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MARITIME FORECAST TO 2050

Energy Transition Outlook 2019

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MARITIME
FORECAST TO 2050

Energy Transition Outlook 2019

FOREWORD

KNUT ØRBECK-NILSSEN

CEO
DNV GL – MARITIME

The DNV GL Maritime Forecast to 2050, part of our Energy Transition Outlook series, was first released in 2017 and since that time has grown into a vision of how the industry can respond to a changing energy landscape. Through the Maritime Forecast we hope to offer guidance, highlight trends, and provide valuable insights for maritime stakeholders.

The strong and ambitious direction set by the International Maritime Organization (IMO) last year, with the release of its greenhouse gas reduction strategy and the growing external pressure on shipping to cut emissions give this year's report its focus. One of the key areas, is to assess how the world fleet measures up in terms of decarbonization and determine the readiness of alternative fuels to scale up to meet wider demand.

Decarbonization could be especially challenging in the deep-sea segment, which generates 80% of the global fleet's CO_2 emissions. Energy efficiency, in both design and operation, will play a key role. In the short sea segment, we are seeing early trials and the use of low- or zero-carbon technologies that could translate to the wider fleet, including batteries and hydrogen.

The current options for the deep-sea trade are limited to LNG which is not carbon neutral, or to biofuels, which are not yet widely available and more expensive.

As we head toward 2050, our Maritime Forecast model suggests that the maritime industry will be characterized by an increasing diversity in fuel choices. With a wider range of alternative and carbon-neutral fuels finding a place alongside traditional bunkers and more established alternatives like LNG.

Fuel flexibility is one of the keys to meeting the decarbonization challenge, as the fuels of today may not be the fuels of tomorrow. Having a picture of the entire fuel ecosystem is vital, as owners, operators, and the industry itself will find it much tougher to adapt to a low-carbon future if they are locked into a single choice. This also applies to storage and onboard tanks, and even to port infrastructure.

To address this concern, we present a 'bridging philosophy' in the report, and look at how flexibility – in terms of fuels, tanks, and engines, can smooth the transition. Just as operators today hedge their bunker choices, owners could hedge their technology choices – giving them a wider range of options to adopt emerging fuels. One of the keys to sustained competitiveness in this changing and uncertain landscape is examining upcoming trends and attempting to future-proof a new vessel as much as possible before it hits the water.

The ongoing energy transition continues to reshape the shipping industry, with much uncertainty on the way to 2050. To be confident in the long-term requires an awareness of the structural changes ahead and the ability to remain flexible as new fuel pathways emerge.

Knut

Knut Ørbeck-Nilssen,
CEO of DNV GL - Maritime

CONTENTS

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

In April 2018, the International Maritime Organization (IMO) adopted an ambitious greenhouse gas (GHG) emissions reduction strategy for shipping. This will impact on costs, asset values and earning capacity more significantly than in the past. The required changes in fuels and technologies will shape the future fleet.

This publication is one of DNV GL's new suite of Energy Transition Outlook (ETO) reports. It provides an independent outlook on the maritime energy future and examines how the energy transition will affect the industry.

Our focus this year is the challenge facing the maritime industry of meeting the IMO GHG-reduction strategy, and the potential implications for the ecosystem of maritime stakeholders. This edition goes deeper into the energy challenge, exploring which fuels are likely to be implemented towards 2050. We investigate influential drivers and identify barriers to overcome in the possible decarbonization pathways. The proposed framework for assessing decarbonization pathways can help maritime stakeholders navigate the future and provide insight into how the GHG-emissions gap can be bridged.

We have two interrelated perspectives. One, the view of policymakers and the industry in general, focusing on decarbonization of the world fleet. The other perspective is that of the shipowner facing difficult short-term decisions with long-term implications, requiring practical approaches for future-proofing assets.

KEY FINDINGS

- To meet the IMO greenhouse gas ambitions, new fuels, alongside energy efficiency, will play a key role.
- Our new barometers will help by showing the decarbonization status of the world fleet and the readiness of alternative fuels.
- Bridging technologies and fuel flexibility can facilitate the transition from traditional fuels, and newbuildings should consider alternative fuel-ready solutions.
- More robust newbuilding strategies can be achieved using a new multi-scenario approach to future-proofing.

FIGURE 1

The world fleet CO_2 Barometer. The charts below the barometer show: (1) the historic CO_2 emissions and carbon-intensity from 2013 to 2018; (2) status of uptake of alternative fuels for the world fleet as of May 2019 including ships in operation and on order.

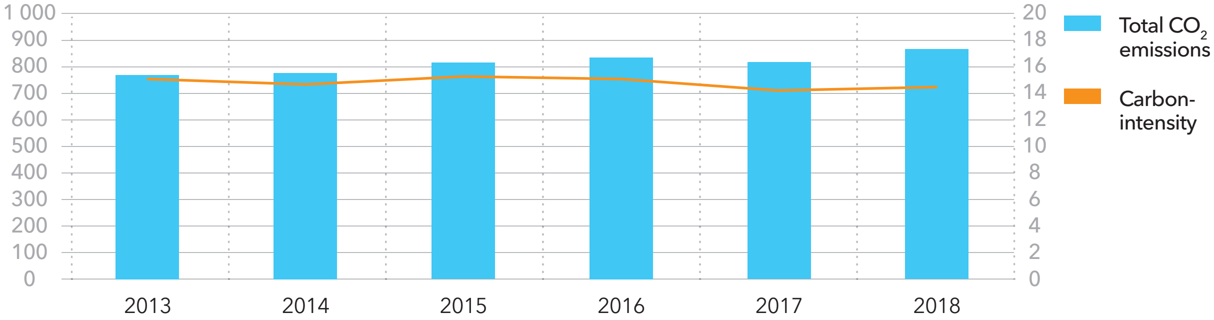
World fleet CO_2 Barometer

Transition pressure

Trend in world fleet CO_2 emissions

Units: CO_2 emissions (million tonnes)

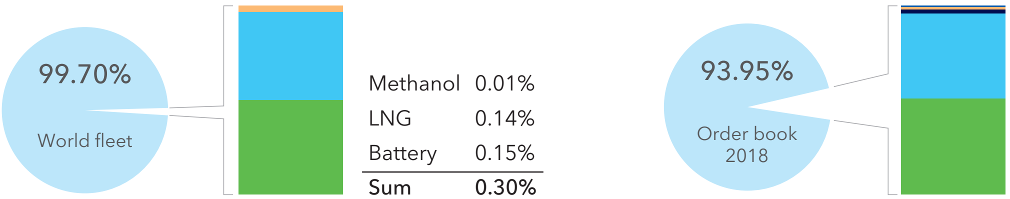
Units: Carbon-intensity (gram CO_2/tonne-mile)



Alternative fuel uptake (percentage of ships)[a]

Ships in operation

Ships on order



Methanol	0.01%
LNG	0.14%
Battery	0.15%
Sum	0.30%

Hydrogen	0.04%
Methanol	0.08%
LPG	0.13%
LNG	2.73%
Battery	3.07%
Sum	6.05%

[a] Source: DNV GL's Alternative Fuels Insight (AFI) portal, https://www.dnvgl.com/services/alternative-fuels-insight-128171

SHIPPING WILL NOT MEET IMO CARBON GOALS UNDER CURRENT POLICIES

To monitor progress towards achieving the IMO GHG ambitions, this study introduces a 'CO_2 Barometer' for the world fleet (Figure 1). The CO_2 Barometer provides a high-level assessment of the status of decarbonization in the form of a 'transition pressure level', reflecting the trend in world fleet carbon dioxide (CO_2) emissions, the uptake of alternative fuels and technologies, and regulations in place to incentivize change.

The CO_2 Barometer shows the total emission level is still increasing, despite efficiency gains. If the IMO targets are to be met, it is vital that uptake of low- and zero-emission technologies should begin on large ocean-going ships in the near future. Uptake of alternative fuels and technologies is slowly starting to pick up pace, as indicated in the CO_2 Barometer. But the vast majority of tonnage ordered still uses traditional fuels. With current policy measures only, the CO_2 Barometer signals that the ambitions in the IMO GHG strategy are not going to be met.

ALTERNATIVE FUEL TECHNOLOGIES CAN BRIDGE THE GAP

Many alternative fuel technologies are available for reducing the GHG emissions of shipping. For alternative fuels and power sources, the technical applicability and commercial viability will vary greatly for different ship types and trades, where deep-sea vessels have fewer options compared with the short-sea segment. It is important to find technically feasible and cost-effective solutions for the deep-sea segment, accounting for more than 80% of world fleet CO_2 emissions. Currently, the only technically applicable alternatives for this are liquefied natural gas (LNG) and sustainable advanced biofuels.

Apart from biofuels, efforts to substitute fossil fuels with carbon-neutral fuels depend heavily on access to non-combustible renewable energy sources. The term carbon-neutral refers to a variety of energy sources or energy systems that have no net GHG emissions or carbon footprint. Apart from biofuels, electricity from renewables (or from zero-carbon sources like nuclear) used in maritime battery applications is currently the only commercially available alternative for carbon-free shipping. This is presently limited to short trades up to approximately one hour; in practical terms this also means for (very) small ships. For the majority of global shipping, battery applications do not provide enough energy to cover the entire length of voyages.

An alternative energy carrier is hydrogen (H_2) produced from carbon-neutral energy resources, such as electricity from renewables. Alternatively, carbon-neutral H_2 can be produced from natural gas (with carbon capture and storage) or from nuclear energy. Using compressed or liquefied H_2 in fuel cells is a realistic option for the short-sea shipping segment in the medium term.

Hydrogen can itself be the basis for different electrofuels. Electrofuels, sometimes referred to as e-fuel, is an umbrella term for synthetic fuels such as diesel, methane and methanol when they are produced from H_2 and CO_2 (carbon-based fuels), or from H_2 and nitrogen (nitrogen-based fuels), and when renewable electricity powers the production.

Biofuels and carbon-based electrofuels are drop-in fuels requiring only limited or no modification to engines and fuel systems to replace or blend with traditional fuels used by internal combustion engines. Nitrogen-based electrofuels such as ammonia can also be produced from H_2; but they require more moderate modification to engines, and to fuel storage and supply systems, to replace traditional fuels. While electrofuels have clear advantages with regards to technical application and GHG-footprint, producing them is currently expensive and energy intensive. For biofuels, the challenges are related to price and sustainable production in sufficient volumes.

