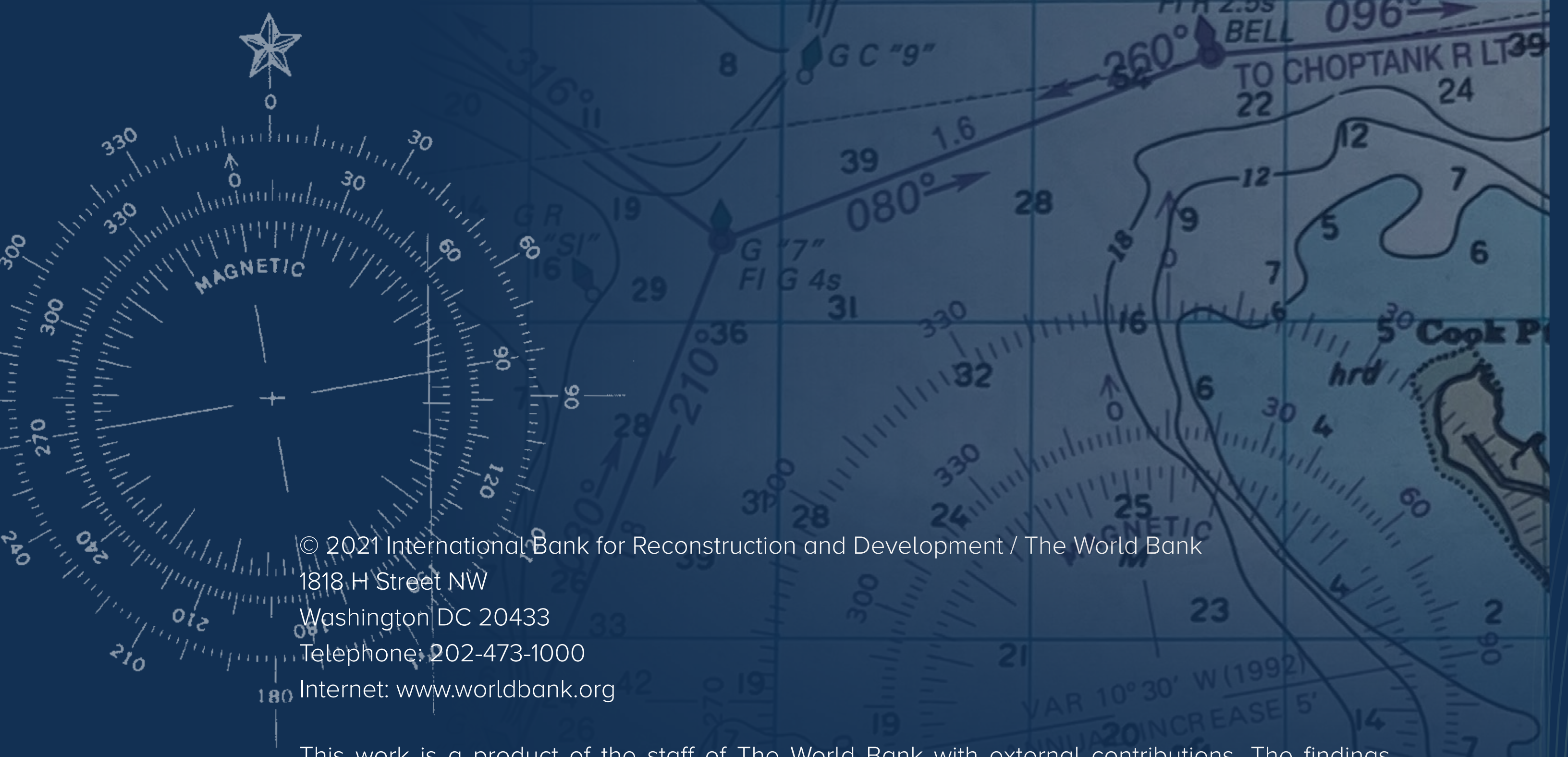
volume 2

THE ROLE OF LNG IN THE TRANSITION TOWARD LOW- AND ZERO-CARBON SHIPPING



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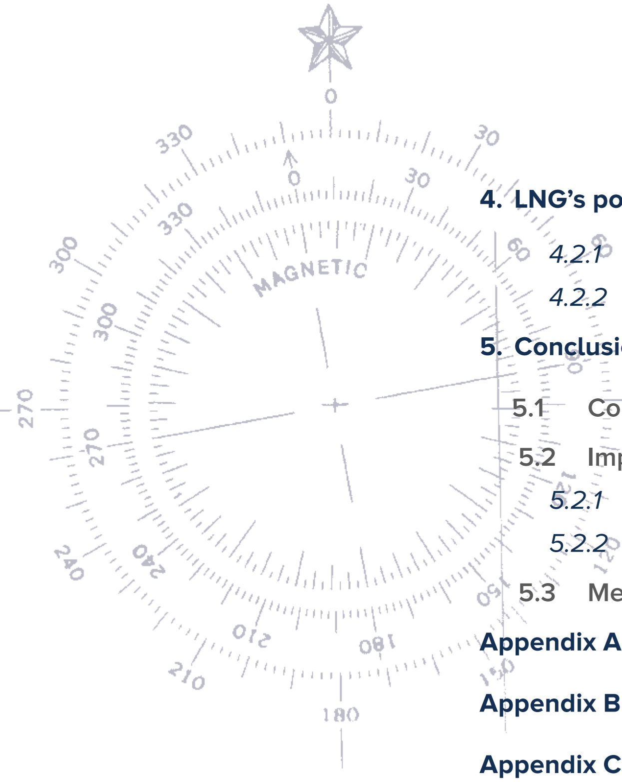
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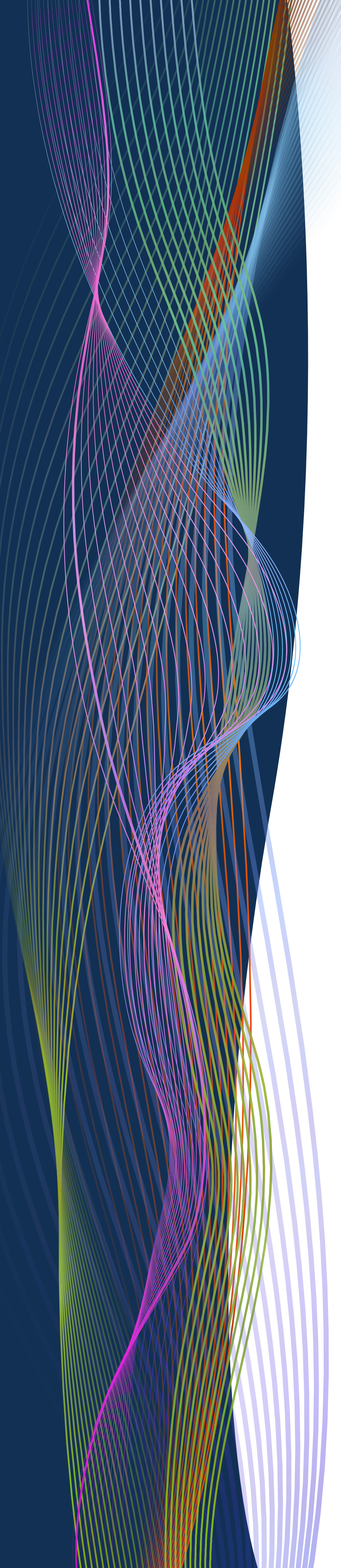
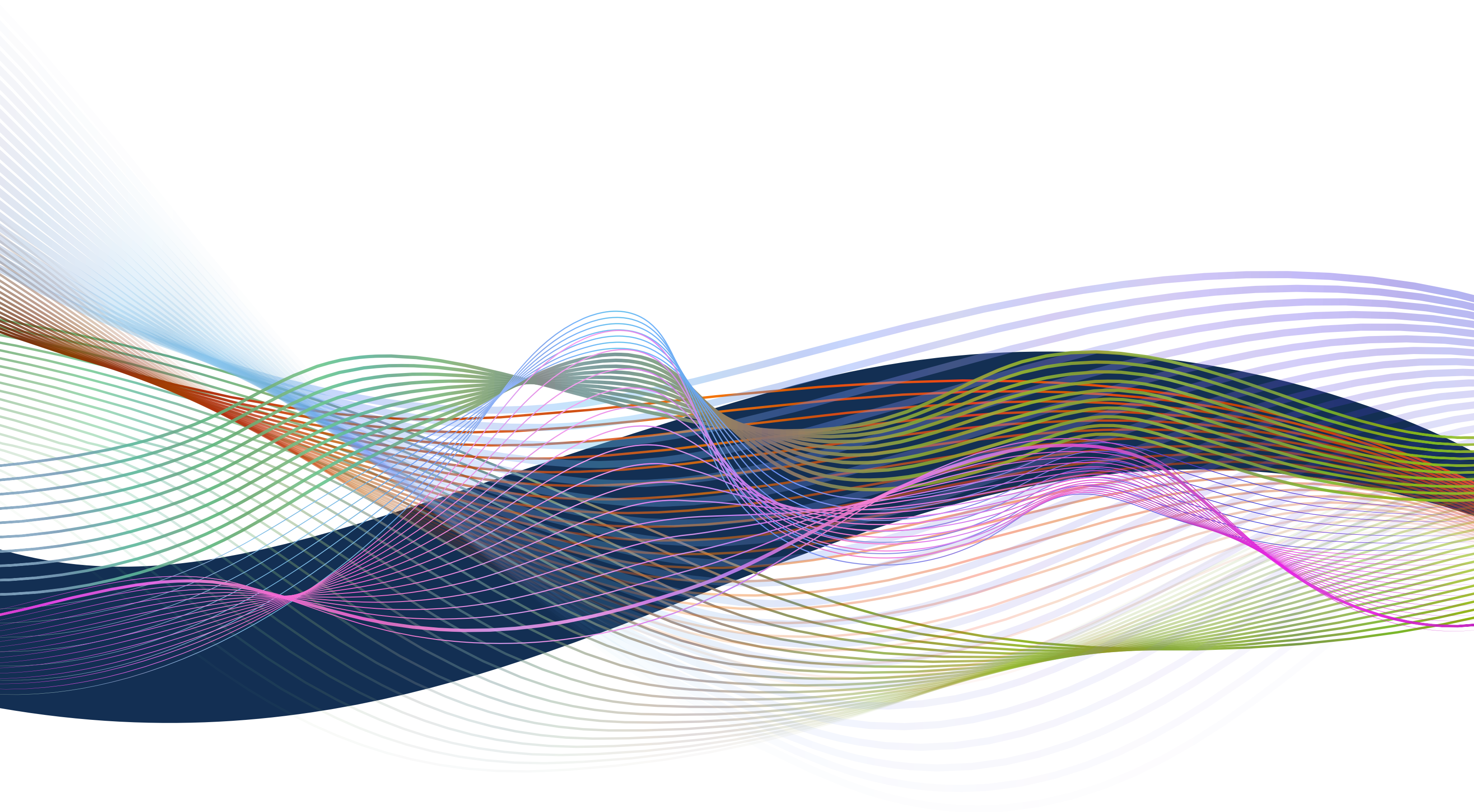


TABLES

PREAMBLE

The World Bank has undertaken analytical work on the prospects of decarbonizing maritime transport. This report *Volume 2: The Role of LNG in the Transition Toward Low- and Zero-Carbon Emission Shipping* outlines this research, and should be read in accompaniment with *Volume 1: The Potential of Zero-Carbon Bunker fuels in Developing Countries,*[1] and *Summary for Policymakers and Industry: Charting a Course for Decarbonizing Maritime Transport.*[2]



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[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. 2021. Summary for Policymakers and Industry: Charting a Course for Decarbonizing Maritime Transport. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/35436 License: CC BY 3.0 IGO.

ACKNOWLEDGEMENTS

The preparation of this report was led by the World Bank, with the expert support of University Maritime Advisory Services.

The World Bank team responsible for this report was led by Dominik Englert and Andrew Losos, and comprised Jennifer Brown, Edoardo Casarotto, Maximilian Debatin, Goran Dominioni, and Nicola Ritsch.

The University Maritime Advisory Services team was led by Tristan Smith, and comprised Carlo Raucci, Chris Thorne, Marie Fricaudet, and Connor Galbraith.

The World Bank Group peer reviewers were Luis Blancas, Alexander Johannes Huurdeman, Ian Twinn. Additional comments and inputs were provided by Mauro Azeredo, Ninan Oommen Biju, Roger Gorham, Stephane Hallegatte, Martin Humphreys, Elif Kiratli, Yin Yin Lam, Susana Moreira, Sergey Mytarev, Gylfi Palsson, and Michael Stanley at the World Bank Group; and by Aoife O'Leary at the Environmental Defense Fund, Peder Osterkamp at the COP26 Climate Champions, Katherine Palmer at Lloyd's Register, Kasper Søgaard at the Global Maritime Forum, Jacopo Tattini at the International Energy Agency.

The World Bank team would like to express its great appreciation to Genevieve Connors, Aurelio Menendez, Alexandrina Platonova-Oquab, and Binyam Reja at the World Bank for their managerial guidance and constructive suggestions during the planning, development and finalization of this research. Their willingness to give their time and support so generously was highly valued.

The World Bank team would also like to thank Dirk Heine for his catalytical role in the Decarbonizing Maritime Transport program at the World Bank. His personal dedication and genuine passion were instrumental in getting the program started.

The World Bank team is particularly grateful to Veronica Gadea and Jeffrey Lawrence at the World Bank for the compelling graphic design.

Funding for this report was provided by the World Bank's Climate Change Group and PROBLUE, an umbrella multi-donor trust fund, administered by the World Bank, that supports the sustainable and integrated development of marine and coastal resources in healthy oceans.

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ABBREVIATIONS

ACRONYM	DEFINITION
BAU	Business as usual
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
DAC	Direct air capture
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EJ	Exajoules
GHG	Greenhouse gas
GWP	Global warming potential
H_2	Hydrogen
HFO	Heavy fuel oil
HPDF	High-pressure injection dual-fuel
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
kt	kilo ton
LBM	Liquefied biomethane
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LSHFO	Low sulfur heavy fuel oil
LSM	Liquefied synthetic methane
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine diesel oil
MJ	Megajoule
mmtpa	Million metric tons per annum
NH_3	Ammonia
N_2O	Nitrous oxide
NO_x	Nitrogen oxide
PM	Particulate matter
RCP	Representative Concentration Pathway
SCR	Selective Catalytic Reduction
SO_x	Sulfur oxide
SMR	Steam Methane Reform
UK	United Kingdom
$	All dollar amounts are US dollars unless otherwise indicated.

EXECUTIVE SUMMARY

LNG AS A BUNKER FUEL

Liquefied natural gas (LNG) used as a bunker fuel has the potential to offer important reductions in atmospheric pollution—that is, air pollutants and greenhouse gas (GHG) emissions—from ships. Compared to traditional oil-derived bunker fuels such as heavy fuel oil (HFO), LNG clearly emits significantly lower quantities of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM). At the same time, it also contains up to 30 percent less carbon per unit of chemical energy (calorific value). Because of this lower carbon content, the use of LNG results in carbon dioxide (CO_2) emissions at combustion that are lower than for traditional oil-derived bunker fuels usually burned in ship engines.

This lower carbon content of LNG allows for a *theoretical* reduction in GHG emissions, yet it remains unclear whether there is a true holistic lifecycle GHG benefit of using LNG relative to oil-derived bunker fuels. The reason for this is that LNG is effectively liquefied methane, and methane is itself a highly potent GHG. Over 20-year and 100-year time horizons, methane is respectively 86 times and 36 times more potent a GHG than CO_2 (IPCC 2013). Therefore, any GHG emissions from unburnt methane released to the atmosphere—called methane leakage or methane slip—can diminish or even entirely offset the theoretical GHG benefit of the use of LNG.

In the current literature, different GHG emissions factors for LNG (depending on the varying methane leakage assumptions applied to LNG production pathways and its use on board vessels) reflect this uncertainty. This leads to a wide range of outcomes in the literature with regard to the GHG benefits from the use of LNG—or disbenefits, if the emissions of methane are assumed to be high. To test the consequences of different scenarios of LNG use, the GHG benefits or disbenefits are not presumed either way. Instead, the consequences of a foreseeable range of methane leakage, GHG emissions, and machinery efficiencies across the lifecycle are analyzed to place bounds on the size of the GHG benefits or disbenefits. These are then discussed in the context of the maritime transport sector's climate targets.

The general uncertainty about LNG's GHG benefits or disbenefits has created tensions within the shipping industry. On the one hand, the use of LNG offers immediate and tangible benefits to air quality. On the other, there are controversies about the capability of LNG to contribute to GHG reductions in both the short and long terms. This report examines those controversies using a combination of literature review, critical analysis of this literature, and new analytical work. The report brings together findings from all these research methods to assess the overall potential and risks of LNG use in shipping. It then uses the findings to identify the likely future role of LNG as a bunker fuel, and the implications of that role for both policymakers and industry.

LNG'S CLIMATE CONUNDRUM

The unresolved question of LNG's lifecycle GHG performance has taken on additional importance with the introduction of the Initial International Maritime Organization (IMO) Strategy on Reduction of GHG Emissions from Ships (known as the "Initial IMO GHG Strategy"). The Initial IMO GHG Strategy, adopted in April 2018, represents the IMO's contribution to the global GHG reductions necessary to achieve the Paris Agreement's temperature goals. The Initial IMO GHG Strategy commits the industry to achieve a minimum 50 percent reduction in the GHG emissions from the international maritime fleet by 2050 relative to a 2008 baseline (IMO 2018b). It also includes the ambition to exceed this target, if possible, by calling for GHG emissions to be phased out as quickly as possible within this century (IMO 2018b). This report's logic is derived from the assumption that the IMO will, at a minimum, achieve the least ambitious interpretation of the Initial IMO GHG Strategy, that is the 50 percent reduction by 2050.

There is a general consensus within the shipping industry that achieving the IMO's climate targets will require significantly limiting the use of fossil fuels, including LNG, and rapidly developing and increasingly using zero-carbon bunker fuels (ICS 2018). Such zero-carbon bunker fuels are expected to emit very low, and ultimately zero, GHG emissions across their full lifecycle, that is production, distribution, and use. If the IMO was to exceed its 2050 climate target, this would effectively rule out all but a small share (for example, 10 percent) of fossil fuel use by mid-century. Consequently, the IMO's climate targets lead to the question whether the shipping industry, as a whole, would be well-advised to further invest in the vessels and supply infrastructure necessary to use LNG at large scale. For the purposes of this report, a large-scale (or significant) uptake of LNG has been defined as greater than 10 percent of the fuel mix in energy terms.

Any major investments in LNG capacity would imply that over the three decades from 2020–2050 the shipping industry would be required to undergo not just one but two major energy transitions: first from oil-derived bunker fuels to LNG, and then from LNG to zero-carbon bunker fuels. This raises the following question: What role is LNG as a bunker fuel likely to play in the years 2020–2050? Or more specifically, will LNG play a "transitional," a "temporary," or a "limited" role in the sector's transition toward low- and zero-carbon shipping? This report seeks to answer this question from the perspective of the shipping industry as a whole, rather than focusing on a particular niche or company.

CURRENT DISCUSSIONS ON LNG'S FUTURE ROLE

Several studies reviewed in the process of compiling this report have examined the potential future role of LNG as a bunker fuel. The literature review highlights the heterogeneity of findings regarding the expected uptake of LNG, both in the short term (up to 2030) and the long term (out to 2050).

There is a lack of consensus in the reviewed literature on the possible role of LNG in the decarbonization of international shipping. Currently, studies can “cherry-pick” from a range of assumptions regarding GHG emissions factors, macroeconomic considerations, technology pathways, and regulatory measures. This selective process can then be used to create seemingly credible narratives for a wide range of LNG uptake outcomes. In reviewing and understanding the assumptions used, this report takes a first step to move beyond the current situation.

The report does not find any clear, strong, and unambiguous short-term drivers which currently point toward LNG's large-scale uptake as a bunker fuel for propulsion purposes. In the short term, the literature suggests, for instance, that the macroeconomic drivers for the uptake of LNG seem uncertain. There may be a present-day price spread between crude oil and natural gas pricing which favors LNG over oil-derived bunker fuels. However, this price spread may or may not remain favorable over the course of this decade or beyond.

Large-scale adoption therefore appears to be at the mercy of the various regulatory mechanisms of the shipping industry. While a review of these regulations identifies some potential drivers for LNG adoption, such as the IMO Sulfur Cap 2020, Emission Control Areas, and the Energy Efficiency Design Index, it also finds that the incentives these policies provide do not appear sufficiently strong to justify expectations of a significant uptake of LNG in the short term.

By far the largest potential policy impact on bunker fuel selection is likely to come from the Initial IMO GHG Strategy and the subsequent detailed policy measures that are to be implemented to achieve the IMO’s climate targets. Following the general consensus in the shipping industry, this report agrees that the Initial IMO GHG Strategy and the IMO’s climate targets are not consistent with the large-scale use of LNG in the long term (ICS 2018, IMO 2018a, GMF 2018). Moreover, this report assumes that the Initial IMO GHG Strategy is also unlikely to be compatible with a significant uptake of LNG in the short term and therefore tests this assumption by analyzing the possibilities of LNG to serve as a “transitional” or “temporary” bunker fuel to meet the IMO’s 2050 climate target.

LNG AS A “TRANSITIONAL” BUNKER FUEL?

To avoid the need for a double investment in zero-carbon fuel supply infrastructure for shipping, proponents of LNG as a transitional fuel often suggest that the infrastructure put in place for LNG could later be reused in a zero-carbon future (“use and reuse”). For example, it could serve compatible drop-in zero-carbon bunker fuels, such as liquefied biomethane (LBM) and green liquefied synthetic methane (LSM). However, this proposition is being increasingly challenged.

While the GHG intensity of LBM and LSM could be consistent with the GHG reduction target set by the Initial IMO GHG Strategy for 2050, there are serious concerns about the availability of sustainably sourced and cost-competitive LBM in a global market where several sectors (for instance, aviation) are likely to compete for the same feedstocks and fuels. Furthermore, the production of LSM appears to remain relatively expensive compared to other zero-carbon bunker fuel alternatives such as ammonia or hydrogen. A parallel review of a large volume of existing literature on alternative zero-carbon bunker fuel options has led to a shortlist of the candidate bunker fuels most likely to dominate the 2040s and 2050s (*Volume 1: The Potential of Zero-Carbon Bunker Fuels in Developing Countries*, see Preamble). Both LBM and LSM variants of natural gas were considered, but consistent with other studies were not found to be economically competitive in the long term.

Overall, the two zero-carbon bunker fuels with the best prospects were found to be ammonia and hydrogen. However, those zero-carbon bunker fuels would require technical infrastructure and onboard technologies that are not aligned with investments in LNG technology and LNG supply infrastructure for shipping. The technical incompatibility of the lower-cost ammonia and hydrogen bunker fuels with LNG assets means that there are significant risks that speak against LNG as a transitional fuel.

LNG AS A “TEMPORARY” BUNKER FUEL?

The existence of significant downside environmental and financial risks, in combination with uncertain upside potential, suggests that it also is unlikely that LNG will play a temporary role in the decarbonization of shipping. In this report, a temporary role refers to a situation where—contrary to a transitional role—investments in LNG-supply infrastructure and LNG-fueled ships are *not* taken advantage of at a second stage where zero-carbon bunker fuels enter the global fleet (“use and stop”). This report provides an analysis and an accompanying reasoning that supports the claim that LNG is not likely to play a temporary role. In particular, it estimates—under idealized conditions—only a moderate, but still uncertain GHG reduction benefit at best. Additionally, it forecasts the need for significant additional capital expenditures to achieve a two-stage conversion (oil to LNG, followed by LNG to zero-carbon) as opposed to a single-stage conversion (oil to zero-carbon only), with the latter implying a limited role for LNG.

This report’s analysis is not intended as a projection of what will happen. It is designed instead to demonstrate the GHG impact that LNG could have when used as a temporary bunker fuel, and to estimate the related cost against a counterfactual scenario in which LNG plays a limited role. This counterfactual scenario is provided by the report *Aggregate investment for the decarbonization of the shipping industry* (UMAS 2020)—see Box 1 for further details. As such, the report examines the impacts of an idealized uptake case for LNG in a world where a very strong commercial driver or regulatory mechanism could effectively mandate its large-scale use. All scenarios used assume that the IMO’s 2050 climate target is met.

BOX 1: NON-LNG DECARBONIZATION COUNTERFACTUAL CASE

In the referenced counterfactual decarbonization trajectory (UMAS 2020), it is assumed that additional policy (for example, a carbon price) will be introduced to incentivize an energy transition of the magnitude that is sufficient to make zero-carbon bunker fuels more competitive relative to fossil fuels. The referenced modelled case evaluates the profit-maximizing solution based on that policy incentive. In such a case, if operators choose to continue using LNG, then on average they will be doing so uncompetitively and with greater total cost of ownership than competitors who operate zero-carbon newbuilds or retrofits.

Comparing the cases assuming LNG's role as a temporary bunker fuel to the counterfactual case, it is estimated that such a two-stage conversion would create a need for additional investments of up to $186 billion during the 2020s (both in the international maritime fleet and on land). It should be noted that these are additional capital expenditures of at least 10-17 percent as shown by Table 1. When these capital flows are discounted to their present value in 2020, using a discount rate of 10 percent, the estimate of the additional capital expenditures associated with a "temporary" use of LNG becomes $98 billion and $82 billion for decarbonization by 2050 and 2070, respectively. As proportions of the discounted total additional capital expenditures for achieving decarbonization, these discounted values then both represent over 30 percent of additional capital expenditures required to achieve full decarbonization. This also indicates the scale of additional capital expenditures investment only, but is not an estimate of the value returned on that investment. Due to the practical limitation imposed by the rate of vessel newbuilds, these investments would lead LNG to capture at most approximately 40 percent in energy terms of the bunker fuel market by 2030.

TABLE 1: ADDITIONAL CAPITAL EXPENDITURES UNDER TWO DECARBONIZATION SCENARIOS FOR A "TEMPORARY ROLE FOR LNG" RELATIVE TO A "LIMITED ROLE FOR LNG"

	DECARBONIZATION BY 2050	DECARBONIZATION BY 2070 (WHILST ACHIEVING A 50 PERCENT GHG REDUCTION BY 2050)
Additional investment in the fleet	$120 billion	$93 billion
Additional investment on land	$66 billion	$76 billion
Total additional investment needed	$186 billion	$169 billion
Total investment needed (as of counterfactual investment)	112-117 percent	110-113 percent

Depending on the methane leakage assumptions used, this market penetration in 2030 would result in either a *peak* GHG benefit of eight percent, or a *peak* disbenefit of nine percent. This would be the case even in an idealized world, with more than significant LNG market uptake and optimistic assumptions regarding LNG's potential for GHG emissions reduction. In any case, the estimated GHG benefits would not be transformative. On the contrary, under less favorable assumptions a significant deployment of LNG would result in even higher GHG emissions than the baseline. That is to say, it remains unclear whether GHG emissions would actually be higher or lower if the industry continued using heavy fuel oil before zero-carbon bunker fuels are scaled up from 2030.

The investment required in these LNG cases would be in addition to the total investments needed to decarbonize shipping in the counterfactual case ($1.0-$1.9 trillion). It would furthermore be required in parts of the industry (that is, fleet and land-side technologies) where the additional LNG investments could not be leveraged or reused for zero-carbon bunker fuels. The temporary use of LNG is, thus, likely to lead to GHG outcomes which may range from moderate GHG benefits to GHG disbenefits—in addition to considerable additional capital expenditures relative to a counterfactual scenario with a rather limited role for LNG.

The analysis also considers the utilization rates of the relatively short-lived LNG assets: if capital of up to $186 billion could be raised, it could likely face significant risks to its return. Of course, capital may be paid off before these risks materialize and before the economic life of the specific LNG asset ends. In this instance, the asset owner may, however, still face residual value or risk other forms of write-down in asset value.

When LNG is expected to play a temporary role in shipping, the demand for LNG (and by association LNG-fueled ships) peaks around the early 2030s and then declines rapidly in a timeframe shorter than the economic life of these assets. One possible consequence of these financial risks could be increased commercial and political pressure to ensure a more gradual phase-out of LNG use and more gradual decline in demand for LNG as a bunker fuel. However, this in turn would create a substantial environmental risk: such technology lock-in could result in large increases in GHG emissions above the declining levels currently required to meet the IMO's 2050 climate target.

This report's modelling therefore reinforces the conclusions from the literature review. The literature review highlights the current lack of a clear, strong, and unambiguous driver for the large-scale uptake of LNG. The analysis based on modelling further concludes that even if a very strong commercial or regulatory driver were present within the shipping industry, the GHG performance and additional capital expenditures of LNG would likely be such as to make significant deployment unattractive from an environmental perspective and with a strong potential to be inefficient from an economic perspective.

A “LIMITED” ROLE FOR LNG AS A BUNKER FUEL

Overall, this report suggests that, even in the short term, LNG may only play a limited role in the decarbonization of the maritime transport sector. A significant transitional role for LNG is mainly jeopardized, amongst other factors, by the questionable supply of sustainably sourced and cost-competitive LBM and LSM. A large-scale temporary role for LNG appears unlikely due to the uncertain GHG benefits, the additional capital expenditures, the risk of stranded assets, and most importantly the risk of a technology lock-in with a GHG emissions trajectory which would be incompatible with the IMO’s 2050 climate target.

Nevertheless, it is possible that some jurisdictions may have a domestic interest to make significant short-term investments in LNG, for instance, to reap the obvious air quality benefits. In such specific cases, the supply and use of LNG could be guaranteed and monitored to show control of unintended methane emissions which would ensure a meaningful GHG benefit relative to conventional oil-derived fuels. Yet there are reasons to believe that these situations may not necessarily materialize because, depending on the technology used on board, the same air pollution benefits can be achieved by zero-carbon bunker fuels, too. There are advantages to addressing both air pollutants and GHG emissions by means of a single solution. This single solution appears particularly relevant as the timescale required for rapidly deploying zero-carbon bunker fuels, that is from 2030 to achieve even the least ambitious interpretation of the Initial IMO GHG Strategy, is short. In any case, at present, these special cases where short-term investments in LNG could be warranted are not expected to create a significant increase in global demand for LNG as a bunker fuel for propulsion purposes.

Consequently, there can be niche circumstances, which are outside of this report’s wider perspective, and which may allow for decisions contrary to the general conclusions. Specific circumstances may speak in favor of niche applications for LNG and against alternative options. These specific circumstances can deviate significantly from the whole-sector assumptions applied in this report and would be related to short-term advantages. Such examples may exist on privileged routes that already benefit from existing LNG terminals at either port, for specific vessel types such as LNG carriers, ferries, cruise ships or coastal vessels, or in special circumstances when there are strong domestic interests as described above.

IMPLICATIONS FOR POLICYMAKERS

As outlined by the Initial IMO GHG Strategy, the shipping industry has firmly committed to reduce and eliminate GHG emissions from ships in line with achieving the Paris Agreement’s temperature goals. In light of this Paris-aligned GHG emissions reduction trajectory, the uncertainties surrounding the GHG benefits of LNG suggest that new public policy support for LNG as a bunker fuel should be avoided. This relates, for example, to policy that provides a regulatory advantage to LNG over oil-derived alternatives in shipping. Furthermore, the same reasoning also suggests that existing policy support for LNG as a bunker fuel should be curtailed. In this regard, the sector's current Energy Efficiency Design Index, for instance, exclusively focuses on downstream CO_2 emissions (that is, due to combustion on board), thereby disregarding any upstream or midstream CO_2 emissions (that is, due to extraction and distribution, respectively) or any non-CO_2 GHG emissions such as methane.

