiatives that will enable the nation to achieve the 2060 carbon neutrality target while strengthening its position as the world's leading shipbuilding nation.

34 See Rui (2020), and news report: https://www.163.com/dy/article/G05IFQFD05509P99.html; https://h2.in-en.com/html/h2-2409258.shtml; https://www.chinaautoms.com/a/new/2021/1110/20153.html; https://news.sciencenet.cn/htmlnews/2021/11/468801.shtm.

35 See news report: https://www.offshore-energy.biz/ccs-awards-chinas-1st-hydrogen-fuel-cell-type-approval/; http://wap.eworldship.com/index.php/eworldship/news/article?id=174932.

36 WinGD. 2021. WinGD expands engine technology investment with Global Test Centre. December 17. https://www.wingd.com/en/news-media/press-releases/wingd-expands-engine-technology-investment-with-global-test-centre/; Maersk. 2021. Maersk partners with China Classification Society on carbon-neutral technologies and standards. September 27. https://www.maersk.com/news/articles/2021/09/27/maersk-partners-with-china-classification-society.

37 China Ministry of Transport. 2021. 14th Five-Year Green Transport Development Plan. http://www.gov.cn/zhengce/zhengceku/2022-01/21/content_5669662.htm.

38 National Reform and Development Commission and National Energy Administration. 2022. Medium- and Long-Term Plan for the Development of China's Hydrogen Energy Industry. https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html.

4.3 Targeted policies needed to secure sufficient supply of low/zero-emission marine fuel

One of the greatest obstacles for widespread use of low/zero-emission propulsion technologies and realizing meaningful GHG benefits, is securing sufficient supplies of truly low/zero-emission fuels.

To achieve China's carbon-peaking and neutrality goals, the government has already set clear targets to boost renewable electricity generation, aiming to increase the total installed capacity of wind and solar power to over 1,200 GW by 2030 (or tripling the current installed capacity) (State Council, 2021). At the same time, regional governments and state-owned energy enterprises are also increasing investment in key technologies that support the production, storage, and transport of hydrogen, as it is key to decarbonizing the refining and industrial sectors, such as steel, cement and chemical production (IEA, 2021a).[39] However, the renewable energy capacity targets were primarily set for meeting the grid electricity demand, and the hydrogen initiatives are currently planned for decarbonizing the industrial and on-road transport sectors. No plan has yet been announced to develop renewable hydrogen, ammonia, or methanol fuel supply for the shipping sector.

For the shipping industry, growing customer demand for zero-emission shipping is driving increasing deployment of low/zero-emission propulsion technologies. This will create a potentially vast export market of core technologies (e.g., electrolyzers) to produce and deliver renewable hydrogen and hydrogen-derived fuels. China could consider adopting targeted policies to boost the supply of low/zero emission marine fuel. Such policies not only could spur the growth of the industry associated with the supply, transport and storage of renewable hydrogen and hydrogen-derived fuels, and secure market opportunities for Chinese companies in the domestic and international market. They could also avoid China's shipping sector relying on overseas production or even imports of low/zero-emission marine fuels in the future.

39 See for example a news report about the ambition of China's largest refiner to expand hydrogen fuel production: https://www.scmp.com/news/china/science/article/3158005/chinas-sinopec-banks-green-hydrogen-xinjiang-solar-powered-plant

4.4 Higher cost of alternative fuels presents a major challenge, but maximizing energy efficiency can lower the transition barrier

No matter which low/zero-emission marine fuel ultimately becomes widely used, costs of these fuels are expected to be higher than that of conventional fuels in the near term. The lower energy density of new fuels also would present a challenge, especially for existing vessels, as more space for fuel tanks would be needed. Disparity in costs and extra fuel storage space requirements present a significant challenge for transitioning to low/zero-emission fuels and may put early adaptors in a disadvantaged position.