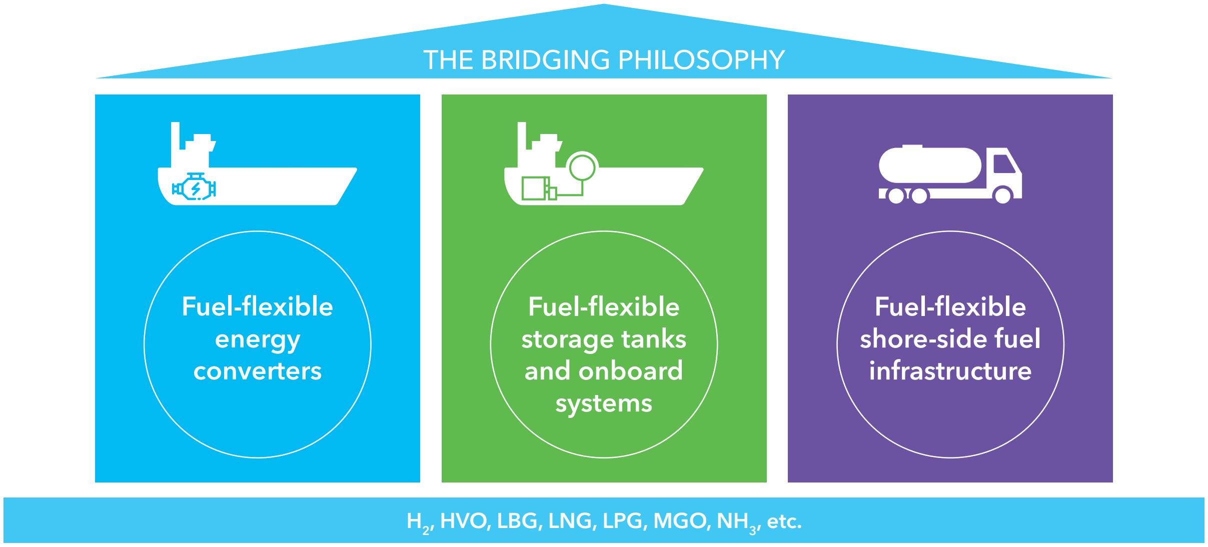
Widespread adoption of low-emission and carbon-neutral fuels could potentially take a long time, factoring in the time needed to properly develop low-carbon fuels, production capacity and infrastructure and to scale this. This study therefore introduces 'bridging technologies' that can facilitate and ease the transition from traditional fuel, via fuels with lower-carbon footprints, to carbon-neutral fuels. The bridging philosophy is built on three flexibility pillars, as illustrated in Figure 2. Fuel-flexible energy converters are essential as bridging technologies. However, but fuel-flexible arrangements for onboard storage and supply systems (allowing fuel switching), as well as flexible shore-side fuel infrastructure, are also needed.

PUBLIC-PRIVATE MECHANISMS NEEDED TO PROMOTE COSTLY TECHNOLOGIES

Technologies and fuels exist to close the emissions gap; but solutions are not ready for large-scale implementation, as indicated in the Alternative Fuel Barrier Dashboard (Figure 3). The ranking of LNG illustrates that the LNG ecosystem has matured as LNG is now available globally and in large volumes. However, bunkering infrastructure is limited, and must expand before widespread uptake of LNG as ship fuel can take place. Rules for safe design and use are in place. The onboard engine and storage technology are still more expensive than the alternatives currently in use onboard, and the capital costs should be reduced to improve competitiveness. The price of LNG fuel can be competitive but varies, and a global market similar to fuel oils and distillates is still not in place.

FIGURE 2

The three pillars of the bridging philosophy enabling use of alternative fuels



H_2, hydrogen; HVO, hydrotreated vegetable oil; LBG, liquefied biogas; LNG, liquefied natural gas
LPG, liquefied petroleum gas; MGO, marine gas oil; NH_3, ammonia
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Moving the markers in Figure 3 rapidly to the right will be of paramount importance for the shipping industry to achieve its ambitions on GHG emissions. Mechanisms stimulating the accelerated uptake of costly technologies should be developed and promoted by public and private actors in partnership. Possible sources of inspiration include the Norwegian NOx Fund and the Green Shipping Programme.[1] Supportive procurement policies, and long-term contracts promoting low- and/or zero-emission shipping provided by charterers/cargo owners and finance, could also help by stimulating uptake of costly technologies.

PROJECTIONS OF CO_2 EMISSIONS AND FUEL MIX FOR THE GLOBAL SHIPPING FLEET

We explore three different CO_2 pathways for the world fleet, where the uptake of energy-efficiency measures, speed reduction, and alternative fuels

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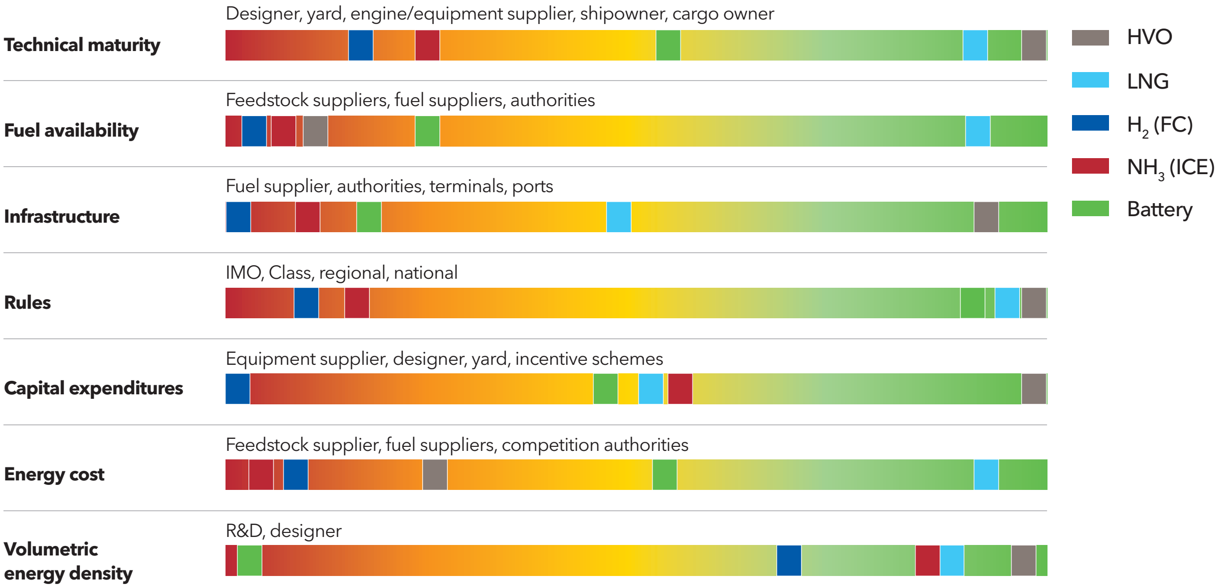
[1] See The NOx Fund at https://www.nho.no/samarbeid/nox-fondet/the-nox-fund/articles/about-the-nox-fund and the Green Shipping Programme at https://www.dnvgl.com/maritime/green-shipping-programme/index.html

FIGURE 3

The Alternative Fuel Barrier Dashboard: Indicative status of key barriers for selected alternative fuels



Technical maturity – refers to technical maturity level for engine technology and systems.
Fuel availability – refers to today's availability of the fuel, future production plans and long-term availability.
Infrastructure – refers to available infrastructure for bunkering.
Rules – refers to rules and guidelines related to the design and safety requirements for the ship and onboard systems.
Capital expenditures (capex) – Cost above baseline (conventional fuel oil system) for LNG and carbon-neutral fuels, i.e. engine and fuel system cost.
Energy cost – reflects fuel competitiveness compared to MGO, taking into account conversion efficiency.
Volumetric energy density – refers to amount of energy stored per volume unit compared to MGO, taking into account the volume of the storage solution.

HVO, hydrotreated vegetable oil; LNG, liquefied natural gas; H_2 (FC), hydrogen in fuel cells; NH_3 (ICE), ammonia burned in internal combustion engines; Battery, full-electric with batteries

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are simulated based on costs, and on existing and imminent policies. Two are pathways to meet the IMO GHG ambitions, while one is what would happen under current policies. The results show that achieving the IMO ambitions is possible, but will require adoption of policies to promote development and uptake of alternative fuels.

The demand for seaborne trade is projected to grow by 39% until 2050. The energy use per tonne-mile will decline by 35% to 40% on average towards 2050 in all projected pathways. This is due to energy-efficiency measures, mainly hull and machinery improvements, and speed reduction, which do not require further policies to promote uptake.

In all modelled pathways, there is a prevalent use of liquefied methane (40%–80% of the 2050 fuel mix). Both fossil and non-fossil primary energy is used to produce the methane. Ammonia is the most promising carbon-neutral fuel option for newbuildings. Another alternative would be a gradual shift on existing ships relying on drop-in fuels compatible with current fuel converters (such as bio/electro-diesel replacing liquid fuels, or bio/electro-methane replacing LNG). The preference for ammonia is due to the lower cost of the converter, storage and the fuel itself compared with H_2 and liquefied biogas (LBG)/synthetic methane. The share of carbon-neutral fuels in world fleet energy needs to be 30%–40% in 2050, in addition to improving energy efficiency, to achieve IMO GHG ambitions.

The 2050 fuel mix is heavily dependent on the specific design of the GHG regulations which are put in place, and on how fuel-converter costs (e.g. diesel engine, marine fuel cell) and fuel prices develop towards 2050. We find that minor changes to the underlying assumptions can significantly alter the outcome. Unless alternative fuels become price competitive with fossil fuels, introducing policy measures is a key component for addressing shipping GHG emissions. Figure 4 shows one possible pathway for international shipping achieving the IMO ambitions; here, regulations will gradually require all newbuilds from 2040 to be almost carbon-neutral.