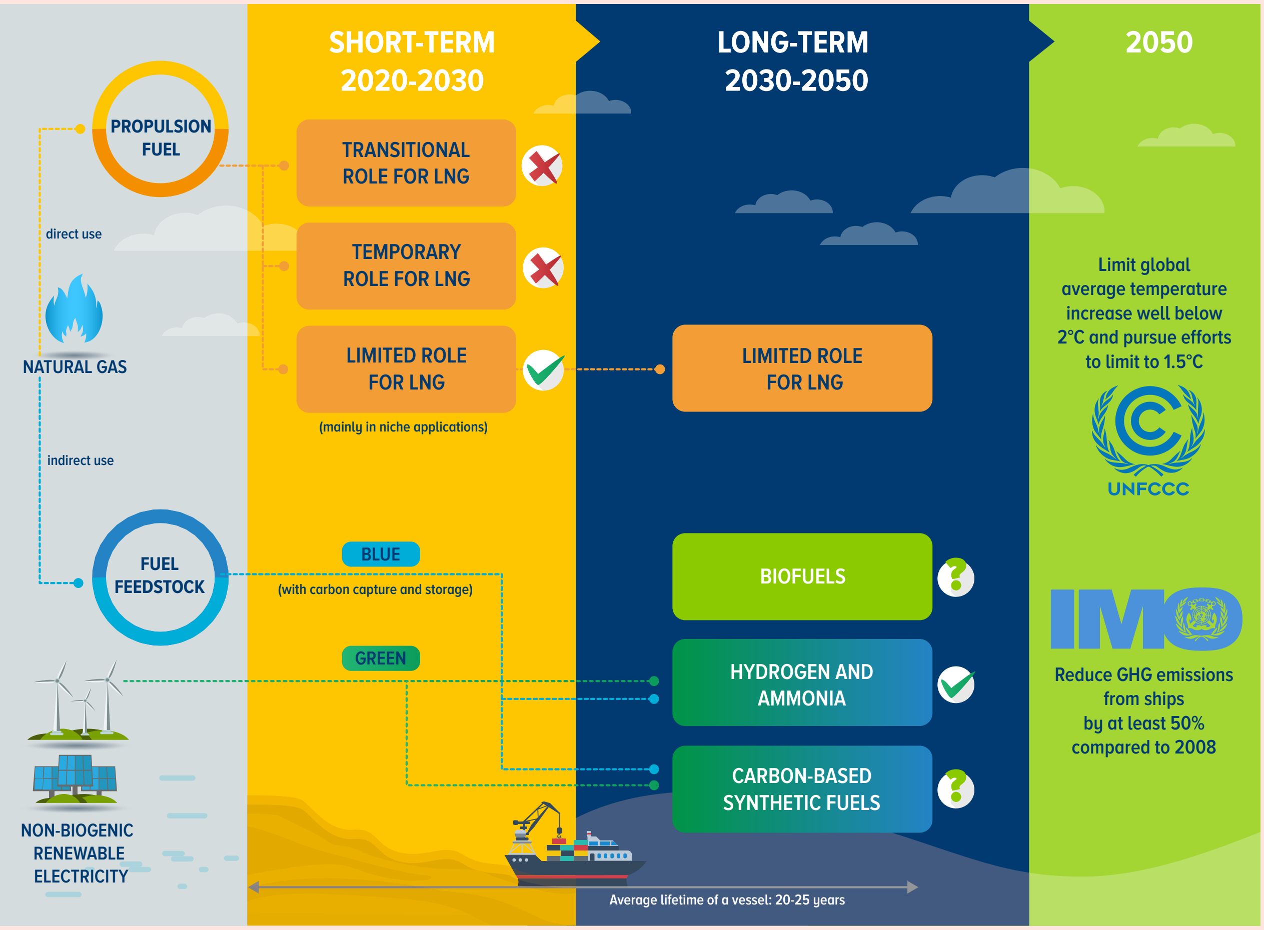
The report highlights the need for urgent and strong policy action to regulate methane emissions both in the supply chain of LNG and in its use on board existing ships and any newbuilds. This will be important regardless of whether LNG becomes a significant bunker fuel or not. For example, although downstream methane emissions could be reduced using newer machinery with lower methane slip levels, this would still not address the risk of upstream and midstream methane emissions in the supply chain. These 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 and distributed. Many of these jurisdictions suffer from generally low regulatory enforcement levels (World Justice Project 2020). However, the increasing public scrutiny questioning the true lifecycle GHG emissions of any fuel used in a decarbonizing world is likely to incentivize such enhanced regulation, too.

Regulating methane is also important to ensure that shipping's existing LNG assets and any that may be built because of commercial-case justification in the short term are effectively shielded from the risk of increased lifecycle GHG emissions relative to conventional oil-derived bunker fuels, and are enabled to maximize their potential social benefits (for air quality in particular). The need for stringent policy to avoid this risk becomes even more important if the actual energy transition in shipping from fossil bunker fuels to zero-carbon bunker fuels were to happen more slowly than anticipated in this report.

The report also presents a strong recommendation to focus public support on the development of policy that effectively accelerates the research, development, and deployment of zero-carbon bunker fuels. Such policies would send another clear signal with respect to LNG's future role, and help mitigate the risks associated with a significant future uptake of LNG.

Finally, the parallel analysis of zero-carbon bunker fuels finds that the most promising candidate options will require zero-carbon hydrogen as a feedstock (*Volume 1*, see Preamble). There are two major production pathways for producing such hydrogen: the first one uses electrolysis powered by 100 percent non-biogenic renewable electricity to produce "green" hydrogen; the second involves using natural gas in conjunction with nearly 100 percent carbon capture and storage to produce "blue" hydrogen. Therefore, in contrast to LNG's direct use as a bunker fuel for propulsion purposes, it is quite possible that natural gas could play an important role in shipping's decarbonization as a feedstock for the production of zero-carbon bunker fuels such as blue hydrogen, as illustrated in Figure 1. More information on zero-carbon bunker fuels in general, and blue hydrogen specifically, can be found in the related *Volume 1* (see Preamble).

FIGURE 1: SUMMARY OF CONCLUSIONS FOR THE ROLE FOR LNG AS A BUNKER FUEL, AND AS A FUEL FEEDSTOCK



Policies to support zero-carbon bunker fuels as mentioned above are advantageous because these are long-term solutions that can solve both the GHG and air pollution reduction challenges faced by shipping. As always, any policy that can provide regulatory clarity and consistency will help industry to make more certain long-term decisions about shipping's decarbonization.

IMPLICATIONS FOR INDUSTRY

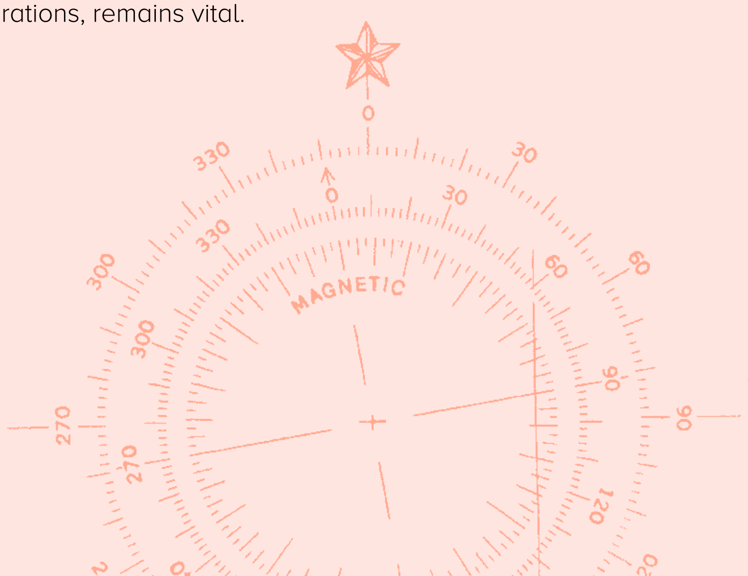
Shipping's decarbonization is not driven by public policy alone. It is also driven by owners, fuel suppliers, financiers, and shareholders managing their own exposure to climate-related investment risks, and by clients and consumers looking to decarbonize their wider scopes of emissions. Making overt decisions contrary to the logical pathway for shipping's decarbonization can therefore pose risks both to compliance with more and more stringent policies implemented in line with the

Paris Agreement's temperature goals, but also in terms of future access to financial capital and market share.

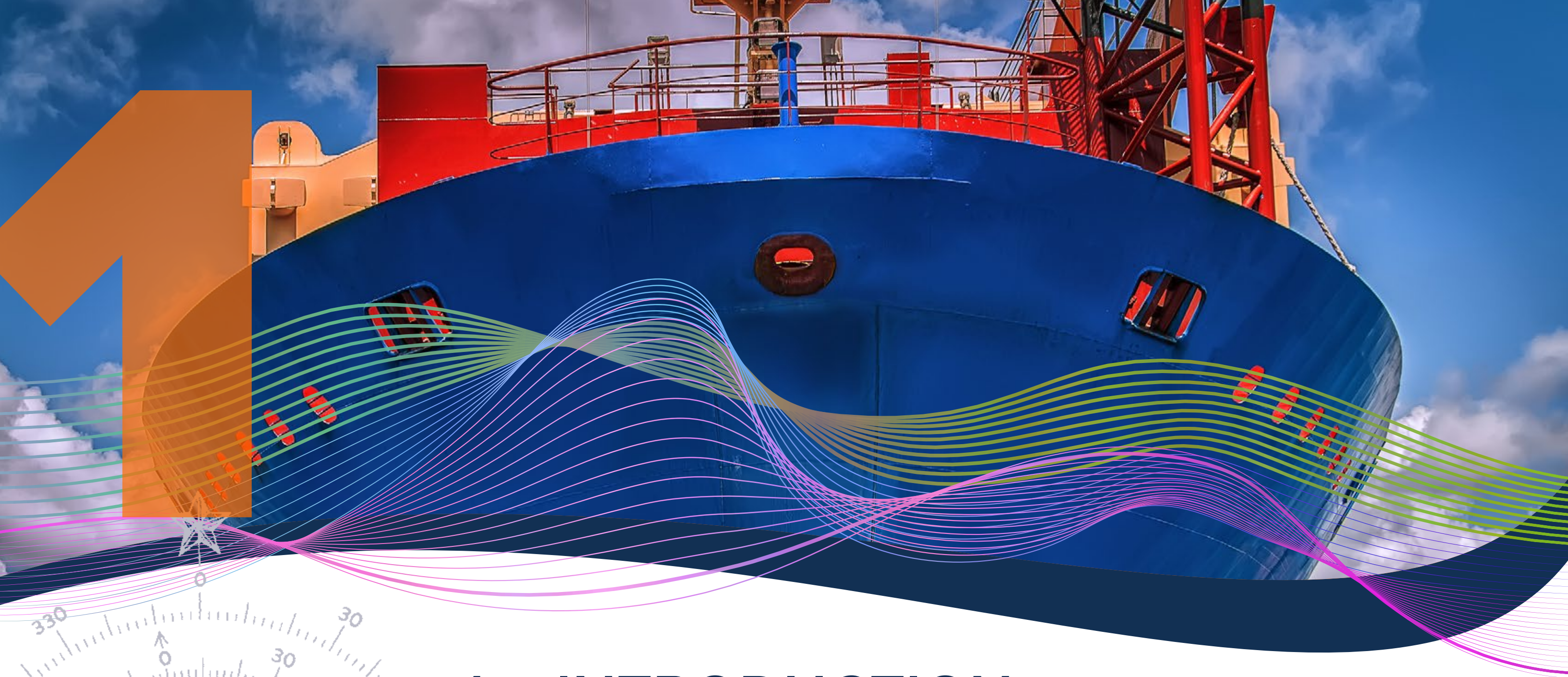
The analysis in this report concludes that LNG is likely to have a limited role as a bunker fuel, with any demand for LNG rapidly declining after 2030. Therefore, to minimize the potential loss of returns, industry stakeholders should consider LNG's questionable long-term competitiveness as a bunker fuel when developing their future business strategies. Furthermore, in light of a world with more and more commitments by public and private players to net zero GHG emissions by mid-century, industry stakeholders should also take into consideration the evolving climate policy landscape and the rising societal pressure in and outside the shipping sector when counting on a significant uptake of LNG as a bunker fuel. Niche-market investments in LNG are likely to face increasing headwinds through the course of the 2020s in such a context.

The current uncertainty within the industry, which does not know for certain yet which specific future zero-carbon bunker fuels to invest in, is understandable. The resulting hesitance in terms of investment decisions is reflected in the current orderbooks for new vessels, where global orders have recently been at the lowest level observed since 1989 (Clarksons Research 2020). While major businesses are already announcing their favored zero-carbon shipping solutions all industry — especially the ones with a lower risk appetite—are well advised to opt for the following: investing in increased energy efficiency and remaining flexible on other investments' compatibility with multiple zero-carbon candidate bunker fuels. Investments in increased energy efficiency represent "no-regret" investments which will benefit any kind of future bunker fuels. Flexibility in ship design will allow using oil-derived bunker fuels up to the moment when the fuel supply can be more confidently switched to zero-carbon bunker fuels. This flexibility can be achieved, for instance, through installing fuel storage and fuel handling equipment that will be compatible with a maximum number of emerging zero-carbon bunker fuels—most likely ammonia and hydrogen (*Volume 1*, see Preamble).

Just as for policymakers, all these current decisions faced by industry will be easier to resolve when there is greater certainty on the availability, prices, and timing of non-oil-derived bunker fuels. Working toward increased clarity through constructive support of the policy development processes, and through multi-stakeholder collaborations, remains vital.




SAFETY FIRST
NO SMOKING



1. INTRODUCTION

Liquefied natural gas (LNG) is viewed by many stakeholders in the maritime transport sector as a potential alternative to conventional oil-derived bunker fuels such as the predominant heavy fuel oil (HFO). Increasing attention has been directed to its deployment in recent years, partly as a consequence of the International Maritime Organization's (IMO) 0.5 percent sulfur emission capping regulation, called "IMO Sulfur Cap 2020", which came into force in 2020 (IMO 2016). The use of LNG rather than HFO can result in significant reductions of sulfur oxides (SO_x) emissions of up to 100 percent, and reductions in nitrogen oxides (NO_x) emissions and in particulate matter (PM) of up to 90 percent (Kristensen 2010). These emissions are collectively referred to as "air pollutant" emissions and are associated with a multitude of negative environmental and health impacts. The impacts include increased premature death rates or reduced crop yields. Shipping emits around 15 percent and 13 percent of all SO_x and NO_x, respectively (IMO 2014). These emissions, combined with a number of other air pollutants such as PM, led shipping to be held responsible for 15 percent of global premature deaths from air pollution— or 60,000 in absolute numbers— in 2015 (ICCT 2019).

Due to lower SO_x, NO_x, and PM emissions, decades-long debates about air pollution and sulfur regulation have promoted the consideration of LNG as a beneficial alternative to HFO. In 2005, these debates and other environmental concerns resulted in the passage of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) which limits, amongst others, SO_x and NO_x emissions from ship exhaust and prohibits deliberate emissions of ozone-depleting substances. The Annex also sets designated Emission Control Areas and more stringent standards for SO_x, NO_x, and PM. Partly as a consequence of this, the sector has built significant experience in handling and using LNG as a cost-effective bunker fuel. LNG, including when it is carried as a cargo and the boil-off from that cargo is combusted, currently represents approximately 3.3 percent of overall energy use in shipping (IMO 2020).

More recently, the debate has culminated in the IMO Sulfur Cap 2020 regulation mentioned above. The 15-year drive for lower air pollutant emissions has created an opportunity for fossil bunker fuels which are cleaner than the incumbent HFO. Current alternatives include LNG, liquefied petroleum gas (LPG), low sulfur heavy fuel oil (LSHFO), and marine diesel oil (MDO), each with different advantages and disadvantages, different implications for the specification, cost and operation of machinery onboard, and different price points and availabilities. For example, it still remains difficult to abate PM emissions from LSHFO or MDO, even if the currently available emissions reduction technologies are fully applied (Lehtoranta et al., 2019).

BOX 2: LIQUEFIED NATURAL GAS (LNG)

LNG, as the name suggests, is a liquefied form of natural gas. Fossil natural gas is extracted from geological features and liquefied to increase its volumetric energy density. This increased density allows LNG to be transported economically on board LNG tanker vessels and distributed around the globe. LNG is a globally traded commodity used across a vast range of energy-intensive sectors.

LNG is a cryogenic liquid stored at approximately -162 degrees Celsius. It therefore requires heavily insulated tanks for storage, and, in some instances, active cooling or re-liquefaction plants. Even in its liquid state, LNG is less energy-dense than oil-derived bunker fuels when assessed on a volume basis.

A further benefit of LNG compared to traditional oil-derived bunker fuels is its relative carbon efficiency. LNG contains up to 30 percent less carbon per unit of chemical energy (calorific value) than the various oil-derived fuels. This gives LNG a theoretical greenhouse gas (GHG) emissions benefit relative to traditional oil-derived bunker fuels. In the maritime transport sector, the GHG performance of bunker fuels has gained more attention due to the IMO's Energy Efficiency Design Index (EEDI) regulation, which mandates energy efficiency measures aimed at reducing GHG emissions from ships.[3] In combination with the significant air pollution benefits, and the framing of EEDI on operational carbon dioxide (CO_2) emissions only, the theoretical GHG benefit of LNG has resulted in further renewed interest in LNG as a bunker fuel.

However, whether the theoretical GHG benefit of LNG can be fully realized in practice remains controversial. LNG is effectively liquefied methane, and methane itself is a GHG which is 86 times more potent than CO_2 over a 20-year period and 36 times over a 100-year time horizon (IPCC 2013). Any emissions of unburnt methane that evaporate into the atmosphere could therefore offset the theoretical climate benefit of burning LNG and could in some cases cause higher total GHG emissions than the use of traditional oil-derived bunker fuels.

The evasion of unburnt methane to the atmosphere—known as "methane leakage or methane slip" —can occur at any point in the fuel's lifecycle, including extraction, processing, transportation, refueling, and combustion in the vessel's internal

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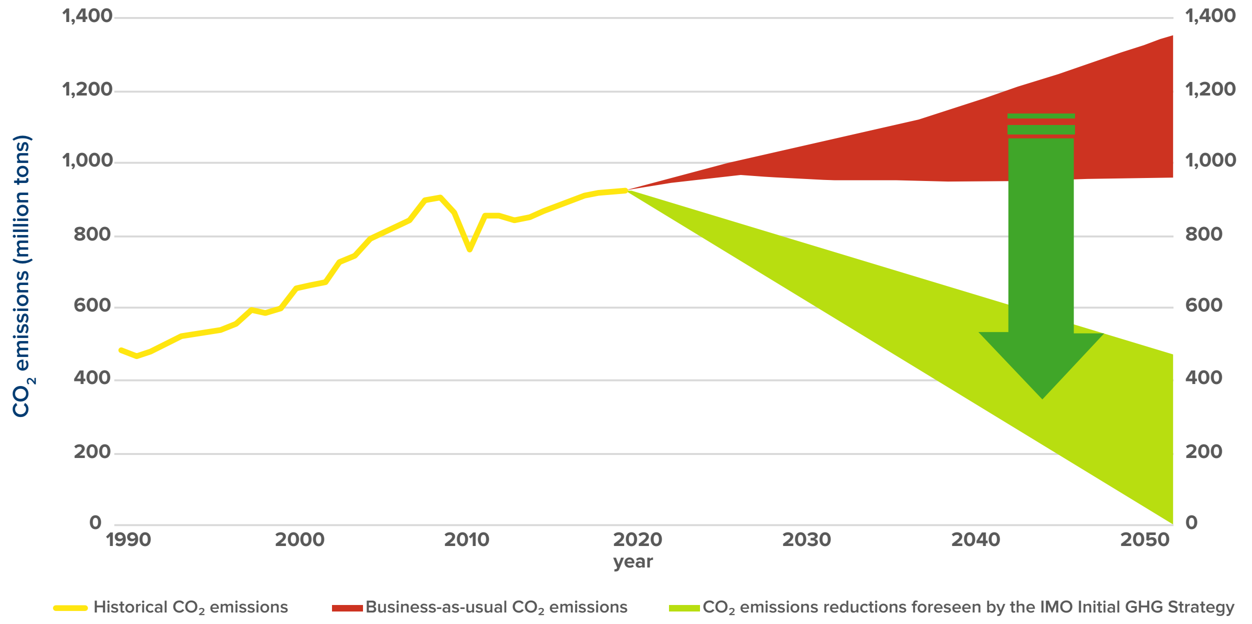
[3] EEDI is part of the IMO's MARPOL regulation (chapter adopted in 2011).

combustion engine. Estimates of methane leakage range widely, with some papers finding an overall 21 percent reduction in GHG emissions (Thinkstep 2019) while others show, in some scenarios, a slight increase on a 100-year Global Warming Potential (GWP) basis (ICCT 2020), always relative to oil-derived fuels.[4]

This uncertainty over the size and direction of the effect of LNG use on GHG emissions has created considerable tension within the maritime industry. On the one hand, the use of LNG clearly results in immediate benefits to air quality and sulfur compliance. On the other, there is concern over the capacity of LNG to reduce net GHG emissions both in the short term and the longer term.

This concern has gained salience following the announcement of the Initial IMO GHG Strategy, which represents the IMO's pledged contribution to the global GHG reductions required to achieve the Paris Agreement's temperature goals (UNFCCC 2016). As shown by Figure 2, the Initial IMO GHG Strategy commits to a minimum 50 percent reduction in GHG emissions from the international maritime fleet by 2050 relative to a 2008 baseline, with the stated ambition of exceeding this reduction, if possible (IMO 2018b). The Initial IMO GHG Strategy also calls for the phasing out of GHG emissions entirely as quickly as possible within this century (IMO 2018b).

FIGURE 2: HISTORICAL AND PROJECTED CO_2 EMISSIONS FROM INTERNATIONAL SHIPPING



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

These targets, in combination with further expected growth in maritime trade and transport, mean that the large-scale use of LNG, a fossil fuel, for ship-propulsion

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[4] In the Thinkstep reference, the 21 percent benefit is achieved for a 2-stroke internal combustion engine with HFO as a reference fuel. A lower benefit is achieved for a 4-stroke internal combustion engine referencing HFO fuel (15 percent), and the GHG benefit is further lowered when comparing against MDO fuel. Detailed discussions of different assumptions in different reports is given in section 2.2.1.

purposes risks being neither consistent nor compatible with the Initial IMO GHG Strategy, and that any use of LNG in the short term must be phased out in the longer term if the IMO's climate targets are to be achieved. Achieving IMO's climate targets will require zero-carbon bunker fuels, at least in the long term, estimated in this report to be from 2030 onwards (see Appendix A).

BOX 3: ZERO-CARBON BUNKER FUELS

This report discusses the use of "zero-carbon" bunker fuels as an essential step in achieving the climate targets of the Initial IMO GHG Strategy. In the context of this report, the general term "zero-carbon" refers to bunker fuels that emit very low, and ultimately zero, GHG emissions (including CO_2 and methane) across their full lifecycle, that is production, distribution, and use. Zero-carbon bunker fuels can be either "effectively" zero or "net-zero" carbon fuels.

An "effectively" zero-carbon bunker fuel is produced using zero-carbon electricity (for example, electricity produced from renewable energy or from natural gas combined with carbon capture and storage (CCS)), thereby avoiding GHG emissions altogether. Within this context, hydrogen (H_2) and ammonia (NH_3), for instance, can represent such zero-carbon bunker fuels. If produced with zero-carbon electricity or natural gas with CCS, they emit no CO_2 across their full lifecycle, including their use in the propulsion machinery on board the ship.

A "net-zero" bunker fuel is one where its production removes a quantity of CO_2 from the atmosphere which is equivalent to that emitted during combustion. For example, both liquefied biomethane (LBM) and green liquefied synthetic methane (LSM) can represent net-zero carbon bunker fuels. They do emit CO_2 during their use in the propulsion machinery on board the ship. However, since they also retrieve CO_2 from the atmosphere during their production (for instance, the growth of biogenic feedstock for LBM or the direct air capture of CO_2 from the atmosphere for LSM), they can be labelled as net zero-carbon bunker fuels.

Both categories may emit small amounts of GHG emissions in their respective upstream processes (for example, land use, harvesting, refining, transport, or processing to capture and store CO_2). As such, the term "zero" is used to label fuels that have a small enough overall GHG impact that they are capable of delivering the IMO's minimum target of a 50 percent absolute reduction by 2050 even when considering these lifecycle GHG emissions, and that with strict management of upstream (mostly land-side) GHG emissions can achieve a complete 100 percent GHG reduction. This consideration of upstream GHG emissions is particularly relevant when natural gas may be used as a feedstock for some zero-carbon bunker fuels initially, and emphasizes the importance of applying a full lifecycle GHG perspective to both fossil and zero-carbon bunker fuels.

More information on zero-carbon bunker fuels can be found in the related *Volume 1: The Potential of Zero-Carbon bunker Fuels in Developing Countries* (see Preamble).

While relying exclusively on LNG as a significant bunker fuel will not be consistent with the IMO's climate targets due to LNG's limited GHG reduction potential, there is an important debate about what short-term role (up to 2030), if any, LNG could play in driving maritime transport sector's decarbonization. Various factors are considered in this debate, including the uncertain GHG effects and the certain air quality and sulfur compliance benefits of LNG use.

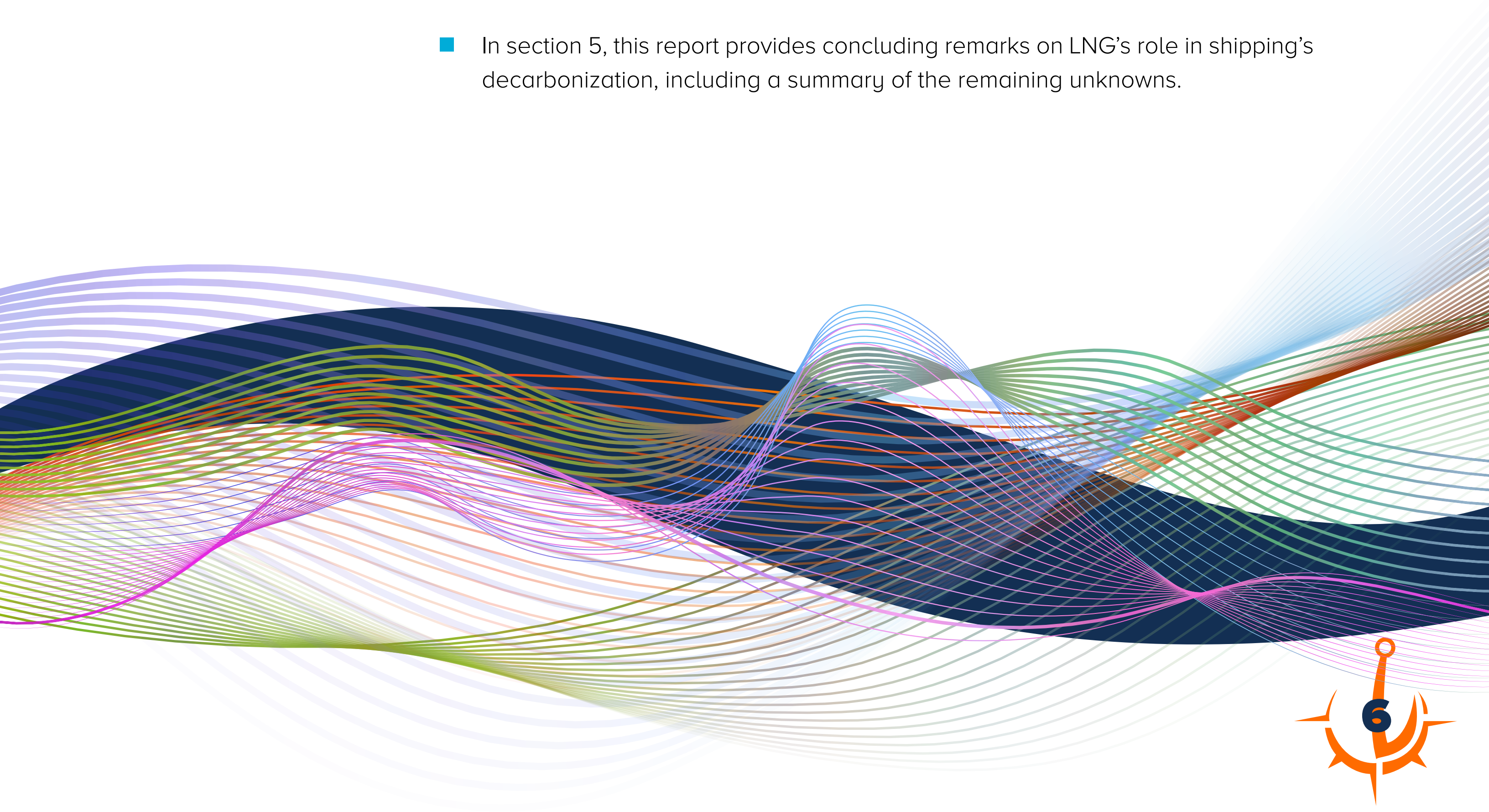
Broadly speaking, maritime industry stakeholders take three basic positions today. This report builds on these positions to carry out a scenario analysis, and thus refers to them as potential "Futures":

1. **Future 1: A transitional role for LNG – "Use and reuse":** Some stakeholders see a transitional role for LNG where investment in supply infrastructure and LNG-fueled ships is paid off by reusing these assets with compatible zero-carbon bunker fuels. For instance, this compatibility with specific zero-carbon bunker fuels would allow for the reuse of the same transport, refueling, and vessel investments originally deployed for fossil-derived LNG. While LBM or green LSM are straightforwardly LNG-compatible (with no or very minor modifications to current LNG specifications), zero-carbon bunker fuels such as hydrogen or ammonia would not be compatible. In this Future 1, the IMO's climate targets are achieved through energy efficiency measures and a shift to LNG-compatible zero-carbon bunker fuels. Alternatively, they could be achieved by retrofitting, at an acceptable cost, supply infrastructure and LNG-fueled ships to use other zero-carbon bunker fuels (DNV GL 2019).
2. **Future 2: A temporary role for LNG – "Use and then stop":** Other stakeholders foresee a temporary role for LNG. In this scenario, fossil-derived LNG could help reduce air pollutant emissions and make some contribution toward GHG emission reductions in the immediate future before zero-carbon bunker fuels become widely available. LNG would be rapidly superseded when those zero-carbon energy sources become available at scale, especially after 2030 (Baresic et al. 2018; ICCT 2020; Lloyd's Register and UMAS 2019).
3. **Future 3: A limited role for LNG – "Limited use overall":** Finally, a third group of stakeholders recommends against using LNG as a bunker fuel for shipping except in niche applications where it is already in use or in circumstances where there is a particularly strong justification. Often studies making this recommendation avoid using LNG as a bunker fuel directly for propulsion purposes. However, they do consider using natural gas as an energy source (in combination with CCS) to produce zero-carbon bunker fuels, for example hydrogen and ammonia (Lloyd's Register and UMAS 2019; Imhof 2019).

