



CHARTING A COURSE FOR DECARBONIZING MARITIME TRANSPORT





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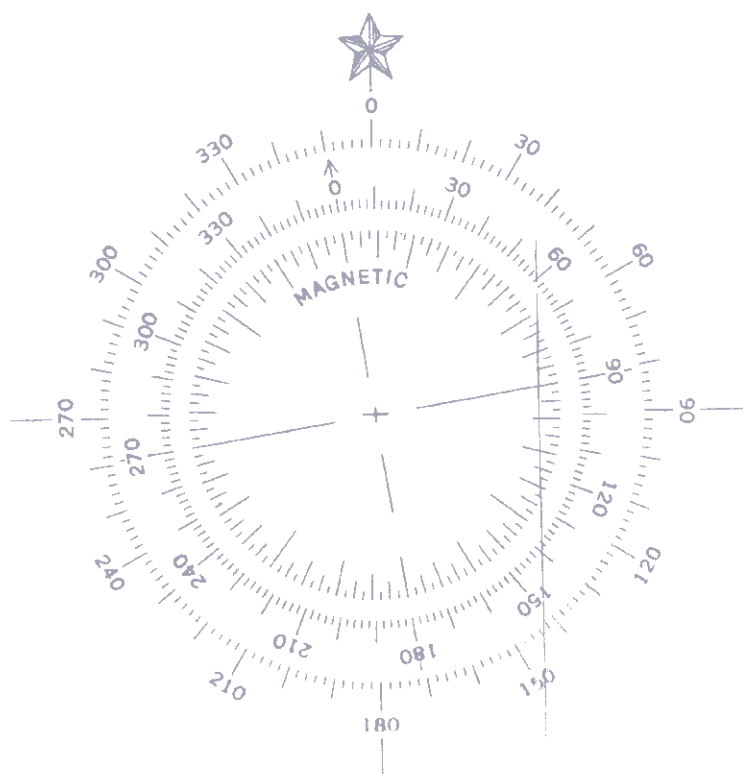
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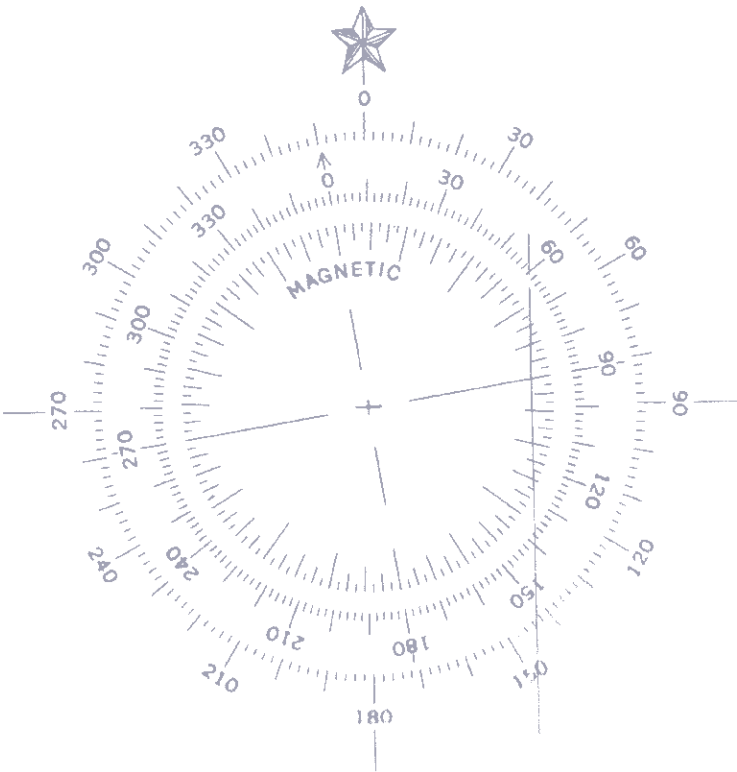
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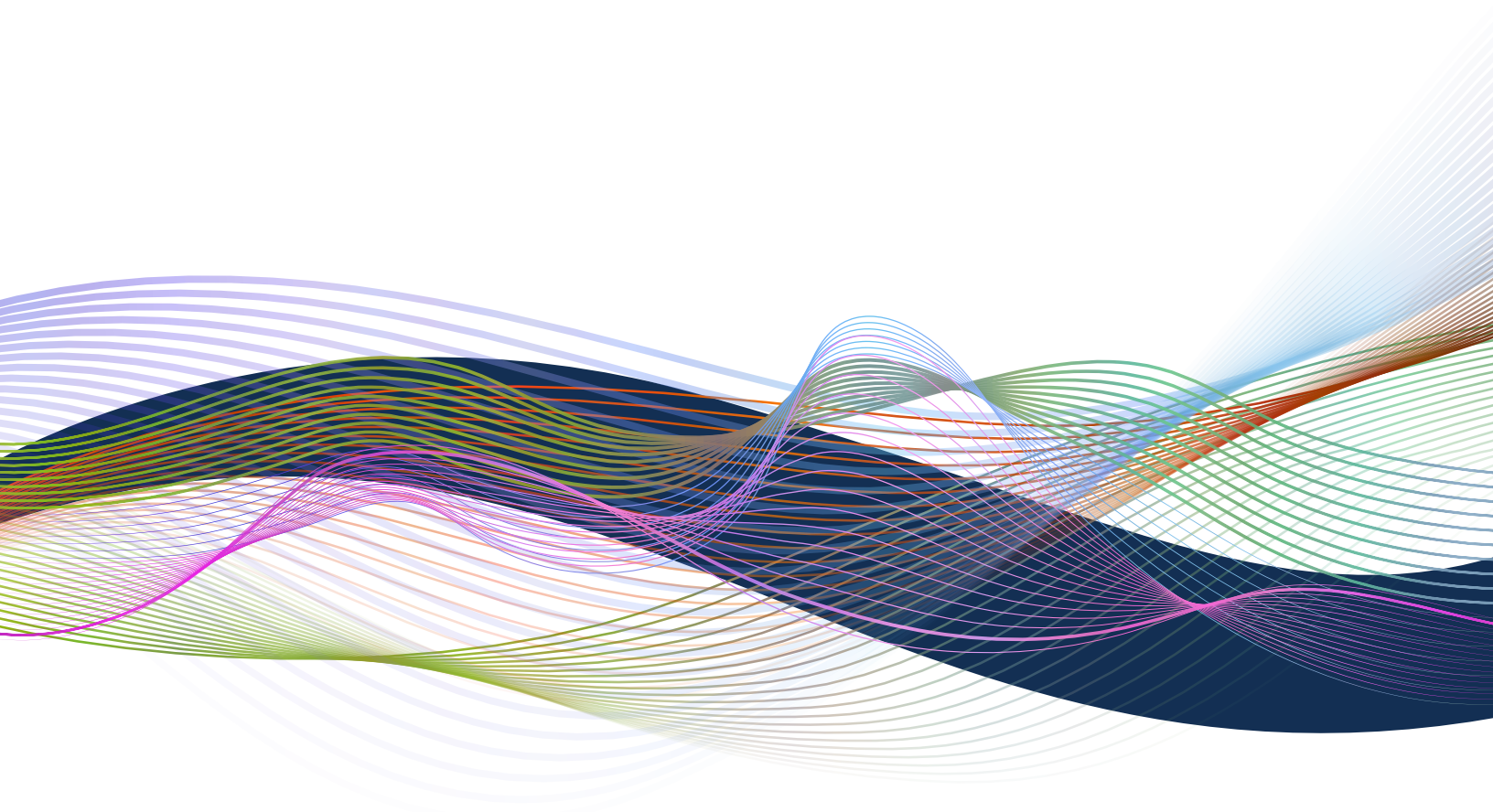
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PREAMBLE

The World Bank has undertaken analytical work on the prospects of decarbonizing maritime transport. This Summary for Policymakers and Industry summarizes this research, as it is presented in the two accompanying and interlinked technical reports—*Volume 1: The Potential of Zero-Carbon Bunker Fuels in Developing Countries*¹ and *Volume 2: The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping*²—which should be read in accompaniment.



1 Englert, Dominik; Losos, Andrew; Raucci, Carlo; Smith, Tristan. 2021. Volume 1: The Potential of Zero-Carbon Bunker Fuels in Developing Countries. World Bank, Washington, DC. © World Bank. <https://openknowledge.worldbank.org/handle/10986/35435> License: CC BY 3.0 IGO.

2 Englert, Dominik; Losos, Andrew; Raucci, Carlo; Smith, Tristan. 2021. Volume 2: The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping. World Bank, Washington, DC. © World Bank. <https://openknowledge.worldbank.org/handle/10986/35437> License: CC BY 3.0 IGO.





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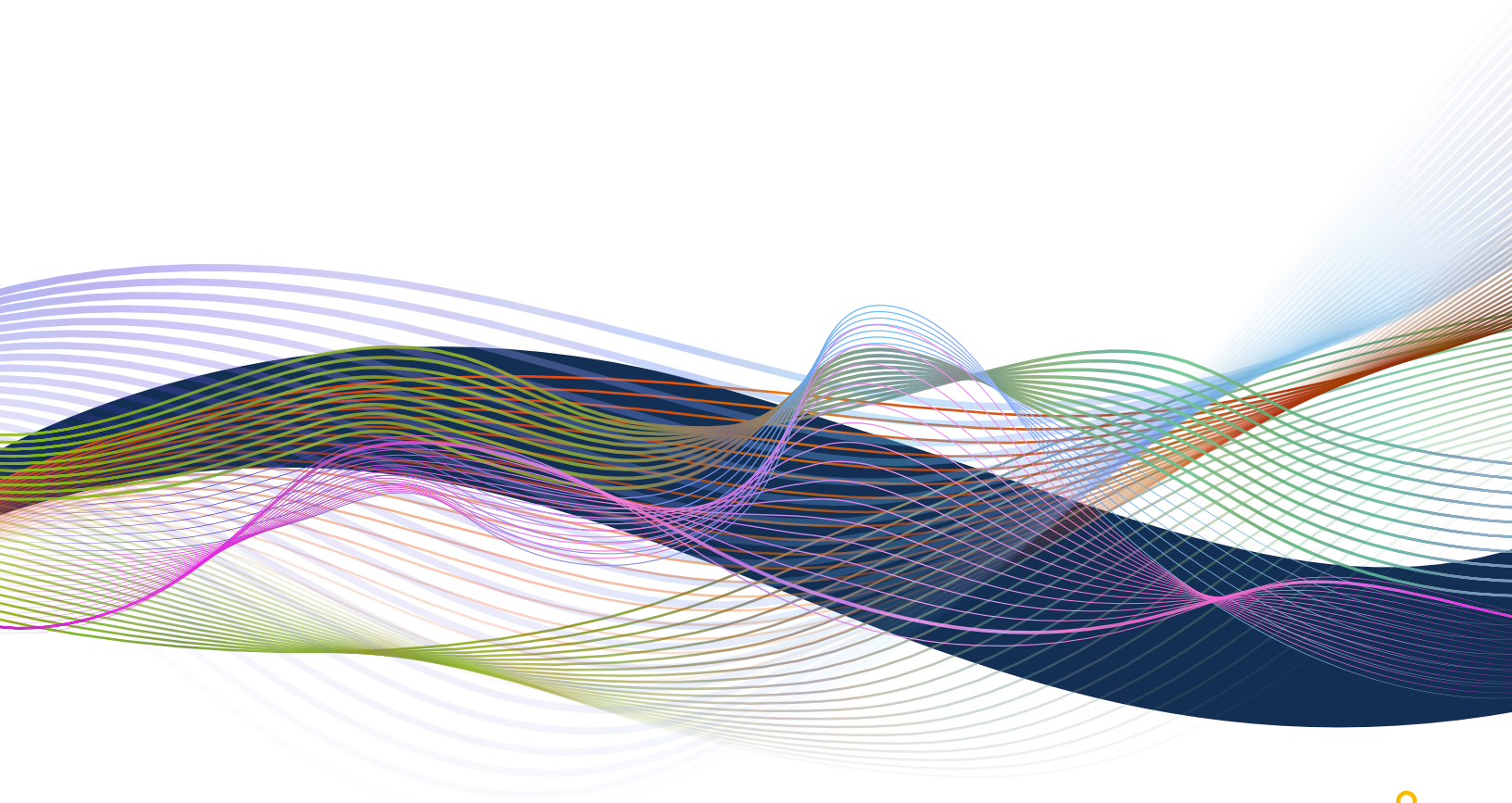
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ABBREVIATIONS

ACRONYM	DEFINITION
CCS	Carbon capture and storage
CO₂	Carbon dioxide
GHG	Greenhouse gas
HFO	Heavy fuel oil
IMO	International Maritime Organization
LBM	Liquefied biomethane
LNG	Liquefied natural gas
LSHFO	Low Sulfur Heavy Fuel Oil
LSM	Liquefied synthetic methane
NO_x	Nitrogen oxide
PM	Particulate matter
RD&D	Research, development and deployment
SO_x	Sulfur oxide
\$	United States dollar





1. INTERNATIONAL SHIPPING: A KEY ENABLER FOR TRADE AND DEVELOPMENT, AND A MAJOR SOURCE OF EMISSIONS

Global maritime transport plays a crucial role in both facilitating trade and fostering economic development at an international scale. Carrying an estimated 70 percent of global trade by value and 80 percent by volume, maritime transport is an essential component of the global transportation network that underpins the daily functions of the world economy.³ In this context, international shipping is often seen as a critical enabler of developing countries' economic advancement, as approximately 60 percent of goods transported internationally by sea are loaded or unloaded in developing countries.⁴ Also, 15 out of the 20 busiest ports globally, by volume, are located in these countries.⁵ In particular, many small island developing states and least developed countries are highly dependent on low-cost international maritime transport for the supply of essential goods such as food, clothing, construction material, or pharmaceuticals.