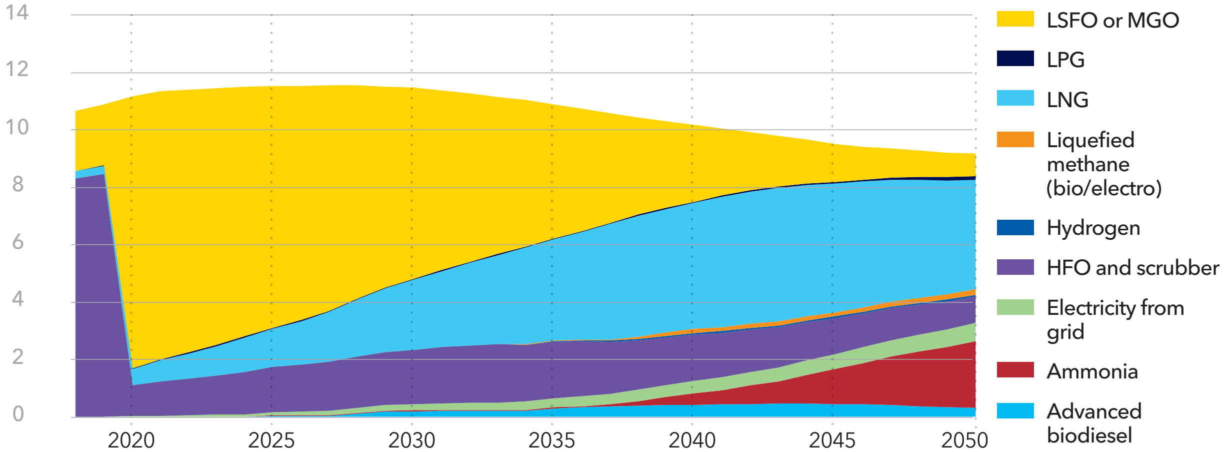
FUTURE-PROOF SHIPS

A shipowner investing in tonnage has to consider the increasing uncertainty in the maritime industry concerning regulatory developments, technological progress, alternative fuels, and changing transport needs. This study further develops a process for a shipowner to future proof ships by preparing for changes that will affect the value and competitiveness of assets. The introduction of a multi-scenario approach will help build resilience and readiness, and provide input to a robust newbuilding strategy.

FIGURE 4

Energy use and projected fuel mix 2018–2050 for the simulated IMO ambitions pathway with main focus on design requirements

Units: EJ/yr



LSFO, low-sulphur fuel oil; MGO, marine gas oil; LPG, liquefied petroleum gas;
LNG, liquefied natural gas; HFO, heavy fuel oil;
Advanced biodiesel, produced by advanced processes from non-food feedstocks

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The process consists of three steps; deciding on key performance indicators (KPIs) and scenarios in which to test the potential investment; then stress testing the design or designs in the established scenarios; and finally evaluating each design's performance. The process is iterative; it is repeated until the result is satisfactory.

We have conducted a case study for a very large crude carrier (VLCC), running model simulations with nine selected design combinations in 16 scenarios spanning the commercial, regulatory and technology opportunity space. The resulting 'competition risk matrix' provides a knowledge-based, structured and systematic best-practice approach to evaluating commercial and carbon robustness of a new ship.

The challenge is to be robust both on financial and environmental KPIs in the short and long term. The results of the case study show that to remain competitive throughout the operating lifetime of a vessel, investing in energy efficiency is paramount. This is because a VLCC built today will compete with vessels built in five, 10, 15 years' time, and must consider future standards to remain competitive.

There is a significant risk that for a vessel built in 2020, the most competitive fuel in the ship's early life will not necessarily be the same as when it is scrapped. Keeping the bridging philosophy in mind when designing a vessel, allowing for flexibility to switch to another fuel during the vessel's operating lifetime, would be crucial in mitigating the risk of becoming a stranded asset.

Illustration of the Triality VLCC

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

This publication is part of DNV GL's 2019 suite of Energy Transition Outlook (ETO) reports. This latest publication provides an independent forecast of the maritime energy future and examines how the energy transition will affect the industry. It significantly updates our 2018 forecast (DNV GL, 2018a).

A global transition towards more use of renewable energy and less of fossil fuels is underway and will progress towards 2050. One consequence is that shipping is experiencing increasing pressure to decarbonize its practices and operations and to reduce emissions to air. In April 2018, for example, the International Maritime Organization (IMO) adopted an ambitious greenhouse gas (GHG) emissions-reduction strategy to achieve for international shipping. This will impact costs, asset values and earning capacity more significantly than in the past. It will shape the future fleet in important ways, particularly in the choice of fuels and technologies.

Our focus this year is on the decarbonization challenge facing the maritime industry, and the potential implications for the maritime ecosystem of stakeholders.[2] This edition goes deeper into the energy challenge, exploring which fuels are likely to be implemented towards 2050. We investigate influential drivers and identify the barriers to overcome in possible decarbonization pathways. The proposed framework for assessing these paths can help maritime stakeholders navigate the future and provide insight into how the GHG-emission gap can be bridged.

We have two interrelated perspectives. One, the view of policymakers and the industry in general, focuses on decarbonization of the world fleet. The other perspective is that of the shipowner facing difficult short-term decisions with long-term implications, requiring practical approaches for future-proofing assets.

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[2] This ecosystem comprises cargo owners, charterers, ports, yards, equipment and service suppliers, fuel suppliers, regulators such as the IMO, EU and national states, classification societies, investors, banks and other financial institutions, and other stakeholders

This study highlights:

- **Main developments in GHG emissions** in recent years for the world fleet, with comparisons against the IMO GHG-reduction trajectory (Chapter 2). We introduce the concept of a carbon dioxide (CO_2) Barometer indicating the status of world fleet decarbonization.

- **An overview of the alternative fuel technologies** available for reducing shipping GHG emissions, and for closing the emission gap (Chapter 3). We also introduce the concepts of fuel flexibility as a bridge towards low-carbon shipping (Chapter 4) and a (stakeholder) ecosystem approach to understand and deal with barriers of concern to the industry (Chapter 5).

- **Projections of CO_2 emissions and fuel mix** for the global shipping fleet toward 2050, consistent with the IMO GHG strategy (Chapter 6). The model focuses on the uptake of a wide range of alternative fuels and carbon-neutral fuels, such as ammonia, biofuel and hydrogen, as well as the size of the fleet, and its energy efficiency.

- **The future-proof ship concept** that we introduced via the carbon-robust framework in 2017. We introduce a newbuilding risk approach to evaluating long-term competitiveness for a range of possible future technology and regulatory scenarios (Chapter 7). This aims to support maritime stakeholders evaluating the long-term competitiveness of their vessels and fleet to future-proof their assets.

We stress that the coming decades to 2050 hold significant uncertainties. These include, for example, economic development, future energy policies, human behaviour and reaction to policies, the pace of technological progress, and pricing trends for existing and new technologies. However, we believe that this uncertainty is manageable. By applying both a structured and knowledge-based approach supported by modelling tools, stakeholders can stay ahead of industry developments and remain competitive moving forward.

OUR SAFETY AND SUSTAINABILITY MISSION

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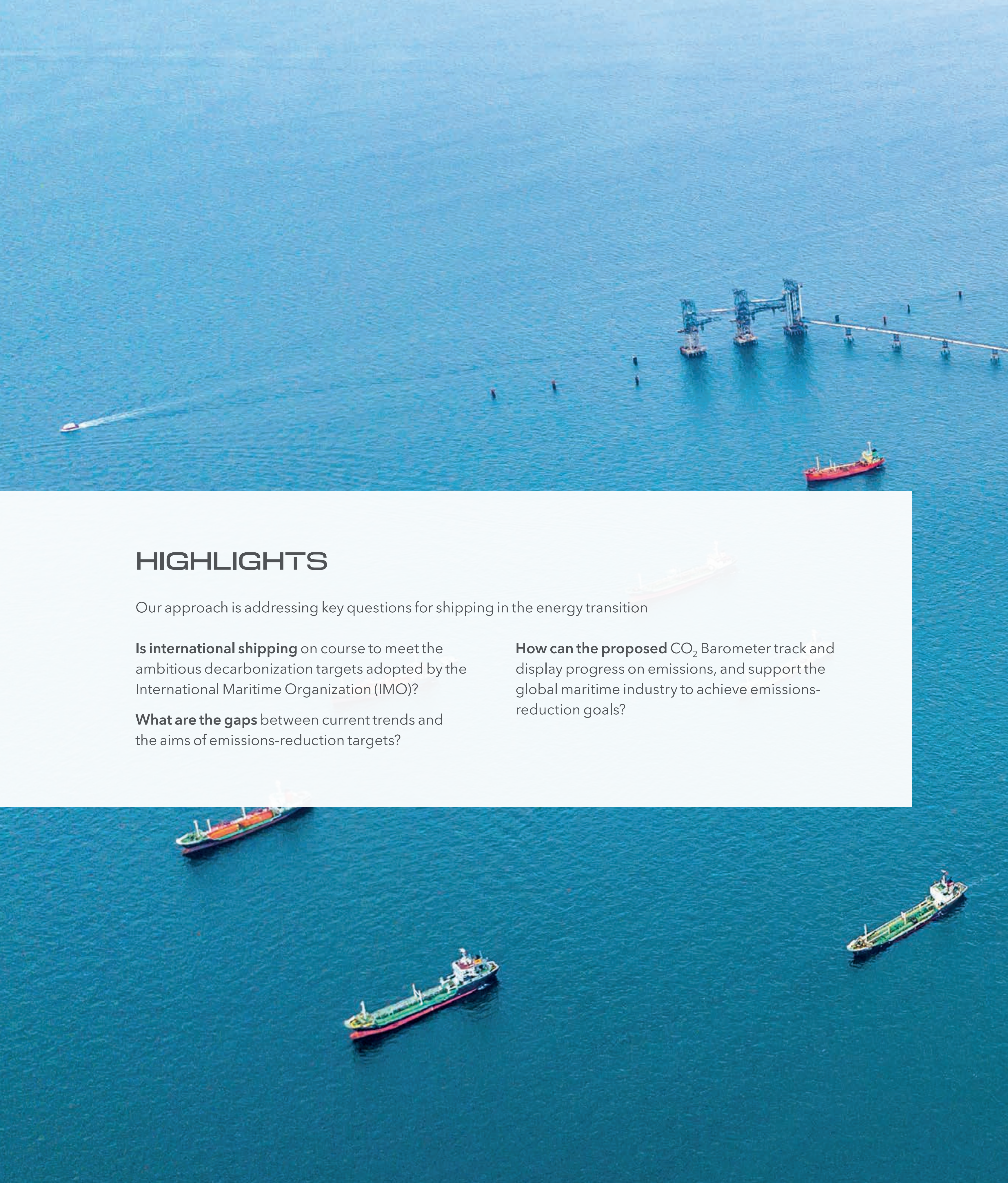
We provide classification, technical assurance, software, and independent expert advisory services to the maritime, oil and gas, and the power and renewable energy industries. We also provide certification services across many industries.