Each of these futures requires investments in different land-based infrastructure and vessels, leading to different potential risks for investors. For instance, any investment in short-term LNG infrastructure would be at risk of being superseded by non-compatible zero-carbon alternatives before the assets reach the end of their economic lives and payback periods. Understanding these potential futures and the factors that influence them, therefore, appears critical to avoiding negative financial and environmental consequences.

This report seeks to clarify LNG's potential role as a bunker fuel in efforts to achieve the climate targets set by the Initial IMO GHG Strategy.

- In section 2, the report first provides an updated literature review, including a summary of the main differences between the studies. The section finds that environmental, macroeconomic, technological, and regulatory factors currently provide rather weak incentives for a significant uptake of LNG in the short term.
- In section 3, the report suggests further that the future supply of LNG-compatible zero-carbon bunker fuels is not expected to be able to satisfy the overall demand for energy from the shipping sector. Together with the weak incentives for significant uptake of LNG, these quantity and price challenges make it unlikely that LNG will play a transitional role in the decarbonization of shipping (Future 1: "Transitional role for LNG").
- In section 4, this report employs a holistic model of the international maritime fleet to quantify the economic and environmental consequences of using LNG as a temporary fuel in the short term (Future 2: "Temporary role for LNG"), before shifting to a non-compatible alternative zero-carbon energy source such as hydrogen or ammonia at some point. This analysis finds that the temporary use of LNG may have an uncertain effect on GHG emissions, ranging from a moderate decrease to a moderate increase. In addition, a large-scale uptake of LNG would likely require substantial additional capital expenditures, and may result in severe financial risks associated with investments in LNG. Overall, this analysis suggests that the use of LNG as a temporary fuel may not be likely, either.
- In section 5, this report provides concluding remarks on LNG's role in shipping's decarbonization, including a summary of the remaining unknowns.



2. LNG'S POTENTIAL AS A BUNKER FUEL

Several studies have analyzed the potential of liquefied natural gas (LNG) as a bunker fuel using different approaches and modelling assumptions. Sub-section 2.1 highlights the differences in projections for the uptake of LNG in shipping across the literature. To show where the sources of uncertainty lie, sub-section 2.2 looks at the differences in assumptions across greenhouse gas (GHG) impacts, macroeconomic considerations, technological requirements, and regulatory measures.

For the purposes of this report, a significant uptake of LNG or LNG as a large-scale bunker fuel are both used synonymously and have been defined as greater than 10 percent of the fuel mix in energy terms.

2.1 LNG UPTAKE PROJECTIONS

This section reviews the state-of-the-art literature on LNG uptake projections. The majority of the uptake projection studies that were reviewed estimate an increase in the use of LNG on board vessels in the coming decades. However, under a decarbonization scenario compliant with the IMO Initial GHG Strategy, the studies also conclude that there will be a shift to one or more zero-carbon energy sources before 2050. The studies reviewed either assume a "transitional" role, where fossil fuel-derived LNG is substituted with either liquefied biomethane (LBM) or liquefied synthetic methane (LSM), or a "temporary" role for LNG, with a future shift toward zero-carbon alternatives such as ammonia or hydrogen, or some combination of both.

2.1.1 Performance of LNG projections relative to historical evidence

The real number of LNG-fueled vessels in operation and on order varies drastically from the early LNG-fueled vessel predictions. In 2015, 63 LNG-fueled ships were in operation, with a further 76 LNG-fueled ships on order (DNV GL 2015). This increased moderately to 175 LNG-fueled ships in operation and 232 LNG-fueled ships on order by 2020 only, despite the IMO 2020 Sulfur Cap regulation and a decade of falling natural gas prices.[5]

The actual uptake of LNG-fueled vessels is extremely modest compared to early predictions forecasting rapid LNG-fueled vessel growth. For example, DNV GL in 2012 predicted that there would be over 1,000 LNG fueled vessels by 2020 (DNV 2012). This forecast was later revised down to between 400-600 LNG-fueled vessels in operation by 2020 due to low oil prices and the slower-than-expected development of bunkering infrastructure cited as key reasons (Oxford Institute for Energy Studies 2018). Furthermore, Lloyd's Register (2012) forecasted that between 100-500 LNG-fueled vessels would be in operation by 2020 under their base case scenario and high case scenario. This divergence on LNG-fueled ships' expected growth compared to reality demonstrates that predictions estimating LNG's future role as a bunker fuel are often overestimated.

2.1.2 Short-term projections (up to 2030)

Looking at the current LNG-fueled maritime fleet and the current order book to predict the evolution of the fleet appears to be the best way to compare the short-term model projections proposed in the literature with actual data from the commercial markets.

The order book shows ships which will be launched and enter into service within approximately three years. In practice, unreported orders, modifications, and cancellations can result in the order book differing from actual outcomes. Still, reference to the order book provides a reasonable means of estimating the fleet composition in the very near term, and therefore a credible basis for projections to 2025.

Maritime Strategies International (MSI 2019) provides a benchmark for short-term model projections, as it predicts the evolution of a LNG-fueled maritime fleet up to 2025 by considering the current LNG-fueled fleet and order book. The analysis does not include LNG carriers which often use the boil-off from cargo as an energy source, because these do not constitute sales of LNG as a bunker fuel and are not indicative of the fuel's potential in the wider fleet. According to this study, LNG-fueled vessels account for ten percent of the order book for vessels over 10,000

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[5] 2020 figures were taken from SEA-LNG Bunker Navigator on 31 December 2020. Available at: https://sea-lng.org/why-lng/global-fleet/. Furthermore, the majority of the LNG-fueled vessels in operation are ferries, offshore supply ships, chemical tankers, and gas tankers. However, crude oil tankers, container ships, cruise ships and oil/chemical tankers represent more than 60 percent of future orders for LNG-fuel (DNV Alternative Fuel Insight 2020).

gross tons. An additional 15 percent are “LNG-ready” as they have anticipated conversion to being LNG-fueled but will need a technical retrofit to achieve this. The projection shows that by 2025, excluding cases where the cargo is consumed onboard LNG carriers, sales of LNG as a bunker fuel may attain a total market share of two percent in energy terms,[6] representing the consumption of some 7 to 9 million tons of LNG per year. By assuming that all of the “LNG ready” maritime fleet is converted to run on LNG prior to 2025, the LNG fuel market would increase to 10 to 11 million tons per year, representing a 3 percent market share in bunker fuel sales on an energy basis in 2025.

FIGURE 3: ESTIMATED LNG UPTAKE BY 2025 AND 2030, PERCENT OF FUEL DEMAND[7]

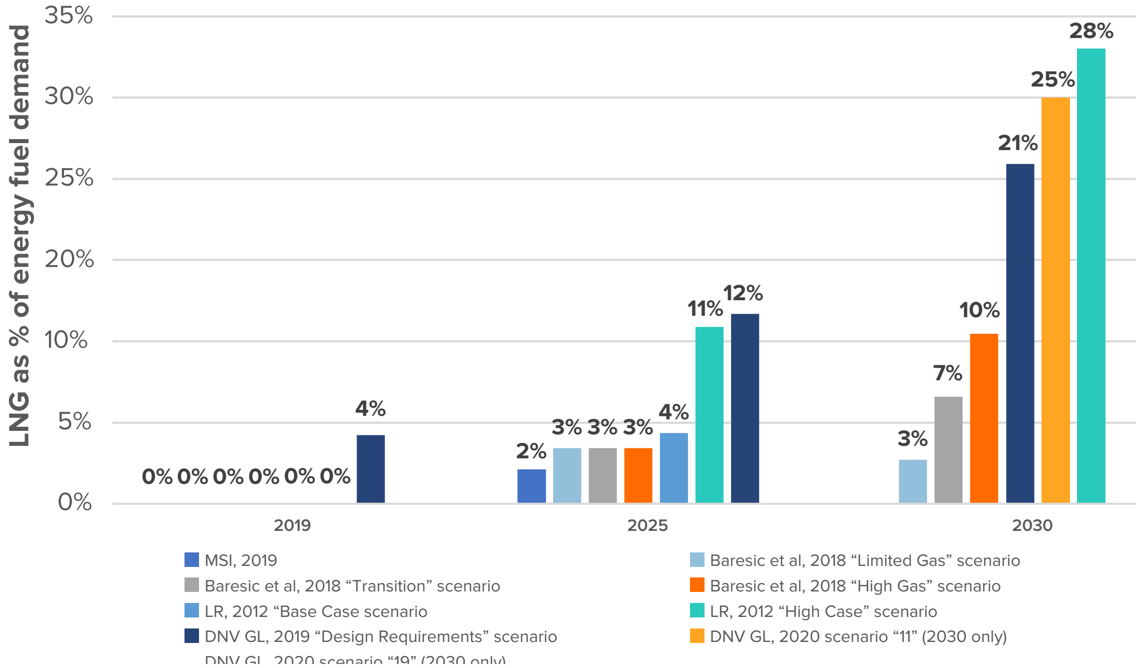

Figure 3 compares various LNG uptake projections found in the literature with those estimated by MSI in 2019 and 2025.[8] Based on these findings, DNV GL (2019) appears likely to be overestimating LNG demand in the near term (12 percent in 2025, compared with about 2 to 3 percent in 2025 from MSI—even when taking into account the omission of LNG carriers in the MSI numbers). DNV GL’s projection of 21 percent uptake by 2030 is also significantly higher than the projections from the other studies reviewed. When considered in combination, DNV (2012) and DNV GL (2019) show similar levels of overestimation relative to what has happened, or is happening, with regard to the uptake of LNG as a bunker fuel.

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[6] Calculated based on data provided in MSI 2019; excluding LNG carriers.

[7] The graph has been constructed using data in the text and in figures provided by the referred articles. Data for MSI 2019 and Lloyd’s Register 2012 were originally expressed in shares of demand expressed in million tons per year. They have been converted to shares of demand expressed in energy terms by using the following fuel densities: 55,000 MJ/t for LNG, and 40,490 MJ/t for HFO/LSHFO (it was assumed that the remaining demand in 2019 and 2025 was covered by HFO and LSHFO). In 2019, LNG share is less than one percent but reported in all the studies. Only Baresic et al. (2018), DNV GL (2019), and DNV GL (2020b) provide an estimate of LNG uptake in 2030.

[8] When share of fuel demand was not directly provided in the reports, they have been estimated based on the data provided in the reports.

In mid-2020, DNV GL provided further insight on their 2030 fuel demand projections. DNV GL (2020b) used 30 distinct scenarios across a range of decarbonization ambitions, shipping demands, and fuel prices. In this report, DNV GL gives a 2030 estimate for LNG as a percentage of marine energy demand for two scenarios (scenarios 11 and 19). These scenarios have different decarbonization pathways, fleet growth projections, and fuel price assumptions. However, both scenarios exhibit similar 2030 LNG penetration estimates, with 25 percent and 28 percent of maritime energy use, respectively. The result is a projected penetration of LNG uptake in 2030 that is broadly similar to the DNV GL's work from 2019. More broadly, this general comparison suggests that there is a considerable degree of uncertainty in short-term LNG projections (2020 to 2030).

2.1.3 Long-term projections (up to 2050)

The IMO Third Greenhouse Gas Study (2014) presents two pathways for LNG bunker fuel use in 2050. However, neither scenario that these pathways are derived from would enable the international shipping sector to comply with the IMO's decarbonization target (2018b). One pathway projects LNG attaining an 8 percent market share by 2050; the other projects a 25 percent market share in the same year. A particularly pertinent result from this study is the suggestion that efficiency improvements would provide a considerably larger reduction in GHG emissions than would a greater degree of LNG penetration. The IMO Fourth Greenhouse Gas Study (2020) incorporates two scenarios for the penetration of alternative bunker fuels. These alternative bunker fuels include LNG, methanol, and ethanol for instance. In the lower bound estimate, these fuels have no penetration by 2050. In the upper bound estimate, these fuels are found to be used by 20 percent of the fleet by 2050. However, no distinction is provided on the share of LNG-fueled shipping relative to the use of methanol and ethanol within that percentage. For that reason, this reference is not used further to understand the potential role of LNG.

In 2018, UMAS published a report that detailed four LNG uptake scenarios for shipping within the European Union by 2050, using the holistic shipping industry model Global Transport Model (GloTraM) (Baresic et al. 2018). These scenarios seek to cover the full range of decarbonization ambition represented by the IMO's commitment to a 50 to 100 percent GHG reduction by 2050, allowing a part of the GHG emissions to be offset in other non-shipping sectors. The report considers the following scenarios:

- "High gas", where low LNG prices are coupled with low penetration by other alternative fuels and significant use of carbon offsetting. This scenario projects LNG penetration of 61 percent of total fuel demand by 2050.
- "Transition", which entails a more limited use of carbon offsetting but with the increased use of hydrogen. The LNG penetration in 2050 under this scenario is 11 percent.

- “Limited gas”, with higher LNG prices and higher biofuel availability. The LNG penetration in 2050 under this scenario is 3 percent.

- “Business as Usual” (BAU), a scenario that did not achieve the decarbonization required by the IMO. The LNG penetration in 2050 under this scenario is 25 percent.

These projection scenarios lead to 2050 LNG penetration rates of 61 percent (“High gas”), 11 percent (“Transition”), 3 percent (“Limited gas”), and 25 percent (“BAU”) of total fuel demand. While the first three projections all represent decarbonization scenarios (albeit in the case of “high gas” this is only achieved through offsetting rather than in-sector GHG emission reductions), LNG’s fossil fuel origins make it impossible to approach zero GHG emissions. This means that in the “high gas” scenario, the dominant source of GHG emissions reduction comes via out-of-sector carbon offsetting. When the use of offsetting is more constrained (as in the “transition” and “limited gas” scenarios), the uptake of LNG is significantly reduced and zero-carbon alternative bunker fuels (for example, hydrogen) form a larger share of the fuel mix. While noting that the report did not consider the potential use of LBM or LSM, the scenarios suggest that LNG may play only a temporary or very limited role in the decarbonization of shipping.

The 2018 UMAS study was undertaken before the Initial IMO GHG Strategy, which seems to emphasize an absolute GHG reduction from within the maritime sector. Many observers have interpreted the Strategy to mean that offsetting GHG emissions is not an option. If so, that would imply that the “high gas” scenario has rather limited relevance for the current policy debate at the IMO.

Some studies suggest that LNG could play a transitional role. Under such a framework, LNG will be succeeded by compatible zero-carbon alternatives. One example of such a study is the “Zero-Emission Vessels: Transition Pathways” paper from Lloyd’s Register and UMAS (2019). This study concludes that LNG could be used as a bunker fuel in the 2020s—if this was part of a transition to LBM and LSM—to remain competitive with other emerging zero-carbon bunker fuels.

DNV GL (2019) is the only study reviewed that explicitly models LBM and LSM as alternative bunker fuels. It includes two projection scenarios called “Focus on operational requirements” and “Focus on design requirements,” respectively. The first projection scenario, when applied to the DNV-GL model, predicts that LNG will be progressively replaced by LBM and LSM, both of which are zero-carbon fuels fully compatible with the existing LNG infrastructure. This would give LNG the status of a “transitional” fuel. In the second projection scenario, fossil LNG becomes a significant part of the bunker fuel mix up to the 2040s. After 2040, LNG will be replaced by non-compatible zero-carbon bunker fuels, particularly ammonia, making LNG a “temporary” fuel.

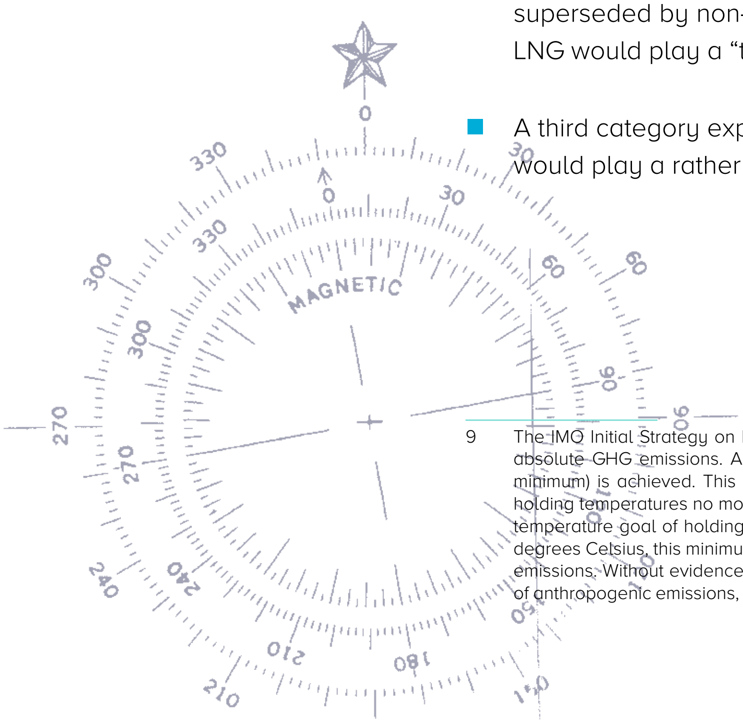
As highlighted in sub-section 2.1.2, DNV GL (2020b) further builds upon their 2019 report by presenting 30 decarbonization scenarios, each with different pathways and 2050 emission reduction outcomes. The report shows that when the least ambitious interpretation of the Initial IMO GHG Strategy[9] is complied with, LNG penetration rates in 2050 vary from zero to 30 percent. In return, when a more ambitious interpretation of the Initial IMO GHG Strategy is implemented that is in line with achieving the Paris Agreement’s temperature goals, then no LNG is utilized in the energy mix irrespective of the fuel price, shipping demand, and regulatory framework assumptions selected.

The International Energy Agency (IEA 2020a) also projects the global energy consumption for international shipping from 2019 to 2070. The projection is based upon their Sustainable Development Scenario, which is broadly consistent with the least ambitious interpretation of the Initial IMO GHG Strategy targets. In this scenario, LNG use peaks in 2040 at five percent before gradually being displaced by zero-carbon bunker fuels, such as ammonia, in the second half of the century. Therefore, it can be assumed that the IEA sees a limited role for LNG in the decarbonization of shipping, too.

Shell (2020) describes a number of long-term future fuel options: hydrogen (which they consider the most promising), ammonia, methanol, biofuels, batteries and nuclear energy. They consider LNG to be a promising fuel because an LNG-fueled vessel can also use other fuels (LBM and LSM). But they do not describe or quantify what they expect the long-run role of LNG to be.

While there is no clear consensus across the studies examined above, they do broadly fall within a constrained set of categories:

- The first category of studies expects the use of some form of liquefied methane gas in 2050, either as LNG (with carbon offsetting or without carbon offsetting), or as zero-carbon LBM or LSM. In this case, LNG would play a “transitional role” in shipping’s decarbonization.
- A second category expects the temporary use of LNG until it is largely superseded by non-compatible zero-carbon bunker fuels in 2050. In this case, LNG would play a “temporary role” in shipping’s decarbonization.
- A third category expects LNG to have no significant adoption. In this case, LNG would play a rather limited role as a marine fuel in shipping.



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[9] The IMO Initial Strategy on Reduction of GHG Emissions from Ships refers to “at least 50 percent” reduction in absolute GHG emissions. A least ambitious interpretation is to assume that only a 50 percent reduction (the minimum) is achieved. This halving of emissions is approximately consistent with a proportionate response to holding temperatures no more than 2 degrees Celsius above preindustrial levels. To meet the Paris Agreement’s temperature goal of holding temperature rise to well below two degrees Celsius and making efforts toward 1.5 degrees Celsius, this minimum achievement would constitute a significant growth in shipping’s share of total GHG emissions. Without evidence that there will be greater GHG reductions occurring on average from other sources of anthropogenic emissions, shipping would therefore not be in line with the Paris Agreement’s temperature goals.

TABLE 2: SUMMARY OF THE PROJECTION STUDIES USED TO UNDERSTAND THE ROLE OF LNG AS A BUNKER FUEL

STUDY	SCENARIO	ASSUMPTIONS	COMPLIANCE WITH THE IMO INITIAL GHG STRATEGY	ROLE OF LNG UP TO 2050	MARKET SHARE BY 2050
IMO Third GHG Study 2014	Lower LNG demand	Constant Emission Control Area (ECA) coverage / stringency	Not compliant	Fossil LNG used in 2050	8% fossil LNG
	Higher LNG demand	New ECAs implemented in the 2030s, doubling the fuel use in ECAs	Not compliant	Fossil LNG used in 2050	25% fossil LNG
Baresic et al. 2018	'High Gas'	Decarbonization with large offsetting, low LNG price. LBM and green methane not considered.	Compliant, but with significant GHG offsetting	Fossil LNG used in 2050 with offsetting	61% fossil LNG
	'Transition'	Decarbonization with limited offsetting, low hydrogen price. LBM and green methane not considered.	Compliant with limited GHG offsetting	Temporary	11% fossil LNG
	'Limited Gas'		Compliant	Never sees significant adoption	3% fossil LNG
	'Business as Usual'	LBM and green methane not considered.	Not compliant	Fossil LNG used in 2050	25% fossil LNG
Lloyd's Register and UMAS 2019	'Renewables dominate', 'Bioenergy dominates', 'Equal mix'	Fuels grouped into four categories: 1) Renewable electricity 2) Bioenergy 3) Natural has with CCS 4) Fossil fuels	Compliant	Transitional	Fossil LNG – Low Possible uptake of LBM (lumped as bioenergy)
DNV GL 2019	'Focus on the operational requirement'	LBM and LSM considered. Significant GHG benefit from fossil LNG and efficiency measures.	Compliant (with fossil LNG providing a GHG benefit)	Transitional, but with significant fossil LNG in 2050	Fossil LNG – High LBM and LSM – High
	'Focus on the design requirement'	LBM and LSM considered.	Compliant (with fossil LNG providing a GHG benefit)	Temporary, but with significant fossil LNG in 2050	Fossil LNG – High LBM and LSM – Low

continues on next page

STUDY	SCENARIO	ASSUMPTIONS	COMPLIANCE WITH THE IMO INITIAL GHG STRATEGY	ROLE OF LNG UP TO 2050	MARKET SHARE BY 2050
DNV GL 2020b	Scenario 11	LBM and LSM considered. High growth in shipping demand with a low electricity price.	Compliant	Temporary, but with significant fossil LNG in 2050	19% fossil LNG
	Scenario 19	LBM and LSM considered. Low growth in shipping demand with a low biomass price.	Exceeds (decarbonization by 2040)	Transitional, but to biomethanol	0% fossil LNG <5% LBM
IEA 2020a	Sustainable Development	Broadly in line with the IMO GHG emissions target for 2050. Maritime shipping does not reach zero emissions until after 2070. Emissions peak in the early 2020s.	Broadly compliant	Never sees significant adoption	<5% fossil LNG

Colored rows denote reports/scenarios that are consistent with, or exceed, the ambition of the Initial IMO GHG Strategy

Table 2 summarizes the results of the referenced studies. It is clear from even a cursory examination that these studies contain a range of results with no consensus on a single outcome. To explain this variability, sub-section 2.2 examines the differences in the assumptions adopted by these studies.

2.2 KEY DRIVERS AND DIFFERENCES IN UPTAKE PROJECTIONS

Many factors can affect the outcome of an uptake projection study. As can be seen from sub-section 2.1.1, even short-term projections are challenging because of the risk of misjudging underlying factors. To provide clarity on the possible market evolution of LNG, it is important to understand and quantify the driving factors that underpin these projections. This sub-section reviews additional studies (i.e., in addition to those shown in Table 2) that provide values for the various driving factors, with the aim of explaining some of the variance in the results.

The driving factors provided in the additional studies can be grouped into the following three categories: GHG impacts, macroeconomic considerations, and technological drivers. The studies reviewed are summarized in Table 3 and are discussed further in this section. Regulation is also an important factor that influences the uptake of LNG, but its influence is not discussed in the reviewed literature outside of those studies highlighted in Table 2. Therefore, section 2.2.4 'Regulatory measures' includes a discussion of the papers highlighted in Table 2.

TABLE 3: SUMMARY OF STUDIES REVIEWED TO IDENTIFY THE KEY DRIVERS OF LNG UPTAKE

STUDY	FUEL CONSIDERED	GHG IMPACTS	MACROECONOMIC CONSIDERATIONS	TECHNOLOGICAL REQUIREMENTS
Stuer-Lauridsen et al. 2010	LNG	Downstream emissions		
TNO 2011	LNG	Combined upstream and midstream emissions by production pathway, and downstream emissions		
Lloyd's Register 2012	LNG		Bunker fuel price	
ICCT 2013	LNG	Upstream, midstream and downstream emissions		LNG bunkering pathways
JRC 2013	LNG	Combined upstream and midstream emissions, by LNG production pathways in the EU		
Oxford Institute for Energy Studies 2018	LNG, LBM, and LSM mentioned	Total GHG emissions (no breakdown)		
ICCT 2018	LNG, LBM, LSM	Availability of sustainable LBM feedstock and LSM	Production cost of LBM and LSM compared to alternative fuels	
MSI 2019	LNG		Share of LNG in the bunkering market; LNG vessels order book	
CE Delft 2020	LNG, LBM, LSM	Availability of sustainable LBM feedstock and LSM	Production cost of LBM and LSM compared to alternative fuels	
GECF 2020	LNG		LNG demand and prices prediction	
ICCT 2020	LNG, LBM mentioned but not studied in detail	Combined upstream and midstream emissions and downstream emissions 20-year and 100-year GWP		
Lindstad 2020	LNG, biofuels including LBM	Combined upstream and midstream emissions, and downstream emissions, by type of engine		
Navigant 2020	LNG, hydrogen, biodiesel, LBM		Best allocation of listed zero-carbon fuels across different sectors of the EU economy (including shipping)	

2.2.1 GHG implications

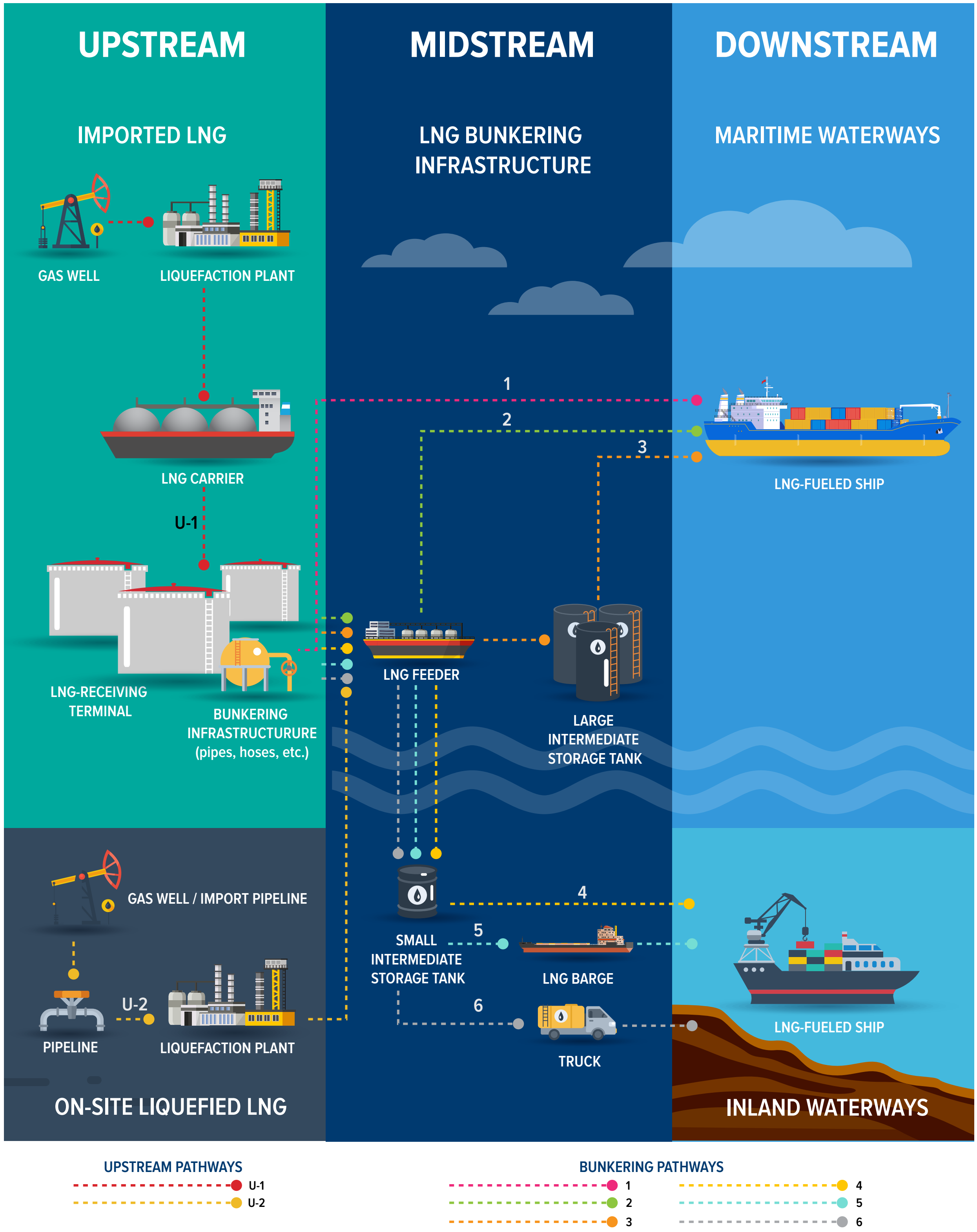
While there is broad agreement on the potential benefit of LNG in terms of reducing air pollutants, the impact of LNG in terms of GHG emissions remains a point of contention. LNG contains up to 30 percent less carbon per unit of chemical energy (calorific value) than oil-derived bunker fuels, but there are significant uncertainties over its lifecycle GHG emissions. These uncertainties arise because the primary component of LNG is methane, which represents a potent GHG if released unburnt into the atmosphere. Any leakage of LNG (and hence methane) at any point in the fuel's lifecycle must therefore be considered when evaluating the total GHG contribution of the fuel.

The potency of methane as a GHG depends on the timeframe under consideration. Methane has a relatively short atmospheric life, with its GHG effect diminishing over time. This means that the Global Warming Potential (GWP) of methane is approximately 2.5 times greater when measured on a 20-year basis than when measured on a 100-year time horizon (IPCC 2013). Over a 20-year timeframe, methane is 86 times more powerful than equivalent CO_2, and over a 100-year timeframe it is 36 times more powerful (IPCC 2013). In the context of introducing new LNG-fueled vessels and retrofits to the market in the short term to meet the IMO GHG emissions reductions targets for 2050, this shorter-term (20-year) warming effect of methane appears as important as its long-term influence (100-year).

Based on the relevant studies, sub-section 2.2.1.1 provides an overview of the uncertainties related to LNG for each stage of its lifecycle.

2.2.1.1 LNG's lifecycle GHG emissions

FIGURE 4: LNG LIFECYCLE PATHWAYS



Source: Baresic et al. (2018)

The classification of LNG's lifecycle GHG emissions in this report follows the terminology presented in Figure 4, and includes upstream, midstream, and downstream GHG emissions. For reference, these lifecycle stages are also known as "well-to-terminal," "terminal-to-tank," and "tank-to-motion," respectively.