In recent years, maritime transport has come under increased pressure to lower, and ultimately eliminate, its negative environmental impacts, especially with regard to climate change and air pollution. Today, the sector faces a plethora of challenges, ranging from adapting to the global pandemic, navigating a global economic crisis and geopolitical tensions, to the need for increased digitalization.⁶

3 UNCTAD (2018)
4 UNCTAD (2019)
5 UNCTAD (2019)
6 Global Maritime Forum (2020a)





However, the most pressing existential issue that the sector experiences is the need to eliminate its negative environmental impacts, especially with regard to atmospheric pollution. These environmental impacts have placed maritime transport under increased public scrutiny. The sector has faced increased pressure to rapidly reduce its significant contribution to climate change and to urgently lower its high levels of air pollution.

Maritime transport accounts for about three percent of global greenhouse gas (GHG) emissions, and emits around 15 percent of some of the world's major air pollutants annually. Today, shipping's GHG emissions account for an estimated 2.89 percent of global anthropogenic GHG emissions—equivalent to the sixth-largest GHG emitting country worldwide⁷—and are expected to rise further without any policy intervention. Over a mere six years from 2013-2018, the sector's total GHG emissions (including international and domestic shipping) grew by nearly 10 percent in real terms.⁸ Without decisive action, these GHG emissions are projected to continue to grow from 90 percent of 2008 emissions in 2018 to an estimated range of 90 to 130 percent of 2008 emissions by 2050.⁹ In terms of air pollution, shipping emits 15 percent and 13 percent of all global sulfur oxides (SO_x) and nitrogen oxides (NO_x), respectively.¹⁰ These emissions, combined with a number of other air pollutants, such as particulate matter, have led shipping to be held responsible for an estimated 15 percent of global premature deaths from air pollution—or 60,000 premature deaths in absolute numbers—in 2015.¹¹

The resulting imperative for the shipping sector to decarbonize and improve air quality represents a major challenge that can be turned into unique development and business opportunities. Reducing emissions—both GHG emissions and air pollutants—from shipping is a political, technological, and financial challenge. Ideally, this challenge should be tackled through collective action on a global scale. While representing a major challenge, these efforts to address emissions from ships are also likely to offer unique opportunities in terms of economic development and infrastructure modernization. Specifically, some developing countries are expected to be able to harness vast domestic energy resources and benefit from the unfolding business opportunities to produce zero-carbon bunker fuels, while simultaneously modernizing their energy and maritime infrastructure.

The Initial International Maritime Organization's (IMO) GHG Strategy aims to reduce absolute GHG emissions by at least 50 percent by 2050. To date, international shipping has not been explicitly included in existing multilateral agreements on climate change mitigation such as the United Nations Framework Convention on Climate Change's Paris Agreement of 2015. Nonetheless, to counter the expected growth of GHG emissions under a business-as-usual scenario, the IMO, a specialized agency of the United Nations responsible for regulating international shipping, adopted the Initial Strategy on the Reduction of GHG Emissions from Ships—known as the Initial IMO GHG Strategy—in April 2018. This action has sent a strong signal to all maritime stakeholders that GHG emissions need to be curbed

7 IMO (2020), World Economic Forum (2018)

8 IMO (2020)

9 IMO (2020)

10 IMO (2014)

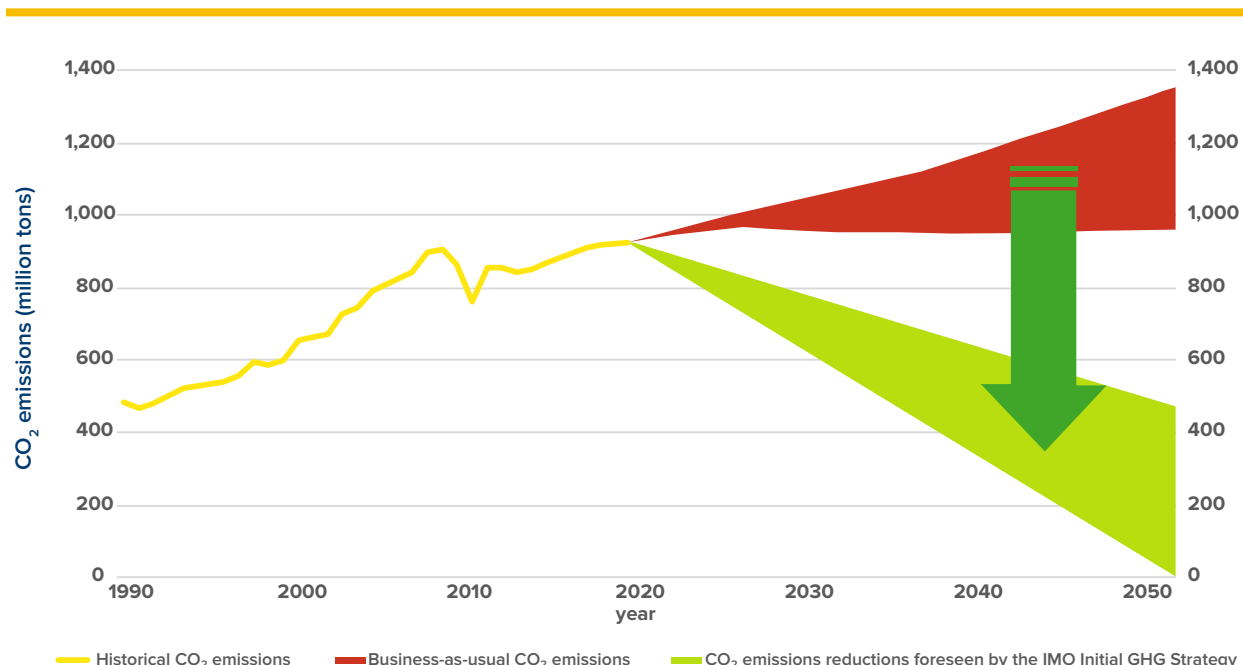
11 ICCT (2019)





immediately and permanently.¹² The Initial IMO GHG Strategy outlines ambitions to reduce international shipping's absolute GHG emissions by at least 50 percent by 2050 compared to 2008 levels, with the aim of pursuing efforts to fully phase out GHG emissions, consistent with the Paris Agreement's temperature goals, as quickly as possible within this century.¹³ Figure 1 illustrates the business-as-usual GHG emissions growth against the shipping sector's GHG emissions reduction commitments.

FIGURE 1: HISTORICAL AND PROJECTED CO₂ EMISSIONS FROM INTERNATIONAL SHIPPING



Source: IMO (2020), IMO (2018b)

To date, from an energy perspective maritime transport is almost entirely dependent on fossil fuels, mainly heavy fuel oil (HFO). Today, the dominant shipping or “bunker” fuel is fuel oil, which includes both HFO, used in combination with exhaust treatment technologies, and a variant generically known as Low Sulfur Heavy Fuel Oil (LSHFO). HFO is a high-carbon, high-sulfur, and highly viscous residual fuel that resembles “tar” until heated, and currently accounts for more than 79 percent of the sector’s energy mix.¹⁴ The remaining 21 percent of the sector’s energy mix is composed of other fossil fuels, such as marine diesel oil and liquefied natural gas (LNG), but does not yet include a significant share of zero-carbon bunker fuels.¹⁵

To achieve the required GHG emissions reductions, an energy transition from fossil to zero-carbon bunker fuels will be needed in shipping. There is a general consensus within the shipping sector that energy efficiency gains alone

¹² IMO (2018a)

¹³ IMO (2018b)

¹⁴ IMO (2020)

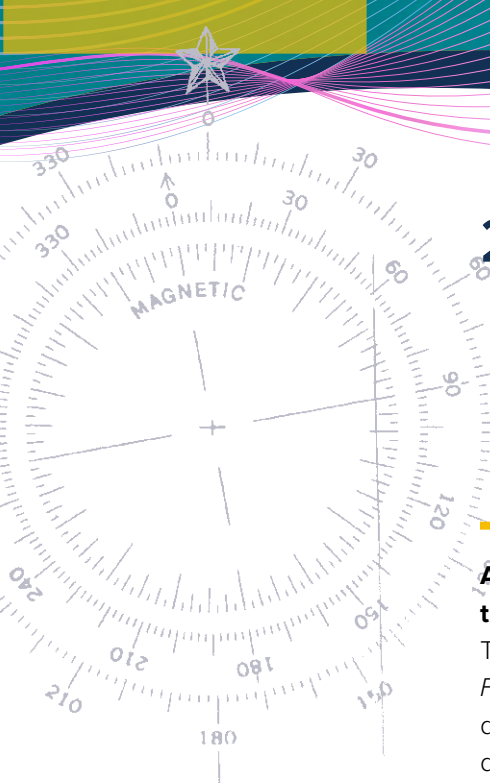
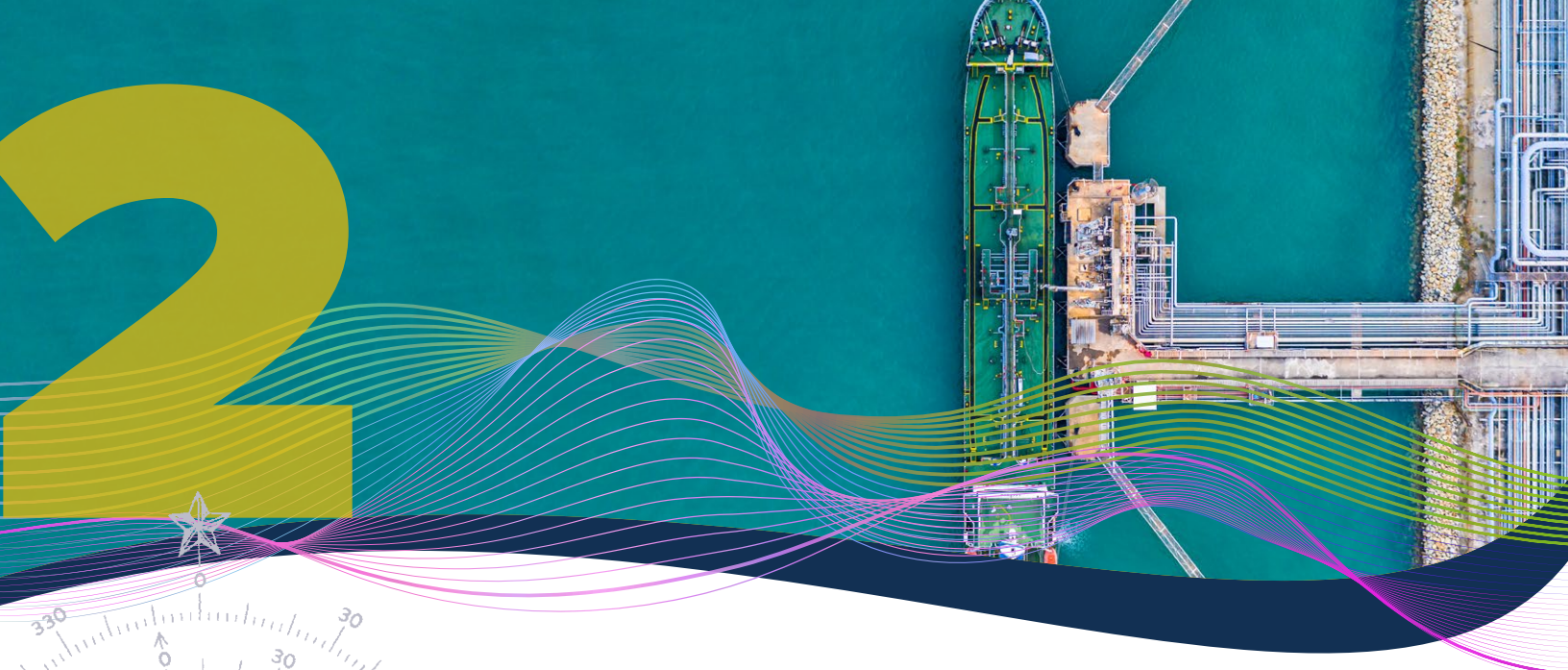
¹⁵ Lloyd’s Register and UMAS (2017)