A no-regret solution to partly address the cost-disparity challenge is to maximize the fuel efficiency of both existing and new fleets, which would reduce fuel consumption, CO_2 emissions, and air pollution. Technologies for improving fuel efficiency already exist, and some have demonstrated cost effectiveness even for retrofitted vessels, such as technologies that harness wind power (e.g., rotor sails), reduce hydrodynamics (e.g., hull air lubrication), or hybrid electric propulsion systems. While the IMO has introduced efficiency improvement requirements (EEDI, EEXI and CII, as discussed in Sec. 1), they are considered too lenient to stimulate the adoption of fuel-efficiency technologies (Smith et al., 2021). China could consider introducing policies to drive more widespread deployment of efficiency-improvement technologies on domestic and international vessel fleets that achieve the dual goal of lowering the barrier for transitioning to low/zero-emission fuels, and directly reducing carbon and air pollution.

4.5 Development of alternative marine fuels should take a holistic view and investment should target fuels that deliver long-term development benefits

Investment and development plans for alternative marine fuels should take a holistic view, taking into account multiple factors, including well-to-wake GHG emissions and energy dependency, with a long-term goal to stimulate production of non-fossil, non-polluting and domestically produced fuels. Some industry stakeholders embrace LNG propulsion as a transition solution because natural gas and the propulsion technology is commercially available, can deliver some CO_2 reduction benefits, and possibly allow for switching to low/zero-emission bio-methane or e-methane when these fuels become available in the future. [40] However, as discussed earlier, studies that surveyed the latest literature suggested that natural gas can at best emit only 9% less GHGs than MGO using a 20-year GWP, and 15% less using a 100-year GWP based on current LNG engine technologies (see Figure 6; Lindstad et al., 2020).

With methane being the second biggest contributor to the climate crisis, engine designers and manufacturers are looking for ways to reduce methane slip and some oil and gas companies have voluntarily committed to reduce upstream methane leakage. [41] However, with no regulations in effect in China, nor under the IMO framework, to control engine methane emissions or well-to-wake GHG emissions from shipping, there is no clear incentive to drive the use of less leaky LNG engine technologies. Consequently, evaluation of the climate benefits of continued investment in LNG-powered ships and fuel infrastructure should best be assessed based on well-to-wake GHG emissions.

As aforementioned, the World Bank and some shipping companies have raised serious concerns over the long-term prospects of LNG. The limited supply and related lack of competitive pricing of sustainably sourced bio-methane calls into question the viability for LNG-fueled ships and infrastructure to transition to renewably produced bio-methane. While LNG engines could run on liquefied e-methane, e-methane is much more costly to produce relative to other low/zero-carbon alternatives like renewable ammonia and hydrogen (World Bank, 2021). Amid concerns

40 See news report: https://cmacgm-group.com/en/launching-cmacgm-jacques-saad%C3%A9-world%27s-first-ultra-large-vessel-powered-by-lng.

41 See for example WinGD's iCER technology (https://www.alfalaval.com/media/news/2020/new-alfa-laval-purecool-developed-with-engine-designer-wingd-enables-up-to-50-methane-slip-reduction/), and the Methane Guidance Principle initiative (https://methaneguidingprinciples.org).

over the long-term sustainability of natural gas, OPEC's World Oil Outlook reported that some orders of LNG-fueled vessels were cancelled in 2021.[42] In September of 2021, Hapag-Lloyd also shelved its plan to retrofit 16 more in-service vessels to sail on LNG after it retrofitted one vessel with a LNG dual-fuel system, noting the unexpectedly high cost of the retrofits—US$35 million—as the reason to change its plan.[43] Therefore the World Bank recommended developing countries with rich renewable resources and located near busy shipping lanes should seize the business and development opportunities in shipping's energy transition. To meet the anticipated growing demand for low/zero-emission marine fuels, these countries should accelerate investment in the production of renewable hydrogen-based fuels, which in turn could reduce their reliance on imported fossil fuels (World Bank, 2021).