HIGHLIGHTS

Our approach is addressing key questions for shipping in the energy transition

Is international shipping on course to meet the ambitious decarbonization targets adopted by the International Maritime Organization (IMO)?

What are the gaps between current trends and the aims of emissions-reduction targets?

How can the proposed CO_2 Barometer track and display progress on emissions, and support the global maritime industry to achieve emissions-reduction goals?

CHAPTER

2

SHIPPING CO_2 EMISSIONS: ARE WE ON TRACK?

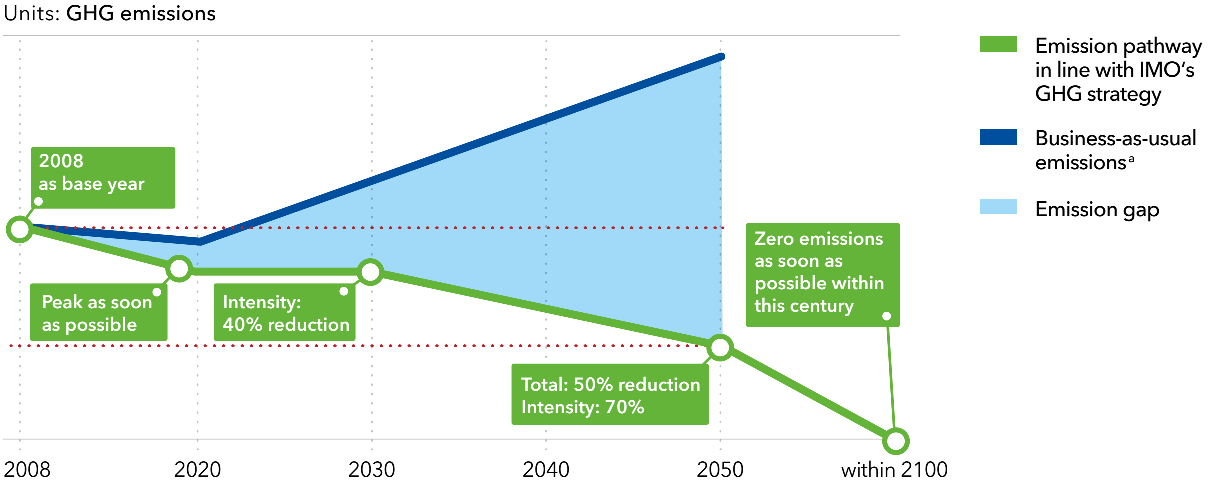
2 SHIPPING CO_2 EMISSIONS: ARE WE ON TRACK?

This chapter tracks world fleet carbon dioxide (CO_2) emissions from 2013 to 2018 and identifies gaps between current trends and the aims of emissions-reduction targets. We introduce the concept of a CO_2 barometer indicating the status of world fleet decarbonization.

In 2018, the International Maritime Organization (IMO) adopted an ambitious strategy to achieve reductions in greenhouse gas (GHG) emissions from shipping. With 2008 as a baseline year, this strategy aims to at least halve total GHG emissions from shipping by 2050, and to reduce the average carbon intensity (CO_2 per tonne-mile) by a minimum 40% by 2030, and 70% before mid-century (Figure 2.1). The IMO's ultimate vision is to phase out GHG emissions as soon as possible within this century.

FIGURE 2.1

IMO strategy for major reductions in GHG emissions from shipping



Total: Refers to the absolute amount of GHG emissions from international shipping.
Intensity: Carbon dioxide (CO_2) emitted per tonne-mile.
[a] Note that the the bussiness-as-usual emissions are illustrative, and not consistent with the emissions baseline used in our modelling (Chapter 6).

Source: DNV GL (2018a)

2.1 WORLD FLEET CO_2 EMISSIONS 2013–2018

This study models historic CO_2 emissions for the world fleet for the period 2013–2018. The modelling uses DNV GL software called MASTER,[3] which is described elsewhere (Mjelde et al., 2014; DNV GL, 2014a; DNV GL, 2018b,c). The model uses global ship-tracking data from the AIS (Automatic Identification System), enriched with ship-specific data from other sources. Our analysis of ship traffic for this report uses global ship movement data from the AIS, which is mandatory for ships ≥ 300 gross tonnes (GT) sailing internationally, and for all cargo ships ≥ 500 GT.

The AIS system covers about 86,000 ships in 2018, and the modelled CO_2 emissions from this fleet amount to 790 million tonnes (Mt). Additionally, the world fleet includes a large number of small fishing vessels and other small ships which do not carry an AIS transponder. The emissions from these vessels are estimated to be 10% of the AIS-based fuel consumption (based on Endresen et al., 2007). The CO_2 emissions estimates for the world fleet total 870 Mt in 2018.

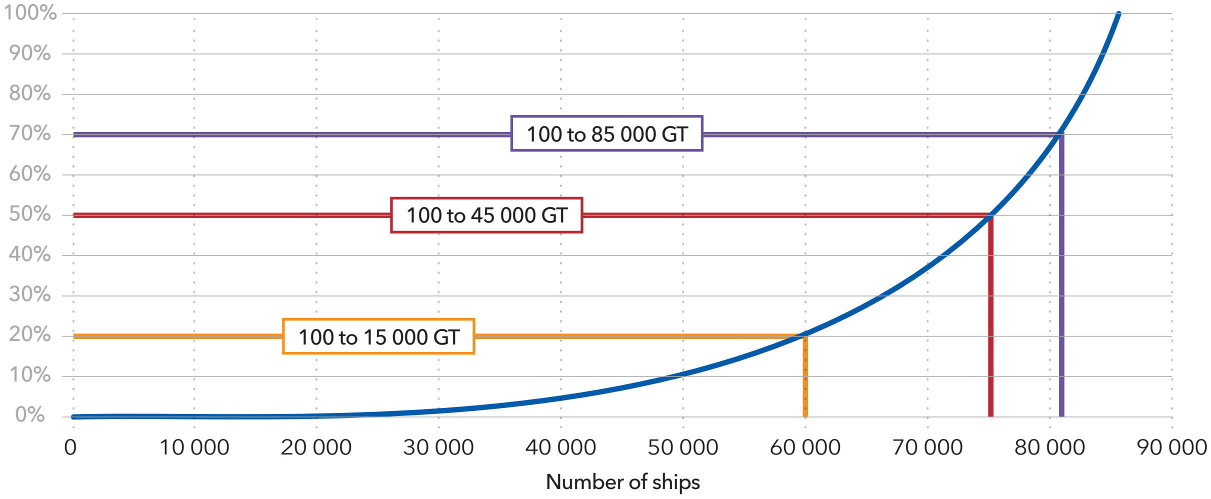
The CO_2 emissions are highly dependent on ship size (Figure 2.2). The AIS model covering 86,000 ships shows that only 6% of the large ships, being more than 85,000 GT, account for 30% of the total CO_2 emissions. Some 13% of the medium and large ships, those above 45,000 GT, account for

[3] MASTER is an acronym for Mapping of Ship Tracks, Emissions and Reduction potentials

FIGURE 2.2

CO_2 emissions from 86 000 ships in 2018 analysed by ship size[a]

Units: Share of CO_2 emissions



[a] Data for this analysis are accumulated CO_2 emissions for 86 000 ships observed in the AIS system in 2018 as a function of ship size in gross tonnage (GT), as calculated in our study.

Source: DNV GL

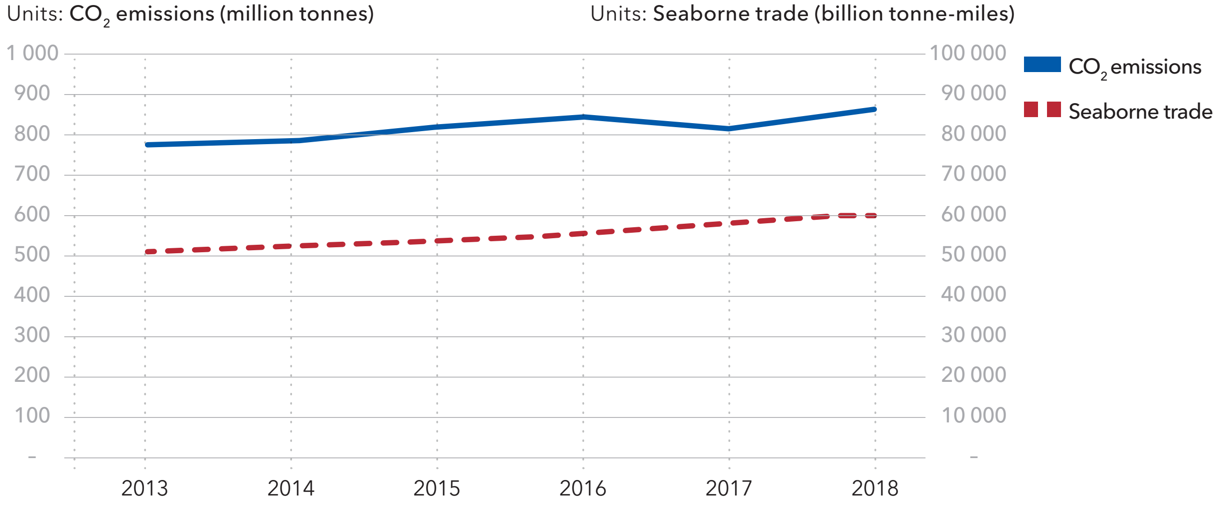
half of the CO_2 emissions. All ships above 15,000 GT account for 80% of the modelled CO_2 emissions and involve only 30% of the entire fleet. If the IMO targets are to be met, it is vital that uptake of low- and zero-emission technologies should begin on large ocean-going ships in the near future.

World fleet CO_2 emissions have grown steadily from 770 Mt in 2013 to 870 Mt in 2018 (Figure 2.3). The International Council on Clean Transportation (ICCT, 2017) similarly reports increased CO_2 emissions for the global fleet between 2013 and 2015, though the absolute emission level in ICCT's study is slightly higher than in this study.

World seaborne trade increased from 50,500 to 60,400 billion tonne-miles between 2013 and 2018, according to the UN Conference on Trade and Development (UNCTAD, 2018). There is a good correlation between the increase in CO_2 emissions estimates for the world fleet and the reported steady growth in seaborne cargo transport over the last six years. If this trend continues, it will be increasingly challenging to reach the IMO's GHG targets for 2050.