will be insufficient to achieve the GHG emissions reductions required by the Initial IMO GHG Strategy, given the sector's sole reliance on fossil fuels combined with the expectations of continued sector growth. Consequently, new zero-carbon bunker fuels will be needed which include, for instance, biofuels, hydrogen and ammonia, or synthetic carbon-based fuels. In this context, zero-carbon bunker fuels encompass bunker fuels which—in terms of GHG emissions—are “effectively” zero (that is where the fuel is produced from non-biogenic renewable electricity) or “net-zero” (that is where the production of the fuel removes a quantity of carbon dioxide from the atmosphere equivalent to that emitted during combustion). These fuels are to power a new generation of vessels, consisting of newbuilds and retrofits, operating with zero-carbon propulsion technologies—either modified internal combustion engines or fuel cells. With the cost-effective use of existing technology on board, zero-carbon bunker fuels and propulsion technologies can address both GHG emissions and air pollutants by means of a single solution.

Zero-carbon bunker fuels are estimated to enter the global fleet and scale rapidly from 2030 to achieve the IMO's 2050 climate target. It is assumed that zero-carbon bunker fuels will need to represent at least five percent of the bunker fuel mix by 2030 to put shipping on a GHG trajectory which is consistent with the Initial IMO GHG Strategy, and the Paris Agreement's temperature goals.¹⁶ As they are not currently used for shipping in any significant quantities, zero-carbon bunker fuels must be scaled up rapidly to achieve substantial absolute GHG emissions reductions. Despite the understanding that zero-carbon bunker fuels and vessels equipped to use them need to be brought up to scale urgently within the current decade, their targeted development and deployment have only recently become part of the industry's discussions.





2. THE PROSPECTS OF ZERO-CARBON BUNKER FUELS FOR DECARBONIZING SHIPPING

A representative selection of zero-carbon bunker fuels was assessed to identify the most promising candidate fuels for shipping's decarbonization currently.

This initial high-level assessment in *Volume 1: The Potential of Zero-Carbon Bunker Fuels in Developing Countries* (see *Preamble*) included biofuels, hydrogen and ammonia, and synthetic carbon-based fuels. Other fuels, such as synthetic diesel and novel biofuels produced from algae, were identified but were not considered in the report due to their anticipated limited significance for the shipping sector.¹⁷

- **Biofuels:** Biofuels, such as biomethanol, bioethanol, and liquefied biomethane (LBM), are produced from biomass and waste streams of biogenic origin. The assessment only considered biofuels produced from feedstock such as solid waste and lignocellulose¹⁸ to avoid any unintended competition with food crops (for example, starch or sugar) and the conversion of forest or natural vegetation to cropland.
- **Hydrogen:** Hydrogen is mainly produced either by separating hydrogen and oxygen through the electrolysis of water powered by renewable electricity ("green hydrogen"), or through steam methane reforming using fossil fuels (for instance, natural gas) in conjunction with carbon capture and storage (CCS) ("blue hydrogen").

¹⁷ Lloyd's Register and UMAS (2017)

¹⁸ Any of several closely related substances constituting the essential part of woody cell walls of plants and consisting of cellulose intimately associated with lignin.

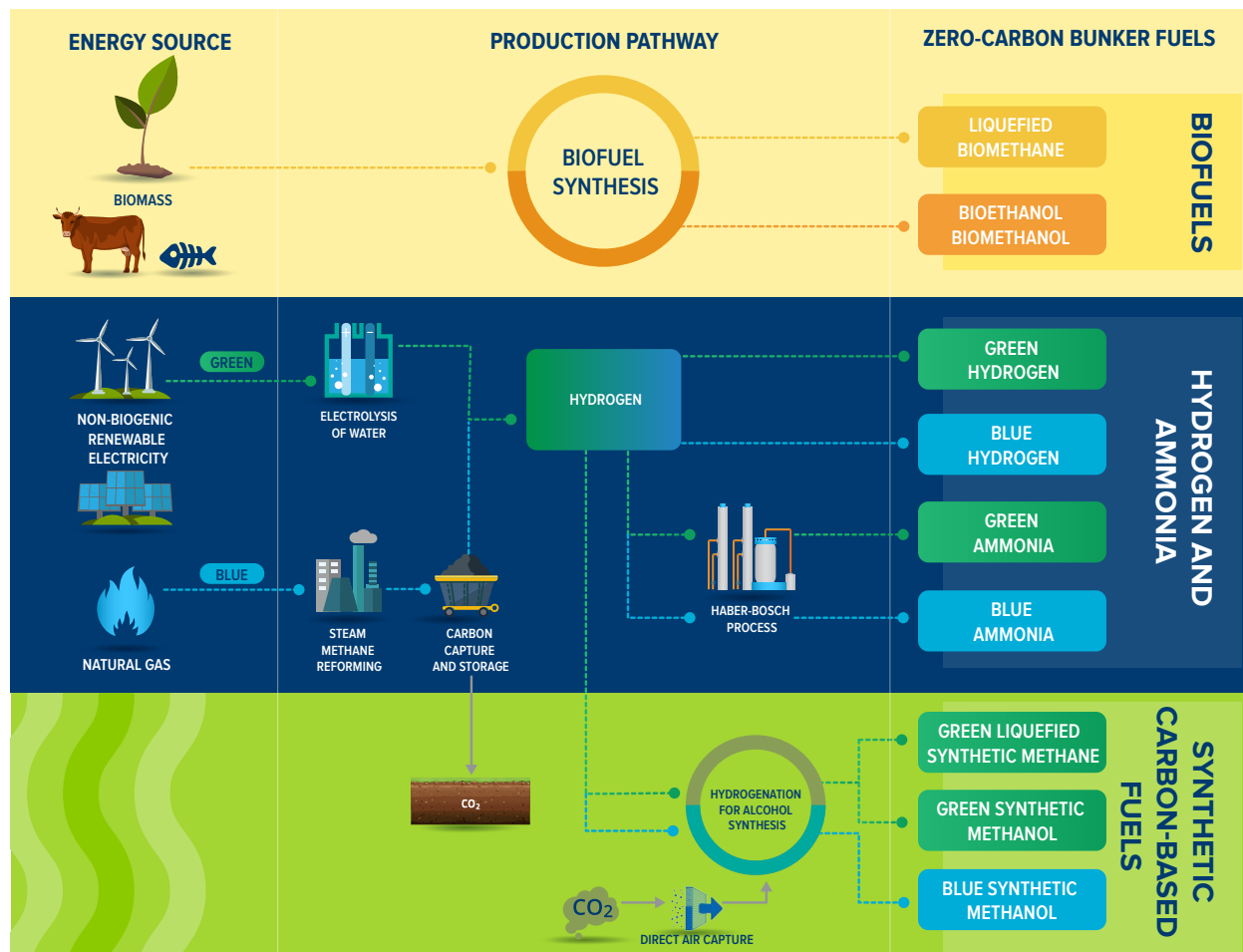




- **Ammonia:** The Haber-Bosch process is the most commonly used means of producing ammonia. It works by combining a supply of hydrogen with nitrogen from the air. It is technically straightforward but requires energy input either from renewable energy or fossil fuels. Ammonia is also often labelled as “green” or “blue” ammonia, depending on the feedstock used to produce the hydrogen input.
- **Synthetic carbon-based fuels:** Synthetic carbon-based fuels are human-made hydrocarbons (for example, methanol) produced by combining carbon and hydrogen in a chemical reaction. The carbon is captured from the atmosphere in the form of carbon dioxide (CO₂) using direct air capture technology supported by renewable energy.

Figure 2 provides an overview of how the assessed zero-carbon bunker fuels are usually produced. It displays the main energy source, illustrates the production pathway, and shows the final zero-carbon bunker fuel as output.

FIGURE 2: ZERO-CARBON BUNKER FUEL OPTIONS FOR SHIPPING





The assessment identified ammonia and hydrogen as the most promising zero-carbon bunker fuels to date. When produced from renewable energy, green ammonia and green hydrogen strike the most advantageous balance of favorable features relating to their lifecycle GHG emissions, broader environmental factors, scalability, economics, and technical and safety implications, compared with the other zero-carbon bunker fuels outlined above (see *Volume 1*).

In addition to other favorable features, ammonia and hydrogen allow for flexibility thanks to their multiple production pathways. Both ammonia and hydrogen can have the benefit of significantly lower lifecycle GHG emissions than conventional fuels by using either non-biogenic renewable energy (“green ammonia” or “green hydrogen”) or natural gas with the use of CCS (“blue ammonia” or “blue hydrogen”) in their production process. This offers additional flexibility in their production: for instance, blue ammonia and blue hydrogen could be produced first to kick-start the shipping sector’s energy transition, before transitioning to green ammonia and hydrogen at a later stage. This strategic benefit can help to reduce any concerns about the initial availability of sufficient renewable energy in the early years of the transition. Nonetheless, the use of blue ammonia and hydrogen remains heavily dependent on proving that effective CCS technologies can be successfully and economically deployed at large scale.

Overall, ammonia seems to be preferable over hydrogen as a zero-carbon bunker fuel. When directly comparing ammonia and hydrogen, the assessment concluded that ammonia is preferred due to its lower onboard storage space and the cost benefits that arise from its higher energy density, lower flammability, and less demanding cooling requirements (that is, -33°C). However, ammonia’s toxicity and corrosiveness require design and management measures to maintain an acceptable level of risk. While hydrogen is more explosive, less energy-dense, and requires relatively bulky and expensive cryogenic storage (that is, -235°C), it is less toxic and corrosive than ammonia. Therefore, appropriate but distinct safety standards, protocols, and equipment will be required before either fuel type can be used on board a vessel. The adoption and implementation of such measures appear more readily achievable for ammonia because it already is among the most widely traded commodities worldwide, with a century’s worth of experience in its safe handling and use on board ships.

Biofuels risk being constrained by the supply of sustainable biomass, and by cross-sectoral competition, and synthetic carbon-based fuels are likely to be less competitive in terms of cost. Biofuels and synthetic carbon-based fuels demonstrate a high technical potential for use as zero-carbon bunker fuels, too. However, the assessment identified critical constraints to their use at a large scale in shipping (see *Volume 1*). Firstly, although identified as being cost-effective to produce in the short term, biofuels are unlikely to serve as a large-scale bunker fuel without a significant technological breakthrough in aquatic biomass production. This is due to increasing competition for land (for example, for food production and land-use change), combined with competing fuel demands by other sectors (for example, power, plastics and aviation).¹⁹ Synthetic carbon-based fuels were identified as being





less competitive from a cost perspective due to lower efficiency in production and the dependence on direct air capture for CO₂ inputs, a technology whose scalability has yet to be proven.