At the upstream ("well-to-terminal") stage, the uncertainty about the level of GHG emissions is dominated by the method of natural gas extraction. In particular, methane leakage may be higher for shale gas than for conventional natural gas extraction, due to the increased gas venting following high-volume hydraulic fracturing (ICCT 2020, based on findings from Howarth 2015). When separately estimated, midstream ("terminal-to-tank") GHG emissions are functions of utilization rates, distribution practices, and infrastructure development. They are driven by the operation of LNG feeder vessels and the associated refueling activities. These GHG emissions are typically assumed to decrease with time, as boil-off rates decrease with a higher throughput of LNG and as infrastructure technology improves (ICCT 2013).

Overall, all studies find high uncertainty in upstream and midstream GHG emissions. Netherlands Organization for Applied Scientific Research (TNO 2011) finds combined upstream and midstream emissions factors ranging from 11 to 23 gCO_2eq/megajoule (MJ); European Commission Joint Research Centre (JRC 2013) from 8 to 23 gCO_2eq/MJ; and ICCT (2013) from 4 to 33 gCO_2eq/MJ. As a global average both Lindstad (2020) and Thinkstep (2019) use 18.5 gCO_2eq/MJ. It must be noted that the difference between studies reflects the various assumptions in the pathways studied (location of production, method of extraction, transportation method, and liquefaction versus compression).

The majority of LNG's lifecycle GHG emissions occur downstream, factoring in both combustion products (including unburnt methane) as well as the methane venting that can occur when maintaining safe fuel tank pressure or during cargo operations. These emissions are rapidly increasing, with downstream methane emissions from maritime transport growing 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 time period (IMO 2020). At this stage, the majority of the uncertainty in GHG emissions levels arise from methane leakage that can occur in the combustion chamber of the ship's engine. Vessels that use LNG as a primary fuel source can generally keep the internal fuel tank pressure low enough to avoid any undesired boil-off directly from the fuel tank, with venting occurring only when the ship is idle for extended periods. The literature review provided in Baresic et al. (2018) show that methane leakage in downstream vessel operation can lead to additional GHG emissions ranging from 2.2 gCO_2eq/MJ for a diesel-cycle gas engine to 70 gCO_2eq/MJ for a vessel operating at 25 percent load.

Overall, studies range in their estimates of the downstream emissions: TNO (2011) estimates 70 gCO_2eq/MJ while ICCT (2013) uses 59 gCO_2eq/MJ. Lindstad (2020) provides a range of downstream emissions ranging between 58 and 73 gCO_2eq/MJ, while Thinkstep find downstream CO_2eq emissions ranging from 60 to 71.3 gCO_2eq/

MJ input, for a low speed two-stroke diesel dual-fuel engine to a medium speed four-stroke Otto dual-fuel engine respectively. A summary of the emission factor estimates is provided in Table 4 below.

TABLE 4: SUMMARY OF GHG EMISSIONS FACTOSR ESTIMATES FOR LNG IN STUDIES REVIEWED

STUDY	UPSTREAM AND MIDSTREAM GHG EMISSIONS FACTORS			DOWNSTREAM GHG EMISSIONS FACTORS		
	METHANE LEAKAGE EMISSIONS FACTORS	SUB-TOTAL GHG EMISSIONS FACTORS	SUB-TOTAL AS SHARE OF TOTAL GHG EMISSIONS FACTORS	METHANE LEAKAGE EMISSIONS FACTORS	SUB-TOTAL GHG EMISSIONS FACTORS	SUB-TOTAL AS SHARE OF TOTAL GHG EMISSIONS FACTORS
Stuer-Lauridsen et al. 2010				31.4-70*		
TNO 2011	1.7-5.9*	11-23	14-25 percent	13*	70	75-86 percent
ICCT 2013	1.6*	4-33	6-36 percent	10.6*	59	64-94 percent
European Commission Joint Research Centre 2013		8-23				
Corbett et al. 2015				2.2 -15.6*		
Thinkstep 2019	4.7	18.3-19	21-24 percent	0.6-14.9	60-71.3	76-79 percent
Lindstad 2020		18.5	20-24 percent	1-16	58-73	76-80 percent
ICCT 2020		21-26	16-30 percent	1-31	60-89	70-84 percent
Minimum estimate	1.6	4	6 percent	1	60	64 percent
Maximum estimate	5.9	33	36 percent	70	89	94 percent

All GHG emissions factors estimates in gCO$_2$eq/MJ of fuel input; figures marked with * have been taken from the literature review in Baresic et al. (2018)

2.2.1.2 LNG's lifecycle GHG emissions compared to conventional bunker fuels

LNG's efficacy as a more environment-friendly substitute for heavy fuel oil (HFO) is closely tied to its air quality benefits, but also to its GHG emissions profile. For the latter, a significant part is determined by the method of natural gas extraction and scale of methane leakage.

As discussed previously, while methane is a potent GHG, its absolute potency depends on the timeframe under consideration. ICCT (2020) concludes that GHG emissions from LNG are highly sensitive to both the GWP time horizon and the onboard technology employed. Under a 100-year GWP horizon, the full lifecycle GHG emissions savings of LNG compared to low-sulfur heavy fuel oil (LSHFO) is estimated to be 16 percent. This assumes that any methane leakage is controlled, including by the use of high-pressure direct injection dual-fuel (HPDF) engines to control downstream emissions. ICCT (2020) figures show that, as of mid-2018, approximately 12 percent[10] of all LNG vessels in operation and on order are equipped with HPDF engines. HDPF engines exhibit lower methane emissions than other types of LNG engine. According to ICCT (2020), measuring GHG impact with a 20-year GWP horizon fully eliminates the abatement potential of LNG, instead increasing its lifetime GHG emissions by two percent (relative to LSHFO) for HPDF vessels and up to 79 percent for cruise ships using standard medium-speed engines.

BOX 4: METHANE LEAKAGE ADVANTAGES OF HIGH-PRESSURE DIRECT INJECTION DUAL-FUEL ENGINES

HPDF engines operate by first injecting a small quantity of marine diesel oil (MDO) fuel at the end of the compression stroke to initiate a combustion event in the same way as in a standard diesel cycle engine. The natural gas is then introduced into this initial combustion event via high pressure in cylinder injection, igniting the gas and producing the main combustion event and the propulsive power. The use of MDO combined with natural gas results in the dual-fuel nomenclature. The high-pressure injection needed to add and mix sufficient natural gas results in the high-pressure part of the designation.

When considering methane emissions, this approach has two main advantages that stem from how the natural gas is introduced, mixed, and burnt at the end of the compression stroke in a HPDF engine. First, no natural gas, and hence methane, can escape during the air induction phase because the natural gas is introduced when the inlet and exhaust ports/values are closed. Second, the natural gas is kept away from the crevices and the relatively cold walls of the combustion chamber where combustion cannot happen. In engines where the natural gas is introduced with the combustion air, these poor combustion regions lead to unburnt natural gas and its major constituent methane being emitted to the atmosphere via the exhaust phase.

2.2.2 Macroeconomic considerations

The uptake of LNG as a bunker fuel will depend on its relative competitiveness, particularly with regards to price. The degree of near-term uptake of LNG is therefore a function of the current and future price of LNG relative to the price of conventional oil-derived bunker fuels.

Previously, weak LNG uptake has been attributed to an insufficient price differential between LNG and HFO, combined with cost and space claim challenges (see below in 2.2.3) in installing the necessary onboard equipment (SEA-LNG 2020). Whilst natural gas has had price advantages relative to crude oil, HFO is also cheaper than crude oil. Therefore, the added vessel capital costs of using LNG as a bunker fuel requires LNG to have a consistent lower minimum price margin relative to HFO in order to justify its use. This price differential varies depending on a number of factors

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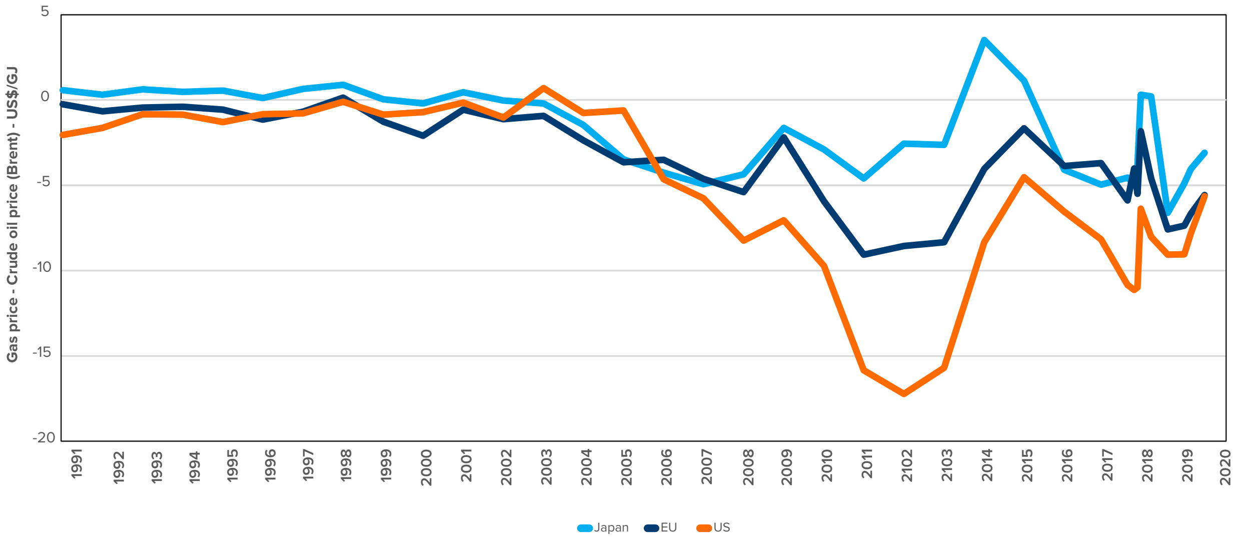
[10] Please note, this percentage represents the proportion of the LNG-powered fleet that use HPDF engines. This is not analogous to the proportion of the LNG fuel consumed by the LNG fleet due to differences in vessel size and duty cycles.

including the payback period required, the installation costs specific to the vessel design and shipyard, and the equipment costs. Thus, it is difficult to generalize the magnitude by which LNG needs to be cheaper than HFO for a clear commercial driver to emerge – except that price differentials as shown in Figure 5 have not resulted in significant orders of LNG-fueled vessels to date (see sub-section 2.1.1).

Another challenge that hinders the ability to identify a commercially viable investment is that the price differential is very difficult to predict due to the complexities of the geopolitical landscape and the globalized market for oil and gas. This prediction difficulty is shown in Figure 5, where the crude oil price is used as proxy for the HFO price given that HFO is a product of crude oil refining. The equivalent data are not presented for HFO price as no similar benchmark prices are available.

Considerable fluctuations in the price spread between natural gas and crude oil can be observed over time and across geographic regions. Regional price differences are in part due to natural gas pricing mechanisms differing across world regions. For example, in the United States, natural gas prices are disconnected from the crude oil reference. In Europe, the share of natural gas sold with reference to the price at European gas trading hubs is growing. In the Asia-Pacific region, the natural gas price is fixed within the long-term crude oil-indexed contracts (TNO 2014).

FIGURE 5: HISTORICAL NATURAL GAS/CRUDE OIL PRICE SPREAD



Source: DNV GL (2020a)

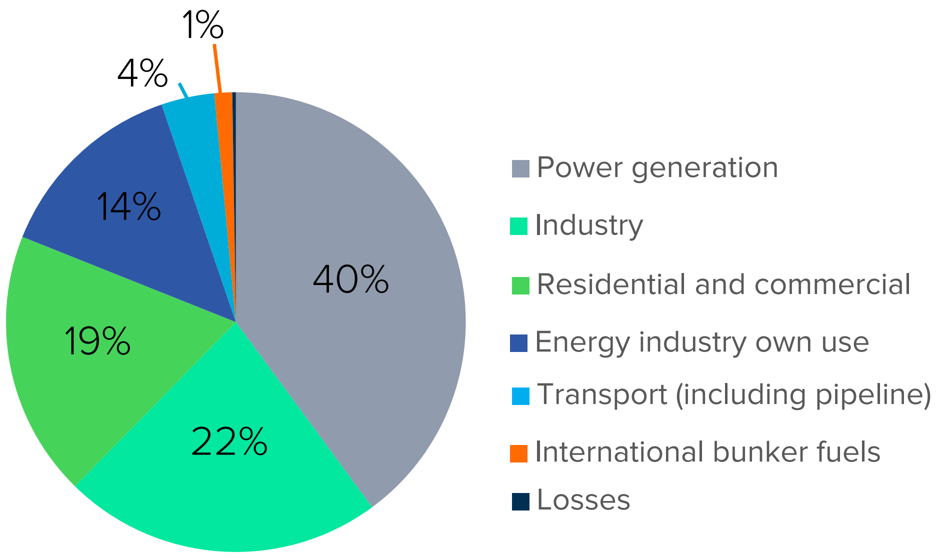
Estimating the future price differential between natural gas and any other fossil-derived bunker fuels becomes even more challenging when considering the potential future uptake of various alternative zero-carbon bunker fuels, such as ammonia or hydrogen. In the short term, it therefore seems unlikely that the maritime industry will receive a high-certainty commercial signal that unleashes the large-scale investment in LNG necessary for significant uptake.

2.2.3 Technological requirements

The lifetime GHG emissions and the total cost of LNG vary considerably depending on the pathway that is taken from the extraction well to the vessel, as well as the onboard technology used to store and burn the LNG. Some of the drivers for this variability are related to technology differences in the ships and infrastructure, which are discussed in greater detail below.

LNG has a variety of uses in the global economy, of which maritime transport is a rather small component. As displayed by Figure 6, less than one percent of global natural gas demand originates from international bunker fuels (IEA 2020b). For this reason, the discussion of technology and investment is typically limited to the mid- and downstream stages of LNG's lifecycle pathways. This is always based on the assumption that the use of LNG in shipping will remain a rather small proportion of global LNG consumption, and that shipping will accordingly have consistent access to independent upstream facilities.

FIGURE 6: GLOBAL NATURAL GAS DEMAND BY SECTOR IN 2019-2020



Source: IEA 2020b

There are at least eight pathways for LNG, from being deposited at a large import terminal to a vessel's fuel tank (ICCT 2013). Yet, one is assumed by Baresic et al. (2018) to be the most likely to occur due to its supply flexibility and low costs. On that pathway, a feeder vessel (~10,000m^3 capacity) is used to perform ship-to-ship refueling directly from the import terminal to LNG-fueled vessels, and is ideally suited to ships requiring over 100m^3 of bunkering fuel. The resulting short turn-around times preclude the need for any intermediate storage. For small inland waterway vessels using LNG, the most likely pathways involve small LNG barges (~3,000m^3

capacity) delivering LNG from the import terminal to small intermediate storage units in less navigable routes. While the use of LNG as a bunker fuel can leverage LNG's existing global supply chain and infrastructure, its costs and implications still need to be taken into account when assessing LNG's application within the shipping sector. Capital infrastructure costs depend on the associated pathways and add a component of cost to the scenarios as a function of the total amount of infrastructure needed specific to LNG's use as a bunker fuel. Appendix C provides further details derived from a research project by the Danish Maritime Authority (DMA 2012).

Installing equipment and operating an LNG-fueled vessel poses complications relative to a typical fuel oil-powered equivalent vessel, with the primary issue arising from the size of the fuel tank required. The energy-density ratio between the two fuels is 1.6, meaning that a larger volume of LNG must be burnt to generate the same amount of energy. Moreover, the cryogenic storage temperatures of LNG require a heavily insulated tank, which in turn takes up an even greater volume of storage space on LNG-fueled vessels. These large tanks are challenging to retrofit into existing vessels, and the larger fuel tanks also leave less volume for cargo, narrowing the range of vessels that can economically use LNG for trade.

2.2.4 Regulatory measures

Scenario modelling, including as in Baresic et al. (2018), indicates that LNG uptake may be highly sensitive to the price differential between LNG and conventional oil-derived bunker fuel options and alternative fuels. For example, when Baresic et al. (2018) apply a range of LNG prices in different scenarios with approximately a ten percent range (the range between upper and lower bound prices), this leads to a large variability in the uptake of LNG between scenarios—including in the period before the implementation of policy to reduce GHG emissions to control for the influence of policy on uptake.

In practice, this price differential is also influenced by the higher infrastructure capital expenditure and reduced global refueling options currently associated with LNG. Since maritime transport accounts for only a small portion of total worldwide LNG demand, its price is primarily determined by factors outside of the maritime industry's control. As maritime policymakers cannot effectively influence prices, regulations governing GHG emissions, air pollutant emissions, and energy efficiency are the only policy mechanisms that can ensure the relative competitiveness of LNG. Some of the variation in the results of the studies considered in sub-section 2.1 come from the different assumptions regarding these policy objectives (mainly air pollution and climate mitigation), the geographic levels at which these policies are implemented (globally, regionally, nationally, or locally), and their stringency.

Two main air pollution policies are considered by the studies reviewed in sub-section 2.1. The first penalizes the use of conventional oil-derived bunker fuels through Emission Control Areas (ECA) where stricter controls are implemented to reduce air pollutant emissions from ships (SO_x, PM, and NO_x). The second applies a global sulfur cap for bunker fuels from 2020 (Baresic et al. 2018; Lloyd's Register

2012; Lloyd's Register and UMAS 2019; and DNV GL 2019). Lloyd's Register and UMAS show, through surveys of tanker owners, that in the short term low-sulfur bunker fuels such as low sulfur heavy fuel oil (LSHFO) are likely to be favored to ensure compliance with these air pollutant emissions regulations, while abatement technologies will become more relevant in the medium term. However, LNG is generally viewed as a viable long-term compliance option (Lloyd's Register and UMAS 2019).

The details of specific future climate-related regulatory measures are uncertain, and the variation in assumptions in the scenarios considered reflect this uncertainty. For instance, the main potential regulatory measures considered in the studies reviewed include:

- **Energy Efficiency Design Index (EEDI) regulation:** a policy tool restricting the construction of new-build vessels that exceed certain carbon intensity limits. Currently, LNG is considered an effective means to comply with the EEDI as only downstream CO_2 emissions are accounted for within this policy framework. This automatically gives LNG a 30 percent lower CO_2 emission per unit of propulsion (ICCT 2020). DNV GL's (2019) "Focus on design requirements" scenario assumes the adoption of more stringent requirements in the EEDI by 2040.

- **Operational requirements:** regulation which applies to all existing ships rather than only newbuilds and includes mandatory energy efficiency measures, speed reduction, and supply-chain optimization. Both scenarios in DNV GL (2019) assume the implementation of operational requirements, with differing levels of stringency.

- **Market-based measures:** a policy that usually comes in the form of carbon pricing. These measures are assumed by several studies like Baresic et al. (2018) and Lloyd's Register and UMAS (2019).

- **Carbon offsetting:** a mechanism that compensates for GHG emissions occurring in one sector by avoiding them in another sector. Carbon offsetting is included in selected scenarios of Baresic et al. (2018).

Varying the stringency of these potential regulatory measures is shown to have a significant effect on the uptake of LNG.

The "business as usual" case in Baresic et al. (2018) assumes that existing regulatory measures included in the International Convention for the Prevention of Pollution from Ships (MARPOL)—for example, EEDI, global ECAs, and global emissions caps on sulfur oxides (SO_x) and nitrogen oxides (NO_x) —remain in place. The other scenarios in Baresic et al. (2018) introduce market-based measures in 2025 and 2030 in the form of carbon pricing, with linkages to carbon offset markets capped at 20 to 30 percent of revenue generated from the carbon pricing. These variations in the regulatory assumptions are the dominant source of the large variation in the LNG uptake across the four scenarios, which ranges from 3 to 61 percent of the fuel market by 2050 in energy terms.

In the absence of a commercial signal giving the maritime industry high certainty, regulation may provide a consistent multi-year incentive to invest in a particular fuel or technology. The various ECA air quality limits are an example of such a policy mechanism. However, while LNG provides inherent SO_x, NO_x, and particulate matter (PM) benefits, the traditional oil-derived bunker fuels can still comply with the current global and ECA air quality regulations, too. Compliance can be achieved through the addition of proven emissions control technologies such as Selective Catalytic Reduction or Exhaust Gas Recirculation. This possibility suggests that ECA air quality limits are unlikely to provide a sufficiently strong stimulus for the uptake of LNG.

Another potential legislative driver for LNG is the IMO's EEDI. Currently, this regulatory framework is used to improve the carbon intensity of vessels through an assessment process and various staged targets. The framework allows for the use of LNG and only accounts for the downstream (operational) CO_2 emissions. Accordingly, it assigns a greater GHG emissions benefit to LNG than its true lifecycle GHG emissions may allow for. For the EEDI, the primary advantage of LNG stems in part from this policy loophole of not including methane emissions, which is likely to be closed in future legislative rounds. New regulations on carbon intensity targeted at the existing fleet and operational carbon intensity regulation are due to be adopted at IMO at MEPC 76 (June 2021). However, given LNG is predominantly a newbuild technology, its main potential driver is expected to remain the EEDI regulation rather than these new regulations.

Until the loophole is closed, EEDI regulation may create some incentive for LNG. However, in its current form newbuild container ships, LNG carriers, and general cargo ships will see an EEDI stringency increase in 2022, brought forward because of evidence that many ships of these types being built are already achieving the 2025-required EEDI levels. The remaining fleet will not see a stringency increase until 2025. Therefore, whilst the EEDI could theoretically drive the uptake of LNG vessels, this is unlikely to be a sufficiently strong driver before 2025, a point at which the landscape of zero-carbon bunker fuels should have further clarified making it easier to judge what to invest in for long-run commercial viability. The EEDI is therefore considered unlikely to drive strong uptake of LNG in the short-term future either.

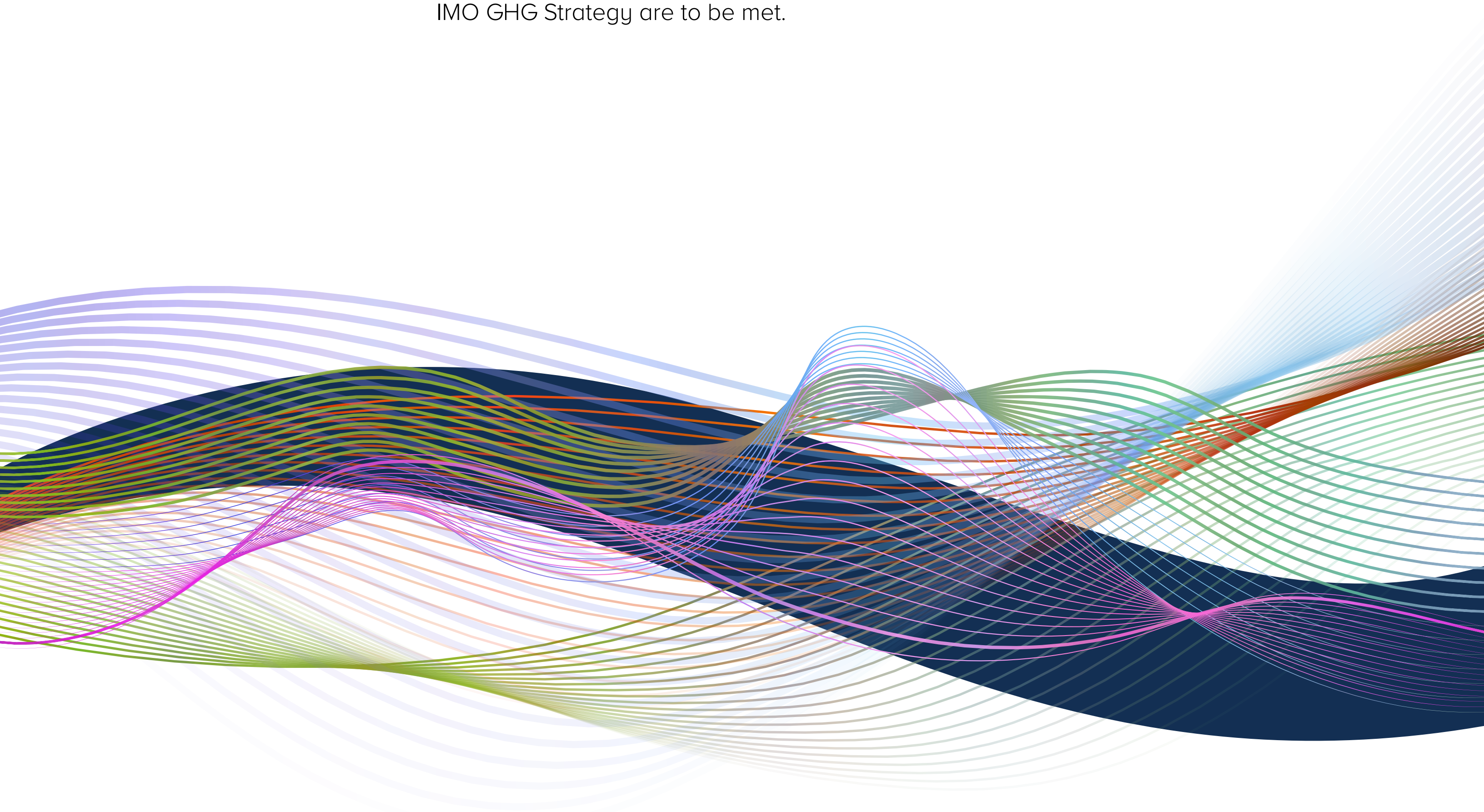
In return, a development that is likely to considerably affect the uptake of LNG is the Initial IMO GHG Strategy. However, it appears unlikely that this policy will spur large investments in LNG since its GHG emissions reduction targets are unlikely to be compatible with the use of LNG alone. The existing literature, for example ICS (2018), is fairly consistent on this point, especially if the offsetting of GHG emissions is excluded and a 20-year global warming potential is used to calculate the lifecycle CO_2eq emissions associated with methane leakage.

In summary, while existing regulations and the Initial IMO GHG Strategy may provide some incentive to adopt LNG in shipping, they are unlikely to be sufficiently strong to drive a significant uptake of LNG as a bunker fuel in maritime transport. In addition, the Initial IMO GHG Strategy is also not likely to spur a significant uptake of LNG. Without a significant growth in demand for LNG as a bunker fuel, large investments in infrastructure supplying LNG to ships do not appear very likely either.

2.3 LESSONS LEARNED

The main lesson to be learned from section 2 is that there is a lack of consensus in the reviewed literature on the possible role of LNG in the decarbonization of international shipping; this lack of consensus is largely explained by the various modelling assumptions used in these studies. Studies can “cherry-pick” from a broad range of assumptions regarding emissions factors, macroeconomic considerations, technology pathways, and regulatory measures. This selective process can then be used to create seemingly credible narratives for a wide range of LNG uptake outcomes. In reviewing and understanding the assumptions used, this report has made a first step to move beyond this current situation.

The report also does not find any clear, strong, and unambiguous driver (including macroeconomic or regulatory incentives) which currently point at LNG's large-scale uptake as bunker fuel in the short term, if the decarbonization targets set in the Initial IMO GHG Strategy are to be met.



3. LNG'S POTENTIAL AS A TRANSITIONAL FUEL

Section 2 shed light on why the role of liquefied natural gas (LNG) in the decarbonization of shipping is a contested issue in the literature. This section argues that there are good compelling reasons to believe that LNG is unlikely to play a transitional role. In particular, it highlights significant supply constraints for zero-carbon bunker fuels that are compatible with LNG to satisfy the energy demand from international shipping.

3.1 COMPATIBILITY REQUIREMENTS

Although significant uncertainty and variability remain in the literature around LNG's lifecycle greenhouse gas (GHG) emissions, there is a broad consensus amongst the studies reviewed that the transition to fossil LNG alone will fall short of achieving the International Maritime Organization's (IMO) stated 2050 GHG emissions reduction target. Some studies therefore suggest a shift to fully compatible net-zero carbon bunker fuels that can reuse LNG infrastructure.

However, re-using LNG infrastructure for zero-carbon bunker fuels, such as ammonia and hydrogen, would require extensive retrofitting. For example, although both LNG and hydrogen require cryogenic treatment, the fuels' storage temperatures are far apart (-160°C and -253°C, respectively) and require different designs, and containment and cooling equipment to be installed (Lloyd's Register 2020). There may also be different safety considerations, given that these fuels present different hazards around explosivity, corrosivity, and toxicity (Lloyd's Register 2020). Therefore, any LNG infrastructure is likely to play a transitional role for liquefied biomethane (LBM) and liquefied synthetic methane (LSM) fuels only.

Part of the controversy in the existing literature on the role of LNG in decarbonizing shipping is due to whether LNG-compatible zero-carbon bunker fuels are assumed to be viable options for shipping. Several studies consider LBM and/or LSM as possibilities (DNV GL 2019; Lloyd's Register and UMAS 2019; and Oxford Institute for Energy Studies 2018). In addition, DNV GL (2019) explicitly assumes that LBM and/or LSM will be available in sufficient quantities to replace fossil LNG. The remaining studies do not assume LBM and/or LSM as an option (Baresic et al. 2018 and Lloyd's Register 2012).

3.2 VIABILITY CONSTRAINTS

Proponents of the use of LNG as a transitional fuel suggest that any LNG infrastructure can be utilized by compatible zero-carbon fuels such as LBM and LSM. This subsection argues that LNG is unlikely to play a transitional role since there are serious concerns about the availability of sustainably sourced LBM for shipping, and since LSM is unlikely to become a cost-competitive bunker fuel. If LBM and LSM did not turn out to be viable zero-carbon bunker fuel options, LNG could not play a transitional role leading to its widespread adoption.

3.2.1 Constraints to the viability of liquefied biomethane as a bunker fuel

The availability of sustainable biomass feedstock—a critical determinant of whether LBM can become a significant bunker fuel in the future—is uncertain. Two factors govern the availability of biofuels such as LBM for shipping. The first is the quantity that can be sustainably produced. The second is cross-sectoral competition for the available biomass from other sectors in a future decarbonized economy. A realistic assessment must account for both factors.

Regarding the first factor, total future global biofuel production is uncertain. A general consensus among experts is that around 70 to 160 exajoules (EJ) of energy could be produced from sustainable biomass in 2050 (CCC 2018; Smith et al. 2014; and IPCC 2018). IEA (2020a), whilst providing an estimate for 2070 rather than 2050, is also reasonably consistent with this range, quoting a feasible range of 100 to 200 EJ of sustainable biomass supply. However, the full range quoted in the literature appears much wider, ranging from 30 to 500 EJ (Winning et al. 2018; Fuss et al. 2018; and IPCC 2018). For LBM specifically, CE Delft (2020) forecasts the maximum conceivable supply in 2050 and estimates that between 37 and 184 EJ could be feasibly produced in a sustainable manner. Finally, Pye et al. (2019) estimate a total LBM production potential (including from waste sources) in 2050 at 34 EJ, which is in line with the lower bound of CE Delft (2002). These figures contrast with this report's estimated energy demand for shipping of approximately 20 EJ in 2050 (see Figure 13, page 44).

Regarding the second factor, cross-sector competition for biomass and related biofuels is likely as these are versatile commodities that can be used to decarbonize a number of economic sectors. Often, competing sectors may be either more efficient users of the biomass (power generation, afforestation, negative emissions, plastic demand, and heating), or sectors such as aviation where the economic value of an energy-dense drop-in fuel may be even more pressing than in the maritime industry. However, the evolution of these global demand markets out to 2050 is not a settled issue in the current literature.