FIGURE 2.3

CO_2 emissions from the world fleet (this study) and seaborne trade (UNCTAD, 2018) from 2013 to 2018



2.2 WORLD FLEET CO_2 BAROMETER

A framework is needed for monitoring current world fleet CO_2 emissions and measuring their trajectory against defined targets and trajectories. This will identify gaps between reality and IMO ambitions, which could trigger mitigation measures. To monitor progress towards achieving the IMO targets, and the effects of any such measures, DNV GL has developed a CO_2 Barometer for the world fleet. This first version is inspired by a CO_2 barometer for Norwegian waters developed by DNV GL for the Norwegian Ministry of Climate and Environment in 2018 (DNV GL, 2019b).

Our new barometer presents a measurement of the status of the world fleet decarbonization. Measurement is based on three parameters:

- The trend in world fleet CO_2 emissions (and carbon-intensity).[4]
- The uptake of alternative fuels and technologies, including ships in the sailing fleet and on order.
- Regulations in place to incentivize change.

These parameters collectively form a basis for a high-level assessment of decarbonization status visualized in the barometer as a transition pressure level. Simply put, if the barometer shows high pressure, the industry is moving in the right direction, on a path to achieve the IMO targets. If the barometer shows low pressure, progress is far from being on the right track.

The CO_2 Barometer's current readout in Figure 2.4 shows low transition pressure, which indicates that total emissions from the world fleet are not moving in the right direction. From 2013 to 2018 there was around 20% growth in seaborne trade. In the same period, total shipping emissions grew by only 13%, indicating improved energy efficiency measured in CO_2 emission per transport work. An analysis of the recently published EU monitoring, reporting and verification (MRV) data[5] shows that ships built after 2013 are significantly more energy efficient than older ships. As newer vessels enter the fleet, we can expect the overall energy efficiency to improve further in the coming years. Despite efficiency gains, the total emission level is still increasing.

Uptake of alternative fuels and technologies is picking up pace, but is still at a level where the vast majority of tonnage ordered uses traditional fuels. The barometer shows that fewer than 1% of ships in the world fleet are using alternative fuels. The current uptakes of low- and zero-emission fuels and technologies are dominated by the short-sea segment and non-cargo ships, and has little impact on total maritime emissions.

Except for the electrification underway of more than 100 car ferries in the short-sea segment, the already implemented alternative fuels are based mainly on fossil fuels. LNG is used by 159 ships in

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[4] Carbon-intensity (gCO_2/tonne-mile) calculated using total emissions, and transport work from UNCTAD (2018)

[5] EMSA: https://mrv.emsa.europa.eu/#public/emission-report, retrieved 6 July 2019

FIGURE 2.4

The world fleet CO_2 Barometer. The charts below the barometer show: (1) the historic CO_2 emissions and carbon-intensity from 2013 to 2018; (2) status of uptake of alternative fuels for the world fleet as of May 2019 including ships in operation and on order.

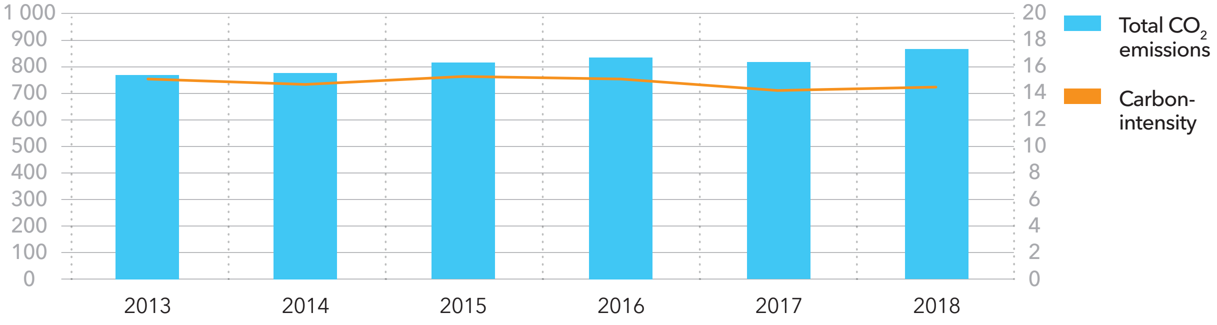
World fleet CO_2 Barometer

Transition pressure

Trend in world fleet CO_2 emissions

Units: CO_2 emissions (million tonnes)

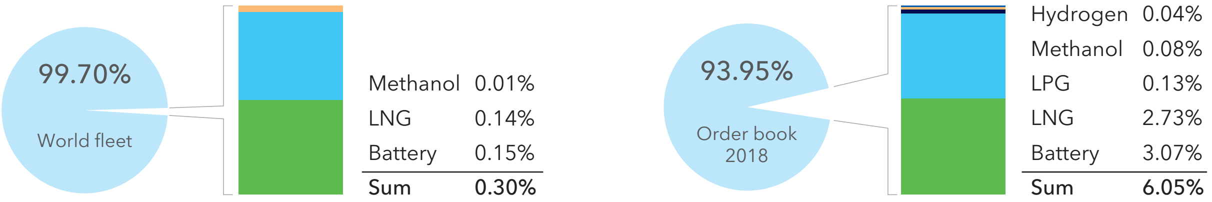
Units: Carbon-intensity (gram CO_2/tonne-mile)



Alternative fuel uptake (percentage of ships)[6]

Ships in operation

Ships on order



Methanol	0.01%
LNG	0.14%
Battery	0.15%
Sum	0.30%

Hydrogen	0.04%
Methanol	0.08%
LPG	0.13%
LNG	2.73%
Battery	3.07%
Sum	6.05%

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[6] Source: DNV GL's Alternative Fuels Insight (AFI) portal, https://www.dnvgl.com/services/alternative-fuels-insight-128171

operation by May 2019 (Figure 2.4).[7] Looking at orders for newbuild ships over the next few years, we find that there will be an increase in LNG ships globally, and in batteries for full-electric or hybrid-electric operations in the short-sea segment.

Global demand for ship transport will increase by about 39% towards 2050 compared to 2018, according to DNV GL Energy Transition Outlook 2019 (DNV GL, 2019a). The ETO Model projects an increase in seaborne transportation in terms of tonne-miles for all trade segments except crude oil and oil products, which peak around 2030. Other studies make significantly higher projections (ITF/OECD, 2019). With 39% seaborne trade growth, the expected emission level under the current adopted policies is projected as one pathway (Current Policies) in Chapter 6. It shows that the total CO_2 emission level will be reduced by 27% in mid-century, compared to 2008. The 2050 ambitions are not achievable with current policies unless carbon-neutral fuels become competitive with current fossil fuels prices, even if the energy efficiency of ships and operations is improved greatly.

The status of regulatory measures that are being developed at the IMO is briefly summarized in the textbox on Page 30.

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[7] DNV GL Alternative Fuels Insight portal, view at www.dnvgl.com/services/alternative-fuels-insight-128171

2.2.1 REGULATING GREENHOUSE GAS EMISSIONS

Meeting the IMO targets for reducing GHG emissions from shipping will necessitate mandatory requirements for individual ships, as well as other policy measures to support the desired development and implementation of new technologies and fuels. The IMO is currently discussing how to follow up the adopted strategy, and is prioritizing and deciding which measures to pursue.

> “To avoid the need for extensive retrofits of engines and fuel systems, technologies and technology-ready solutions must be available by 2030 as far as is possible.

SHORT-TERM MEASURES TO ACHIEVE AN EMISSION PEAK AND TO ENSURE THAT IMO’S 40% CARBON-INTENSITY REDUCTION TARGET IS MET IN 2030

These measures must target both existing vessels and ships built from now until 2030. Given the usual timeframe for developing new international shipping regulations, it is unlikely that any fresh regulatory scheme can be in place before 2023.

The IMO is therefore looking at using the existing Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) frameworks to impose mandatory requirements in the short term.

MEDIUM- AND LONG-TERM MEASURES TO REACH THE 70% CARBON INTENSITY TARGET AND A 50% ABSOLUTE EMISSION REDUCTION IN 2050

In the medium and long term, large-scale use of carbon-neutral fuels is required. These are not available in large quantities today. Regulations for individual ships are needed to push implementation as these fuels are not expected to be economically competitive within the next few years. Supportive policy is required to promote and develop the establishment and large-scale production of alternative fuels to the point where they are available, and at acceptable prices.

More than 70% of the fleet sailing in 2050 will have been built after 2030. Hence, to avoid the need for extensive retrofits of engines and fuel systems, technologies and technology-ready solutions must be available by 2030 as far as is possible.

Standards based on lifecycle assessment will be needed to evaluate the carbon intensities of the different fuels. This will potentially enable biofuels satisfying such sustainability criteria, and synthetic fuels to be accounted for as carbon-neutral. Such standards will prevent the use of ‘zero-carbon’ fuels made by carbon-intensive processes; for example, hydrogen produced from natural gas, oil or coal without carbon capture.

The IMO is also considering new mechanisms for reducing emissions, possibly including market-based measures.


ECO POWER
CONTAINER SHIP

HIGHLIGHTS

Alternative fuels could help to decarbonize shipping if barriers to their use are lowered

Electricity? Hydrogen? Ammonia? Biofuels? LNG, or others? Which alternative fuels are the most promising candidates for this purpose in the short to longer term?

What are the advantages and disadvantages of various emerging and potential combinations of energy converters and alternative fuels?

Which fuel-cell technologies could penetrate furthest and fastest into which shipping segments, and how could this emerging trend be accelerated?

How can stakeholders in the industry overcome the limitations that onboard storage capacity and onshore bunkering infrastructure place on uptake of alternative fuels?

CHAPTER

3

ALTERNATIVE FUEL TECHNOLOGY

3 ALTERNATIVE FUEL TECHNOLOGY

This chapter examines how several alternative fuel technologies could help to decarbonize shipping. We focus on different converters and their flexibility, providing key characteristics for gas-fuelled engines, fuel cells, and battery electric power systems.

Policy developments and stakeholders' engagement over the next decades will drive shipowners to identify, evaluate and use technologies, fuels and solutions that help decarbonize their ships, reduce energy consumption, and meet other environmental requirements. The drive for decarbonization in global industrial value chains will also drive logistics optimization including measures such as increased fleet utilization and speed reductions.

In last year's Maritime Forecast to 2050, we presented an overview of decarbonization solutions including logistics optimization, technical and operational energy-efficiency measures, and carbon-neutral fuels (DNV GL, 2018a). Figure 3.1 presents a high-level overview of these divided into four categories. In this edition, we focus on the category with the highest reduction potential, but also significant uncertainty: fuels and energy sources.