3. THE ROLE OF LIQUEFIED NATURAL GAS IN SHIPPING'S ENERGY TRANSITION

Interest in LNG as a bunker fuel for shipping initially stemmed from the fuel's inherent air quality benefits relative to oil-derived bunker fuels. Before the adoption of the Initial IMO GHG Strategy, LNG had been explored as a promising bunker fuel option due to its significantly lower quantities of SO_x, NO_x, and particulate matter, leading to important air quality improvements. As a result of this exploration, the sector has built significant experience handling and using LNG as a cost-effective bunker fuel which has resulted in LNG representing approximately 3.3 percent of overall energy use in shipping, albeit predominantly in applications where it is carried as a cargo and where its use is an efficient way to manage the boil-off of cargo during transit.²⁰ In general, LNG has a variety of uses in the global economy, in which its use as a bunker fuel for maritime transport accounts for less than one percent of global natural gas demand.²¹

While LNG's air quality improvements are undeniable, there is debate within the sector as to what extent LNG may be able to contribute to decarbonizing shipping. LNG is a fossil fuel and does emit CO₂ during its combustion, similar to oil-derived bunker fuels. Therefore, it is generally accepted that LNG will not be able to fully decarbonize maritime transport, nor achieve the GHG emissions reductions of the Initial IMO GHG Strategy on its own, even if combined with energy efficiency measures. Next to its undeniable air quality benefits relative to oil-derived bunker fuels, LNG offers a theoretical carbon advantage of up to 30 percent less CO₂ emissions at combustion, compared to oil-derived bunker fuels. However, any GHG emissions advantage of LNG needs to consider not just CO₂ reductions in operation

²⁰ IMO (2020)

²¹ IEA (2020)





(for example, when it is used on board a ship), but its full lifecycle GHG emissions relative to conventional fuels.

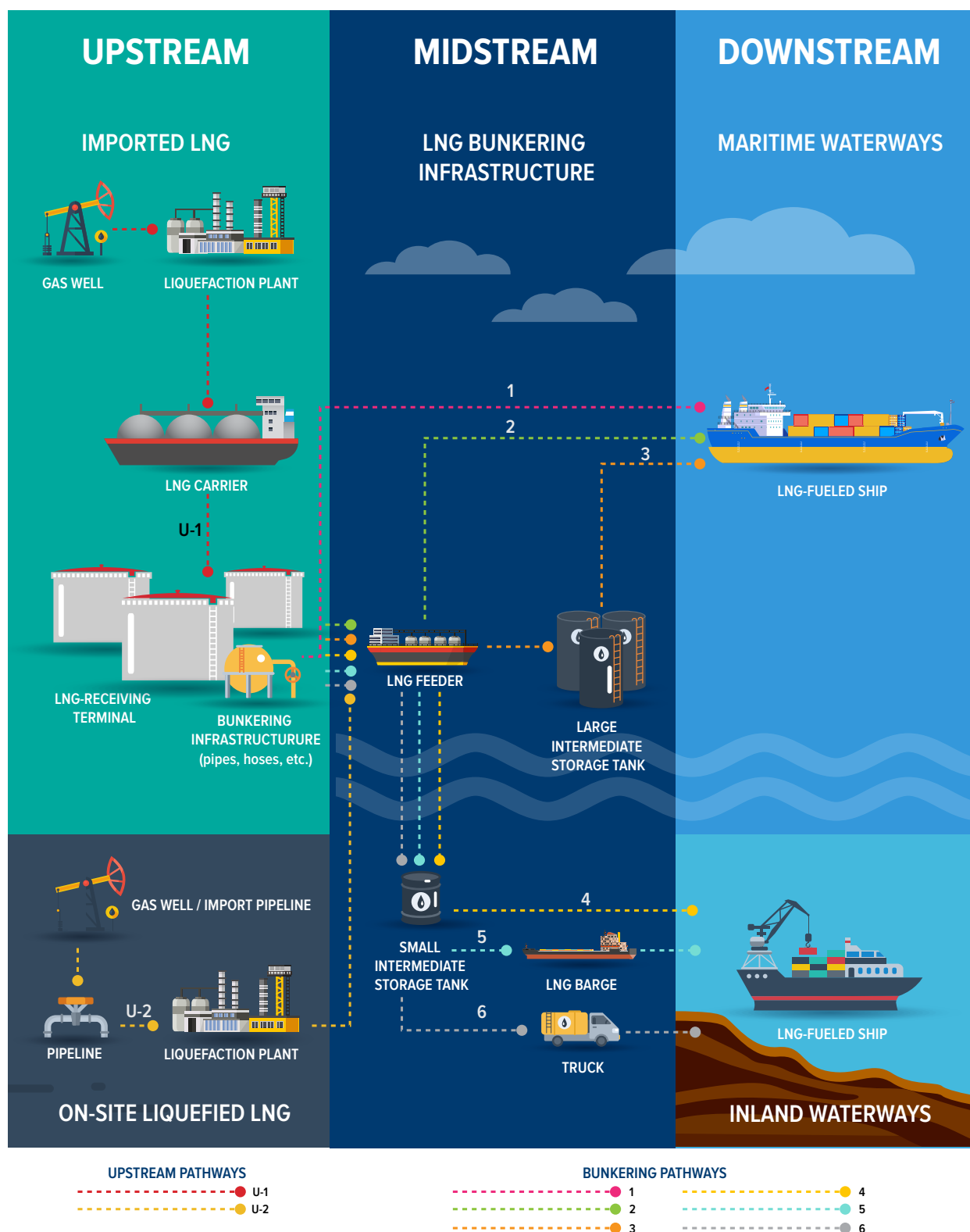
Specifically, LNG use has an inherent risk of methane escaping into the atmosphere, known as “methane leakage” or “methane slip,” throughout its lifecycle. This is true for any use of natural gas, not only its use as a liquefied bunker fuel. As methane is estimated to be 86 times more potent a GHG than CO₂ over a 20-year period (and 36 times over a 100-year time period), even small volumes of methane leakage can diminish GHG and climate-related justifications for using LNG as a low-carbon substitute for oil-derived fuels.²² Leakage of methane toward the estimated upper-bound values suggested in the literature can result in LNG having even higher lifecycle GHG emissions than oil-derived bunker fuels.

Methane leakage in LNG when it is used as a bunker fuel can occur at each stage of the fuel's lifecycle, as illustrated in Figure 3. However, the volume of methane leakage depends on many factors, ranging from where the natural gas is extracted and how it is distributed (upstream and midstream GHG emissions, accounting for about 6-36 percent of GHG overall emissions) to what type of engine is used to burn it (downstream GHG emissions, accounting for about 64-94 percent of overall GHG emissions). For example, from an upstream GHG emissions perspective methane leakage is estimated to be higher for shale gas than for conventional natural gas due to the increased gas venting associated with high-volume hydraulic fracturing.²³ With regard to downstream GHG emissions, the significance of the engine type is illustrated by the fact that downstream emissions of methane from maritime transport (GHG emissions produced during combustion in the vessel's engines) grew by 151 percent between 2012 and 2018—despite only a 28 percent increase in the use of LNG as a bunker fuel over the same period.²⁴ This disproportionate increase is due to the fleet increasing the use of LNG in dual-fuel internal combustion engines, which tend to emit more methane than steam boilers, and is evidence that downstream methane emissions are material and growing.

22 IPCC (2013)
23 ICCT (2020)
24 IMO (2020)



FIGURE 3: LNG LIFECYCLE PATHWAYS²⁵





It therefore appears important to examine the role that LNG is likely to play in shipping's decarbonization: a transitional role, a temporary role, or a limited role. *Volume 2: The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping* (see *Preamble*) presents such an analysis and examines whether LNG can be expected to play a significant role²⁶ in the sector's bunker fuel mix in light of the Initial IMO GHG Strategy. Given LNG's inability to sufficiently decarbonize maritime transport due to its limited GHG reduction potential and further expected growth in demand for shipping services, three different roles for LNG were analyzed: a transitional role, a temporary role, and a limited role.

Firstly, LNG is often discussed as a transitional fuel whereby LNG infrastructure and vessels could later be reused from 2030 onward with compatible zero-carbon bunker fuels ("use and reuse"). This scenario would help address the concern that the substantial capital expenditures for LNG supply infrastructure for shipping could not be leveraged to support the ultimate use of "drop-in" zero-carbon bunker fuels. "Drop-in" fuels are fuels that could make use of LNG supply infrastructure and LNG-fueled vessels without requiring that these be substantially modified. Zero-carbon bunker fuels which are fully compatible with LNG infrastructure and vessels are LBM and green liquefied synthetic methane (LSM).

However, current evidence suggests that neither LBM nor LSM are likely to represent a significant share of zero-carbon bunker fuels in the mid- to long-term future. In the case of LBM, there are expectations of limited availability and therefore lack of price competitiveness of sustainably sourced LBM. As already mentioned earlier, this is because estimates of the available supply are significantly lower than the potential demand given that several sectors like aviation, for instance, are very likely to compete for this commodity and its feedstocks. In the case of LSM, while not constrained by biogenic input sources, its production is expected to be more expensive than other zero-carbon bunker fuel alternatives, such as ammonia or hydrogen.

Furthermore, the two currently most promising zero-carbon bunker fuel options identified would not be "drop-in" solutions for LNG infrastructure and vessels. Current front-runner fuel options, ammonia and hydrogen, as identified in *Volume 1*, would not be able to reuse existing LNG technology for shipping. This is due to technical compatibility constraints in terms of containment and cooling equipment or safety measures with regard to explosiveness, corrosiveness, and toxicity. In combination with the challenges of LBM and LSM, therefore, no strong argument can be made that, relative to conventional bunker fuels, LNG is likely to play a transitional role that enables the long-term decarbonization of shipping.

Secondly, it also appears rather unlikely that LNG may play a temporary role until 2030 before it is rapidly supplanted by emerging zero-carbon bunker fuels ("use and stop"). This conclusion results from the uncertain GHG benefits, the financial implications with regard to additional capital expenditures, the risk of stranded assets, and the risk of a technology lock-in which will make it more challenging to achieve the IMO's climate targets.

²⁶ For the purposes of this report, a significant role has been defined as greater than ten percent of shipping's fuel mix in energy terms.



The GHG advantage of LNG as a bunker fuel remains uncertain with modelling projecting that a temporary use of LNG as a bunker fuel may lead to anything from modest GHG benefits to modest GHG disbenefits. In the modelling undertaken in *Volume 2*, the fleet-wide GHG emissions resulting from a high growth rate of LNG as a bunker fuel up to 2030 (that is, all vessel newbuilds will use LNG as its sole energy source) were estimated. Depending on the extent of methane leakage assumed, a peak GHG benefit of eight percent or a peak GHG disbenefit of nine percent are found by 2030, relative to a scenario with minimal further LNG use in maritime transport.

The range of methane leakage assumptions is a consequence of the uncertainties related to how methane leakage could be controlled and minimized in the future. For example, although downstream methane emissions (that is, those resulting from combustion on board) could be reduced using new machinery with lower methane slip levels, this would not address the risk of upstream and midstream methane emissions (that is, those resulting from extraction and distribution, respectively). In sum, the potentially wide margin of error on LNG's lifecycle GHG emissions derived from the current literature cannot conclusively demonstrate that LNG would unequivocally lead to fewer GHG emissions than oil-derived bunker fuels in shipping.

The temporary use of LNG is also expected to result in additional capital expenditures at least 10 to 17 percent greater when compared with a direct shift to zero-carbon bunker fuels. It was estimated that the use of LNG as a temporary fuel would require between \$169 and \$186 billion of capital expenditures.²⁷ This would be in addition to the estimated \$1.0 to \$1.9 trillion investment required to transition directly to zero-carbon bunker fuels.²⁸ This additional capital expenditure (up to \$186 billion) would be a consequence of the necessary two-stage conversion for both infrastructure and vessels (HFO to LNG and LNG to zero-carbon bunker fuels) compared to a one-stage conversion (HFO directly to zero-carbon bunker fuels).

A temporary role of LNG may also increase the risk for stranded assets and for a technology lock-in of LNG challenging the IMO's climate targets. As explained above, LNG bunkering investments may not be leveraged and reused for zero-carbon bunker fuels, and it is quite possible that future substantial investments in worldwide LNG supply infrastructure and vessels may become stranded. This would expose investors to return risks. Whilst some of the estimated \$186 billion of investment may be paid down during the coming decade, that figure is indicative of the upper bound of capital at risk under the scenarios analyzed.