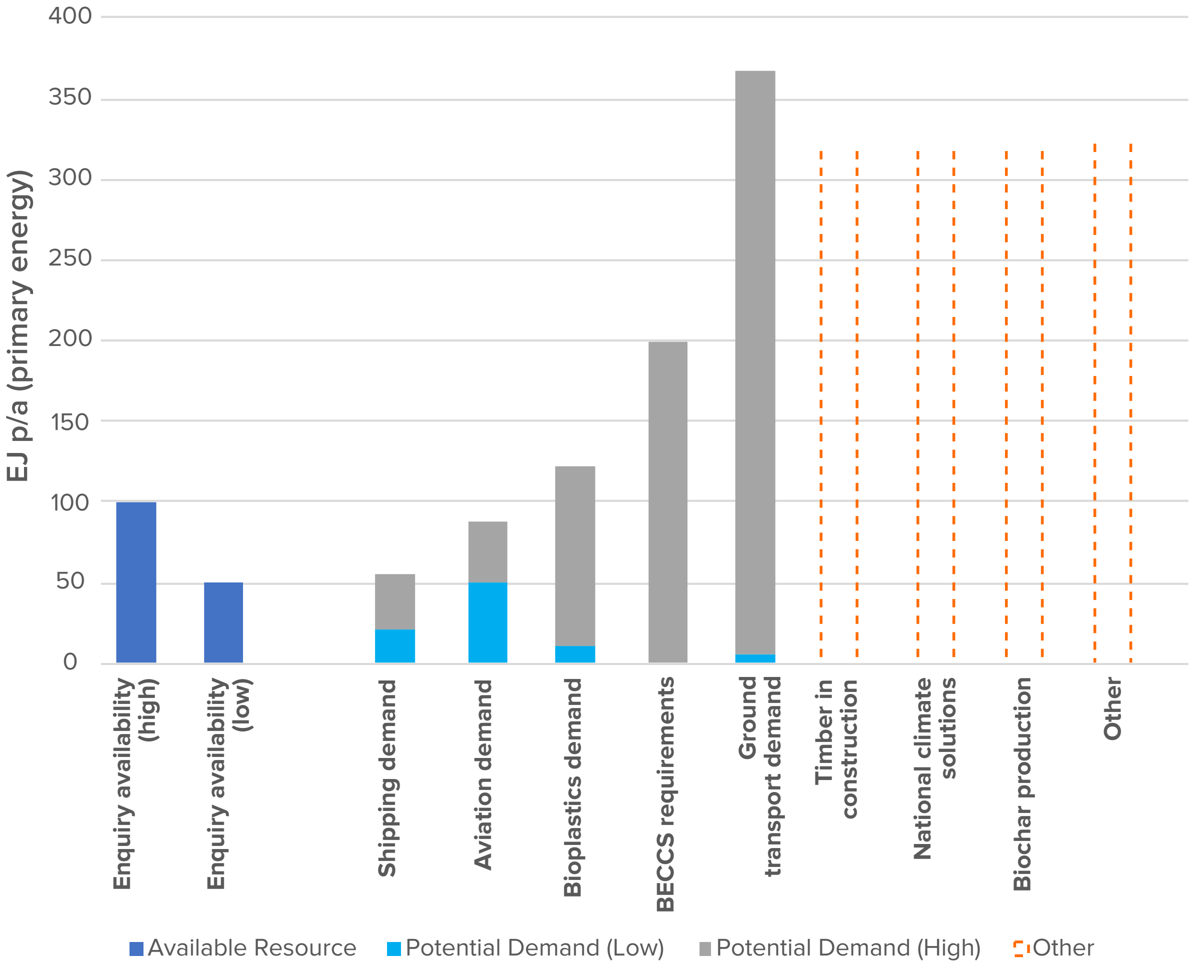
A number of demand scenarios exist at an energy system level, with the Intergovernmental Panel on Climate Change (IPCC 2018), for instance, providing the total primary energy requirement and the biomass availability for their 1.5°C scenarios. Under the assumptions made in their report, the share of bioenergy is expected to increase to around 15 to 25 percent of total energy supply. Despite electrification, bioenergy continues to be important to industry, building, and transport sectors (with heavy-duty vehicles and aviation representing major demand sectors), while biomass combustion for electrical power in combination with carbon capture and storage (CCS) provides a “carbon sink” for net reductions in atmospheric carbon dioxide (CO_2). In this scenario, approximately 6 to 22 EJ of biofuels would be available for the *total* transport sector (IPCC 2018).

The IPCC’s whole energy system view is further supported by the more recent work of the IEA (2020a), where bioenergy represents 20 percent of primary energy in 2070 in their “Sustainable Development Scenario”. This primary energy supply is exposed to a similar mix of demands as described by IPCC (2018), resulting in 16 EJ of energy being made available to the *total* transport sector. That total includes bioenergy obtained from cultivation for energy use as well as bioenergy derived from waste sources.

In the IEA “Sustainable Development Scenario,” this *total* transport sector supply is further sub-divided into a resulting biofuel energy use in shipping of approximately 1.6 EJ. Compared to a total energy use estimated by IEA of just 8.4 EJ by shipping in 2050 (much lower than the approximately 20 EJ estimated in this report), this implies that biofuels could cover approximately 15 percent of the quoted total shipping energy demand maximum. Therefore, meeting shipping’s energy demand using mostly biofuels such as LBM seems a challenging proposition. This conclusion is also echoed by Shell (2020). Whilst not presenting a quantitative assessment, the study states: “Biofuels are considered unlikely to be the dominant future fuel for shipping. This is because the sector would need huge volumes [of biofuels], and other sectors such as aviation and road transport are likely to be more able to pay the cost.”

In Figure 7, Sustainable Shipping Initiative (2019) highlights the bioenergy availability with the likely demand from a range of sectors, neatly summarizing the challenge of meeting significant shipping demand with biofuels.

FIGURE 7: PROJECTED AVAILABILITY OF SUSTAINABLE BIOFUEL BY 2050 COMPARED TO POTENTIAL DEMAND FROM A SELECTION OF INDUSTRIAL SECTORS AND/OR OTHER POTENTIAL USES OF BIOFEEDSTOCK



Source: Chart compiled by Forum for the Future using data from Energy Transitions Commission (ETC); ICCT; International Civil Aviation Organization (ICAO); IPCC; UK CCC; World Energy Council. Courtesy of SSI. See SSI 2019 for further details on the references used.
Note: Dashed columns represent other sectors that will potentially create additional demand for sustainable feedstock and for which data are currently not available

A further threat to the viability of LBM in shipping is its competitiveness relative to other options in terms of total cost of operation. Total cost of operation includes, for example, the costs of the fuel as supplied at a bunkering terminal, the cost implications of installing the technologies to use the fuel onboard, the cost of implications for cargo capacity, and so forth. Lloyd's Register and UMAS (2020) estimate that the total cost of operation of biomethanol-powered ships in the short term (up to 2030) will be approximately one-half the total cost of ownership of an LBM-powered ship. Both types of biofuels—biomethanol and LBM—have significant overlap in their respective feedstock (crops and agricultural residues). Therefore, from a competitiveness perspective, it is likely more cost-effective to use such feedstock for a zero-carbon bunker fuel such as biomethanol, with lower total cost of ownership than LBM.

To summarize, several studies (IPCC 2018; IEA 2020a; and Shell 2020) call into question whether sustainable biomass will be available in the large quantities needed to cover shipping's zero-carbon energy needs. Next to the challenge of scalability, there are also uncertainties that whatever supply may appear may not be cost-competitive relative to other options. This does not mean that there would be no prospects for the supply of LBM at all, but LBM may not necessarily be the first choice for the sector. It could rather be seen as a fallback for those owners who may have no option to easily retrofit their vessels to the zero-carbon fuel option favored by the majority of the market.

3.2.2 Constraints to the viability of green liquefied synthetic methane as a bunker fuel

In theory, LSM appears much less constrained than LBM in terms of supply and represents a very scalable fuel. LSM is produced by combining zero-carbon hydrogen and atmospheric carbon to synthesize methane. In the future, large quantities of zero-carbon hydrogen are likely to be produced via renewable electricity. In turn, this means that the limit on zero-carbon hydrogen production is likely to be the availability of renewable electricity. Obtaining sufficient quantities of atmospheric CO_2 will also not present an issue.

The primary constraint on LSM's viability appears to be its cost, which arises from two factors. The first is that the direct air capture (DAC) technology used to capture carbon for synthesis still has uncertain capital expenditure costs. In addition, the CO_2 extraction process requires a significant amount of energy which needs to be paid for and considered. The second constraint is that a significant quantity of input energy is required to combine the carbon (from the CO_2) with the zero-carbon hydrogen to create green LSM. These processes are likely to make LSM significantly more expensive, including on a total cost-of-operation basis, than zero-carbon hydrogen or ammonia and ultimately less attractive from an economic perspective (*Volume 1: The Potential of Zero-Carbon Bunker Fuels in Developing Countries*, see Preamble).

The related *Volume 1* (see Preamble) reviewed a large number of existing studies on alternative zero-carbon bunker fuel options and shortlisted candidate bunker fuels most likely to dominate the 2040s and 2050s. Both LBM and LSM variants of natural gas were considered, but consistent with Lloyd's Register and UMAS (2017) and Lloyd's Register and UMAS (2020) these fuels were not found to be economically competitive in the long run. The two options showing the most favorable results against the criteria defined were ammonia and hydrogen. These latter fuels, however, will need infrastructure, onboard technologies, and hence capital investments that are not aligned with investments in LNG infrastructure and technology for shipping.

3.3 LESSONS LEARNED

In summary, section 3 has illustrated that there are good reasons to believe that LNG is unlikely to play a transitional role in the decarbonization of shipping. Two main arguments support this statement. First, there are likely severe constraints to the sustainable supply of compatible biofuels, such as LBM, that is one option allowing the reuse of LNG infrastructure in the shipping sector. Therefore, the profitability of investments in LNG infrastructure cannot rely on the reuse of this infrastructure for other fuels. Second, other LNG-compatible zero-carbon bunker fuels such as green LSM are expected to be less attractive from an economic perspective than their direct competitors such as hydrogen and ammonia.

This also suggests that LNG may play only a temporary or limited role in the short-term decarbonization of the shipping sector. To provide further data to test this conclusion, the next section attempts to quantify what a significant deployment of LNG's use as a bunker fuel would look like. Specifically, section 4 looks at LNG as a temporary fuel (that is, Future 2: "Temporary role for LNG" as noted above) and quantifies the GHG emissions and financial implications across a range of scenarios.

4. LNG’S POTENTIAL AS A TEMPORARY FUEL

Section 4 presents an estimate of the greenhouse gas (GHG) impact, required capital expenditures, and GHG and economic risks associated with deploying a liquefied natural gas (LNG) fleet and related infrastructure on a temporary basis. In light of the International Maritime Organization’s (IMO) 2050 climate target, this section seeks to answer the following guiding questions:

1. **GHG implications:** What would be the potential short-term consequences for GHG emissions from ships if LNG was used as a temporary fuel at large scale (that is greater than 10 percent of the fuel mix in energy terms)?
2. **Financial implications**: How much additional investment would be needed to deploy the corresponding infrastructure and fleet if LNG served as a temporary large-scale fuel?
3. **Risk implications**: What may be the potential risk of stranded assets associated with LNG as a temporary fuel?
4. **Technology “lock-in” implications**: What could be the consequences of an LNG technology pathway “lock-in”?

To address these questions, three sets of LNG uptake cases have been developed, modelled, and examined. Of the three uptake cases presented in Table 5 the “Baseline” and “Near-term substitution” cases achieve the climate targets of the Initial IMO GHG Strategy as modelled in the Global Transport Model (GloTraM), a techno-economic model of the global freight transport system, focused on international shipping. While Case I has been linked to Future 3 expecting “a limited role for LNG”, Cases II and III have been derived from Future 2 assuming “a temporary role for LNG”. The prospects of Future 1 suggesting “a transitional role for LNG” have already been discussed and discounted earlier.

TABLE 5: SUMMARY OF LNG UPTAKE CASES FOR LNG AS A TEMPORARY FUEL

CASE	ASSUMED EVOLUTION OF LNG UP TO 2030 AND 2050	ASSUMED EVOLUTION OF ZERO-CARBON BUNKER FUELS UP TO 2030 AND 2050	BASED ON	ACHIEVES THE INITIAL IMO GHG STRATEGY TARGETS?
I. Baseline[11]	No significant uptake of LNG	Rapid uptake of zero-carbon bunker fuels from 2030	Future 3	Yes
II. Near-term substitution	From 2021, every newbuild vessel is LNG-powered resulting in a significant shift from oil-derived bunker fuels to LNG up to 2030; from 2030 to 2050 the use of LNG rapidly declines	Rapid uptake of zero-carbon bunker fuels from 2030	Future 2	Yes
III. Long-term lock-in	As above prior to 2030. Post 2030 the use of fossil LNG is prolonged due to technology lock-in	Slow uptake of zero-carbon bunker fuels from 2030	Future 2	No

Sections 2 and 3 of this report provide relevant references and reasoning that suggest that LNG's short-term and long-term roles as a propulsion fuel for international shipping may be rather limited. In practice, this means that the "Baseline" case should be considered the most likely outcome in the maritime transport sector. In contrast, the "Near-term substitution" and "Long-term lock-in" cases represent theoretical "what if" cases designed to highlight the implications of a significant LNG uptake up to 2030. The relative likelihoods of these Cases II and III are not important for this assessment. Case II, "Near-term substitution," is used to answer questions one and two, and Case III, "Long-term lock-in," addresses questions three and four. The detailed assumptions used within the three cases modelled by GloTraM and the model's credentials can be found in Appendix A. These assumptions are deemed to be the most appropriate or the most likely to occur.

The actual decarbonization trajectory of the international maritime fleet is currently unknown as it is a function of a myriad of policy, commercial, and technological outcomes. Therefore, on top of these three cases, two major decarbonization scenarios, both consistent with interpretations of the Initial IMO GHG Strategy, are considered. The first considers "full decarbonization by 2050," and the second a 50 percent GHG emissions reduction by 2050 with "full decarbonization by 2070." These two scenarios are included to test for potential sensitivity of the results to the stringency of the case and the speed of decarbonization. In all cases considered, the assessment applies a 100-year global warming potential (GWP) of 25 for methane leakage. This GWP is even more conservative than the IPCC revised GWP for methane (that is, 36 over a 100-year period) and enables the modelling in this assessment to remain consistent with the referenced studies and data sources.

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[11] This is equivalent to the least-cost decarbonization scenario in UMAS (2020).

This analysis assumes that there is currently a reasonable likelihood of either decarbonization—by 2050 or 2070—trajectory. On the one hand, full decarbonization by 2070 is a likely scenario as it results in approximately a 50 percent reduction in absolute GHG emissions by 2050, which is a stated ambition in the Initial IMO GHG Strategy. On the other hand, these ambitions may be increased when the IMO agrees its revisions to the Initial IMO GHG Strategy in 2023, and conducts further reviews every five years. This is because of the higher GHG reduction imperative (across all sectors) provided by the Paris Agreement's temperature goals (UNFCCC 2016), the explicit link to the Paris Agreement's temperature goals made in the Initial IMO GHG Strategy, and the increasing numbers of governments setting their domestic GHG emissions reduction objectives to be in line with reaching zero GHG emissions by 2050 (or in some cases even sooner).

Furthermore, major commercial shipping stakeholders such as Maersk, BP, and Shell have already made commitments to achieve net-zero carbon emissions across their operations by 2050, strengthening the full decarbonization commitment of the shipping sector by or shortly after 2050 (Maersk 2019, BP n.d., and Shell n.d.). Others like the BW Group, which owns and operates one of the world's largest gas shipping fleet, or Trafigura, one of the largest ship charterers, have called for the IMO to facilitate an economically viable decarbonization route for the industry by adopting a carbon price on bunker fuels (BW Group et al. 2019, Trafigura 2020). However, stakeholder actions are not limited to individual organizations. Many forward-looking industry players have joined the Getting to Zero Coalition, which works toward "commercially viable zero-emissions vessels operating along deep-sea trade routes by 2030, supported by the necessary infrastructure for scalable zero-carbon energy sources including production, distribution, storage and bunkering" (Getting to Zero Coalition 2019). This has already led to the development of common industry-wide decarbonization frameworks, such as the Poseidon Principles or the Sea Cargo Charter, highlighting how the industry strives to make progress on aligning its operations and financing with the IMO's climate targets (Poseidon Principles n.d., and Sea Cargo Charter n.d.).

4.1 GHG IMPLICATIONS

What would be the potential short-term consequences for GHG emissions from ships if LNG was deployed as a temporary fuel at large scale?

A recent study commissioned by the Global Maritime Forum (see UMAS 2020) estimates the evolution of the international maritime fleet for both the 2050 and the 2070 decarbonization scenarios. Both scenarios forecast a massive uptake of zero-carbon ammonia to achieve these decarbonization objectives, and only a niche uptake of LNG (see Figure 10 on page 39). As a result, these scenarios can be used to create a baseline fleet evolution from now until 2050 that uses little LNG (the "Baseline" case). This baseline maritime fleet provides a viable GHG emissions pathway and is used as the basis for calculating the impact of additional LNG use on GHG emissions from ships.

To calculate the GHG impact of LNG, a contrasting case with LNG as a temporary fuel ("Near-term substitution" case) is created by forcing the adoption of LNG-fueled vessels into the international maritime fleet. For that purpose, the LNG adoption rate is set at 100 percent for newbuilds after 2021, thus mimicking the implementation of either an extremely effective policy mechanism, or the presence of an overwhelming commercial benefit. This means that any ship built after 2021, that uses fossil fuel in the "Baseline" case, is an LNG powered vessel within the "Near-term substitution" case.

To ensure that the "Near term substitution" fleet still achieves full decarbonization by 2050 or 2070, the LNG vessels are either retrofitted or superseded by zero-carbon vessels, which are mainly ammonia-powered (see section 4.2.2 for further details and Figure 13 for the fleet fuel use versus time). Again, this mimics the implementation of an effective policy decarbonization policy or significant commercial benefits. By calculating the evolution of GHG emissions in this "Near-term substitution" case, a direct comparison can be made to the "Baseline" case.

As discussed previously, the GHG benefits of using LNG are uncertain and depend on the pathways for sourcing LNG and the type of LNG engines installed on board. This uncertainty is represented by the assumption of differing emissions factors—that is gCO_2eq/megajoule (MJ)—across the reviewed studies as discussed in sub-section 2.2.1.1, and illustrated in Table 4.

From these studies, an upper and lower bound for total lifecycle emissions factors are derived and the potential GHG emissions implications computed. The emissions factor ranges used are shown in Appendix B. By combining the proposed range of emissions factors with the contrasting LNG uptake "Near-term substitution" case, the GHG impact of a temporary, but significant, LNG adoption case can be calculated.

Figure 8 illustrates the evolution of pure CO_2 emissions where the impacts of any methane leakage are ignored and where decarbonization is achieved by 2050. Figure 8 shows that under idealized conditions a significant, but relatively moderate, GHG benefit could be generated across the modelled international maritime fleet, peaking at a 15 percent benefit in 2031.[12]

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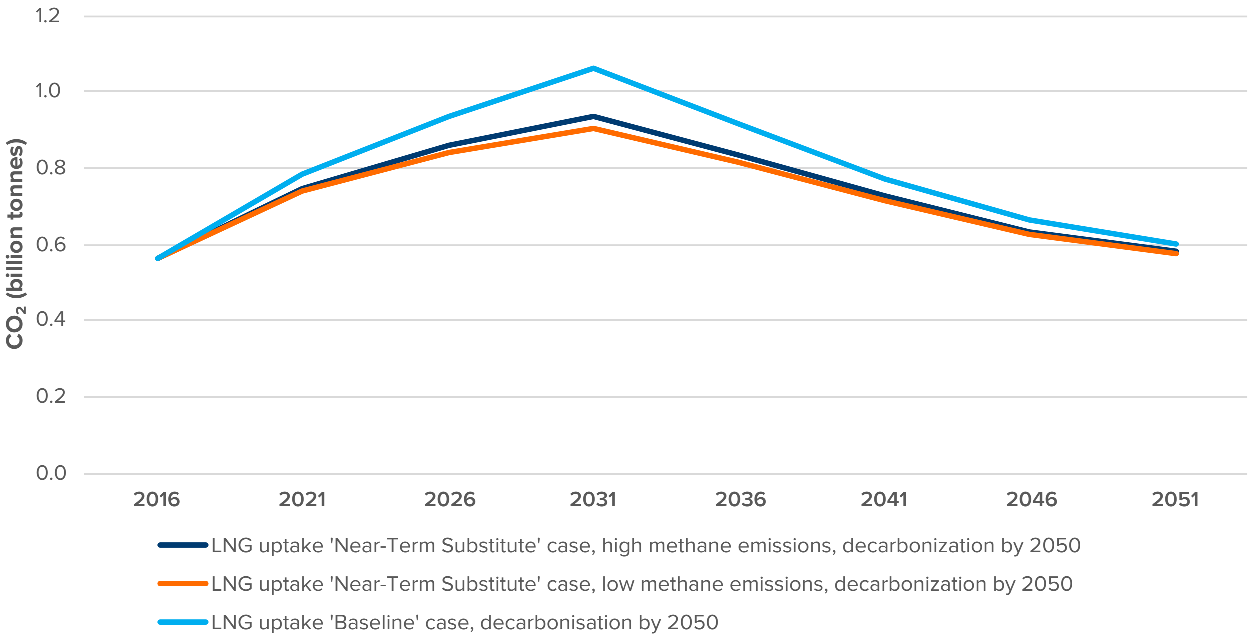
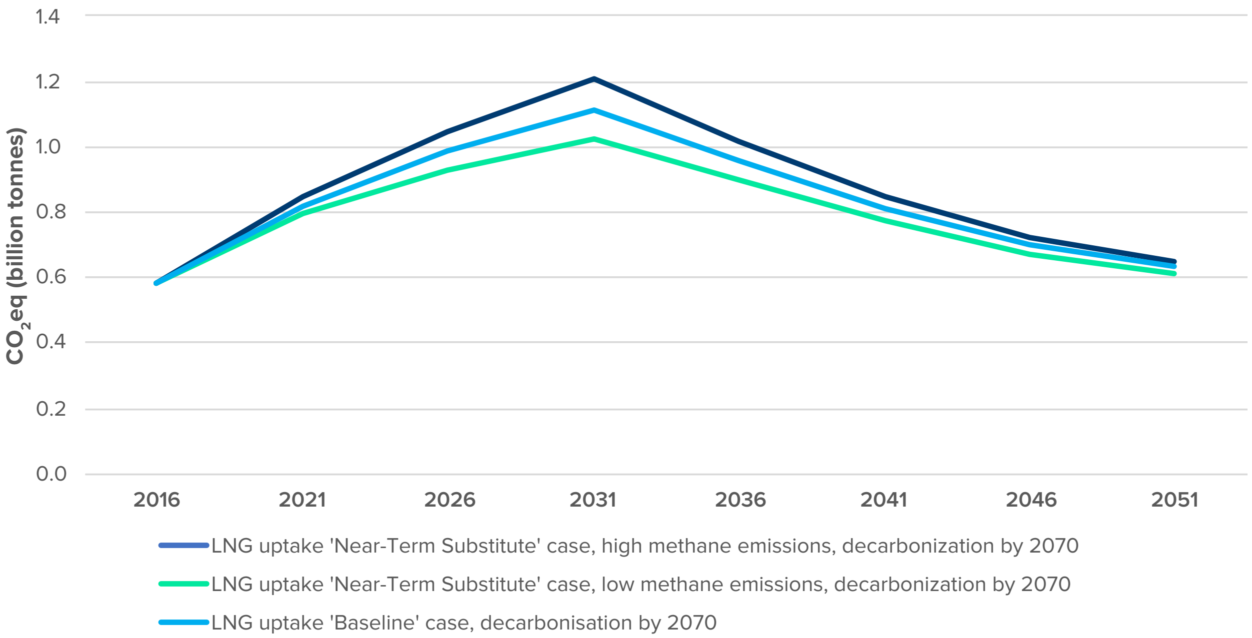
[12] The modelling is undertaken in time steps of five years and under the assumption of a linear evolution of relevant parameters between each time step. This explains why a gradual change is observed after 2016 leading up to the first modelled time step in 2021. The last modelled time step is 2051. This description of the modelling approach also applies to all subsequent results presented in section 4.

FIGURE 8: TOTAL LIFECYCLE CO$_2$ EMISSIONS (INCLUDING UPSTREAM, MIDSTREAM, AND DOWNSTREAM EMISSIONS)



This figure does not include the impacts of any methane leakage.

FIGURE 9: TOTAL LIFECYCLE CO$_2$eq (INCLUDING UPSTREAM, MIDSTREAM, AND DOWNSTREAM EMISSIONS).



This figure includes the impact of methane leakage using the 100-year GWP of 25 as outlined above.

Figure 9 accounts for methane leakage and shows the lifecycle CO_2eq GHG emissions for the scenario where decarbonization is achieved by 2070. Figure 9 shows that even in an idealized case, with significant market uptake of LNG, a longer decarbonization timeframe (decarbonization by 2070 rather than by 2050), and optimistic assumptions regarding LNG's potential for GHG reductions, the estimated GHG benefits of eight percent are not transformative relative to the baseline.

Figure 9 also demonstrates that once methane leakage is accounted for, using the range of emissions factors present across the literature, the GHG benefits of LNG are significantly diminished. Indeed, under the high methane emissions assumption, the use of LNG may even result in an *increase* of nine percent in GHG emissions. This provides support for urgent and strong policy action to regulate methane emissions both in the supply chain of LNG and in its use on board ships. Only such regulation could help avoid a worst-case scenario where a shift to LNG increases GHG emissions instead of reducing them. Such regulation would become even more important if the maritime transport sector's move away from fossil fuel use in the maritime fleet turned out to be slower in reality compared to the scenarios anticipated here.

Given the expected peak of the GHG benefits generated by LNG in the 2030s, considering the 20-year GWP of methane appears relevant. Under these circumstances, the GWP of methane changes from 25 to 86. Due to limitations in input flexibility in the modelling used to test this sensitivity case, the GWP change can be implemented on downstream emissions only. This change in perspective further diminishes the GHG benefits of the LNG uptake "Near-term substitution" case. In 2031, the GWP change on downstream alone causes CO_2eq emissions to increase from 1.16 to 1.45 billion tons (+25 percent) under the "'high methane emissions" assumption. Under the "low methane emissions" assumption, CO_2eq emissions increase from 1 to 1.12 billion tons (+12 percent). When a GWP of 86 is adopted for methane, even the "low methane emissions" assumption provides no material benefit over the "Baseline" case.

The modelling above shows that uncertainties around input variables such as emissions factors for methane mean that a range of possible GHG emissions are associated with deploying LNG in the "Near-term substitution" case. In no case is the generated GHG benefit transformative. For example, depending on the methane leakage assumptions used, the LNG market penetration would result in a GHG benefit of eight percent in 2030 in the optimistic case. In contrast, under conservative assumptions CO_2eq emissions from a significant LNG uptake may turn out to be nine percent higher in 2030 than the baseline. This analysis suggests that the expectation that short- to mid-term use of LNG would provide a significant GHG benefit appears to be questionable.

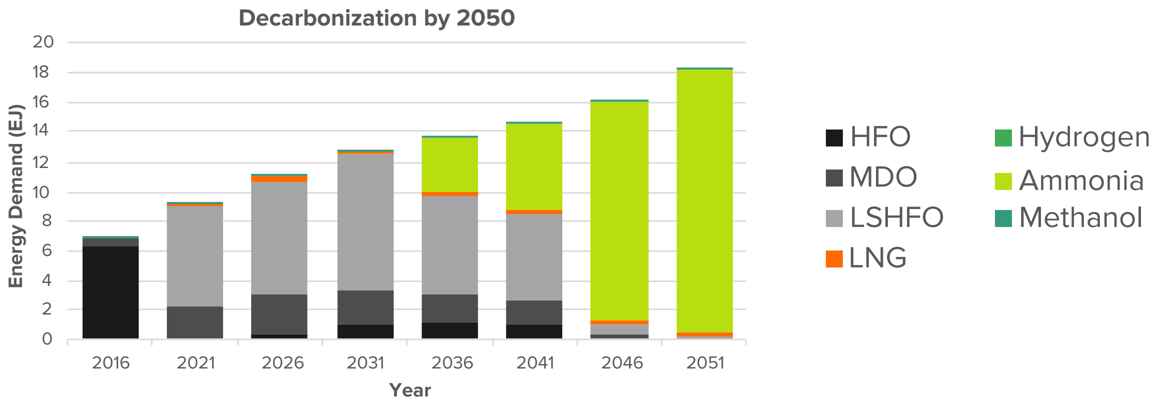
4.2 FINANCIAL IMPLICATIONS

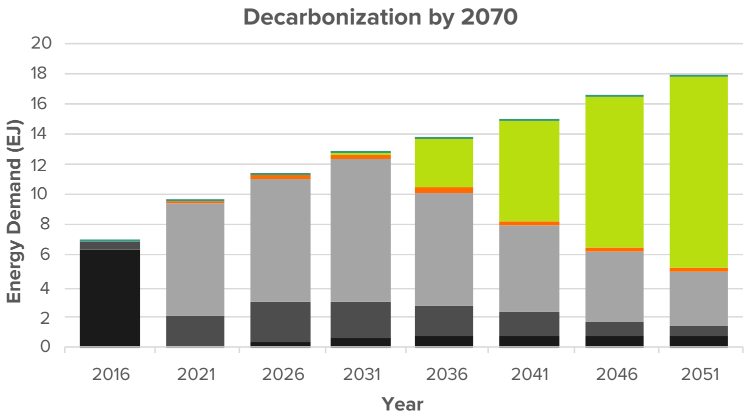
4.2.1 Investments required to decarbonize international shipping

What is the scale of investment needed to decarbonize international shipping?

The investment cost of the LNG uptake “Baseline” case is taken from UMAS (2020). This is the same set of international maritime fleet evolutions as used in sub-section 4.1. UMAS (2020) estimates the investment costs for the two decarbonization scenarios (by 2050 and by 2070) over the fuel pathways shown in Figure 9. As mentioned previously, the modelling of both scenarios finds a significant uptake of ammonia to achieve the decarbonization objectives, and only a niche uptake of LNG. As a result, these scenarios can be used to understand the investment needed for the “Baseline” case (based on Future 3: “A limited role for LNG”). This “Baseline” case assumes a single-stage conversion, meaning a direct shift from oil-derived fuels to zero-carbon ammonia produced by either renewable electricity or natural gas in conjunction with carbon capture and storage (CCS).

FIGURE 10: EXPECTED FUEL MIX FOR INTERNATIONAL SHIPPING UNDER TWO DECARBONIZATION SCENARIOS (“BASELINE” CASE)





Source: UMAS (2020) LNG uptake “Baseline” case (based on Future 3: “A limited role for LNG”)

The scope of the assessment includes the capital expenditures necessary to build the upstream, midstream, and downstream infrastructure from the point of energy availability to the supply of bunker fuel to the vessel. For instance, the capital expenditures here do not include the infrastructure needed to generate the renewable electricity consumed in the generation of hydrogen required for ammonia, or the capital needed to extract natural gas and transport it to a terminal. However, in the case of renewable electricity, the assessment does include some upstream investments such as for the electrolyzers and liquefaction plant necessary to turn electrical energy into zero-carbon hydrogen. In the case of natural gas, it includes the steam methane reformation and CCS plant necessary to generate zero-carbon hydrogen via this alternative route. Furthermore, the capital expenditures also include the marginal cost of either building new or retrofitting existing vessels to run on the various fuel types used on the decarbonization pathway outcomes from the model. These vessel costs include the costs of any efficiency technologies selected by the techno-economic model used in UMAS (2020).