FIGURE 3.1

Overview of technologies and fuels and their GHG-reduction potential (%)

LOGISTICS AND DIGITALIZATION	HYDRODYNAMICS	MACHINERY	FUELS AND ENERGY SOURCES
Speed reduction	Hull coating	Machinery improvements	**LNG/LPG**
Vessel utilization	Hull-form optimization	Waste heat	**Electrification**
Vessel size	Air lubrication	Engine de-rating	**Biofuel**
Alternative routes	Cleaning	Battery hybridization	**Hydrogen etc.**
>20%	10%-15%	5%-20%	0%-100%

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3.1 DECARBONIZATION OF SHIPPING: PHASING IN CARBON-NEUTRAL FUELS

For most alternative fuels and power sources, the technical applicability and commercial viability will vary greatly for different ship types and trades. In broad terms, the world fleet can be divided into deep-sea shipping and short-sea shipping.

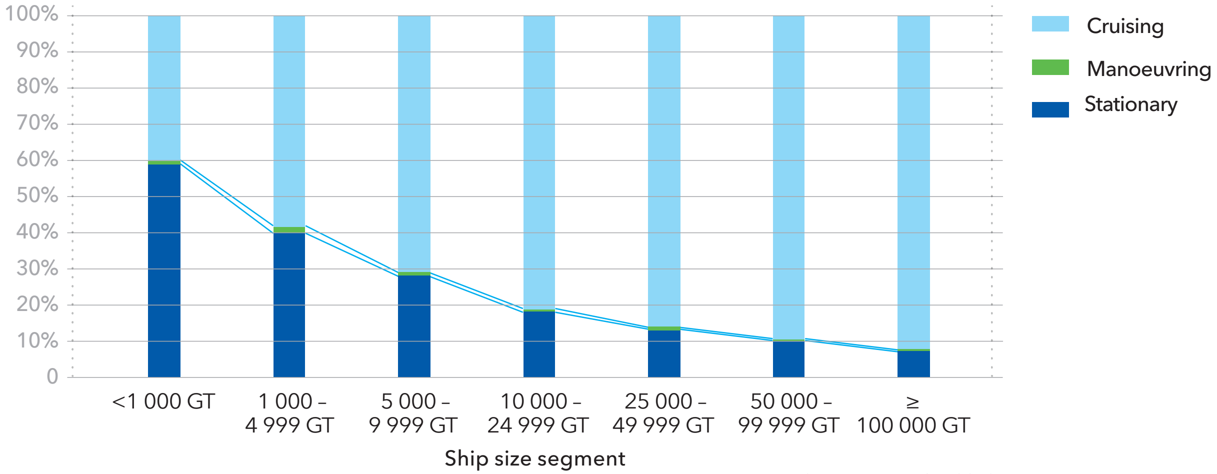
Deep-sea shipping comprises large ocean-going ships, and a very large proportion of their energy consumption relates to propulsion of the ship at steady speed over long distances. These vessels are today driven by mechanical, direct- or geared-driven, two-stroke combustion engines. These engines are highly energy efficient for this purpose. The ships require fuel that is globally available, and the fuel energy-density is important to maximize the space available for the transport of cargo over long distances.

Vessels in the short-sea segment are typically smaller, with more varied operational profiles and a greater share of their time and energy is spent on purposes other than steady propulsion (Figure 3.2). For these ships, the shorter distances and highly variable power demands often make electric or hybrid-electric power and propulsion systems (including diesel/gas electric) more efficient than traditional mechanical drives. Having an electrical power distribution system allows for more efficient energy distribution over a wide range of engine load profiles. It also increases flexibility for using energy from batteries, fuel cells and waste heat as well as renewable sources (e.g. solar, wind, waves). For short-sea ships, the potential share of energy consumption to be optimized by batteries and fuel cells is higher than for deep-sea ships.

FIGURE 3.2

Share of fuel used in each operational mode in 2017 by ship size segment

Units: Percentages



Source: DNV GL, 2018a

3.1.1 CARBON EMISSIONS VARY BY SHIPPING SEGMENT

The deep-sea shipping segment produces more than 80% of the CO_2 emissions from the fleet (Figure 2.2). So, it is important to find technically feasible and cost-effective solutions for this segment. It is likely that future decarbonization options for such ships will largely depend on replacing the fossil fuel burnt in their large diesel/dual-fuel engines during cruising (Figure 3.2) with fuels that emit low or no greenhouse gases (GHG). Regardless of such a switch, further energy optimization will also be of vital importance operationally and technically. It can include greater introduction of electric energy storage and power transmission systems and will ease the shift in fuels. The decarbonization options for short-sea vessels are more diverse and include more alternative power sources and driveline configurations.

While specific options available to different ship segments may vary, decarbonization of shipping will require substitution of fossil fuels by carbon-neutral fuels. The term carbon-neutral refers to a variety of energy sources or energy systems that have no net GHG emissions or carbon footprint. They include:

- Fuels with no carbon emissions at the stack – such as electricity, hydrogen (H_2) and ammonia (NH_3) – provided that production of the fuel is also carbon neutral. Such fuels can for instance be produced from renewable energy, nuclear energy and fossil energy with carbon capture and storage (CCS).
- Fuels with carbon emissions at the stack, such as biofuels and electrofuels (synthetic fuel), provided that the carbon contained in the fuel is sustainably sourced and would otherwise have been part of the natural carbon cycle. That is to say that combusting it does not lead to more CO_2 entering the atmosphere than would have been the case through the natural carbon cycle. Energy and land use for producing such fuels must also be carbon neutral.

3.1.2 BIOFUELS START TO GAIN TRACTION IN THE MARKET

Sustainable biofuels are flexible alternatives. They can be blended with conventional fuels or used as drop-in fuels fully substituting conventional fossil fuels. A drop-in fuel can be used directly in existing installations without significant technical modifications. For this reason, biofuels may be well suited to substitute for oil-based fuels in the existing ship fleet.

The most promising biofuels for ships are biodiesel and LBG, liquefied biogas consisting primarily of methane. Some examples of biofuels include HVO, hydrogenated vegetable oil; BTL, biomass-to-liquids; and FAME, fatty acid methyl ester. FAME is not a drop-in fuel, as the allowable blending concentration for it is limited to 7% by international standard ISO 8217:2017. Biodiesel is most suitable for replacing marine diesel oil (MDO) and marine gas oil (MGO), and LBG for replacing liquefied natural gas (LNG) as a ship fuel.

The uptake of biofuels in shipping is limited, but several demonstration projects have been testing the technical feasibility of various biofuels. HVO is currently used on several ferries[8,9] operating in Norway. In addition, Norway's coastal passenger fleet Hurtigruten recently signed a contract with Trondheim-based Biokraft to deliver biogas from 2020 to 2027.[10]

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[8] https://www.biofuel-express.com/ta-fergen-til-operaen-i-kobenhavn-med-neste-my-fornybar-diesel-hvo/?lang=no and https://www.neste.us/californian-cruise-company-red-and-white-fleet-switches-neste-my-renewable-diesel

[9] 'They become the world's first first ferries to [run] only [on] biofuel [Transl.]', T Svensvold, TU, 25 September 2015, viewed at www.tu.no

[10] https://www.newsinenglish.no/2019/05/23/hurtigruten-to-fuel-ships-with-biogas and https://e24.no/naeringsliv/hurtigruten/hurtigruten-inngaar-rekordavtale-om-biogass/24627061

A recent study pointed out that HVO is currently available at commercial scale, which allows for very high GHG-reductions when using waste oils and fats. This makes it the most attractive short-term option to decarbonize shipping (E4tech, 2018). Analysis by the International Energy Agency (IEA, 2017) addresses the limitations to global biodiesel production based on existing oil crops and animal fats, as well as competition for it between shipping and other sectors such as aviation and road transport. IEA points out that expanding use of marine biofuels would require its production to be based also on lignocellulosic feedstocks, i.e. plant dry matter. The fact that biodiesel and bioethanol can be produced from waste and lignocellulose may increase the availability of biofuel for shipping. Recent developments in engine technology have also introduced dual-fuel engines that can burn ethanol, thus increasing the potential uptake of biofuel.

3.1.3 PROSPECTS FOR HYDROGEN AND ELECTROFUELS

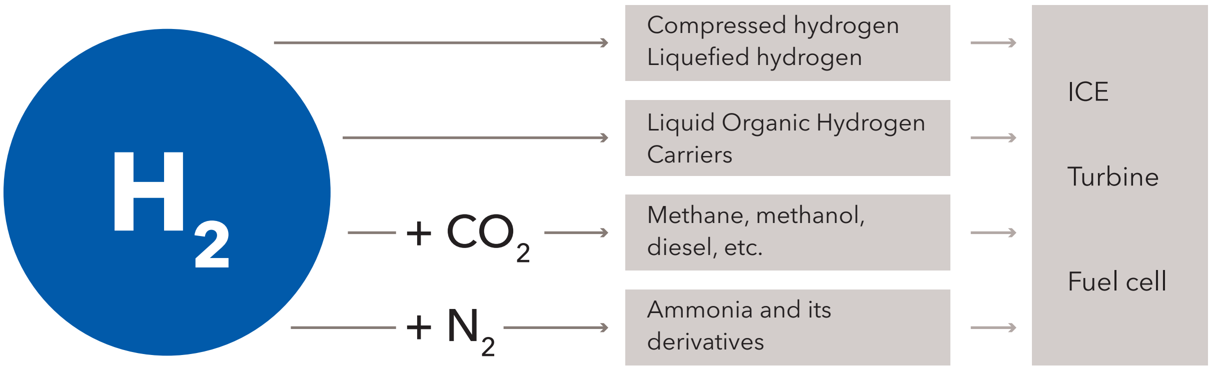
Apart from biofuels, efforts to substitute carbon-neutral fuels for fossil ones depend heavily on access to non-combustible renewable energy sources. Electricity from renewables (or from zero carbon sources like nuclear) used in maritime battery applications is the only commercially available alternative now for carbon-free shipping. This is presently limited to short trades up to approximately one hour, in practical terms this also means for (very) small ships. For the majority of global shipping, battery applications do not provide enough energy to cover the entire length of voyages (see Section 3.2.4).

One alternative energy carrier is hydrogen (H_2) produced from carbon-neutral energy resources, such as electricity from renewables. Alternatively, carbon-neutral H_2 can be produced from natural gas, with CCS, or from nuclear energy. Using compressed or liquefied hydrogen in marine fuel cells is a realistic option for the short-sea shipping segment in the medium term. Current barriers to this relate to: the high investment cost; the maturity of hydrogen as a fuel; its availability and price; the onboard storage space required; and, potential safety and approval requirements.