One possible consequence of these financial risks could be a technology lock-in of LNG. It cannot be excluded that these financial implications of capital at risk and stranded assets may increase commercial and political pressure on policymakers to ensure a slower and more gradual phase-out of LNG. This in turn

²⁷ These numbers are not discounted to their present value in 2020. For more information, see *Volume 2: The Role of LNG in the Transition Toward Low- and Zero-Carbon Shipping*

²⁸ Global Maritime Forum (2020b)



would create a technology lock-in of fossil fuels resulting in large increases in GHG emissions above the declining levels currently required to meet the IMO's 2050 climate target.

Thirdly, a limited role for LNG as a bunker fuel in niche applications appears most likely (“limited use overall”). Having examined both a transitional and temporary role for LNG, the analysis did not identify any overall clear, strong, and unambiguous driver for LNG's large-scale uptake as a bunker fuel for propulsion purposes—even on a short-term basis up to 2030. Therefore, from the perspective of the sector as a whole, LNG's role as a bunker fuel is likely to be concentrated in niche applications. Examples could include its use on pre-existing routes that already benefit from existing LNG terminals at either port, with specific vessel types such as LNG carriers where cargo can be used as fuel and ferries, cruise ships, or coastal vessels where air quality benefits are highly relevant, or in special circumstances when there may be strong domestic interests favoring LNG.

Conversely, natural gas in its *non-liquefied* state may play a different and more important role as a feedstock in kick-starting the commercial production of zero-carbon bunker fuels. Rather than serving as a bunker fuel combusted in a shipping engine, natural gas may be used as a feedstock in combination with CCS to produce blue hydrogen or blue ammonia. In the early stages of decarbonization, before enough renewable electricity supply becomes available to generate green hydrogen or green ammonia economically and at scale, natural gas with CCS could offer a viable way of reducing GHG emissions significantly on the way toward full decarbonization.

Figure 4 summarizes the potential roles of using natural gas either as a bunker fuel or a fuel feedstock. It shows that natural gas in conjunction with CCS may be better suited to kick-start the production of zero-carbon bunker fuels rather than playing a transitional or temporary role as a bunker fuel in its liquefied form.

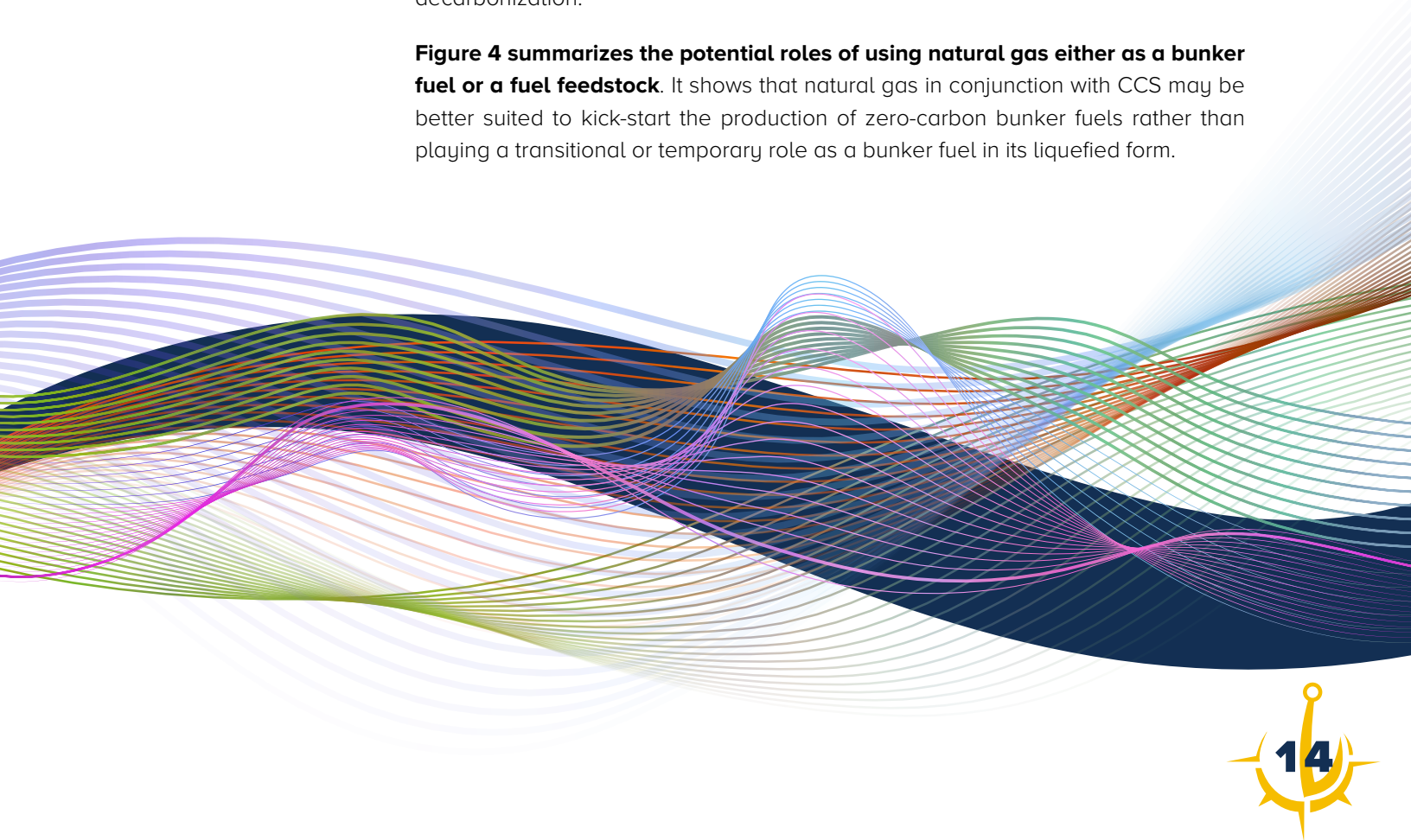
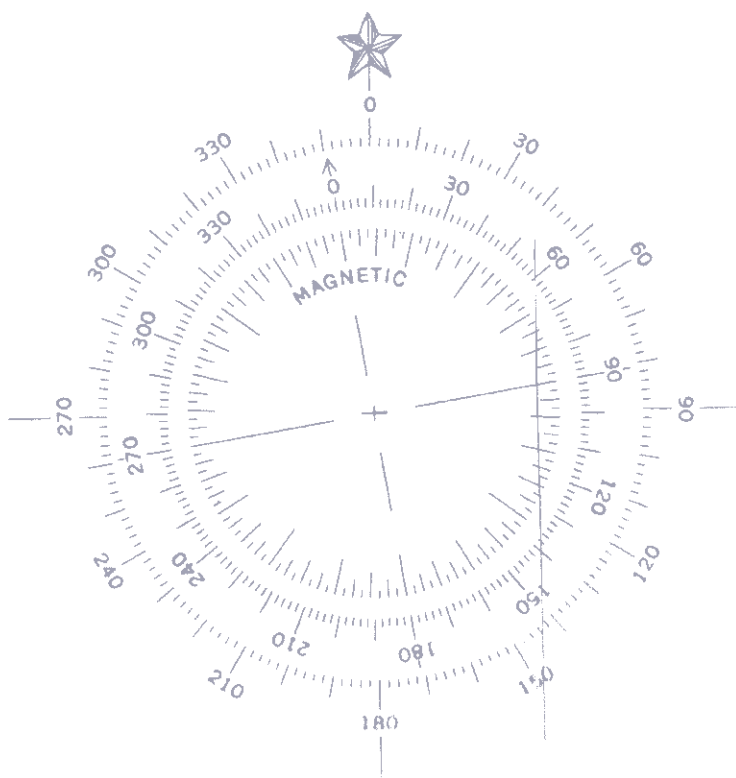
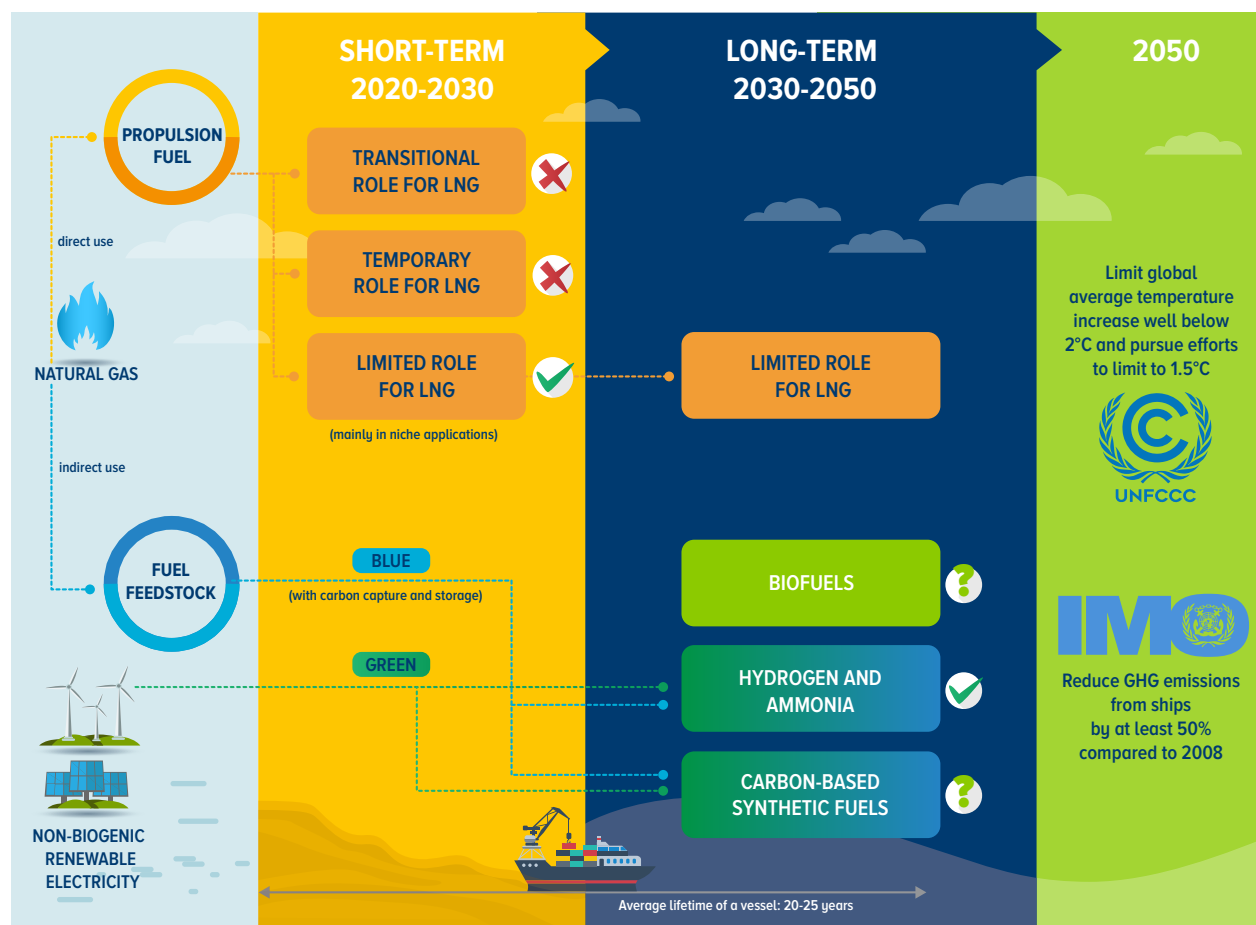




FIGURE 4: SUGGESTED ROLES FOR NATURAL GAS AS A BUNKER FUEL, AND AS A FUEL FEEDSTOCK IN SHIPPING'S DECARBONIZATION





GARAGE
DECK 5
CC2



4. OPPORTUNITIES FOR DEVELOPING COUNTRIES IN ZERO-CARBON SHIPPING

Investments of more than \$1 trillion will be needed to reach the IMO's 2050 climate target, according to estimates. Using the example of green ammonia, the investments required for the international maritime transport sector to reduce GHG emissions from ships by at least 50 percent by 2050 are estimated at \$1.0 to \$1.4 trillion. To fully decarbonize the sector in the same time frame, these estimates increase to between \$1.4 and \$1.9 trillion.²⁹ Of those amounts, 87 percent are anticipated to be in land-based infrastructure, such as hydrogen production, ammonia synthesis, and storage and bunkering infrastructure, while only 13 percent of the investments would be made in the ships themselves.³⁰ As a comparison, the global investments in the energy sector were \$1.85 trillion³¹ in 2018 alone.³²

Decarbonizing shipping represents a more than \$1 trillion investment opportunity, including for countries that have traditionally not participated in the global bunker fuel market. Unlike conventional bunker fuels dependent on crude oil, zero-carbon bunker fuel production requires an abundant supply of renewable energy in the fuel-producing country. As illustrated by Figure 5, this expected realignment of the global bunker fuel market represents a new opportunity for countries lacking conventional fossil fuel reserves but benefitting from a large potential for renewable energy generation to enter the market as producers. Moreover, the lower energy density of ammonia and hydrogen compared to HFO is likely to result in more frequent refueling, and thereby the development of more decentralized zero-carbon bunker fuel hubs around the world.