Based on the scope of the assessment outlined above and in the report *Aggregate investment for the decarbonization of the shipping industry* (UMAS 2020), the scale of cumulative investments needed between 2030 and 2050 to achieve decarbonization by 2070 is approximately $1.0 to $1.4 trillion. When fully decarbonizing shipping by 2050, additional investments of approximately $400 to $500 billion would be required over 20 years, increasing the total investment needed to $1.4 to $1.9 trillion.

In this assessment, the time value of money has been ignored and the capital expenditures have simply been summed across the two decades to provide a magnitude estimate of the capital needed and present the scale of that capital. This is because this quantification has not been intended for comparative purposes. In return, all the underlying modelling to estimate the technology and fuel choices made at discrete points in time do include representation of the time value of money using a discount rate of 10 percent (see Appendix A).

The investments required depend mainly on the production method for the zero-carbon hydrogen needed to produce ammonia as a hydrogen carrier. Figure 11 shows the total investment in infrastructure required for the three different methods of hydrogen production. These methods include electrolysis production, production based on steam methane reformation with CCS, and a mix of the two.

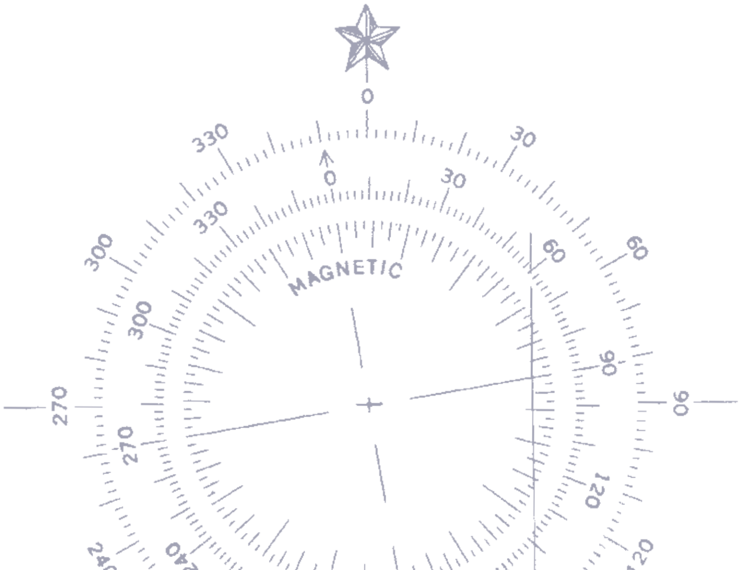
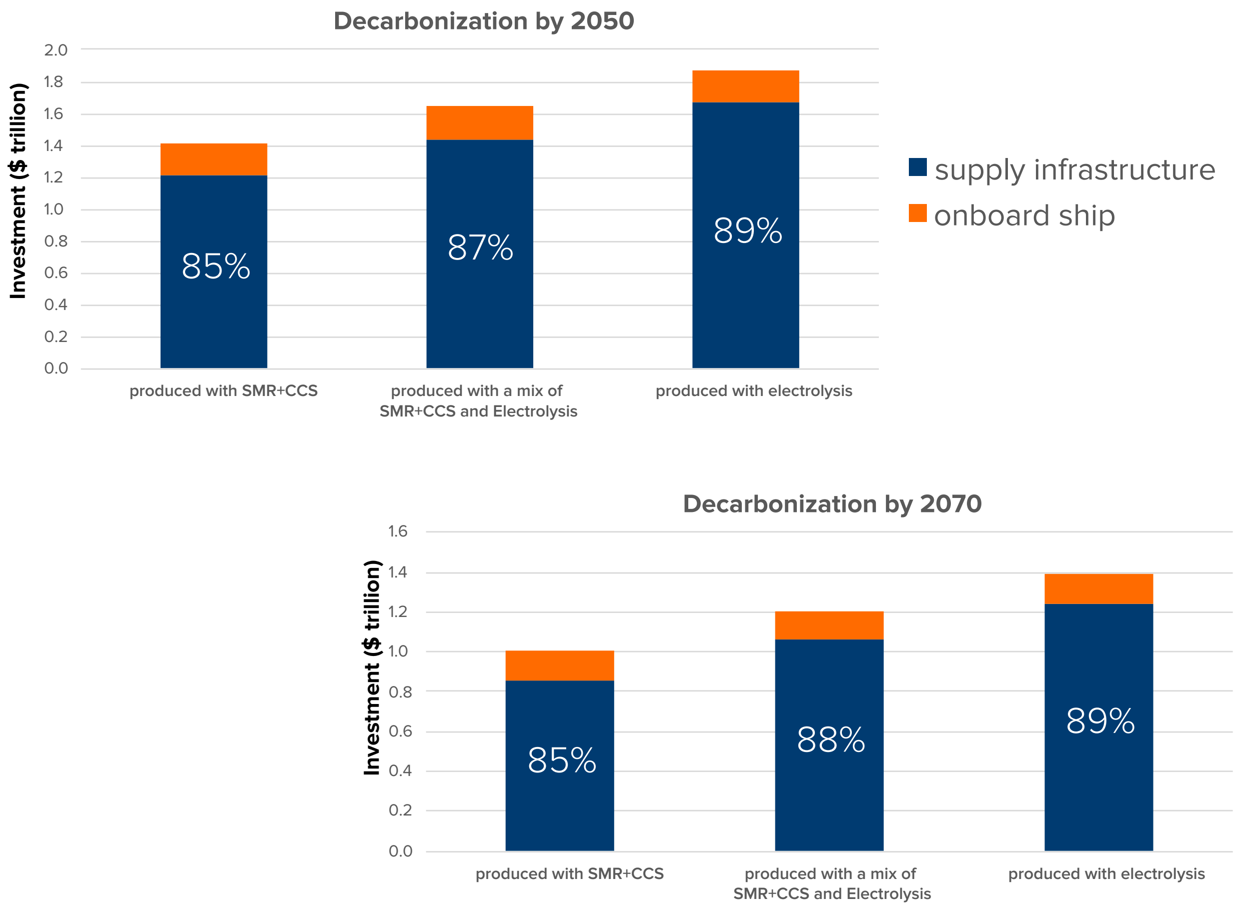
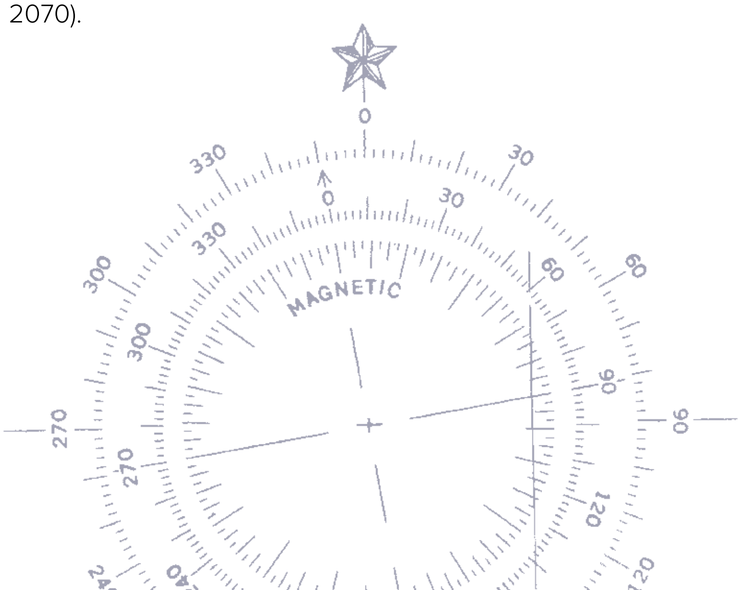


FIGURE 11: AGGREGATE INVESTMENT BY DECARBONIZATION SCENARIOS (“BASELINE” CASE)



Source: UMAS (2020)

The investment needs can be broken down into two main areas. The first area covers the ship-related investments, and the second refers to the land-based investments. Figure 11 shows that the land-based investments dwarf the ship-related capital expenditures. The overall breakdown of the investment needs for the LNG uptake “Baseline” case (Figure 11) is similar across the two decarbonization scenarios (decarbonization by 2050 and 2070).



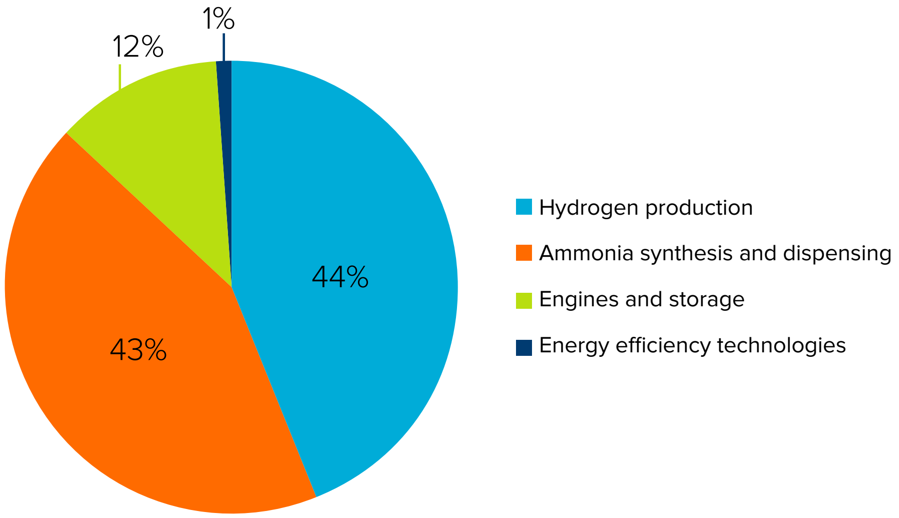


FIGURE 12: CAPITAL EXPENDITURES BREAKDOWN

Source: UMAS (2020)

Figure 11 and Figure 12 show that the scale of investment needed to decarbonize the shipping sector is significant and that most of this investment is tied to producing zero-carbon ammonia and hydrogen.

4.2.2 Investments required for the use of LNG as a temporary fuel

How much additional investment would be needed to deploy the corresponding infrastructure and fleet if LNG served as temporary fuel at large scale?

In the LNG uptake "Near-term substitution" case, a significant use of LNG as a bunker fuel is forced into the shipping fleet from 2021 onwards as described in sub-section 4.1. This leads to additional capital expenditures relative to the baseline case, which does not find any significant uptake of LNG. The evolution of the assumed maritime fleet is identical to the one used to assess the GHG implications in sub-section 4.1.

In the LNG uptake "Near-term substitution" case, a two-stage conversion can be observed: first from oil-derived bunker fuels to LNG, followed by LNG to zero-carbon bunker fuels. Due to the technical challenges associated with retrofitting LNG technology to existing vessels powered by heavy fuel oil (HFO), it is assumed that all newbuilds from 2021 will be LNG-powered vessels and the existing oil-powered fleet remains in service until the end of its economic life. Again, from the 2030s, under the modelled constraint of a gradually reducing level of absolute CO_2 emissions (see Appendix A), from the 2030s onwards the fleet then transitions to a zero-carbon fleet comprised of ammonia-powered vessels to fulfill the targets of the two decarbonization scenarios. As in the "Baseline" case, the final zero-carbon transition is achieved through a mix of ammonia newbuilds and retrofits (this time mostly from LNG to ammonia given the prevalence of LNG as a bunker fuel by 2030 rather than from HFO/LSHFO to ammonia as in the "Baseline" case).

The resulting fuel mix in the LNG uptake "Near-term substitution" case is provided in Figure 13. Under the two scenarios of full decarbonization by 2050 and by 2070, this case based on Future 2, "Temporary role for LNG," shows a rapid increase in LNG use between 2021 and 2031.

Under the "Full decarbonization by 2070" scenario, LNG's share in the bunker fuel mix rises to approximately 40 percent by 2031, before declining from 2031 as the bunker fuel mix shifts rapidly toward ammonia (see Appendix A). This increase in LNG market share is greater than the upper bound scenarios examined in the literature review in section 2 (the highest share projected was 21 percent), but provides a useful test case for comparison with the LNG "Baseline" uptake.

Under the "Full decarbonization by 2050" scenario, about 47 percent of the fleet (in terms of number of ships) use LNG as a temporary fuel in 2031. This value is driven by the assumption that every newbuild from 2021 uses LNG as a bunker fuel, and is influenced both by the average lifetime (total time at sea) of an individual ship, as well as the rate of demand growth and growth in fleet size. By 2036, the share of the total fleet using LNG as a bunker fuel drops to 22 percent due to the rapid retrofitting of LNG ships to ammonia. This retrofitting is driven by the need to achieve the rate of CO_2 reduction specified for the decarbonization scenario (Appendix A). Retrofitting becomes necessary as the required CO_2 reduction cannot be achieved through the combination of zero-carbon newbuilds and energy efficiency alone. This also makes it necessary to switch from fossil fuels to zero-carbon bunker fuels in the existing fleet.

Once such a policy driver for ammonia is in place, it will be primarily the younger fleet that will experience retrofits since newer ships have a longer period for return on investment. Less retrofitting is expected for the vessels that are 15 or more years old, where a retrofit return would need to be shorter and appears less financially compelling. These dynamics reveal a potential investment risk for the land-side LNG infrastructure, since the declining LNG throughput may become insufficient to service the long-term debt payments under such a sharp market contraction.

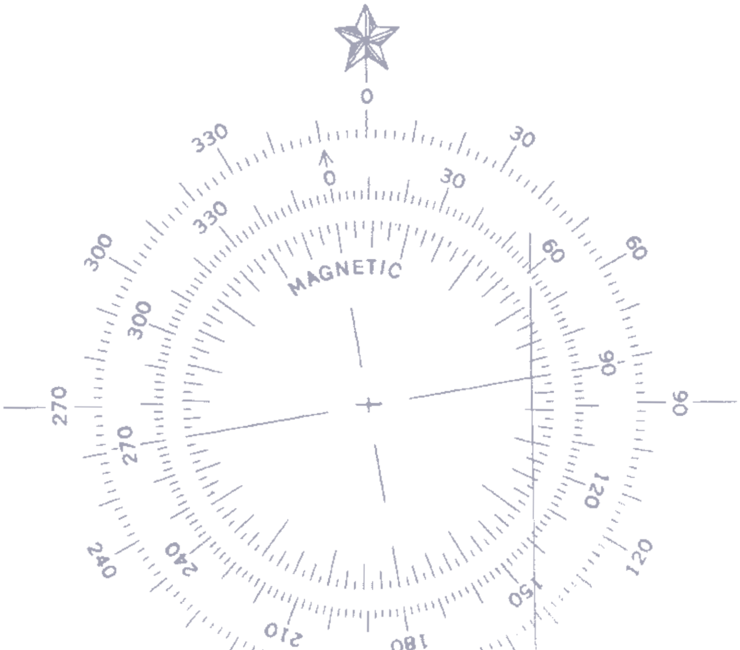
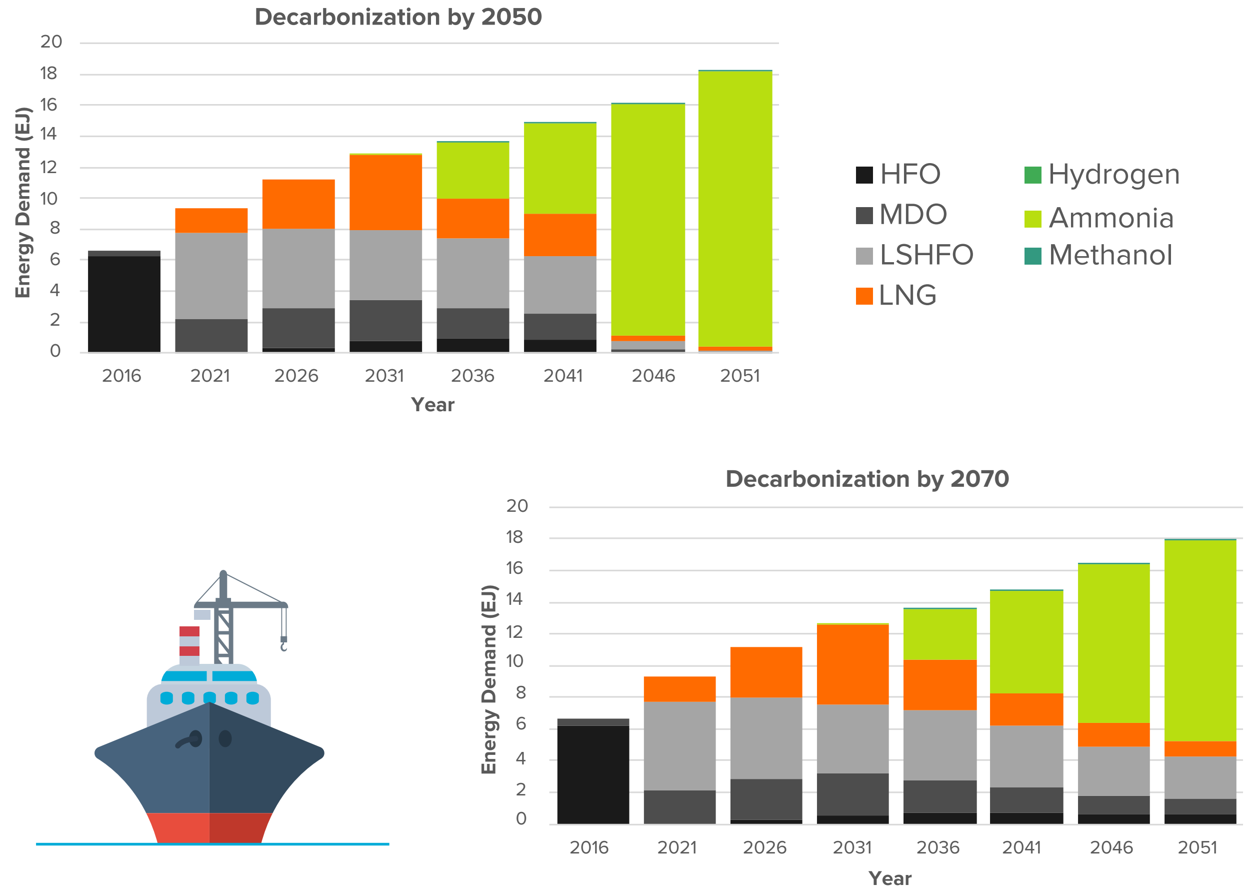


FIGURE 13: EXPECTED FUEL MIX FOR INTERNATIONAL SHIPPING UNDER TWO DECARBONIZATION SCENARIOS ("NEAR-TERM SUBSTITUTION" CASE)



Based on Future 2: "Temporary role for LNG"

This analysis of the fleet composition over time provides two important insights:

- **Risk for the LNG fleet:** The introduced LNG vessel fleet may almost immediately be retrofitted to ammonia to meet the IMO's decarbonization target of at least a 50 percent reduction in GHG emissions by 2050. In many instances, this could be within the first dry-dock period. This is likely to challenge the economics of these vessels, with many owners opting to hold older vessels and switch directly from an oil-derived fuel to a zero-carbon fuel in a single-stage conversion (as suggested by UMAS 2020).

- **Risk for the LNG infrastructure:** There is also a risk that any corresponding LNG infrastructure becomes underutilized from 2036 onwards. The market turnover rate limiting the rate at which LNG vessels can naturally enter the maritime fleet, coupled with the imperative of the zero-carbon transition, may result in less than 10 years of significant LNG demand from shipping. This presents a financial risk for any investors in related infrastructure.

The additional investment costs of the LNG uptake “Near-term substitution” case have been calculated by subtracting the total costs of the LNG uptake “Baseline” case. This step allows examination of the aggregate investment implications of a two-stage conversion (oil to LNG, followed by LNG to zero-carbon) relative to a single-stage conversion from the current oil-derived bunker fuels directly to zero-carbon bunker fuels. This process is repeated for both decarbonization scenarios: full decarbonization by 2050 and full decarbonization by 2070. The additional investment costs include:

- Additional capital investment in an LNG-compatible fleet (for example, the marginal LNG-related costs relative to a standard oil-powered vessel)
- Additional capital investment in land infrastructure (for example, additional bunkering infrastructure and LNG delivery barges)

The capital expenditure assumptions used for onboard equipment (in the maritime fleet) and the capital expenditure assumptions used for LNG supply chain (land-based infrastructure) are provided in Appendix C. For the LNG supply pathways, only the midstream capital expenditures are included. This is based on the assumption that wherever LNG will be bunkered, there will be an LNG exporting or importing terminal nearby with sufficient capacity to serve shipping. This assumption is backed by the maturity of existing global LNG infrastructure, which is currently used to trade LNG as a commodity in the broader energy system (especially in North America, Asia, Europe, the Middle East, and Australia). However, in certain geographies where this synergy may not yet necessarily exist (for example, Africa), a bespoke LNG terminal or a liquefaction plant may be needed to enable the supply of LNG as a bunker fuel. Consequently, the capital expenditure for the supply pathway would further increase, and the current cost assumptions would be rather optimistic.

Table 6 displays the additional capital expenditures associated with LNG-powered vessels and land-based infrastructure for LNG. For each of the decarbonization scenarios shown in Table 6—decarbonization by 2050 (left); decarbonization by 2070 (right)—the following Figure 14 illustrates the growth of LNG demand alongside annual and cumulative total land-related capital expenditures. This figure, combined with Table 6, shows that a significant but temporary shift to LNG adds at least a further 10-17 percent to the total investment needed on top of the basic $1.0 to $1.9 trillion to decarbonize shipping. As stated previously, the capital expenditure premiums relate to the marginal infrastructure and vessel investments needed to deliver the decarbonization scenarios.

Figure 14 has a small increase in capital expenditures (and therefore cumultative capital expenditures) in 2051. This is because the lifetime of some of the assets is estimated as 20 years, and by 2051 the earlier investments would need replacing/updating. Whilst the modelling estimates this late need for new capital expenditures due to the assumptions used and the continued (albeit falling) demand, in practice with these demand profiles this may not occur and could constitute a small constraint on supply volumes of LNG by 2051. Further capital will be required throughout the period for any non-fuel/energy-related investment needs over this period (for example, refinancing of fleet, financing other retrofits and maintenance, financing new-build tonnage, and financing port and cargo capacity).

As these additional investments will primarily relate to the fleet- and land-based infrastructure enhancements before the large-scale investments in zero-carbon bunker fuels begin around 2030, the annual investments for LNG will be high in the period 2021 to 2031, but then rapidly decrease. There is little difference in the total additional investment between decarbonization by 2050 and by 2070. This is because the difference between these scenarios is primarily in the speed of the shift to ammonia in the period 2031 to 2051, and there appears to be little difference between the scenarios in the preceding years.

TABLE 6: ADDITIONAL CAPITAL EXPENDITURES OVER THE PERIOD TO 2051, UNDER TWO DECARBONIZATION SCENARIOS IN THE “NEAR-TERM SUBSTITUTION” CASE

	DECARBONIZATION BY 2050	DECARBONIZATION BY 2070 (WHILST ACHIEVING A 50% GHG REDUCTION IN 2050)
Additional investment in the fleet	$120 billion	$93 billion
Additional investment on land	$66 billion	$76 billion
Total additional investment needed	$186 billion	$169 billion
Total investment needed (as of counterfactual investment)	112–117 percent	110–113 percent

“Near-term substitution” case (based on Future 2: “Temporary role for LNG”) relative to the “Baseline” case (based on Future 3: “A limited role for LNG”).

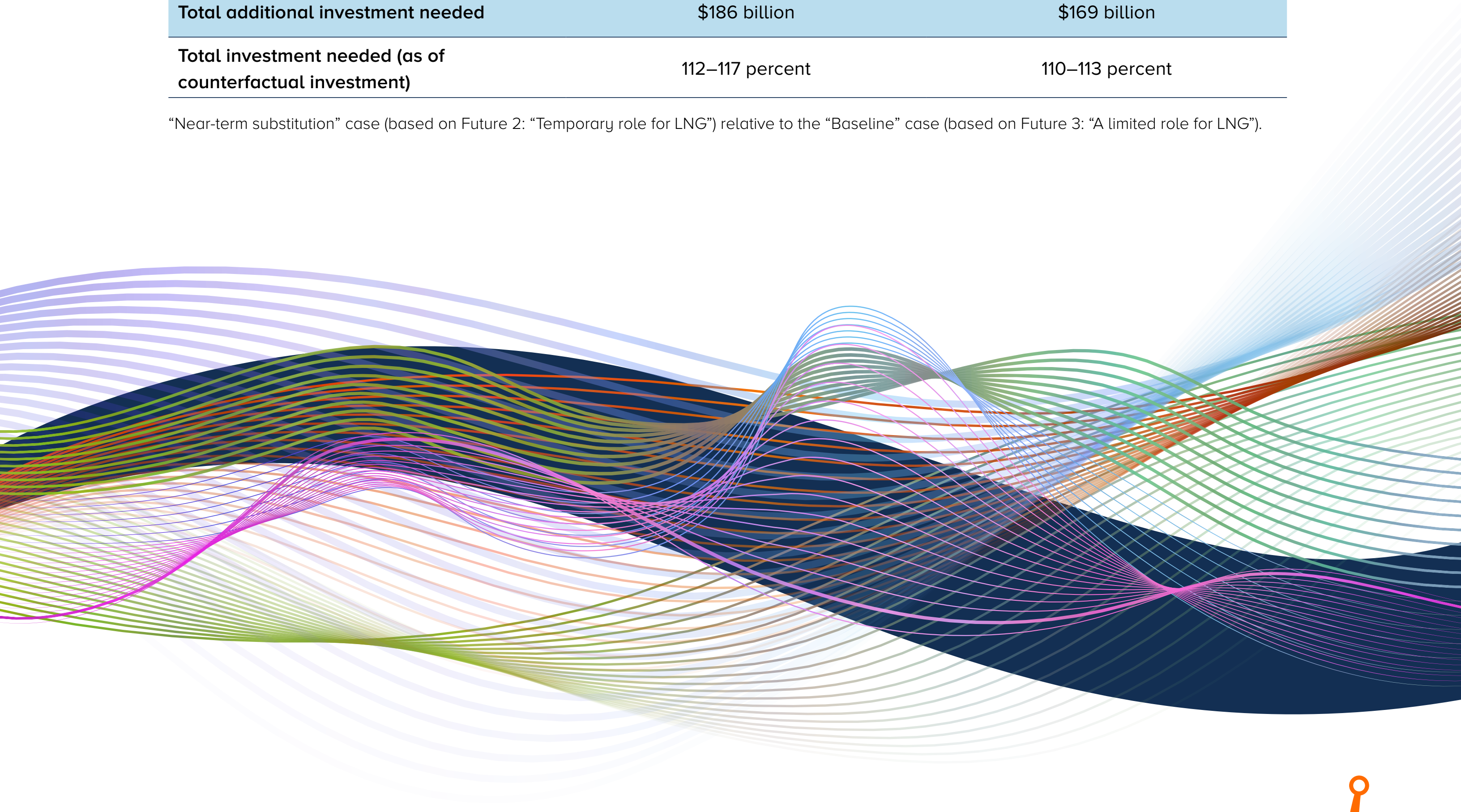
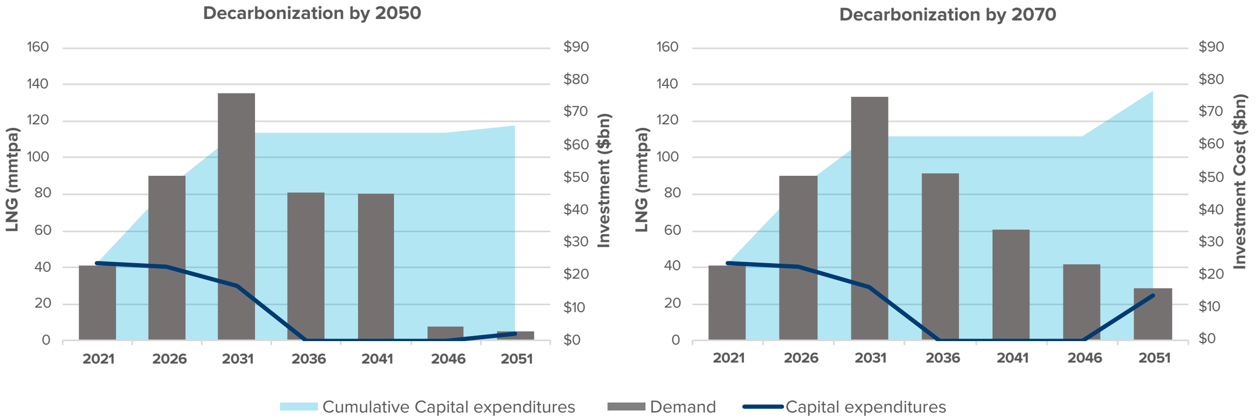


FIGURE 14: LNG DEMAND, LAND INFRASTRUCTURE CAPITAL EXPENDITURES PER ANNUM, AND CUMULATIVE LAND INFRASTRUCTURE CAPITAL EXPENDITURE PROJECTIONS UNDER TWO DECARBONIZATION SCENARIOS



By combining the modelling outcomes of sub-sections 4.1 and 4.2, it can be estimated that a “temporary” though significant use of LNG by the international maritime fleet is likely to lead to moderate-to-negative GHG benefits and an additional capital cost of at least 10–17 percent compared to a “baseline” case with a limited role for LNG. It would likely require an additional capital investment of between $169 billion and $186 billion. When these capital flows are discounted to their present value in 2020, the nearer term capital expenditures on LNG become more significant relative to the longer term (and therefore more discounted) capital expenditures on ammonia. With a discount rate of 10 percent, the estimate of the additional capital investments associated with a “temporary” use of LNG becomes $98 billion and $82 billion for decarbonization by 2050 and 2070, respectively. As proportions of the discounted total additional capital expenditures for achieving decarbonization, these discounted values then both represent over 30 percent of additional capital expenditures required to achieve full decarbonization.

This financial amount is provided as an indicative value to demonstrate the scale of the additional capital and costs required if LNG was to play a temporary role in shipping’s decarbonization. It should be understood as the upper bound of the capital that is at risk of premature write-down as demand for LNG falls off from the 2030s onwards. It is an upper bound value since much of this capital may have already generated a return as it progressed through some of its economic life before the write-down starts. The exact amount at risk depends on how the market foresees the decarbonization scenarios described here, the actual paybacks set, and how (and whether) any demand contraction for LNG materializes in practice. However, given the magnitude of the upper bound of capital at risk, this suggests that any financial risks would benefit from being carefully assessed for robustness to a contraction in demand for LNG as a bunker fuel. Therefore, it appears important to understand the financial viability of potential LNG vessels and infrastructure, and the risk of them becoming stranded assets.[13]

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[13] Stranded assets are defined as assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities” (Caldecott, Tilbury, and Carey 2014).

4.3 RISK OF STRANDED ASSETS

What may be the potential risk of stranded assets associated with LNG as a temporary fuel?