Hydrogen can itself be the basis for different electrofuels (Figure 3.3). Electrofuels, sometimes referred to as e-fuel, is an umbrella term for

FIGURE 3.3

Utilization of renewable energy through hydrogen storage pathways



Key: CO_2, carbon dioxide; H_2, hydrogen; N_2, nitrogen; ICE, internal combustion engine

Source: Inspired by Päivi et al. (2018)

synthetic fuels such as diesel, methane and methanol when they are produced from H_2 and CO_2 (carbon-based fuels), or from H_2 and nitrogen (nitrogen-based fuels such as ammonia), using renewable electricity to power the production. Carbon based fuels are drop-in fuels requiring only limited modification to engines and fuel systems to replace (or blend with) traditional fuels used by internal combustion engines. The electrofuels are therefore excellent bridging fuels during the energy transition in maritime (see Chapter 5). Another advantage of carbon-based electrofuels is that, like conventional fuels, they can have a high energy density. Synthetic fuel needs similar onboard storage as conventional fuel used today.

While electrofuels have potential advantages, producing them is currently expensive and energy intensive (e.g. Brynolf, 2014; Cerulogy, 2017). It is not as energy efficient as the direct supply of electricity for powering battery ships, nor as efficient as using hydrogen. The European Federation for Transport and Environment (2017) says direct supply of this kind results in 73% of the electricity produced being available as energy for use in transport. In contrast, using hydrogen in a fuel-cell vehicle is 22% energy efficient, and the figure for electrofuels is only 13%, which means that 87% of the energy is wasted. Low efficiency ultimately impacts on fuel cost. The actual impact in terms of price differences will be highly dependent on the price of electricity. However, when electricity prices are low, the greater efficiency losses with electrofuels become less relevant.

Ultimately, the future application of various carbon-neutral fuels will depend on how the advantages and disadvantages of each option add up for a particular ship or ship segment. For some segments, fuel cost will outweigh capital expenditure requirements. For others, onboard storage space requirements will be the determining factor. Lower prices for renewable energy will in general make several carbon-neutral fuels more competitive.

3.1.4 OVERCOMING THE STORAGE CAPACITY BARRIER TO ALTERNATIVE FUELS

Storage capacity is a key barrier to many alternative fuels and will need solving in the coming decades. The physical characteristics of the fuel will determine how it is stored and fitted on a vessel. Figure 3.4 charts the volumetric energy density and gravimetric energy density of different fuel alternatives.[11] Data for a lithium nickel manganese cobalt oxide (NMC) battery cell are included for comparison. The arrows indicate the decrease in energy density when also taking into account the weight and volume of the storage solution required for some of the alternatives. In particular, the energy density of the energy carriers in gas phase will be greatly affected when including high-pressure equipment for compression and/or insulation for cooling. To get the complete picture on storage needs, efficiency of the alternative energy converters should also be considered. Moving the deep-sea fleet over to zero-carbon fuels will require developing alternative storage mediums and arrangements, such as ammonia and Liquid Organic Hydrogen Carriers (LOHC) (e.g. MariGreen, 2018; Päivi et al., 2018; IRENA, 2018). It will also need increased focus on energy efficiency and, possibly, more frequent bunkering than today.

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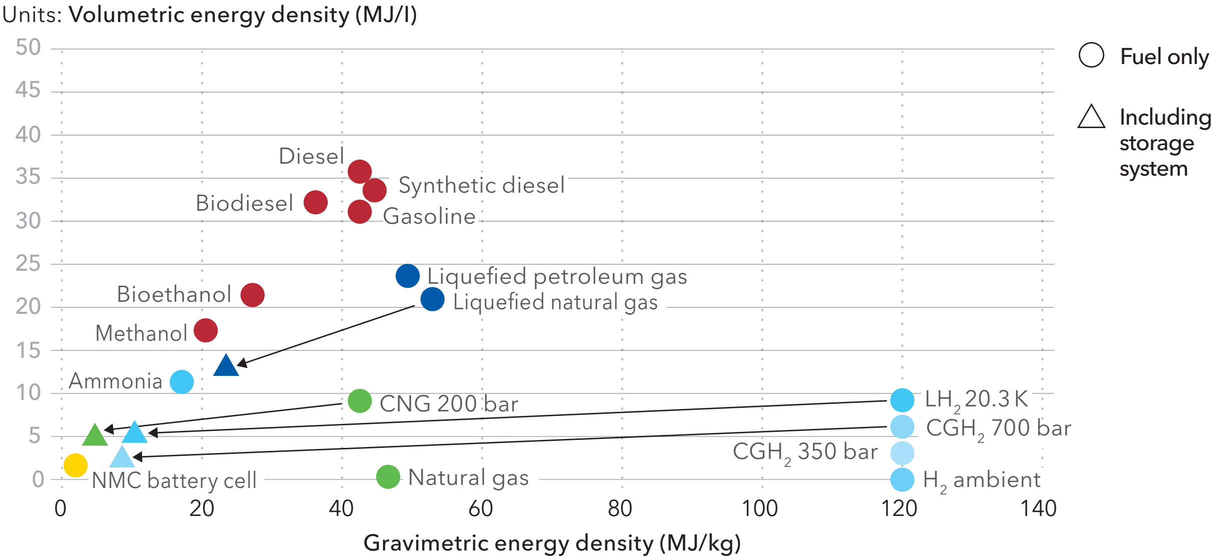
[11] Energy density is the amount of energy stored per unit volume (volumetric energy density) or per unit weight (gravimetric energy density)

FIGURE 3.4

Comparison of gravimetric and volumetric storage density for fuels



Note: Arrows show shifts in energy density when storage is required.

Key: CGH$_2$, compressed gaseous hydrogen; CNG, compressed natural gas; H$_2$ ambient, hydrogen at ambient temperature; LH$_2$ 20.3 K, liquefied hydrogen at 20.3 kelvin; NMC, lithium nickel manganese cobalt oxide

Source: Inspired by Shell (2017) and MariGreen (2018)

The advantage of liquid fuels – those that are liquid at atmospheric temperature and pressure – are that the storage tanks can be easily integrated into a vessel's current structure. This saves cost, weight and in most cases, space compared with gas fuels. Gas fuels require independent or non-integrated storage tanks that are insulated and/or can contain pressure. These tanks are costly and often more challenging to integrate onboard, placing more restrictions on how much fuel can be stored and hence restricting a vessel's operating range. This can be visualized as interval time between bunkering and is generalized in Figure 3.5 as an illustration of operating range.

> “Moving the deep-sea fleet over to zero-carbon fuels will require developing alternative storage mediums and arrangements, such as ammonia and Liquid Organic Hydrogen Carriers.

FIGURE 3.5

A generalized illustration of bunkering intervals for different type of fuels

Fuel type	Typical generalized bunkering intervals	
Electricity in batteries	🕒	Hours
Compressed hydrogen	🕒🕒	Hours – Days
Liquefied hydrogen	🕒🕒🕒	Days
Liquefied ammonia	🕒🕒🕒🕒🕒🕒🕒🕒🕒	Weeks – Month
Liquefied natural gas	🕒🕒🕒🕒🕒🕒🕒🕒🕒	Weeks – Month
Methanol	🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒	Months
Oil-based fuel	🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒🕒	Months

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3.2 ENERGY CONVERTERS FOR ALTERNATIVE FUELS

The world fleet is mostly powered by diesel engines and fuelled by marine oils, i.e. heavy fuel oil (HFO) and marine gas oil (MGO). Marine diesel engines are a type of internal combustion engine (ICE) which can be further categorized into: slow-speed two-stroke engines with a maximum 300 revolutions per minute (RPM); medium-speed engines (300–900 RPM and normally four-stroke); and, high-speed four-stroke engines (more than 900 RPM). The slow-speed engines are typically used by the larger cargo ships. These vessels have the largest share of total installed power in the world fleet, and account for most of the maritime fuel consumption and emissions. However, medium-speed engines used for propulsion and auxiliary power generation dominate by number of engines (about 55%), followed by high-speed engines (about 27%) and slow-speed engines (about 18%) (Trozzi, 2010). Ships are using these converters in different propulsion configurations; for example, in conventional direct-driven systems, diesel-electrical (including dual-fuel) and hybrid systems propulsion. About 4,000 ships – nearly 5% of the global fleet – are driven by electricity in diesel-electric propulsion, hybrid propulsion and all-electric battery drive systems. This is according to the European Commission-initiated report Electrification of the Transport System (EU, 2017).

A new era started when four-stroke gas engines (dual-fuel or gas only) were adopted from 2000, allowing use of LNG (Figure 3.6 and Section 5.1). Until the dual-fuel engines were introduced in the

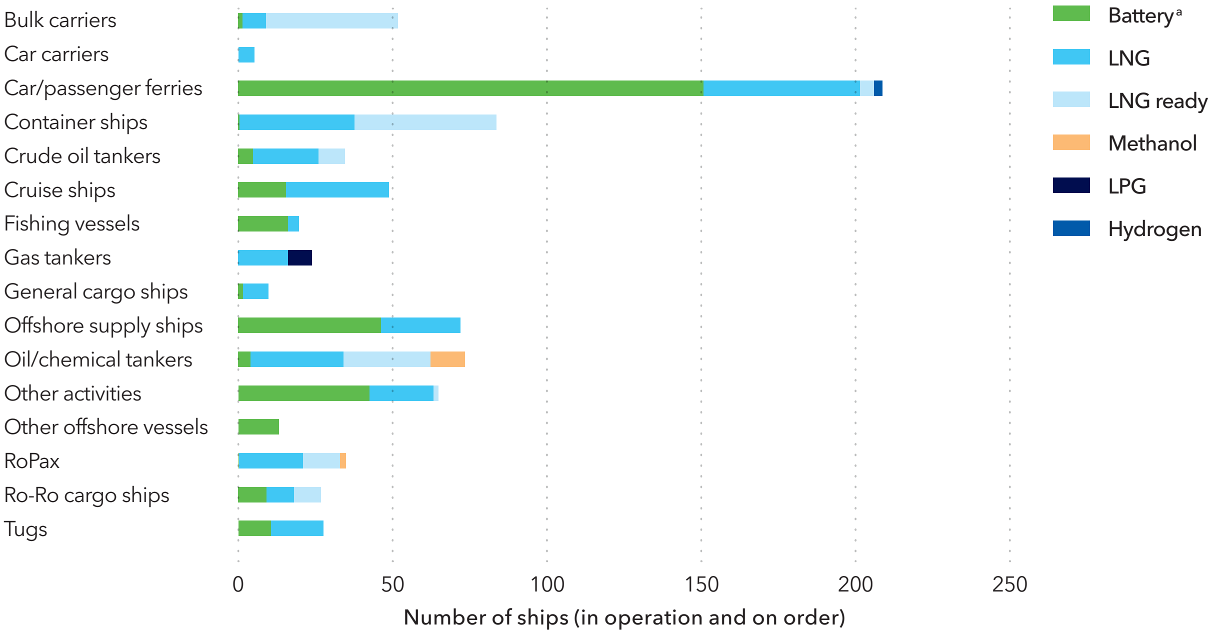
early 2000s, LNG was used only by LNG carriers capable of burning boil-off-gas in their steam turbines. In 2011, high-pressure two-stroke dual-fuel engines were introduced, allowing use of either LNG, or HFO/MGO. Fuel flexibility was further enhanced recently, when such engines could also use ethanol, dimethyl ether (DME), liquefied petroleum gas (LPG), and methanol. LPG carriers and chemical tankers could then consider utilizing cargo as fuel, an option reflected in the current uptake (Figure 3.6).