²⁹ Global Maritime Forum (2020b)

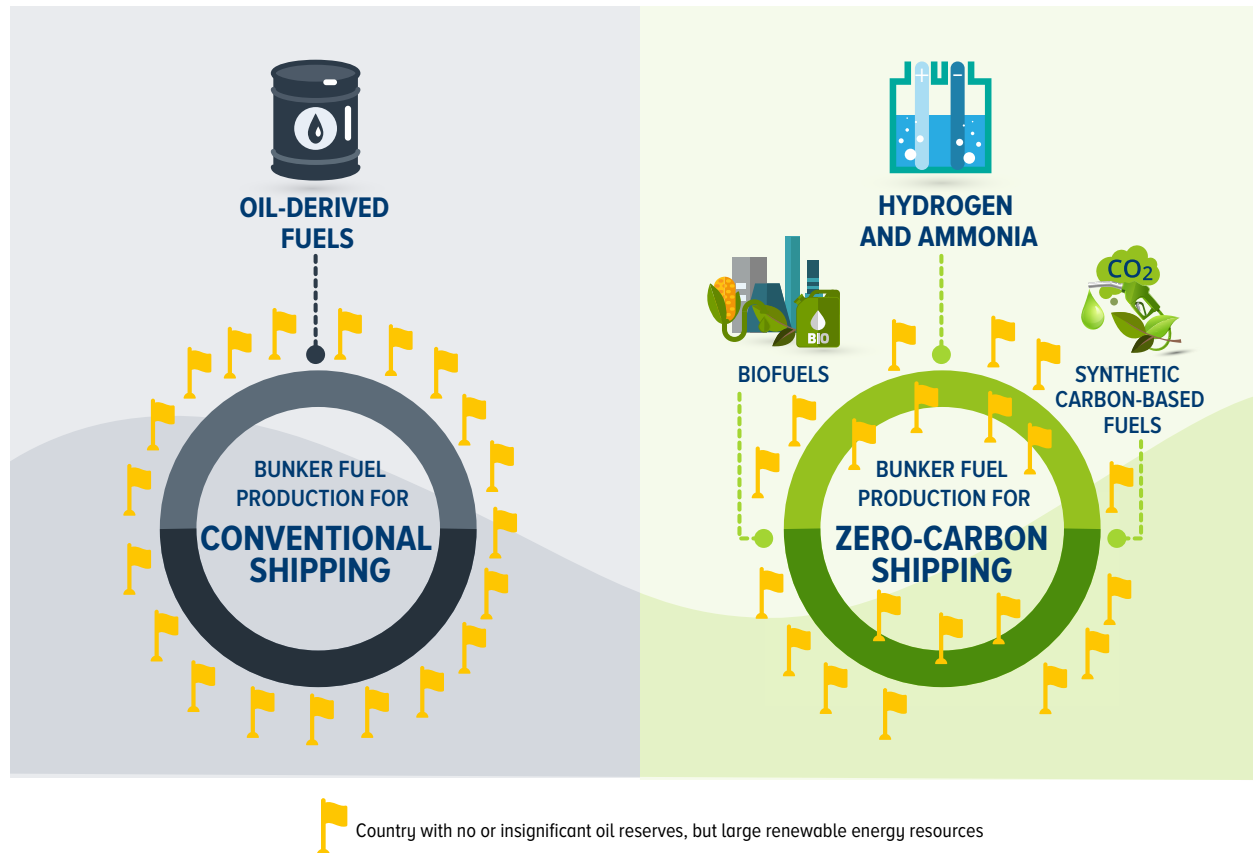
³⁰ Global Maritime Forum (2020b)

³¹ The total global investments of \$1.85 trillion include investments in the power sector, oil and gas supply, energy efficiency, coal supply and renewables for transport and heat.

³² IEA (2019)



FIGURE 5: POTENTIAL REALIGNMENT OF THE GLOBAL BUNKER FUEL MARKET THROUGH ZERO-CARBON SHIPPING



To identify countries well positioned to become future producers of zero-carbon bunker fuels, an initial high-level assessment was conducted. This assessment

aims to help national policymakers identify how national comparative advantages could best be leveraged to produce zero-carbon bunker fuels (see *Volume 1*). The report suggests a preliminary list of countries that likely are well positioned to produce green or blue ammonia and hydrogen for maritime transport. Not only would such an engagement enable countries to export ammonia and hydrogen as a bunker fuel, it would likewise enable them to improve and enhance domestic energy systems by using excess renewable electricity generation to store that energy in ammonia and hydrogen, and conversely by using excess ammonia and hydrogen to compensate for intermittent renewable electricity.

Table 1 shows the five criteria used to estimate the potential of different countries to supply zero-carbon bunker fuels for shipping by 2050. An aggregate score was derived for each country for each of the following production scenarios:



1. **First scenario:** Blue ammonia and hydrogen production from natural gas with CCS;
2. **Second scenario:** Green ammonia and hydrogen from renewable energy sources; and
3. **Third scenario:** Blue ammonia and hydrogen from natural gas with CCS initially, before moving to green ammonia and hydrogen from renewable energy production eventually.

TABLE 1: CRITERIA FOR INITIAL HIGH-LEVEL ASSESSMENT OF ZERO-CARBON BUNKER FUEL PRODUCTION POTENTIAL

CRITERION	WEIGHTING JUSTIFICATION	WEIGHT
1. Energy resources required	The most important factor for a country to become a major producer of zero-carbon bunker fuels is deemed to be its access to the key energy resources required for production.	50 percent
2. Shipping volumes	Large current shipping volumes can indicate a natural demand. However, a country could also become a major fuel producer even if shipping volumes at its domestic ports were relatively low today.	20 percent
3. Geographic location	Although a convenient geographic location is clearly advantageous, a country could be located further away from shipping activities and still become a major producer and/or exporter thanks to the relatively low share of transportation costs in overall supply costs.	12.5 percent
4. Regulatory framework	While a favorable regulatory framework offers an advantage when advancing the zero-carbon fuels transition within a country, it is not necessarily a prerequisite for a country to become a large-scale producer of zero-carbon ammonia or hydrogen as long as a strong economic driver exists.	12.5 percent
5. Potential to leverage existing infrastructure	Pre-existing infrastructure is an advantage. However, it is neither indispensable nor sufficient for a country to produce the volumes of zero-carbon ammonia and hydrogen needed to meet future shipping demand.	5 percent

Using these criteria, the analysis finds that many countries are well positioned to produce a significant proportion of shipping's ammonia bunker fuel demand by 2050. That demand is estimated to be 17.8 exajoules,³³ which corresponds to approximately the total energy supply of Japan in 2017.³⁴ The results of the scoring in *Volume 1* are illustrated in the heatmaps shown in Figures 6-8. Notably, the heatmaps show that a significant number of developing countries, too, are well placed to produce zero-carbon bunker fuels for shipping. These promising candidates often benefit from a large domestic renewable energy potential and/or natural gas supply and CCS potential, combined with being close to major sea-borne trading routes and having high volumes of maritime trade in their ports. However, it is important to note that this initial high-level assessment does not yet take into consideration the cost competitiveness of each country's ammonia and hydrogen production.

³³ UMAS (2020)

³⁴ UN DESA (2018)