The "Near-term substitution" case (Future 2: "Temporary role for LNG") estimates declining LNG demand from its peak in 2030 (as shown in Figure 15). This means that the infrastructure built in the 2020s, sized for this peak, will continue serving the LNG demand out to 2050. The potential utilization rate of such infrastructure would inevitably fall as LNG demand wanes. Utilization improves once again in the late 2040s as the infrastructure built in the 2020s retires and can be replaced with much smaller-scale assets to serve the remaining legacy demand. This rapid drop in demand and in the related utilization rate of existing LNG infrastructure may lead to concerns about the financial viability of the LNG infrastructure.

The modelling assumes that, during the 2020s, large-scale and long-life LNG infrastructure will be installed as investors expect the traditional (approximately) 20 years payback period. As the growth in demand for LNG slows in the mid-2020s and the actual demand starts to decrease after 2031, it is assumed that the LNG supply chain infrastructure will be replaced with smaller-scale and shorter-life infrastructure.

The level of risk of stranded assets in the LNG uptake "Near-term substitution" case is particularly sensitive to the level of demand foresight in the LNG supply market. Good foresight allows better decisions to be made around the intended economic size and lifetime of any LNG infrastructure investments, and the options to manage the period of declining demand. For example, the likelihood of an asset becoming stranded could be reduced through the use of smaller-scale and shorter-life LNG infrastructure targeted at enhanced flexibility in phasing out supply as demand falls. This could also be done by extending the life of the older large-scale assets beyond 20 years, as demand falls, to avoid the need for newbuild LNG assets in the 2040s.

From a financial perspective, capital expenditures may be paid off before these stranded asset risks materialize and before the end of the economic life of the LNG asset. Yet in this instance the asset owner may still face a residual value risk with a lower price than expected if the asset is then to be sold on the second-hand market. Furthermore, the asset owner may also risk other forms of write-down in asset value, for example due to new regulation or strengthening negative perception of methane emissions, which may influence the need for a costly retrofit to control methane emissions, or a reduced asset life.

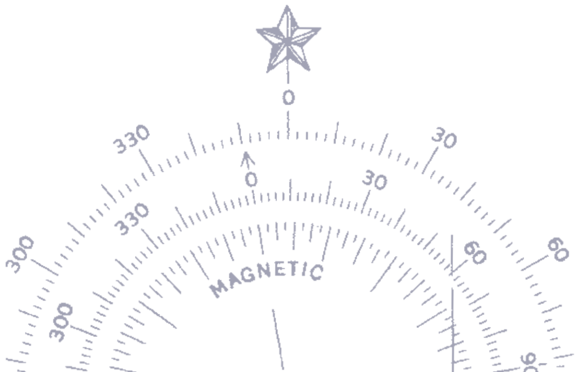
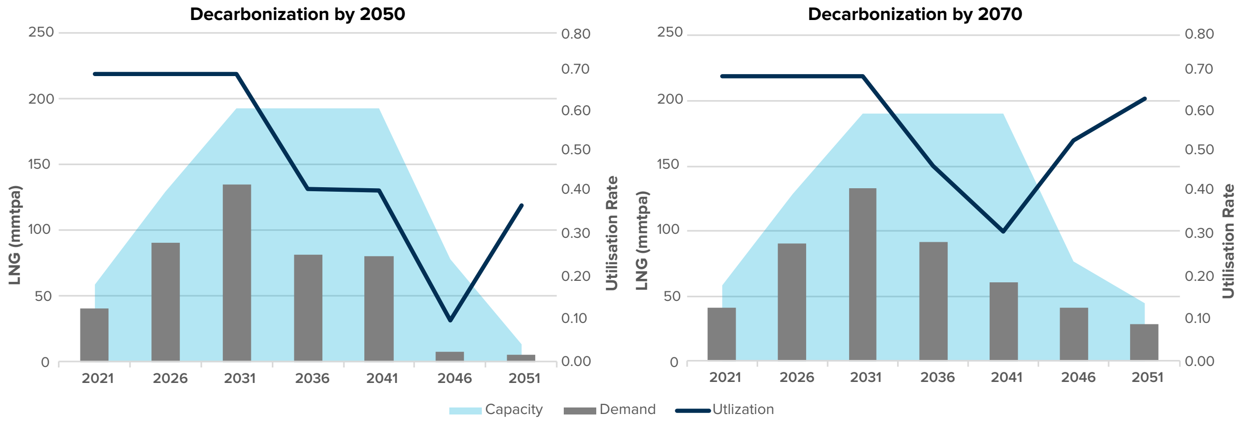


FIGURE 15: LNG DEMAND, CAPACITY, AND UTILIZATION RATE PROJECTIONS UNDER TWO DECARBONIZATION SCENARIOS (“NEAR-TERM SUBSTITUTION CASE”)



Due to the rapid drop in demand and therefore utilization rates around the middle of the 2030s, there may be a serious risk of stranded assets within the LNG supply chain for shipping. This could possibly create a degree of political pressure countering decarbonization incentives as investors seek to minimize potential losses. If this political pressure results in a delay of the decarbonization pathway, this outcome could further exacerbate the GHG emissions risk, threatening IMO’s 2050 climate target. Such market inertial effects are termed as “technology pathway lock-ins,” or, in this specific case, as “LNG lock-in.” The next sub-section of this report attempts to quantify the amount of additional GHG emissions that could result from various scenarios of a fossil LNG lock-in.

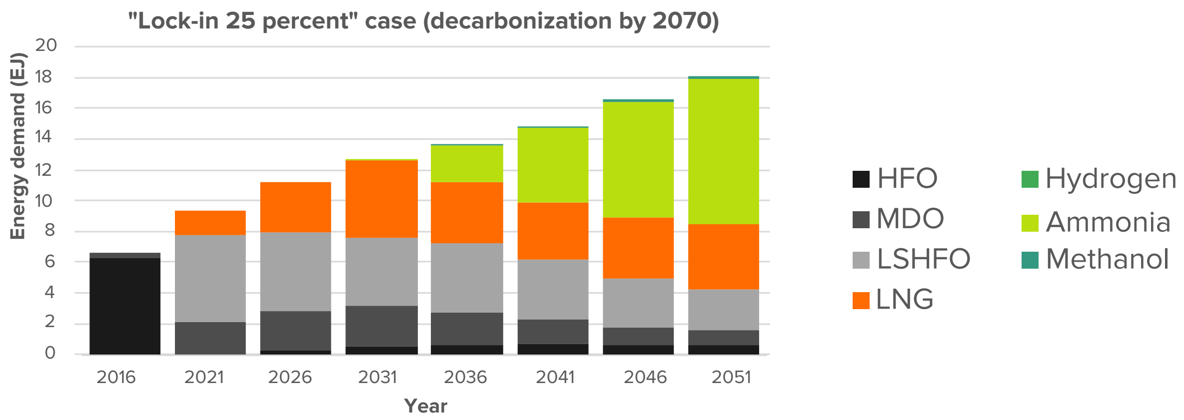
4.4 RISK OF A TECHNOLOGY LOCK-IN

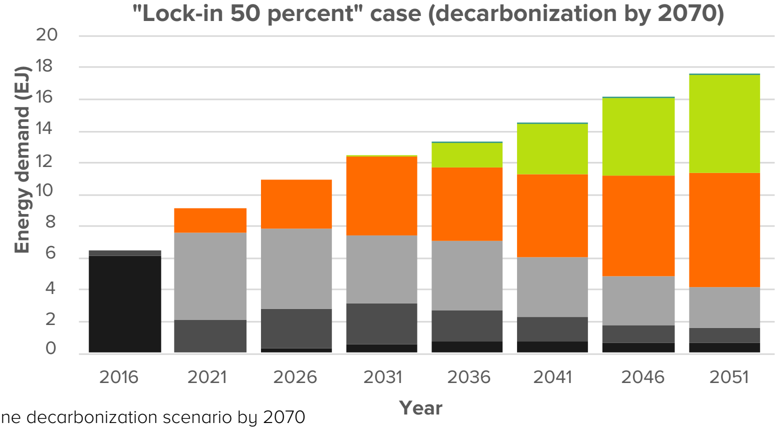
What could be the consequences of a fossil-derived LNG technology pathway “lock-in”?

A major environmental concern associated with a significant temporary deployment of LNG is the potential risk for a GHG emissions “lock-in.” As can be seen from sub-section 2.2.1, this would be at odds with IMO’s GHG emissions reduction target for 2050. This sub-section quantifies the GHG impact of a potential fossil LNG lock-in using the fleet composition underlying the “Near-term substitution” case as a starting point.

Building upon the cases explored in the previous sub-sections (“Baseline” and “Near-term substitution”), two additional lock-in cases are analyzed. The starting point is the “Near-term substitution” case (based on Future 2: “Temporary role for LNG”) that delivers full decarbonization by 2070 and meets the IMO’s GHG emissions reduction target of at least 50 percent by 2050. These two new cases are labelled LNG uptake "Long term lock-in 25 percent" and "Long term lock-in 50 percent." These lock-in suppositions refer to a situation where the LNG-powered maritime fleet is maintained just to service the infrastructure debt, despite the IMO's decarbonization 2050 target. "Long term lock-in 25 percent" assumes that 25 percent of the ammonia demand present in the relevant LNG uptake "Near-term substitution" case will be displaced by LNG. Similarly, "Long term lock-in 50 percent" assumes that 50 percent of the ammonia demand is offset by continous demand for LNG. The resulting fuel mixes are provided in Figure 16.

FIGURE 16: EXPECTED FUEL MIX FOR INTERNATIONAL SHIPPING UNDER TWO CASES ("LOCK-IN 25 PERCENT" AND "LOCK-IN 50 PERCENT")



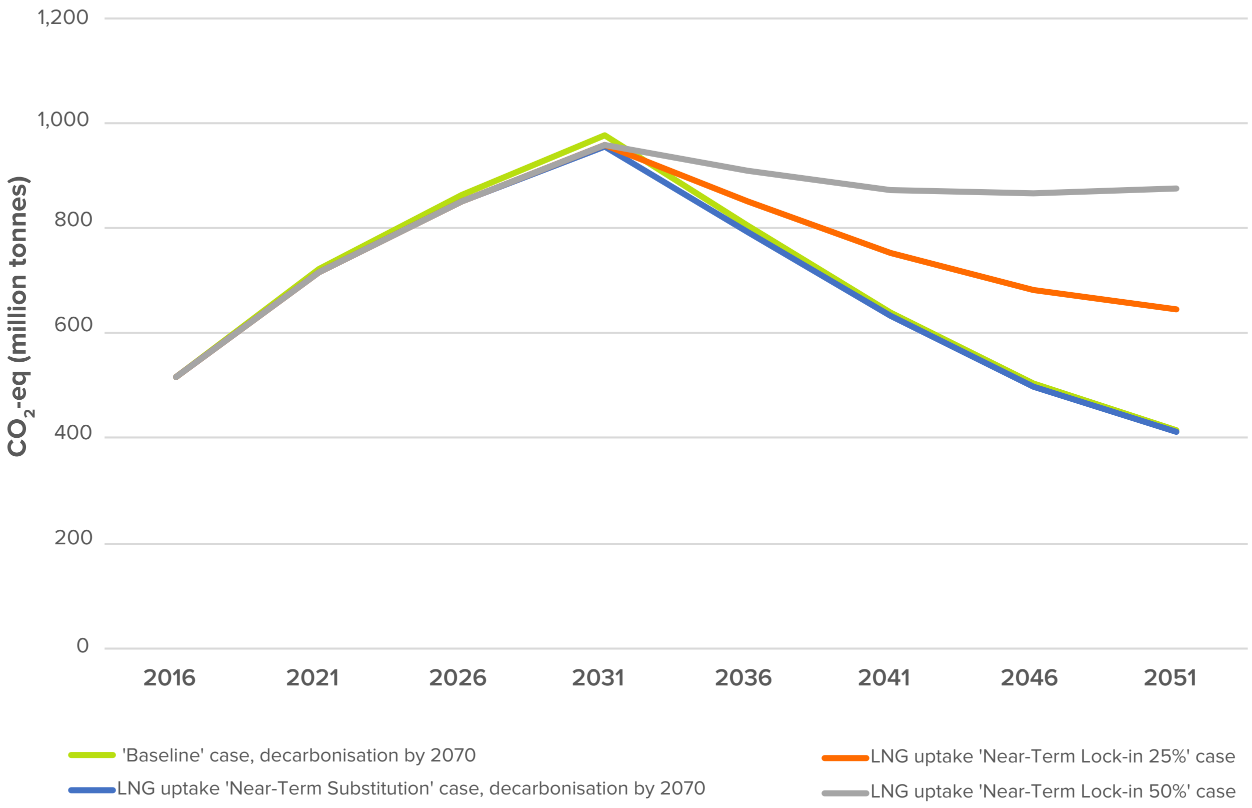


Both based on Future 2 ("Temporary role for LNG") and one decarbonization scenario by 2070

The assumed bunker fuel mixes lead to several GHG emissions trajectories. Figure 17 shows a comparison between both the lock-in cases and the two prior cases, "Baseline" and "Near-term substitution," using mid-methane emissions (an average of the identified high and low bounds for methane leakage, see Appendix B). The comparison is shown only for the full decarbonization by 2070 scenario. Under the mid-methane emissions assumptions, as can also be shown for the case with low methane assumptions in Figure 9 (on page 37), the three cases that all have significant uptake of LNG by 2031 result in a small reduction in peak CO_2eq emissions relative to the baseline case.

In the lock-in cases, the cumulative *operational* (downstream only) CO_2eq emissions increase by 5 to 14 percent relative to the non-lock-in cases. In absolute terms, this means that if the use of LNG continued—ignoring any climate policy such as a stringent carbon price on bunker fuels that would force the international maritime fleet to comply with the IMO's decarbonisation 2050 target—this would result in approximately 1,300 and 3,500 million tons, respectively, of additional cumulative GHG emissions up to 2051. Such excess emissions represent 1.5 to 4 years of current annual GHG emissions from ships and would further call into question shipping's GHG emissions-reductions trajectory consistent with the Paris Agreement temperature goals.

FIGURE 17: DOWNSTREAM EMISSIONS TRAJECTORIES UNDER DIFFERENT LNG UPTAKE CASES



If the upstream and midstream GHG emissions associated with the use of LNG also were considered, this would result in approximately 1,900 and 4,200 million tons, respectively, of additional cumulative GHG emissions for the period spanning 2020–2050.

4.5 LESSONS LEARNED

This section provides a scenario analysis of the potential use of LNG as a temporary bunker fuel in shipping's decarbonization. The analysis suggests that the direction and magnitude of the effect of a temporary use of LNG on GHG emissions is uncertain, ranging from a moderate decrease to an equivalent moderate increase. In contrast, a significant uptake of LNG would require substantial additional capital expenditures, and these investments may be challenged by the market evolution. Overall, this analysis suggests that the use of LNG as a transitory fuel is likely to face challenges in terms of environmental and financial risks.

5. CONCLUSIONS AND OUTLOOK

5.1 CONCLUSIONS

At the start of this report the following questions were posed: What would the role of liquefied natural gas (LNG) as a bunker fuel in the years 2020–2050 look like? Offering significant air quality benefits, could LNG also make an important contribution to the targets set by Initial International Maritime Organization (IMO) Greenhouse Gas (GHG) Strategy and the sector's transition toward low- and zero-carbon shipping?

The conclusions of this report have been developed through a logic that starts with the Paris Agreement's temperature goals, considers shipping's GHG emissions trajectory and the associated fuel mix that would be required to meet those goals, and assumes that appropriate policy would be introduced to achieve those outcomes. The Initial IMO GHG Strategy is consistent with this logic. Within this context, there is consensus across the literature and industry that LNG cannot form a large proportion of the bunker fuel mix in 2050 due to its carbon intensity (ICS 2018, IMO 2018a, GMF 2018).

This means that three main possibilities for the role of LNG as a bunker fuel can be imagined:

1. **Future 1: A transitional role for LNG** – "Use and reuse."
2. **Future 2: A temporary role for LNG** – "Use and then stop."
3. **Future 3: A limited role for LNG** – "Limited use overall."

Analyzing these possibilities has helped to answer the questions posed above. In general, the literature review in section 2 shows that the short-term environmental, macroeconomic, technological, and regulatory drivers for the uptake of LNG at large scale (greater than 10 percent of fuel mix in energy terms) appear relatively weak. The main policy driver affecting the industry in the timeframe 2020 to 2050 is likely to be the Initial IMO GHG Strategy. As discussed above, the Strategy, however, does not represent a driver for a significant uptake of LNG either. No other major commercial driver or regulatory mechanism could be identified to drive the large-scale uptake of LNG in the period before the shift to zero-carbon bunker fuels in the 2030s.

The compatibility as well as viability discussions in section 3 discount the possibility of Future 1 ("Transitional Role for LNG"). The future zero-carbon bunker fuels compatible with LNG infrastructure, liquefied biomethane (LBM) and liquefied synthetic methane (LSM), are not likely to be available and competitively priced at the volumes needed to meet shipping's total energy demand by 2050. It also appears likely that there will be much more scalable and cost-effective zero-carbon alternatives, such as ammonia and hydrogen (*Volume 1: Volume 1: The Potential of Zero-Carbon Bunker Fuels in Developing Countries,*, see Preamble). This does not rule out that some LBM and LSM may be available, most likely at a price premium relative to the fuel that becomes the mainstream zero-carbon alternative. That LBM and LSM supply could be harnessed for those existing LNG assets for which a business case can be made despite the price premium. Yet there are substantial caveats to the prospects of methane variants like LBM and LSM to serve as fallback options for LNG assets that would otherwise become stranded. These caveats, in return, do not support the argument that LNG is likely to play a significant transitional role in shipping's decarbonization.

Section 4 provides further data suggesting the likely limited role for LNG in the decarbonization of shipping. It compares the implications of an *idealized* Future 2 ("Temporary role for LNG"*)* based on a potential temporary role for LNG, with Future 3 ("A limited role for LNG"*)*, which foresees a rather limited role for LNG. The analysis shows that if there were a very strong commercial or regulatory driver for LNG, then this could provide a variety of potential outcomes. These outcomes range from moderate, but not transformative, GHG benefits to moderate GHG disbenefits depending on the assumptions found in the literature. The maximum GHG benefit would be eight percent lower GHG emissions in 2030, while the maximum disbenefit would be nine percent higher GHG emissions in the same year.

The analysis in section 4 also examines the aggregate investment implications of a two-stage conversion (oil to LNG, followed by LNG to zero-carbon) relative to a single-stage conversion from the current oil-derived bunker fuels directly to zero-carbon bunker fuels. A single-stage conversion would imply a limited role for LNG. The capital expenditure for Future 2 ("Temporary role for LNG") ranges at least between 110 to 117 percent of the capital expenditure needed to implement Future 3 ("A limited role for LNG"). This may amount to up to $186 billion of additional capital expenditure. The temporary use of LNG therefore results in a range of GHG outcomes from moderately better to moderately worse alongside considerable additional capital expenditure relative to the counterfactual without a significant role for LNG.

Section 4 also considers the utilization rates of the relatively short-lived LNG assets. This analysis shows that, even if the additional capital of up to $186 billion could be raised, it would likely face financial risks due to the steep decline in LNG demand from the mid-2030s onwards. One consequence of these financial risks could be commercial and ultimately political pressure to ensure a more gradual phase-out and decline in demand for LNG as a bunker fuel. However, this would, in turn, create an environmental risk in the form of technology lock-in and important increases in cumulative GHG emissions from ships.

This analysis does not exclude the possibility that some jurisdictions may have a strong domestic interest to make significant short-term investments in LNG, for instance, to achieve the obvious air quality benefits of LNG over traditional heavy fuel oil (HFO)-powered vessels. This is particularly true of particulate matter emissions, which remain difficult to abate when using low sulfur heavy fuel oil (LSHFO) or marine diesel oil, even if the currently available emission-reduction technologies are fully applied (Lehtoranta et al. 2019). In such cases where LNG is adopted, the supply and use of LNG should be monitored to show control of methane emissions, thus ensuring a meaningful GHG benefit relative to conventional oil-derived fuels.

However, these situations may not necessarily materialize since, depending on the technology used onboard, the same air quality benefits could be achieved by zero-carbon bunker fuels, too. Burning hydrogen does not emit anything but water vapor anyway. Yet, while not emitting any sulfur oxides (SO_x) or carbon dioxide (CO_2), the combustion of ammonia leads to nitrogen oxides (NO_x) and nitrous oxide (N_2O) (a potent GHG and ozone depleting substance commonly known as laughing gas) emissions. However, these can be abated through existing technologies such as Selective Catalytic Reduction (SCR) which are commercially available today. The related costs and the resulting exhaust levels of NO_x and N_2O are comparable to the current use of SCR with fossil fuels (Alfa Laval et al. 2020). Consequently, there are advantages to addressing both air pollution and GHG emissions with a single solution, especially as the timescale required for rapidly deploying zero-carbon bunker fuels (from 2030 to achieve the least ambitious interpretation of the Initial IMO GHG Strategy targets, until 2050) is short. In any case, at present, these potential special cases where short-term investments in LNG could be warranted are not expected to create significant global demand for LNG as a bunker fuel.

By discounting Future 1 (“Transitional role for LNG”*)* and Future 2 (“Temporary role for LNG”), the report concludes that Future 3 (“A limited role for LNG”*)* appears to be the most likely possibility that still meets the IMO’s climate target.

Still, there may be niche circumstances outside of this report’s global whole-sector perspective which may allow for decisions contrary to the general conclusions here. Niche applications for LNG may exist where specific circumstances speak in favor of LNG and against alternative options. These niche circumstances can deviate significantly from the whole-sector assumptions applied in this report. It is therefore possible that for individual cases, industry stakeholders may be able to make investments on a timescale, or in such a manner, that they can crystallize benefits (for example, reduced air pollutant emissions) and effectively mitigate major risks related to LNG. These risks include a rapid demand reduction for LNG after 2030, or any regulation that more clearly calls into question the commercial viability of shipping’s LNG assets in the long term.

Such niche circumstances are mostly related to short-term advantages. Examples of short-term advantages may exist on privileged routes that already benefit from existing LNG terminals and favorable LNG bunker pricing and availability at either port, for specific vessel types such as LNG carriers, ferries, cruise ships, or coastal vessels, or in special circumstances when there are strong domestic interests favoring LNG. For instance, a liner ship may be designed to be operated on a route with existing favorable access to LNG supply at prices which are expected to remain competitive relative to oil-derived fuels for the entire duration of the 2020s and at a spread to oil-derived bunker fuels which enables the LNG capital expenditure premium to be paid off well in advance of any need for a retrofit to zero-carbon fuel. In a second example, a ferry, cruise ship, or coastal vessel may spend significant time in operation away from port (and therefore out of access to cold ironing or shore power), but still near centers of population. It may therefore reap a disproportionately higher benefit from the reduced air pollutant emissions of LNG.

Additionally, niche circumstances may also result from anticipated restricted access to zero-carbon bunker fuel options on a ship’s pre-existing route, relative to global average availabilities of such fuels. Yet this may still mean that the identified challenges to LNG’s long-term competitiveness are likely to be reflected in the second-hand pricing of these assets toward the end of this decade.

Based upon this conclusion, Table 7 provides the answers to the key questions posed at the beginning of this report.

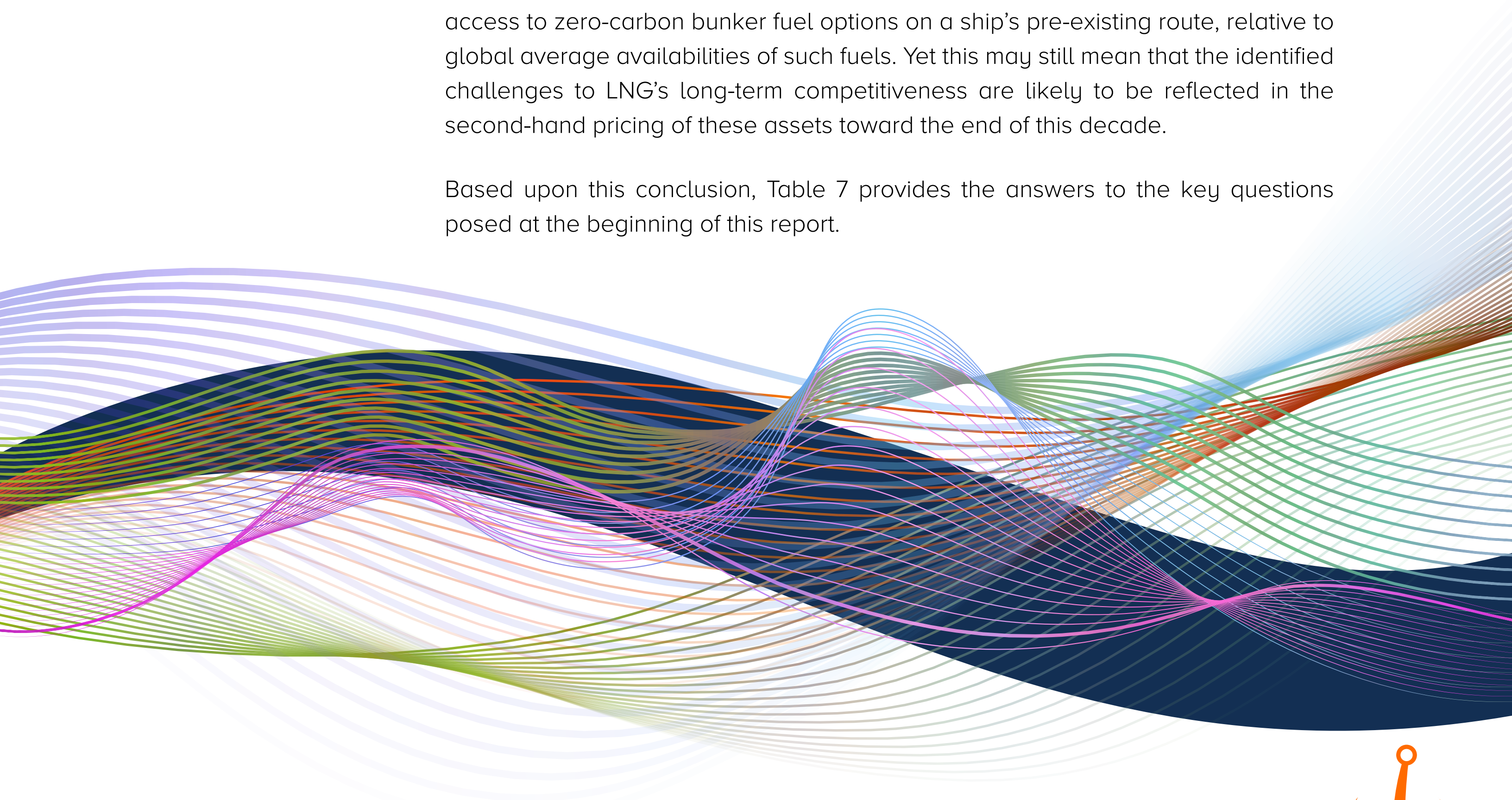
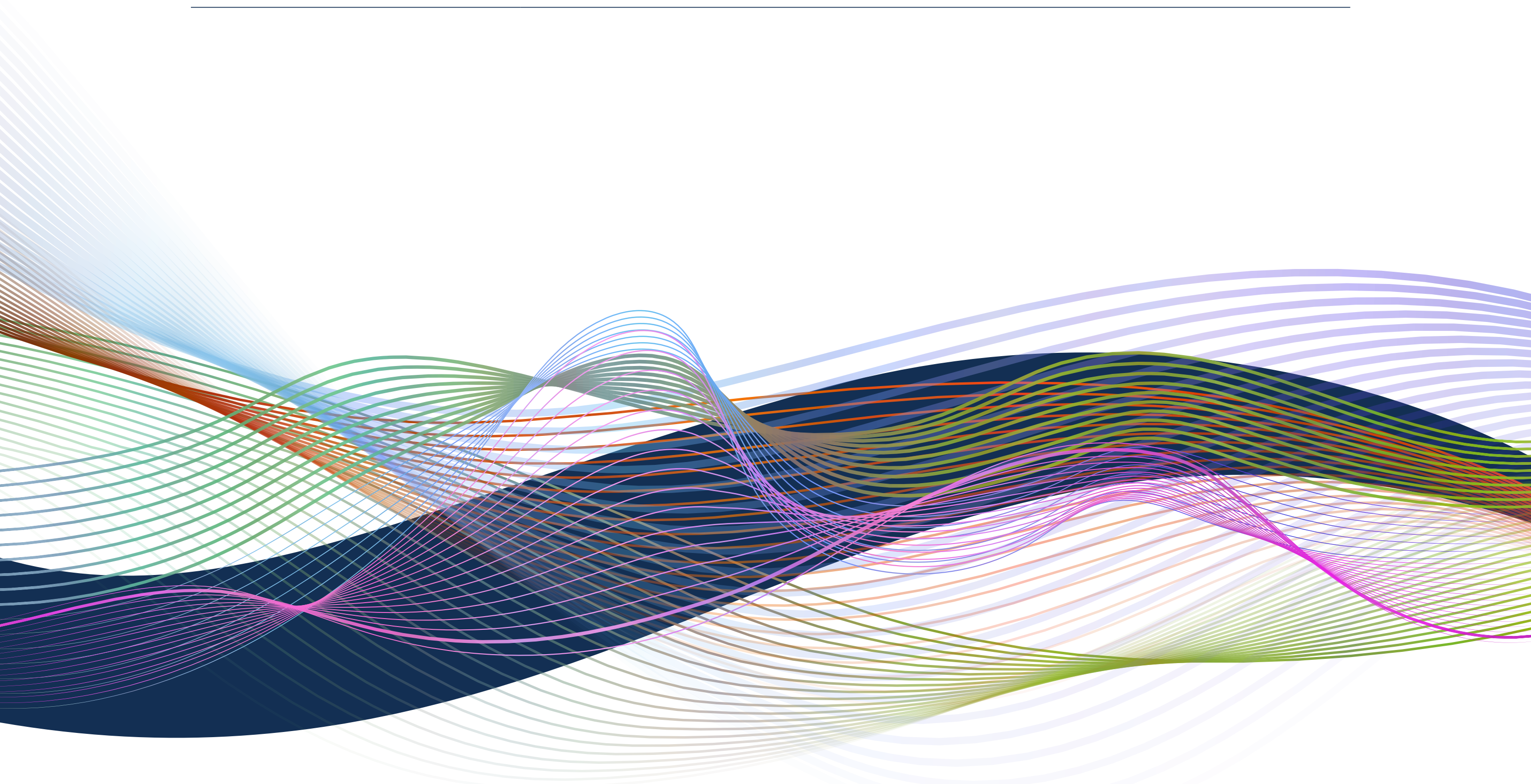


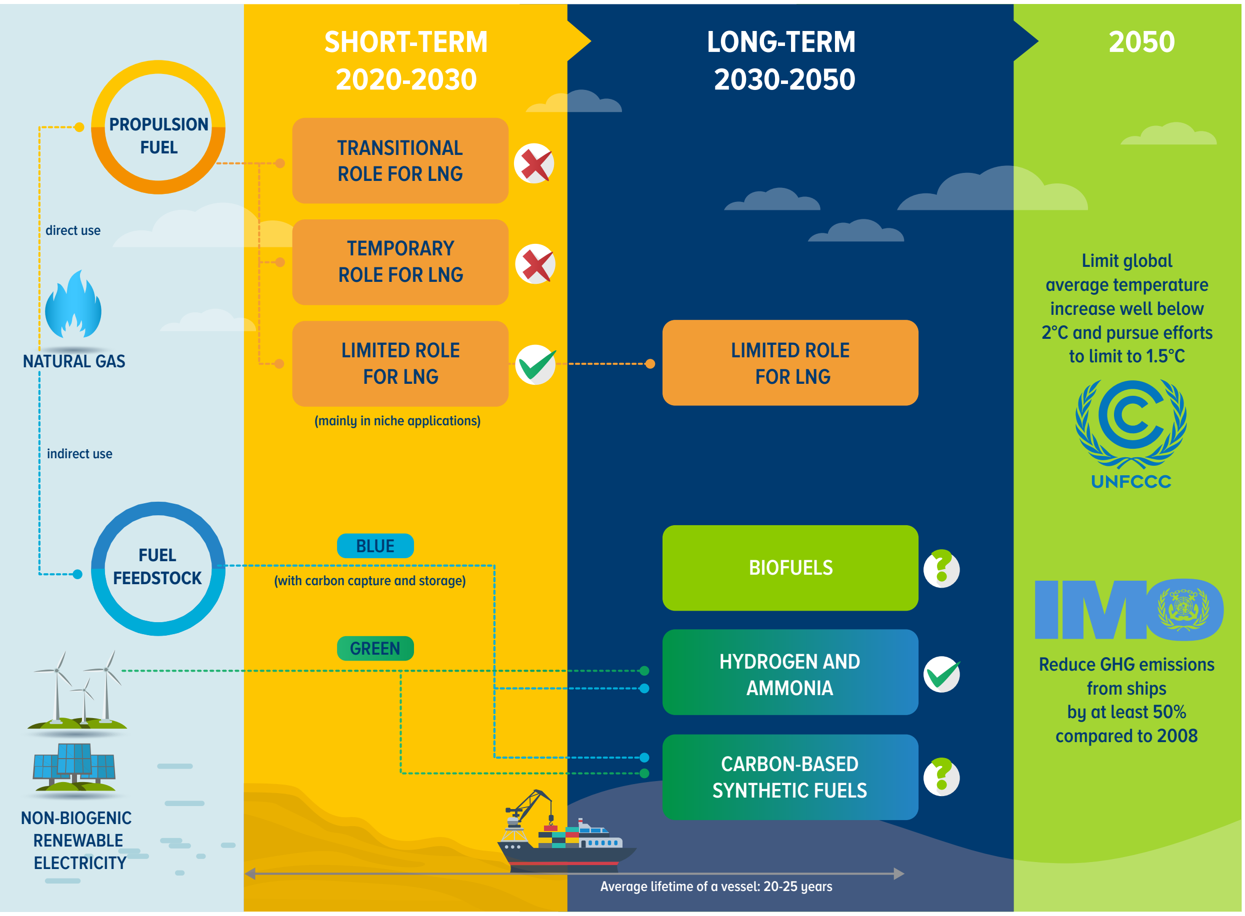
TABLE 7: REPORT KEY QUESTIONS AND CORRESPONDING ANSWERS

QUESTION	ANSWER
What would the role of LNG as a bunker fuel in the years 2020–2050 look like?	LNG is likely to play a rather limited role as a bunker fuel. Its share of the fuel market is likely to grow during the 2020s. By 2030, it may account for up to ten percent of the bunker fuel market in energy terms, or up to a maximum of 40 percent if every newbuild was to become LNG fueled during this decade. Beyond 2030, the demand for LNG as a bunker fuel is expected to decline, with the speed of decline being uncertain and highly dependent on future climate policy and zero-carbon fuel market developments. Demand for LNG as a bunker fuel may end by the early 2040s, or potentially as late as the early 2050s (according to the least ambitious interpretation of the Initial IMO GHG Strategy). A portion of the fleet that is fueled by LNG by 2031 may subsequently move to using LBM or LSM. Alternatively, it may be more competitive for these vessels to be retrofitted to the fuel type that becomes the dominant zero-carbon bunker fuel, which is currently most likely to be ammonia or hydrogen.
Offering significant air quality benefits, could LNG also make an important contribution to the Initial IMO GHG Strategy targets and the sector's transition toward low-and zero-carbon shipping?	While air quality benefits from the use of LNG are instant, tangible, and valuable, its use should be limited to those circumstances where no preferable alternatives are available, and the GHG and financial risks are acknowledged and mitigated. These restrictions are likely to prevent LNG from becoming a large-scale bunker fuel in line with IMO's climate target for 2050.