From a well-to-wake perspective, GHG reduction benefits of natural gas remain uncertain and using LNG as a marine fuel may further dependence on fossil natural gas. Owing to these concerns the international community is starting to shift their focus towards reducing further investment in LNG-powered vessels and bunkering infrastructure. In the long-term countries would be better off to target investment in domestically produced, non-fossil, non-polluting fuels, such as renewable hydrogen and ammonia, to support shipping decarbonization.

42 OPEC. 2021. 2021 World Oil Outlook 2045. https://www.opec.org/opec_web/en/publications/340.htm.

43 Thomsen, Jens. 2021. Hapag-Lloyd scraps further LNG retrofitting of vessels: More expensive than expected. ShippingWatch. October 1. https://shippingwatch.com/carriers/Container/article13330724.ece.

5. Recommendations

A successful transition to GHG-free shipping requires zero-emission vessels; zero-emission fuels; fuel storage and bunkering infrastructure; and the demand for zero-emission shipping services. China is one of a very few countries in the world with a leading shipbuilding sector, a high potential for generating renewable energy, and is an important global hub of shipping activities with many of the world's busiest ports. The vast scale of shipping activities and the presence of industry leaders along the entire shipping value chain place China in an advantageous position to be able to:

(1) develop emissions-free vessels and their key components (e.g., fuel cells, batteries and alternative fuel engines),

(2) ramp up research and development of technologies for producing low/zero-emission marine fuels, expand fuel production capacity,

(3) establish port infrastructure for supplying low/zero-emission fuels.

The country stands to benefit from spearheading such a transition. First, doing so could contribute to achieving China's carbon peaking and neutrality targets and ecological civilization goal. Second, there is a compelling case for strengthening the competitive position of the nation's shipbuilders, shipyards, and ship and marine equipment manufacturers.

For global shipping to reach zero-emissions by 2050, the sector would inevitably require large number of zero-emission new build ships as well as a massive retrofitting of existing vessels for zero-emission fuels in the 2030s (Smith et al., 2021). China's large domestic shipping market can serve as a test bed for core technologies for use in new low/zero-emission vessels or retrofitting existing ones. Through learning from doing, local shipyards and companies along the zero-emission shipping value chain can develop the capability and capacity to achieve cost-reduction and be in a competitive position to export their services and products to the international market. On the fuel side, with the expectation of a growing demand for zero-emission marine fuels, China could also benefit from investing in developing the capacity to manufacture equipment for producing, storing, and bunkering zero-emission fuels that not only could serve the domestic market but also the global market.

To achieve these goals, China would need to further scale up support for R&D and demonstration projects and impose regulations that will drive the development and catalyze early adoption of low/zero-emission solutions. At the same time, local regulatory agencies would need to work closely with the classification societies to develop operational practices and standards that ensure safe and reliable use of new low/zero-emission fuels.

Below are some specific policy recommendations for consideration.

5.1 Adopt GHG and energy efficiency regulations for the domestic shipping fleet

Regulatory certainty will spur investment in the research, development, and deployment (RD&D) of alternative fuel and propulsion systems, and energy efficiency technologies. While incentives are essential for supporting first-movers' efforts to showcase viability, mandatory regulations are imperative to foster widespread uptake of these solutions.

(1) ***Add GHG-related requirements to marine engine standards***
Regulators can consider adding GHG emissions requirements (including methane and CO_2) when updating air emissions standards for domestic marine engines which will be applicable to new domestic vessels. Including GHG-related emission limits in the marine engine standards, which took effect in 2020, could push the development of low/zero-emission fuels and propulsion systems that ensure co-control of GHG and air emissions.

(2) ***Set energy efficiency requirements for new vessels and vessels in operation***
Efficiency improvement on their own could reduce the rate of climate and air pollution of each vessel and could also lower the transition barrier to adopting low/zero-emission fuels. China has a large fleet of in-service vessels (over 115,000 river vessels and 10,000 coastal vessels). Setting energy efficiency standards for new and existing domestic vessels could help mainstream energy efficiency technologies, which would in turn create the scale needed to drive down the cost of these technologies. The new and in-service vessel efficiency requirements adopted by the IMO for international vessels—EEDI, EEXI and CII—are useful reference for developing efficiency requirements for China's domestic vessels.