FIGURE 6: HEATMAP INDICATING THE POTENTIAL OF COUNTRIES TO PRODUCE BLUE AMMONIA/HYDROGEN FOR SHIPPING

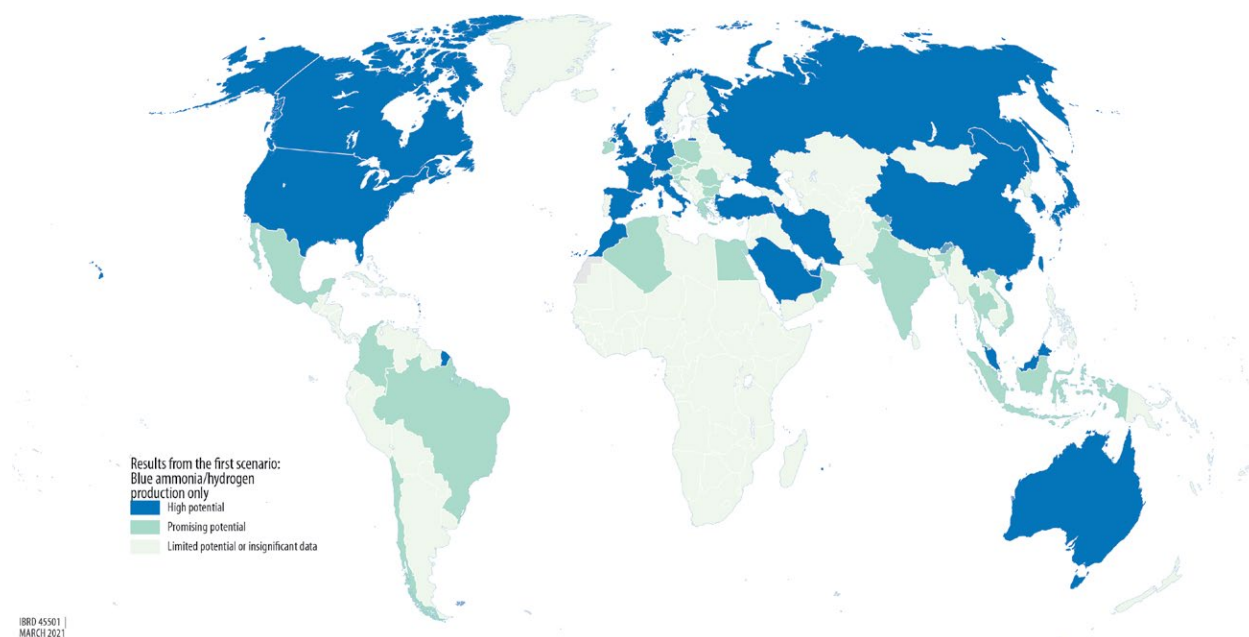


FIGURE 7: HEATMAP INDICATING THE POTENTIAL FOR COUNTRIES TO PRODUCE GREEN AMMONIA/HYDROGEN FOR SHIPPING

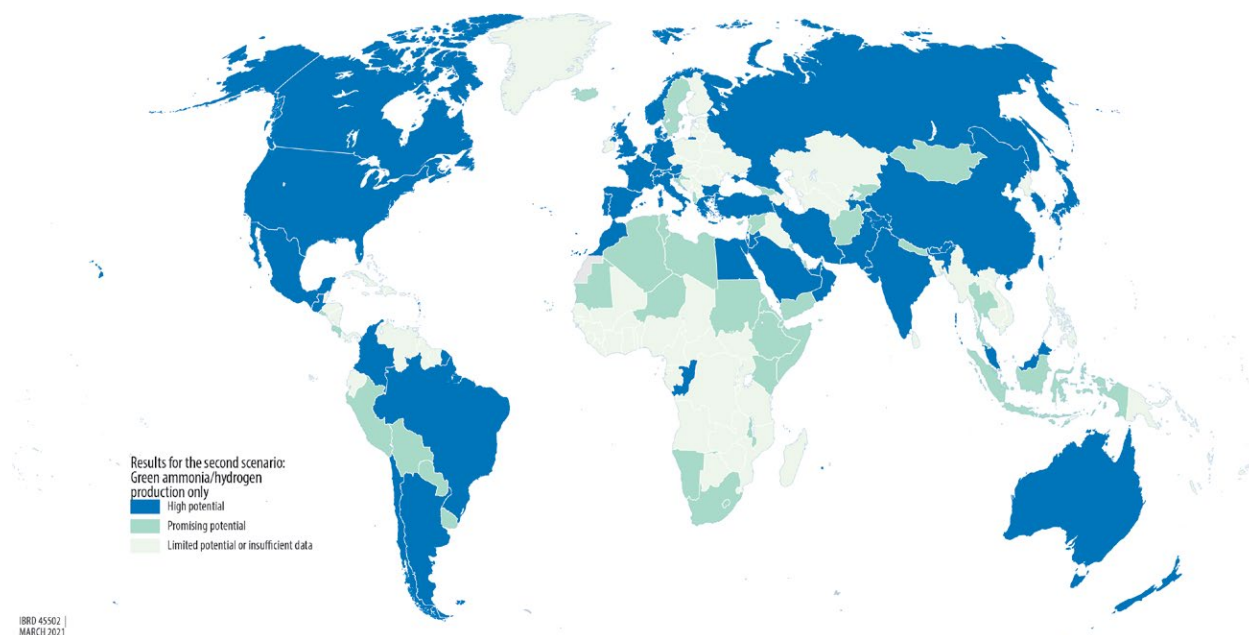
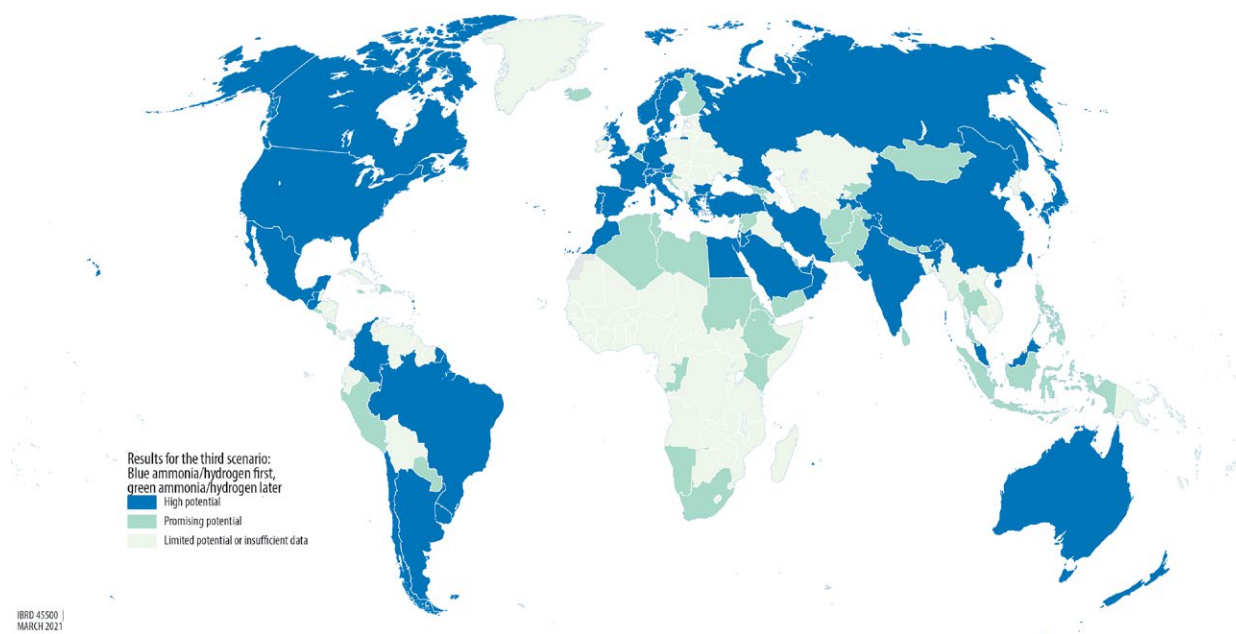




FIGURE 8: HEATMAP INDICATING THE POTENTIAL FOR COUNTRIES TO PRODUCE BLUE AMMONIA/BLUE HYDROGEN INITIALLY, BEFORE SHIFTING TO GREEN AMMONIA/GREEN HYDROGEN PRODUCTION FOR SHIPPING EVENTUALLY



Following the initial high-level assessment, four developing countries which scored highly on the criteria used were selected for a first quantitative analysis through country case studies. Brazil, Malaysia, and India all ranked among the top developing countries well positioned to become future producers of zero-carbon bunker fuels. The small island developing state of Mauritius was also selected as an alternative example due to its national interest in becoming a future bunker fuel hub and to ensure more balanced regional and economic representation. The country case studies are summarized in Table 2.

TABLE 2: OVERVIEW OF KEY FINDINGS FROM THE COUNTRY CASE STUDIES

	PRODUCTION PATHWAY ANALYZED	ENERGY RESOURCES CONSIDERED	POTENTIAL SUPPLY OF GLOBAL SHIPPING DEMAND FOR AMMONIA BY 2050 ³⁵	CAPITAL EXPENDITURES NEEDED
Brazil	Blue ammonia	Natural gas with CCS	2-9 percent	\$24-\$107 billion
India	Green ammonia	Solar	10-27 percent	\$147-\$385 billion
Mauritius	Green ammonia	Solar and wind	0.3-0.5 percent	\$1.6-\$2.7 billion
Malaysia	First blue, then green ammonia	First natural gas with CCS, then solar	1-10 percent	\$17-\$138 billion

³⁵ This assumes that, by 2050, the entire international fleet will be fully decarbonized using ammonia.



- **Brazil (blue ammonia):** Brazil has extensive reserves of natural gas and a high potential for on- and offshore CCS sites, enabling it to cover its regional shipping market and export any excess ammonia and hydrogen to the international shipping market (for example, Panama or Rotterdam). Furthermore, Brazil is home to five of the 100 largest ports globally in terms of cargo handled, providing for a large potential market.³⁶ With capital investments ranging from \$24 to \$107 billion,³⁷ Brazil could meet 2 to 9 percent of global zero-carbon bunker fuel demand for shipping in 2050.
- **India (green ammonia):** India is favorably located close to crucial bunkering hubs (including Singapore and Fujairah) and major shipping routes between Asia, the Middle East, and Europe. Furthermore, India receives the 11th highest annual container throughput globally and has a high potential to produce inexpensive renewable electricity, leaving excess solar for other national needs.³⁸ Together, these factors would enable India to meet 10 to 27 percent of global zero-carbon bunker fuel demand for shipping in 2050, with capital investments estimated to be between \$147 to \$385 billion, not including the capital needed for renewable electricity generation.
- **Mauritius (green ammonia):** Mauritius is strategically located on the East-West route in the Indian Ocean, linking Asia, Africa, and South America. It has a high potential for solar and offshore wind energy generation to provide the necessary energy supply. This could result in Mauritius producing 0.3 to 0.5 percent of global zero-carbon bunker fuel demand or 3 to 5 percent of Africa's zero-carbon bunker fuel demand in 2050, representing an investment requirement between \$1.6 to \$2.7 billion.³⁹
- **Malaysia (blue ammonia with a transition to green ammonia):** Due to its favorable geographic location close to Singapore, the world's largest bunkering hub, and anticipated ability to capture demand from continued economic growth in Asia, Malaysia has the potential to capture 1 to 10 percent of the global zero-carbon bunker fuel market, requiring an investment in the range of \$17 to \$138 billion.⁴⁰ Likewise, Malaysia was ranked fifth in container port throughput in 2017, suggesting high domestic demand.⁴¹ Malaysia is also particularly well positioned to produce blue ammonia and hydrogen due to its natural gas reserves and CCS potential that could be leveraged in the first fuel deployment phase. Later, it could use its abundant solar potential, which is more than sufficient to meet both its domestic electricity demand and the zero-carbon bunker fuel supply scenarios considered. Green ammonia could then be used to capture excess solar electricity at times of low domestic need.

36 AAPA (2016)

37 This estimate does not include the capital required to extract and transport the natural gas feedstock.

38 Indian Ports Association (n.d.)

39 This estimate does not include the capital needed for renewable electricity generation.

40 This estimate does not include the capital required to extract and transport the natural gas nor the renewable electricity generation.

41 UNCTAD (n.d.)



5. CONCLUSIONS AND OUTLOOK

5.1 KEY FINDINGS

Green ammonia and hydrogen appear to be the most promising zero-carbon bunker fuel for shipping to date. The analysis provided in *Volume 1* assessed candidate zero-carbon bunker fuels that are currently most likely to enable the maritime transport sector to fully decarbonize. In particular, green ammonia and green hydrogen were identified as today's most promising options, when compared to biofuels and synthetic carbon-based fuels, due to their relative balance of favorable features such as lifecycle GHG emissions, broader environmental factors, scalability, economics, and technical and safety implications.

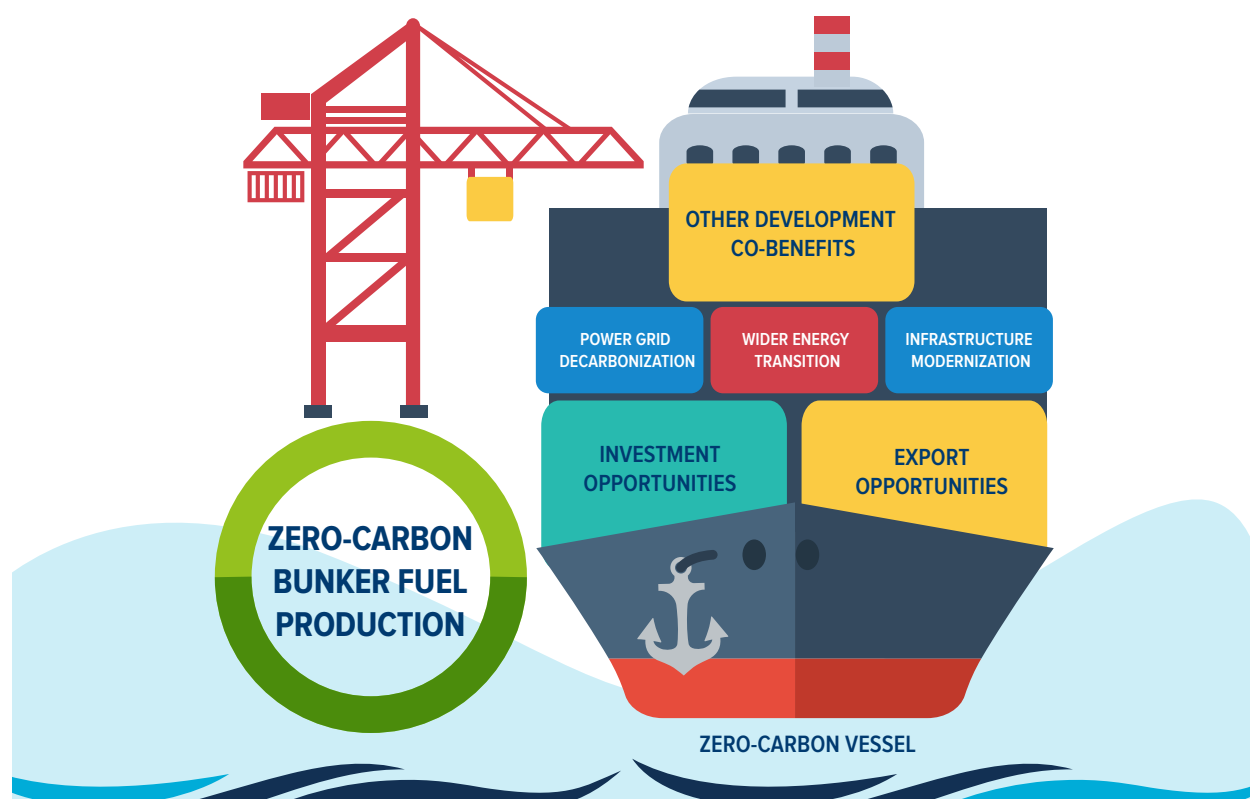
LNG is estimated to play a rather limited role in the transition toward low- and zero-carbon shipping, being mostly used in niche applications. Analysis from *Volume 2* estimates that LNG is likely to play a limited role as a bunker fuel both before 2030 and from 2030 to 2050. The report reached this conclusion because of the lack of an unequivocal argument for GHG benefits, in combination with the weakness of other commercial or technological justifications associated with LNG serving as a transitional or temporary fuel. Nonetheless, LNG is still expected to be used in niche applications such as on privileged routes with existing supply infrastructure, in specific vessel types, or in places with strong domestic interests favoring it.