5.2 IMPLICATIONS

FIGURE 18: SUMMARY OF CONCLUSIONS FOR THE ROLE FOR LNG AS A BUNKER FUEL AND AS A FUEL FEEDSTOCK



5.2.1 Implications for policymakers

As outlined by the Initial IMO GHG Strategy, the shipping industry has firmly committed to reduce and eliminate GHG emissions from ships in line with achieving the Paris Agreement's temperature goals. In light of this Paris-aligned GHG emissions reduction trajectory, the uncertainties surrounding the GHG benefits of LNG suggest that new public policy support for LNG as a bunker fuel should be avoided. This relates, for example, to policy that provides a regulatory advantage to LNG over oil-derived alternatives in shipping. Furthermore, the same reasoning also suggests that existing policy support for LNG as a bunker fuel should be curtailed. In this regard, the sector's current Energy Efficiency Design Index, for instance, exclusively focuses on downstream CO_2 emissions (that is, due to combustion on board), thereby disregarding any upstream or midstream CO_2 emissions (that is, due to extraction and distribution, respectively) or any non-CO_2 GHG emissions such as methane.

The report highlights the need for urgent and strong policy action to regulate methane emissions both in the supply chain of LNG and in its use on board existing ships and any newbuilds. This will be important regardless of whether LNG becomes a significant bunker fuel or not. For example, although downstream methane emissions could be reduced using newer machinery with lower methane slip levels, this would still not address the risk of upstream and midstream methane emissions in the supply chain. These 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 and distributed. Many of these jurisdictions suffer from generally low regulatory enforcement levels (World Justice Project 2020). However, the increasing public scrutiny questioning the true lifecycle GHG emissions of any fuel used in a decarbonizing world is likely to incentivize such enhanced regulation, too.

Regulating methane is also important to ensure that shipping's existing LNG assets and any that may be built because of commercial-case justification in the short term are effectively shielded from the risk of increased lifecycle GHG emissions relative to conventional oil-derived bunker fuels, and are enabled to maximize their potential social benefits (for air quality in particular). The need for stringent policy to avoid this risk becomes even more important if the actual energy transition in shipping from fossil bunker fuels to zero-carbon bunker fuels were to happen more slowly than anticipated in this report.

The report also presents a strong recommendation to focus public support on the development of policy that effectively accelerates the research, development, and deployment of zero-carbon bunker fuels. Such policies would send another clear signal with respect to LNG's future role, and help mitigate the risks associated with a significant future uptake of LNG.

Finally, the parallel analysis of zero-carbon bunker fuels finds that the most promising candidate options will require zero-carbon hydrogen as a feedstock (*Volume 1*, see Preamble). There are two major production pathways for producing such hydrogen: the first one uses electrolysis powered by 100 percent non-biogenic renewable electricity to produce "green" hydrogen; the second involves using natural gas in conjunction with nearly 100 percent carbon capture and storage to produce “blue" hydrogen. Therefore, in contrast to LNG’s direct use as a bunker fuel for propulsion purposes, it is quite possible that natural gas could play an important role in shipping’s decarbonization as a feedstock for the production of zero-carbon bunker fuels such as blue hydrogen, as illustrated in Figure 18. More information on zero-carbon bunker fuels in general, and blue hydrogen specifically, can be found in the related *Volume 1* (see Preamble).

Policies to support zero-carbon bunker fuels as mentioned above are advantageous because these are long-term solutions that can solve both the GHG and air pollution reduction challenges faced by shipping. As always, any policy that can provide regulatory clarity and consistency will help industry to make more certain long-term decisions about shipping’s decarbonization.

5.2.2 Implications for industry

Shipping’s decarbonization is not driven by public policy alone. It is also driven by owners, fuel suppliers, financiers, and shareholders managing their own exposure to climate-related investment risks, and by clients and consumers looking to decarbonize their wider scopes of emissions. Making overt decisions contrary to the logical pathway for shipping’s decarbonization can therefore pose risks both to compliance with more and more stringent policies implemented in line with the Paris Agreement’s temperature goals, but also in terms of future access to financial capital and market share.

The analysis in this report concludes that LNG is likely to have a limited role as a bunker fuel, with any demand for LNG rapidly declining after 2030. Therefore, to minimize the potential loss of returns, industry stakeholders should consider LNG's questionable long-term competitiveness as a bunker fuel when developing their future business strategies. Furthermore, in light of a world with more and more commitments by public and private players to net zero GHG emissions by mid-century, industry stakeholders should also take into consideration the evolving climate policy landscape and the rising societal pressure in and outside the shipping sector when counting on a significant uptake of LNG as a bunker fuel. Niche-market investments in LNG are likely to face increasing headwinds through the course of the 2020s in such a context.

The current uncertainty within the industry, which does not know for certain yet which specific future zero-carbon bunker fuels to invest in, is understandable. The resulting hesitance in terms of investment decisions is reflected in the current orderbooks for new vessels, where global orders have recently been at the lowest level observed since 1989 (Clarksons Research 2020). While major businesses are already announcing their favored zero-carbon shipping solutions, all industry stakeholders—especially the ones with a lower risk appetite—are well advised to opt for the following: investing in increased energy efficiency and remaining flexible on other investments’ compatibility with multiple zero-carbon candidate bunker fuels. Investments in increased energy efficiency represent “no-regret” investments which will benefit any kind of future bunker fuels. Flexibility in ship design will allow using oil-derived bunker fuels up to the moment when the fuel supply can be more confidently switched to zero-carbon bunker fuels. This flexibility can be achieved, for instance, through installing fuel storage and fuel handling equipment that will be compatible with a maximum number of emerging zero-carbon bunker fuels—most likely ammonia and hydrogen (*Volume 1*, see Preamble).

Just as for policy-makers, all these current decisions faced by industry will be easier to resolve when there is greater certainty on the availability, prices, and timing of non-oil-derived bunker fuels. Working toward increased clarity through constructive support of the policy development processes, and through multi-stakeholder collaborations, remains vital.

5.3 METHODOLOGICAL OUTLOOK

There are currently close to 200 LNG-fueled ships operating in the world. This relates to a global LNG bunker fuel market of 500 kilo ton (kt) in 2019. In the near-term, this market is expected to grow to 3,500 kt of LNG by 2023 (MSI 2019). Although this growth appears significant, it remains marginal compared to the overall bunkering market. LNG will take a maximum fuel market share of three percent in 2023. Indeed, this figure represents an optimistic scenario where all LNG-ready ships will ultimately run on LNG (MSI 2019). Port authorities are increasingly investing in LNG bunkering infrastructure. In particular, EU policy requires at least one LNG bunkering port in each member state; several ports are under development in North America; and China is expected to be able to service the LNG demand of all vessel types. Other bunkering infrastructure includes truck loading, bunkering vessel loading, local storage, tank-to-ship, and other uses.

Key areas of uncertainty are still present in the forecast order book of new LNG-fueled vessels. The outcome of any LNG uptake modelling is particularly sensitive to both the forecasts of physical LNG availability, and the LNG price relative to both conventional oil-derived fuels and future zero-carbon fuels.

Further analysis can help to reduce the uncertainties in this initial technical report. Input assumptions on costs and prices, as well as performance of the technologies, can all be iterated and refined. The fleet and routes can also be modelled in greater granularity. This may be particularly important for the smaller ship types that make up many of the domestic fleets in operation globally. It is not currently anticipated, however, that any of these refinements would substantially affect the conclusions drawn in this report. Nevertheless, they may help clarify some of the niche roles for LNG as a bunker fuel. It should be noted that improving the granularity of this work is important when conducting a future development analysis for a particular country or region. Such an analysis is recommended as part of any future work.

Extensive further analysis could be undertaken in particular around the sensitivity to the results in this report and the commercial implications highlighted. A key assumption in this report has been that as the zero-carbon energy and fuel sources become prevalent, the main mechanism of change for the existing fleet will be to retrofit a vessel, which creates a need for additional capital requirements. However, it may be the case that many fossil-fueled ships (including LNG-fueled ships) will instead be prematurely scrapped, with financial consequences to the capital provider and asset owner. Should this occur, a more detailed analysis of the shipping market dynamics would be required than that included here. Such an analysis would enable a more precise understanding of the risk of asset stranding than has been possible in this report.

As stated in the conclusions, this report suggests that LNG is unlikely to achieve a significant market share (greater than 10 percent by energy) of the bunker fuel market. The potential implications of this conclusion on the economic growth of the developing world have not been considered. Such a development analysis is outside the scope of this report, but it is recommended that such an analysis be included in any future work program on this topic. This proposed analysis needs to consider the implication of lower on-vessel LNG consumption in the near term (to 2040) balanced against the potential upsides that come from the production, distribution, and use of zero-carbon fuels like hydrogen and ammonia. World Bank (2021) outlines a method for the identification and assessment of key production locations and assesses four developing nation locations as examples. It is of note that many of the fuel-production methods analyzed within this work utilize natural gas combined with CCS to create a range of zero-carbon energy carriers. This would allow for the use of natural gas reserves by developing nations where an economically viable geological carbon storage site is available.

APPENDIX A – MAIN ASSUMPTIONS AND CREDENTIALS OF GLOTRAM

Section 4 has made use of the Global Transport Model (GloTraM), a techno-economic model of the global freight transport system, currently focused on international shipping. The details of GloTraM are described in the modelling work of Smith et al. (2019), but the guiding assumptions used to derive the three LNG uptake cases discussed in section 4 were as follows:

- **Demand for shipping**: There is significant growth in demand for shipping, consistent with the Third International Maritime Organization (IMO) Greenhouse Gas (GHG) Study, and the Intergovernmental Panel on Climate Change (IPCC) scenario Representative Concentration Pathway (RCP) 2.6 (global average temperature increases of approximately two degrees Celsius, and a significant shift in demand away from fossil fuel use). This demand scenario is used because the modelling work for this report was undertaken before publication and availability of the Fourth IMO GHG Study. The more recent study includes continued expectations of significant growth in demand for shipping to 2050, albeit in relative terms lower estimates than the Third IMO GHG Study. The lower estimates relate both to the differences in the gross domestic product scenario assumptions used, as well as differences in the modelling method used to forecast transport demand (the latter including the use of a new freight transport demand forecasting model in the Fourth IMO GHG Study, which estimates lower values for the growth rates of future demand). The consequence of these lower demand growth scenarios, if all else is equal, is expected to be a modest reduction in the volume growth of zero-carbon fuel, albeit no change in the general finding that fossil fuel will need to be substantially or fully substituted with zero-carbon fuel by 2050.

- **Profit-maximizing decisions:** Unless explicitly stated otherwise in this modelling, shipowners and investors make profit-maximizing decisions in their selection of ship specification and operation, against the backdrop of evolving regulation, technology costs, and energy/fuel prices.

- **Discounting:** The modelling uses a discount rate of 10 percent in all economic calculations.

- **Bioenergy supply**: No significant quantity of bioenergy (for example, liquefied biomethane) becomes available for use in shipping (due to supply pressures on land use and numerous other demand sources).

- **Existing regulations:** All existing regulations under the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI (on GHG and air pollution) are applied and complied with.

- **Additional policy:** An additional policy (in this case the application of a carbon price) is used to incentivize absolute GHG emissions reduction. This is used as a modelling mechanism to enable the target carbon dioxide (CO_2) trajectory. The model is solved iteratively with variations in the CO_2 price. The CO_2 price is used as a generic policy lever to stimulate a variable amount of uptake of both energy efficiency and alternative fuel options. It is a proxy for a range of potential policy option packages that may be applied to regulate international shipping by the IMO, but which remain uncertain because they are currently under development.

- **Modelled fleet:** The modelling is focused on the ships most unambiguously associated with international shipping: container ships, oil tankers, bulk carriers, ferries, and cruise ships. This fleet accounts for approximately 70 percent of the GHG emissions from international shipping as estimated in the Third IMO GHG Study. An approximate scaling up of these results can be used to estimate their implications for total international shipping and domestic shipping, but this would assume that their transition pathways are identical, and that costs and GHG emissions scale linearly.

- **System boundaries:** The modelling system boundary is on the interface between shipping and the energy system. Fuel supply chain capital costs are inclusive of all the components bespoke for the production, transport, and storage of bunker fuel but not the production of the electricity, oil, or natural gas that is used as a feedstock of those bunker fuels. The further upstream (e.g., feedstock production) processes are included in the lifecycle GHG emissions estimation and their costs are represented through feedstock prices.

The decarbonization scenarios are solved by specifying a limit on the absolute GHG emissions applied to each time step from 2026. This limit value is set according to a trajectory of constantly reducing all GHG emissions from 2026 onwards, until a value is reached in 2050 (either an absolute reduction in downstream/operational GHG emissions of 50 percent by 2050, approximately consistent with achieving full decarbonization by 2070, or a reduction of 100 percent). This emission trajectory is an interpretation of the Initial IMO GHG Strategy, which specifies as an ambition a "path of CO_2 reductions consistent with the Paris Agreement temperature goals." Whilst that statement and the accompanying absolute and relative GHG and carbon intensity targets remain ambiguous, a judgment is applied that this implies a peaking of absolute emissions in the 2020s followed by a steady decline to the absolute 2050 target values. In practice, many different trajectories may be conceived by the IMO. The judgment is justified as the Paris Agreement's temperature goals are a function of cumulative GHG emissions and not the absolute levels in 2050. This means that the GHG emission trajectories to 2050 will need to be monotonically reducing from an imminent peaking of emissions, to avoid a significant growth in shipping's overall share of anthropogenic contribution to climate change.

The modelling finds a solution for the most cost-effective composition of the fleet at each time step using the input options for reducing shipping's GHG emissions, the growth in demand, and the target absolute GHG emissions. The finding that zero-carbon bunker fuels are needed from 2030, regardless of whether the total fleet reaches zero GHG emissions in 2050 or 2070, is a consequence of all these interacting factors. The growth in demand and the constraint on GHG emissions drives an increase in energy efficiency relative to the baseline fleet performance in 2016. However, that increase in energy efficiency has a diminishing return as the most cost-effective options increasingly penetrate the fleet. Under diminishing energy efficiency-derived carbon intensity improvements, zero-carbon bunker fuels are then needed to achieve absolute reductions in GHG emissions in spite of growing demand. The 2030 date estimated for the introduction of zero-carbon bunker fuels could be postponed if any one or more of the following conditions arose:

1. The demand in growth for shipping is significantly lower than projected. As indicated above, the Fourth IMO GHG Study assumes lower demand growth to 2050, but no significant difference to 2030, which is the demand growth period most relevant to the date when zero-carbon bunker fuels enter the fleet.
2. There are greater energy efficiency improvements in practice than as estimated by this modelling. However, recently agreed new energy efficiency regulation at the IMO Marine Environmental Protection Committee (MEPC) 75 does not include strong enforcement or high stringency and therefore may not produce high compliance or significant improvements in efficiency by 2030.
3. Instead of a gradual decline in GHG emissions from the 2020s, these continue to rise/peak in the 2030s and decline more steeply thereafter (if maintaining the same level of cumulative emissions), or if shipping's share of anthropogenic emissions increases and is compensated for by an average greater reduction in emissions across all other sectors.
4. The Paris Agreement's temperature goals are not achieved.

GloTraM was originally developed during the years 2010–2013 as part of the United Kingdom (UK) government-funded research project "Low Carbon Shipping – A Systems Approach." The model and its supporting evidence base and assumptions have received significant UK research funding investment (totaling approximately $6 million) since the initial UK government funded project. GloTraM has been used for a number of studies (including for submission to the IMO GHG debates, separate studies commissioned by the European Commission and the UK government, as well as to inform the corporate strategy of several multinationals). It is continuously improved and revised, and formed a major component of the evidence base used in the debates leading up to the adoption of the Initial IMO GHG Strategy. A key study in those debates is IMO ISWG-GHG 1-INF.2 "A scientific study on possible targets and their associated pathways" produced using GloTraM (2016).

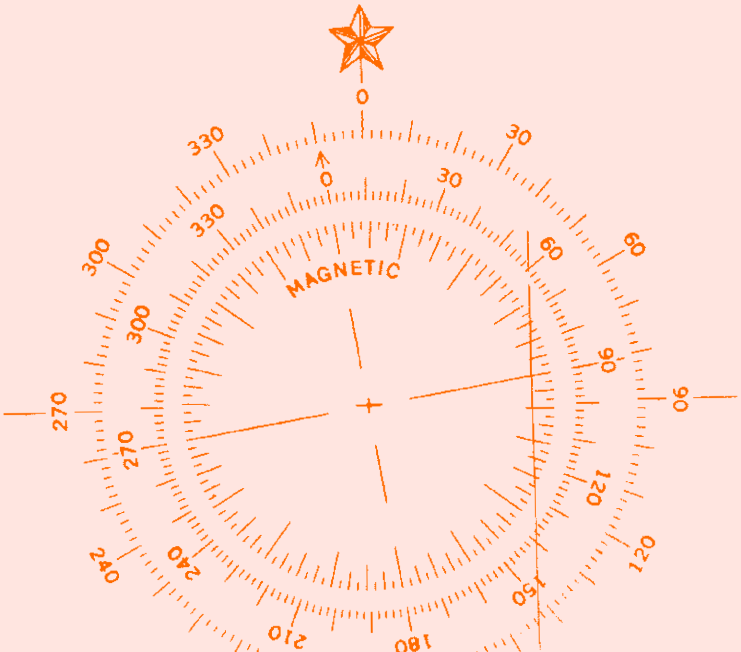
APPENDIX B – GHG EMISSIONS FACTORS

To calculate the Greenhouse Gas (GHG) emissions impact at each stage of the liquefied natural gas (LNG) lifecycle, GHG emissions factors for both carbon dioxide (CO_2) and CO_2 equivalent (CO_2eq) at the up- and midstream stages and at the downstream stage (onboard operational stage) have been applied. These factors are summarized in Table 8. High and low LNG GHG emissions factors represent the degree of uncertainty surrounding methane leakage in the up- and midstream processes, as well as the variety of pathways that can be taken. In calculating the CO_2eq value for each fuel, only methane and nitrous oxides were considered, with Global Warming Potentials (GWP) of 25 and 298, respectively (IPCC 2007). As stated within the main report, this GWP for methane is more conservative than the IPCC's revised GWP for methane (reference IPCC 2013 that now gives a GWP figure of 36 over a 100-year period); however it enables the modelling in this assessment to remain consistent with the referenced studies and data sources.

TABLE 8: GHG EMISSIONS FACTORS

	LNG HIGH	LNG LOW	HFO	MDO	LSHFO	H2	NH3	METHA-NOL
Up- and midstream CO_2eq	24.67	8.00	10.37	10.09	10.37	3.90	12.36	2.00
Up- and midstream CO_2	8.73	2.91	8.40	7.98	8.40	3.67	12.23	2.00
Downstream CO_2eq	73.87	59.69	78.0	76.5	78.0	0.0	0.0	69.0
Downstream CO_2	50.0	50.0	76.8	75.3	76.8	0.0	0.0	69.0

All numbers in gCO_2eq/MJ
Sources: Energy Technology Institute 2016; UMAS 2018b; JRC 2013



APPENDIX C – ASSUMPTIONS OF LNG ONBOARD TECHNOLOGY AND SUPPLY CHAIN

LNG ONBOARD TECHNOLOGY

Capital expenditure for LNG-compatible internal combustion engines and associated storage technology is assumed to be $1.4 million/MW (Smith et al. 2019).

LNG SUPPLY CHAIN

Capital investments for each year were estimated from a baseline per-unit cost using information from existing liquefied natural gas (LNG) infrastructure assets, across the up- and midstream components. Unit components were then scaled up by annual maritime LNG demand, with an assumed utilization rate of 70 percent. Unit costs for each component are scaled to the annual throughput of a large LNG storage tank, chosen for its long lifetime and accurate capacity metrics. This utilization rate can be lower in years where demand has decreased faster than assets have depreciated, which is assumed to occur at the rate of the component with the shortest expected lifetime. Table 9 outlines each component and its key operational and financial parameters, alongside data sources.

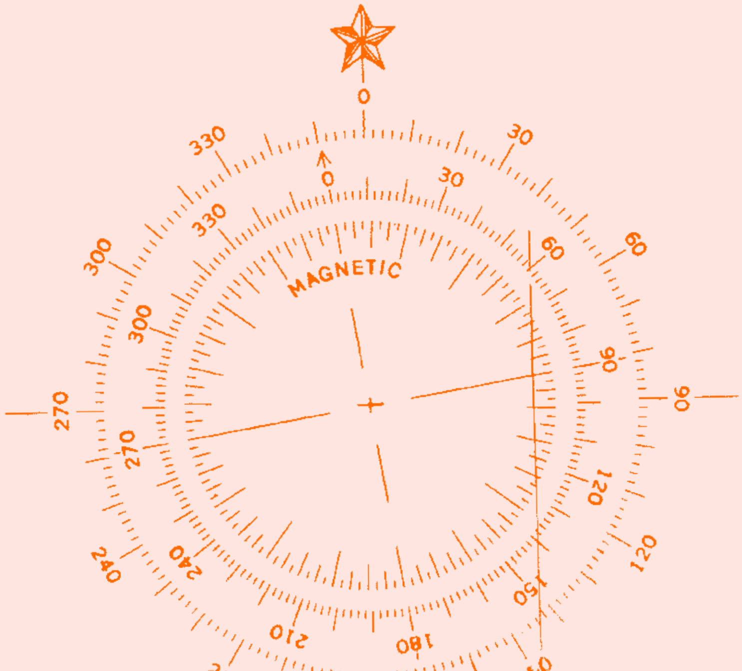


TABLE 9: LNG SUPPLY INFRASTRUCTURE PARAMETERS

COMPONENT	UNIT CAPACITY (MMTPA)	UNIT COST ($ MILLION)	SCALED COST ($ MILLION)	LIFE-TIME (YEARS)	PATHWAY	SOURCES
Pipelines	1	3.6	2.317	20	All	DMA 2012
Liquefaction plant	1	181.5	115.5	20	All	DMA 2012
Large LNG storage	0.636	130.9	130.9	35	3	DMA 2012, EC 2015
Small LNG storage	0.008	8.7	690.8	35	4, 5, 6	DMA 2012, EC 2015
LNG feeder vessel	1.559	60.7	24.8	20	2, 3, 4, 5, 6	DMA 2012
LNG bunker vessel	0.486	41.9	54.9	20	5	DMA 2012
LNG Truck	1	10.35	6.586	20	6	Laaveg 2013, DMA 2012
Other (berth, services, administration)	1	64.2	40.8	20	All	Laaveg 2013, DMA 2012

LNG can take multiple routes from the gas well to the vessel fuel tank. For the purposes of providing representative estimates of the overall costs, a compound is produced by combining multiple pathways. This is done by combining assumptions for each of the different pathways, as was also undertaken in a study by UMAS (2018a). The guiding assumption is that supply will tend toward the most cost-effective supply pathway. LNG demand is allocated with a ratio of 10 percent, 80 percent, and 10 percent to the mix of the three pathways with the 80 percent dominant majority being the lowest-cost supply chain.

The LNG demand scenarios are calculated using the Global Transport Model (GloTraM)—a holistic model developed by the UCL Energy Institute—on a five-yearly basis. Yearly LNG demand is then linearly interpolated between these values. The necessary infrastructure capacity to support the next year's demand is calculated such that a maximum of 70 percent of capacity is utilized. Assets are assumed to be decommissioned after 20 years, reducing available capacity. Interest, discount rates, and amortization are not considered in this assessment.

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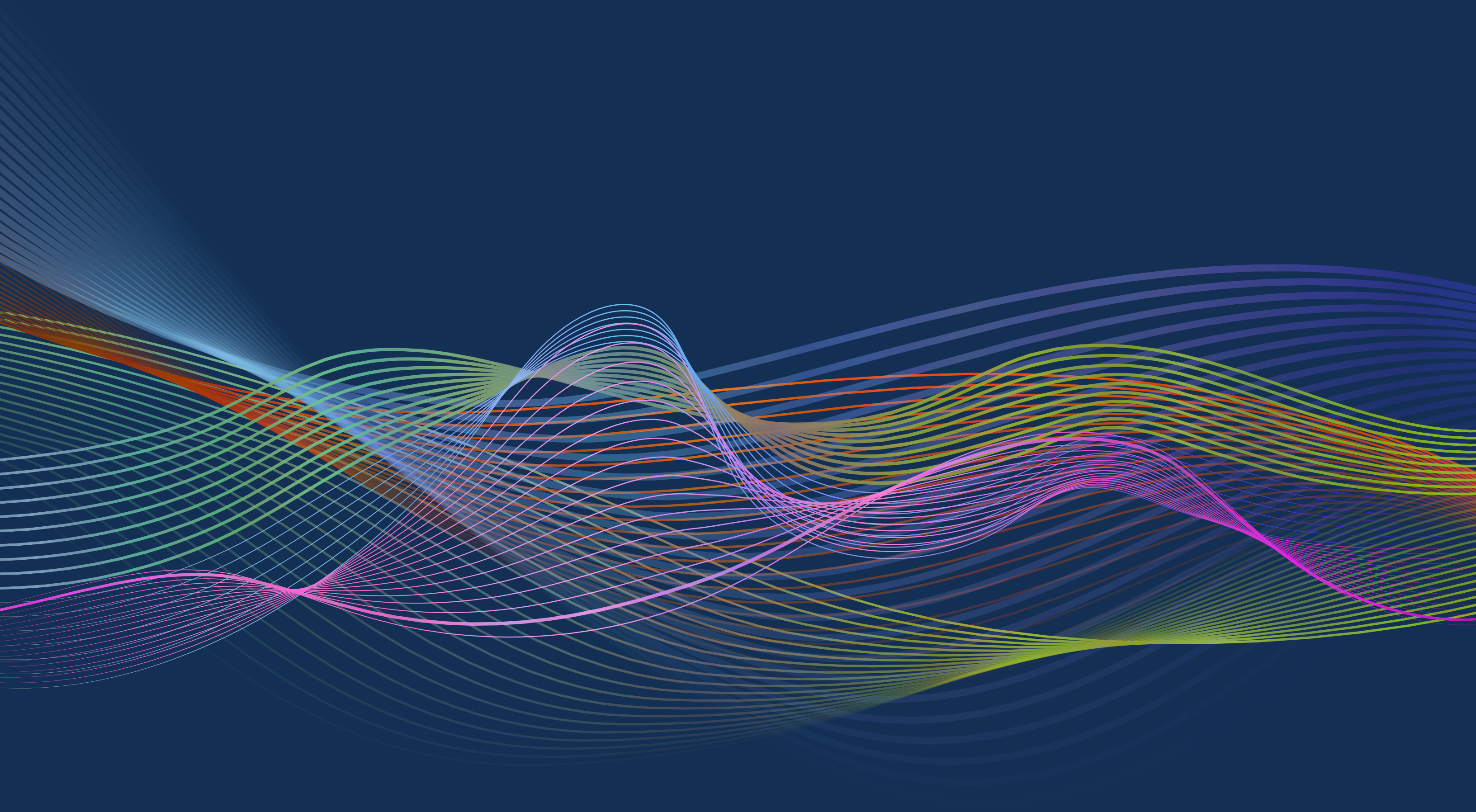

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