(3) ***Explore setting GHG-intensity standards for shipping fuels, based on well-to-wake GHG emissions***
Production of electricity, hydrogen, ammonia, and methanol in China still rely heavily on coal. How these fuels/energy carriers are produced does not change their chemical properties.

Hence hydrogen produced from fossil fuel is used the same way on ships as renewable hydrogen. The same is true for ammonia, methanol and electricity. To effectively differentiate low/zero-emission fuels and catalyze their uptake, it would be critical to develop a well-to-wake GHG-intensity certification scheme for marine fuels in tandem with introducing a carbon intensity limit for fuel used on board ships to drive the gradual uptake of low/zero-emission fuels. The proposed FuelEU Maritime regulation can serve as a reference for designing a GHG-intensity standard for marine fuels in China.

5.2 Support a number of pilot port regions to scale up demonstration projects for vessels powered by low/zero-GHG emission fuel

Demonstration projects are essential to validate the technical and commercial feasibility of technologies for producing low/zero-emission fuels and marine propulsion technologies that can run on such fuels. These projects also allow regulators to develop and shape standards and operational practices for supplying new fuels that ensure safe delivery, storage and bunkering, which would build public confidence for switching to these new fuels.

(1) ***Increase funding to scale up demonstration projects***

China has launched a number of pilot projects of battery electric and hydrogen fuel cell-powered vessels. These pilots highlighted the main challenges encountered, including high capital and operation costs, high costs of building bunkering/recharging infrastructure, and safety concerns during bunkering/recharging operations, etc. (Yang, 2020).

With climate now a high policy priority, and ozone and PM pollution remaining a major concern, it makes sense to scale up funding to support demonstration projects that focus on low/zero-emission fuels and technologies that can co-control air and climate pollutants. These projects should also engage key leaders along the value chain (shipbuilders, ports, fuel providers, and ship operators) to address economic, technical, and operational challenges, as well as safety concerns. As discussed earlier, in the near-term battery electric propulsion and hydrogen fuel cell systems would be most suited for domestic inland and coastal shipping, and ammonia- and methanol-powered systems are promising for oceangoing shipping, so it follows that the new projects could focus on these technologies.

(2) ***Provide funding to support the development of core technologies for producing and supplying low/zero-emission fuels, and test and perfect them through demonstration projects***

A lack of supply infrastructure for low/zero-emission fuels will be a major obstacle for expediting shipping's green transition. Investing in the development of core technologies for producing, transmitting, storing, and bunkering these new marine fuels, and testing them through pilot projects, is an effective way to build the know-how and capacity of Chinese component manufacturers. By participating in pilot projects, local manufacturers of those core technologies could become more competitive and be in a better position to serve the global market when demand for these fuels grow in the future.

In the past decade, policymakers in China have shown great success in supporting battery makers to become dominant global suppliers of electric vehicle (EV) batteries. That was accomplished by initiating pilot projects that allowed core technologies to be developed and refined, then moving to large scale deployment by incentivizing the use of new energy vehicles in the vast domestic market. This placed the manufacturers in a good position to reduce production cost through economies of scale. Similarly, government policies could support the development of electrolyzers and core components of the fuel supply chain. By initiating demonstration projects that enable equipment manufacturers to build the capacity through learning by doing, and then reducing production cost by scaling up to serve the domestic market, these manufacturers could become globally competitive. By doing so, Chinese manufacturers would be ready to help the global maritime world leapfrog from dirty fossil fuels to new clean technologies.

(3) ***Set a long-term, zero-emission target for selected segments of domestic vessels in the pilot regions***

Setting a long-term target provides regulatory certainty to R&D investment by engine and equipment makers through ensuring future demand for low/zero-emission technologies and fuels. Zero-emission targets could be set for vessel segments that are more ready to adopt new fuels, such as ferries, cruise ships, and cargo ships serving fixed routes. The pilot region governments could consider offering funding support to early movers—ship owners and ports that switch early to low/zero-emission technologies—for purchasing new ships and building bunkering infrastructure, and subsidizing poorer communities that are most impacted due to the mandate.