Natural gas could play an important enabling role for zero-carbon bunker fuel production. When used as a feedstock for hydrogen production in conjunction with CCS, natural gas has the potential to kick-start the commercial production of blue ammonia and hydrogen in the years before sufficient renewable electricity supply becomes available for full production of green ammonia and green hydrogen.



Many countries that have not been traditional energy exporters, including many developing countries, could enter the future market for zero-carbon bunker fuels from 2030. In this more inclusive market, these potential new producers and suppliers can take advantage of a global investment opportunity of at least \$1 trillion. Consequently, this would create the opportunity for some countries to shift from being energy importers to being energy exporters.

FIGURE 9: OPPORTUNITIES FOR DEVELOPMENT CREATED BY ZERO-CARBON BUNKER FUEL PRODUCTION



Additionally, zero-carbon bunker fuels could support developing countries in achieving their overall decarbonization and infrastructure modernization more flexibly and at lower cost. With the large majority of expected investments required for land-based infrastructure in renewable energy generation and hydrogen production, a particular win-win for developing countries would be to leverage these investments for their own domestic energy sector as well as maritime and non-maritime infrastructure needs as illustrated by Figure 9. For instance, green ammonia and green hydrogen can have a broad range of applications in developing countries offering economies of scale through sector coupling.⁴² Taking advantage of versatile technologies like power-to-gas, sector coupling links several sectors (for instance, power, gas, and transport) to provide greater flexibility and to achieve overall decarbonization in a more cost-effective way.



5.2 IMPLICATIONS FOR POLICYMAKERS

Zero-carbon shipping can offer unique opportunities for wider economic, energy, and industrial development to developing countries. As zero-carbon bunker fuels enter the global fleet, many more countries—both developed and developing countries—may enter the bunker fuel production market for the first time (see *Volume 1*). Developing countries could harness national comparative advantages, for instance in terms of renewable energy potential and geographic location, to enhance, modernize, and decarbonize their domestic energy systems for a range of applications, of which shipping is only one. For instance, they could consider producing and storing green ammonia and hydrogen from renewable electricity during periods of low demand for power from regular consumers. This approach would help to compensate for the intermittency of renewable energy supply. The green ammonia and hydrogen produced from excess renewable electricity could then be used in the country's wider industrial applications, or sold as an export commodity in global markets, including the emerging market for zero-carbon bunker fuels.

Policy interventions such as carbon pricing are needed to enable the zero-carbon bunker fuel transition in shipping and should support developing countries in their energy transitions. A cost-effective policy that could significantly contribute to and drive clarity for an international enabling environment would include the adoption of a meaningful carbon price for bunker fuels—ideally on a global scale. A proportion of the revenues from such a market-based measure could be used to help support the necessary research, development, and deployment (RD&D) of zero-carbon bunker fuels. At the same time, the revenue recycling should also include targeted investments in developing countries with the aim to ensure a fair and equitable energy transition, making sure that countries with less modern maritime infrastructure or in more remote geographic locations do not suffer from disproportionately negative impacts. These targeted investments would help to unlock those developing countries' full potential to contribute to shipping's future zero-carbon bunker fuel supply chain.

Public support through the IMO or national action is needed to accelerate crucial RD&D for zero-carbon bunker fuels and enable industry to make confident long-term investment decisions about shipping's decarbonization. The findings from *Volume 1* strongly suggest that RD&D of zero-carbon bunker fuels need to be accelerated if the Initial IMO GHG Strategy 2050 target and eventual full decarbonization of shipping are to be achieved. Without these fuels, the industry will continue relying on highly polluting HFO and other fossil fuels, leading to increased GHG emissions within the sector. The public sector—globally at the IMO, regionally, or nationally—can play a key role in this transition by helping accelerate the commercialization of zero-carbon bunker fuels. Public support will be instrumental and can include: a clearly articulated industrial strategy for hydrogen production, incentive schemes for renewable electricity generation, and financial or fiscal support for pilot and demonstrator projects for zero-carbon bunker



fuel production and use at scale and under real-life conditions. This public support would create an enabling environment where industry stakeholders and financial investors can eventually make confident long-term investment decisions about shipping's decarbonization.

A full lifecycle GHG perspective should be applied to any bunker fuel considered as a low- or zero-carbon alternative to HFO. *Volume 2* also makes it evident that policymakers are well-advised to consider the full lifecycle GHG emissions of any potential low- or zero-carbon bunker fuel. This applies both to LNG and zero-carbon bunker fuels, and is necessary to avoid merely displacing GHG emissions from one part of the fuel's lifecycle to another. For example, a specific bunker fuel may ultimately be able to curtail the downstream GHG emissions associated with its combustion in a vessel. However, the fuel may still have higher GHG emissions associated with its extraction (upstream) or distribution (midstream). In such cases, the same low- or zero-carbon bunker fuel may unintentionally lead to higher overall GHG emissions than traditional oil-derived alternatives.

To put shipping on a Paris-aligned GHG emissions trajectory, new public policy in support of LNG as a bunker fuel should be avoided, existing policy support should be reconsidered, and methane emissions should be regulated. The Initial IMO GHG Strategy commits to first reduce and then phase out GHG emissions from ships in line with achieving the Paris Agreement's temperature goals. Given this commitment, *Volume 2* suggests that policymakers should avoid developing new public policies that support LNG use as a bunker fuel. The analysis also highlights the value of reassessing and possibly reducing existing policy support for LNG as a bunker fuel to manage the climate change risks associated with its large-scale adoption in that role. Additionally, the analysis finds that urgent and robust policy action is needed to regulate existing methane emissions throughout the LNG supply chain and its use on board ships. For instance, upstream methane emissions often present a much more complex problem that is not strictly technological in nature, but would require regulatory changes and enforcement across the numerous jurisdictions where LNG is extracted. Many of these jurisdictions suffer from generally low regulatory enforcement levels.⁴³ Without such action to regulate methane emissions throughout the LNG supply chain, existing LNG use in shipping risks causing even higher lifecycle GHG emissions than the use of conventional oil-derived fuels.

43 World Justice Project (2020)



5.3 IMPLICATIONS FOR INDUSTRY

Increased awareness of the specific commercial risks and opportunities related to the emergence of zero-carbon bunker fuels will be key. The production of zero-carbon bunker fuels at the scale needed to effectively decarbonize the shipping sectors offers a significant commercial opportunity and is an area that can be expected to receive increasing policy support. However, these investments bring a certain level of risk as illustrated by the following three scenarios. First, there is a risk that initial policy support for the new fuels will not be sufficient or sustained—or at least that uncertainty would arise about the timescales for when that support would take effect. This uncertainty is unlikely to persist due to the growing public pressure for governments and industry stakeholders to address the current climate crisis, but it does make timing of entry difficult to judge. Second, zero-carbon bunker fuel infrastructure may not become fully cost-competitive at the pace expected. As a consequence, planning to time expansion and wider opportunities also will remain difficult to judge. Third, there may be initially limited availability of specialized financial mechanisms that can support the commercialization of zero-carbon bunker fuels in addition to equity and other debt finance sources.

While industry stakeholders are becoming increasingly vocal about their favored zero-carbon shipping solutions, more risk-averse businesses can prepare for the sector's energy transition by focusing initially on “no-regret” options and increased flexibility. As the landscape of zero-carbon bunker fuels is becoming clearer with more announcements by major players about their long-term fuel choices, industry stakeholders with a lower risk appetite can opt for investments in increased energy efficiency and maximum fuel flexibility in future ship design. The former represents “no-regret” investments which will benefit any kind of future bunker fuels; the latter offers the flexibility to continue using oil-derived bunker fuels up to the moment when the fuel supply can be more confidently switched to zero-carbon bunker fuels. This allows the industry to prepare effectively for zero-carbon bunker fuel opportunities while remaining flexible on how and when to take advantage of those opportunities.

Industry stakeholders engaging in constructive support to policy development are likely to increase certainty on availability, pricing, and timing of zero-carbon bunker fuels—to their own benefit and that of the sector. They will benefit from identifying the scenarios in which potential risks related to zero-carbon shipping are material, and then implement mitigation strategies should those scenarios start to materialize. Therefore, industry stakeholders are well-advised to constructively support the policy development process through multi-stakeholder collaboration, thereby increasing predictability for themselves and the sector as a whole. Stakeholders are also advised to identify multiple foreseeable scenarios for how the energy transition may evolve and test robustness of investment decisions against these scenarios.



The advantage of multiple production pathways of hydrogen may still lead to increased investment uncertainty in the beginning. Industry stakeholders should also acknowledge that the expected transition of larger energy systems can create stranded assets. Initially increased investment uncertainty may be a result of the actual technological advantage of being able to produce hydrogen from both renewable energy (“green”) and natural gas combined with CCS (“blue”). For example, suppliers who have invested in blue hydrogen may be left with stranded assets should green hydrogen become competitive sooner than expected. It is likely to take some time for clear global centers of production and supply chains to emerge.

Investment decisions regarding the large-scale use of LNG as a bunker fuel should take into account the wide range of financial and regulatory risks identified. To avoid the risks of stranded assets and opportunity costs, industry stakeholders should consider aligning their business strategy with the likelihood that LNG will play a rather limited role as a bunker fuel. Given the financial and regulatory risks, LNG as a bunker fuel may end up benefitting only individual industry stakeholders who can make investments in niche applications on a limited timescale and who therefore can effectively mitigate the major risks related to its use as a bunker fuel.

5.4 OUTLOOK FOR FURTHER WORK

Additional research can help to underline or challenge the consideration of ammonia and hydrogen as the most promising zero-carbon bunker fuels to date. *Volume 1* provides initial evidence that green ammonia and green hydrogen are likely to be the future key zero-carbon bunker fuels for shipping. However, it cannot be ruled out that over time other zero-carbon bunker fuels may become able to contribute even more competitively to shipping’s decarbonization efforts. Thus, there is a need for ongoing work to regularly update and refine the analysis of comparative advantages of different candidate fuels. Such work would provide further insights as additional research becomes available, and especially as the first practical pilot and demonstration projects conclude.

Further work on the potential of countries to become zero-carbon bunker fuel producers should look into issues of cost competitiveness and sector coupling. The framework used to assess countries based on their potential for producing zero-carbon bunker fuels should be understood as an *initial high-level* assessment. It is not a definitive research process. However, it does provide a first-of-its-kind methodological basis for identifying countries that would benefit from further detailed analysis. Such work should particularly focus on a broader cost competitiveness analysis, as well as an analysis of how ammonia and hydrogen for shipping can contribute to the broader energy system transition in each country.



The remaining uncertainty regarding LNG's role in shipping's future fuel mix can be reduced through additional sensitivity analysis. While the uncertainty of LNG's long-term role in the sector remains a barrier and a risk to capital investment, further sensitivity analysis can help reduce these uncertainties by changing the assumptions on costs, prices, and the performance of the technologies—and by exploring the different ranges of uptake of LNG under non-linear GHG reduction trajectories. This can further strengthen robust decision-making on how much shipping can ultimately rely on LNG to reduce its carbon footprint, and the likely timings that can be expected for a return on any investment. The fleet used can also be modelled with greater granularity. These refinements, however, are not expected to affect the conclusions of *Volume 2* substantially, though they would add clarity to LNG's niche bunker fuel roles.

More varied assumptions can be made on the future of fossil-fueled vessels consequent to the large-scale deployment of zero-carbon bunker fuels. Lastly, the analysis assumes that the existing fleet will be retrofitted once zero-carbon bunker fuels become commercially available. However, an alternative scenario to this would occur if ship owners decided to scrap their fossil-fueled fleet directly. In that case, a more detailed shipping market dynamic analysis would help the industry understand the interaction and likely scenarios around proportions of newbuilds, scrappage, and retrofits during the sector's energy transition.





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