(4) ***Participate in bilateral and/or multilateral collaboration program for creating green shipping corridors (e.g. Clydebank Declaration)***

The international green shipping corridor programs offer a valuable opportunity for pilot port cities in China to collaborate with like-minded governments and industry leaders to jointly develop clean port infrastructure and fuel handling regulations and protocols, and devise incentive programs and requirements to mobilize demand for zero-emission shipping. Such collaboration would be particularly important for Chinese shipping technology providers to trial locally developed low/zero-emission technologies for use in international shipping. The Shanghai-Los Angeles Green Shipping Corridor Partnership sets an excellent example that more ports in China can follow.

5.3 Ensure that shipping becomes an integral part of China's actions to transition to a carbon-neutral economy

Renewable hydrogen is widely recognized as a core part of the strategy to decarbonize multiple sectors, including refining, ammonia and methanol synthesis, steel production, and shipping. In China, major state-owned enterprises, including Sinopec, Ningxia Baofeng Energy Group, and Baowu Steel Group, are starting to build renewable hydrogen production plants, and investing in the RD&D of hydrogen storage and transmission infrastructure.[44] These projects could help scale up production and increase the supply of renewable hydrogen in China's industrial clusters, which are often located near major ports. To enable the shipping demonstration projects to tap into these new supplies of renewable hydrogen, ammonia, and methanol, it would be key to ensure that national and regional governments coordinate the shipping demonstration projects with other industry efforts.

44 See news report: https://www.scmp.com/news/china/science/article/3158005/chinas-sinopec-banks-green-hydrogen-xinjiang-solar-powered-plant; https://jpt.spe.org/inner-mongolia-greenlights-chinas-biggest-hydrogen-deal-yet; https://www.bloomberg.com/news/articles/2021-08-18/china-approves-renewable-mega-project-focused-on-green-hydrogen.

6. Concluding Remarks

There is an emerging consensus among public and private actors that shipping should fully decarbonize by 2050 to align with the 1.5°C Paris Agreement goal. To catalyze the uptake of low/zero-emission marine fuels and technologies, many large shipping customers and charterers have committed to a minimum zero-carbon fuel usage. Major shipping financiers and insurers have also promised to incorporate alignment with IMO decarbonization goals in their portfolio assessments. Cities are exploring how to establish green shipping corridors that enable zero-emission ships to serve major maritime routes, including a partnership between Shanghai, Los Angeles, and industry leaders to create a green corridor within this decade.

While it remains uncertain which zero-emission fuel(s) will dominate in the future, the picture has become clearer when assessing the long-term GHG reduction potential, cost-effectiveness and scalability of each potential fuel. Electricity and hydrogen fuel cells have been demonstrated to be technically feasible and scalable as potential zero-emission fuel solutions for river and coastal ships. They are also more energy efficient from a system-wide perspective. For deep-sea shipping, ammonia and methanol stand out as the most promising low/zero-emission solutions within this decade, while hydrogen could be a long-term promising solution with strategic planning for bunkering infrastructure. Even though natural gas is still embraced by some industry stakeholders, there are growing energy security concerns and increasing doubts about its GHG reduction benefits.

China can be an important contributor to expedite the green transition of the shipping sector given its vast shipping fleet, world-leading shipbuilders and engine makers, and expansive network of big ports. The country also stands to benefit from facilitating such a transition as it means reducing air and climate pollution from ships and port activities. By introducing policies to stimulate energy efficiency improvements and encouraging research, development and the uptake of low/zero-emission fuels and technologies, China could boost the technical capacity and sharpen the competitive edge of its shipbuilders, equipment makers, and port operators. These actors would be essential for enabling the production of affordable and accessible climate-friendly fuels and technologies that are key for decarbonizing shipping around the world.

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