A rapid uptake of battery-electric propulsion systems by ferries/passenger ships and service vessels has also occurred over recent years (Figure 3.6). Marine fuel cells are expected to emerge over the next years, providing higher efficiency and thereby lower fuel consumption and emissions compared to combustion engines. Fuel cells will also accommodate alternative fuels such as hydrogen and ammonia (NH_3). Some fuel-cell technologies also allow for fuel flexibility.

Handling different fuels may require different energy converters. This chapter describes key characteristics of the alternative converter systems emerging for shipping, including gas- and dual-fuel engines, battery-electric propulsion systems, and marine fuel cells.

FIGURE 3.6

May 2019 status of uptake of alternative fuels by ships in operation and on order



[a] Includes fully electric vessels, and chargeable and non-chargeable hybrids.

Source: AFI, DNV GL

3.2.1 PURE/DUAL-FUEL GAS ENGINES BURNING LIQUEFIED NATURAL GAS

LNG is viewed as an attractive fuel for global shipping as it has potential to reduce emissions to air and is priced competitively compared with liquid marine fuels. There are four main gas engine concepts. Figure 3.7 summarizes their key technical characteristics, including emission-reduction potential, additional cost compared with marine diesel/gas oil, and the current uptake of each of the four concepts.

The emission reduction achieved is related to the engine technology used on board, and varies primarily in regard to methane slip and nitrogen oxides (NOx) emissions. CO_2 emissions from an LNG-fuelled engine are generally lower than for diesel because LNG contains less carbon and more energy per mass unit. The actual GHG emission reduction is highly dependent on the amount of methane slip in the combustion cycle.

Different types of gas engines (pure gas, dual fuel) may be further categorized by the combustion cycle (Diesel, Otto) and pressure level (high, low). Low-pressure engines may experience methane slip as well as knocking. However, NOx emissions are significantly reduced, and compatible with the IMO NOx Tier III limits, even without additional NOx-reducing technology. High-pressure engine types will – due to the high pressure and combustion cycle – experience very limited methane slip. However, they require additional NOx-reducing technology to comply with IMO Tier III. Recent studies with high-pressure engines show a tank-to-propeller GHG reduction of about 20%–24% compared to MGO when methane slip is factored in. The equivalent reduction for low-pressure engines is in the range of 0%–18% (two-stroke and pure gas four-stroke in the higher end) (Stenersen and Thonstad, 2017; Lindstad et

Wärtsilä 31 DF:
Dual fuel four-stroke engine

The Wärtsilä 31 is recognized by Guinness World Records as the world's most efficient four-stroke diesel engine.

al., 2018; DNV GL, 2019c). Using LNG as fuel significantly reduces or eliminates emissions of sulphur oxides (SOx), particulate matter (PM) and black carbon.

The newbuilding cost of LNG-fuelled ships has typically been about 10%–30% higher than for equivalent diesel-fuelled ships (Æsoy et al., 2011; DNV GL, 2015b, DNV GL 2019c), though it is typically less than 20% in recent installations. Also, LNG fuel tanks require typically two to three times the volume of fuel-oil tanks with the same energy content. The extra investment needs to be compensated for by lower operational expenses, which will depend on oil/gas prices, maintenance cost as well as the regulatory landscape.

The uptake of ships with LNG as a fuel is included in Figure 3.7 showing the number of LNG ships in operation and on order. With around 300 ships in operation or on order, and applications around the globe and in most ship segments, LNG is currently the most used alternative fuel option. Large volumes of natural gas are available today and in the coming decades to further grow this position, but there is still a lack of infrastructure and bunkering facilities for shipping globally (for more details see Section 5.2).

The larger vessels with two-stroke engines account for some 65% of global fuel consumption by shipping (Buhaug et al., 2009). Recent years have seen an increase in gas-fuelled ships with this engine type. About 20% of the current uptake of LNG-fuelled vessels are larger cargo ships with slow-speed, two-stroke LNG engines. An increased uptake of such engines could significantly contribute to reducing shipping GHG emissions.

Figure 3.7 also highlights the flexibility of varying engine types for potential conversion to non-fossil fuels in the future. Biomethane/liquefied biogas (LBG) could be attractive low-carbon alternatives to LNG, and could utilize existing and upcoming LNG infrastructure.

In addition to fuel flexibilities included in Figure 3.7, the option exists to blend in hydrogen (H_2) without necessarily encountering major technical challenges.

3.2.2 DUAL-FUEL ENGINES BURNING LIQUID PETROLEUM GAS AND OTHER LOW-FLASHPOINT LIQUIDS

Three main options for using LPG as ship fuel are in: two-stroke diesel-cycle engines; four-stroke, lean-burn Otto-cycle engines; or in gas turbines. Currently, only one example of a two-stroke dual-fuel engine model is commercially available, the MAN ME-LGI series. In 2017, a Wärtsilä four-stroke engine (34SG series) was commissioned for stationary power generation. This engine had to be de-rated to maintain a safe knock margin. Wärtsilä offers an alternative technology that requires installation of a gas reformer to turn LPG and steam into methane by mixing them with CO_2 and hydrogen. This mixture can then be used in a regular gas or dual-fuel engine without de-rating. Only two-stroke engines are thus currently available for direct use of LPG. DNV GL has found the cost of installing LPG systems on a vessel to be roughly half that of an LNG system if pressurized Type C tanks are used in both cases.

FIGURE 3.7

Key characteristics for four gas-engine concepts

		Pure gas four-stroke (Low pressure)	**Dual-fuel four-stroke** (Low pressure)	**Dual-fuel two-stroke** (Low pressure)	**Dual-fuel two-stroke** (High pressure)
TECHNICAL CHARACTERISTICS	Typical application	Short-sea		Deep-sea	
	Power range (megawatts)	0.5–10 MW Medium to high speed	1–18 MW Medium speed	5–65 MW Slow speed	2.5–90 MW Slow speed
	Combustion cycle/fuel injection	Otto cycle (pre-mixed)			Diesel (diffusing)
	Gas supply pressure	4–6 bar		<16 bar	>300 bar
	Thermal efficiency	42%–49%	40%–45%	48%–51%	50%–53%
	Issues	Methane slip, knocking, backup fuel	Methane slip, knocking	Methane slip, knocking, pre-ignition	Possible gas leakage at high pressure
LNG EMISSIONS REDUCTION POTENTIAL	GHG	5%–15%	0%–10%	15%–18%	20%–24%
	NOx	85%–90%	75%–90%		25%–30% Require EGR/SCR
	SOx	>98%			92%–97%
	PM	>99%	95%–98%		N/A
Additional investment needs (ship)		15%–20%			
Other OPEX (ex. fuel)		~0%			
CONVERTER FUEL FLEXIBILITY	Fossil	LNG			
			MGO/HFO		
	Non-fossil	Liquefied biogas (LBG)			
		Synthetic methane (electrofuel)			
			Biodiesel		
			Synthetic diesel (electrofuel)		
CURRENT UPTAKE	LNG ships in operation	29	88	25	
	LNG ships on order	8	53	30	

Key assumptions for estimating emission reduction: All emissions are tank-to-propeller only. Reduction potential is compared with using MGO. GHG (25 Global-Warming Potential), SOx (compared to 0.5 S m/m), PM (per mass).

Note that:

- The engine efficiency is based on a engine load of 25%–100%.
- In addition to the indicated fuel flexibility, technically feasible retrofit options are under development (or exist) to enable other alternative fuels such as ammonia, methanol and hydrogen. There are also options for mixing in alternative fuels, including hydrogen.
- The information is mainly from a comprehensive review of LNG literature (DNV GL, 2019c), though other sources are also considered. Current uptake of LNG is based on data collected from the AFI portal.

Key: EGC, exhaust gas recirculation; SCR, selective catalytic reduction

LPG is mainly sourced as a by-product of either oil and natural gas production or oil refining. It can also be produced from renewable sources, for example as a by-product of renewable diesel production. A large network of LPG import and export terminals is available around the world, but the development of a bunkering infrastructure remains a barrier to its use as a maritime fuel.

Methanol is attracting increased attention as a ship fuel. It contains no sulphur and is liquid at ambient air conditions, making it easy to store on ships.[12] The additional costs of installing methanol systems (e.g. ICE, fuel tanks, piping) on vessels are roughly one third of those associated with LNG systems. Methanol can be stored in standard fuel tanks for liquid fuels, if certain modifications are made to accommodate its low-flashpoint properties. The IMO is developing requirements for methanol as fuel within its International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuel (known as the IGF Code).

The two main options for using methanol as fuel in conventional ship engines are two-stroke diesel-cycle engines or four-stroke, lean-burn Otto-cycle ones. Wärtsilä's four-stroke engines running on methanol are in operation on the passenger ferry Stena Germanica. In addition, seven chemical tankers (methanol carriers), are using methanol as a fuel. Several methanol demonstration projects, such as Leanship, Methaship, SPIRETH and PILOT, have focused on engine conversion and testing (FCBI Energy, 2015). According to FCBI Energy (2015), the cost of retrofitting a ship to switch from diesel to a dual-fuel methanol/diesel fuel has been estimated to be EUR 250–350 per kilowatt for large, 10–25 megawatt engines. As part of a project called GreenPilot, small methanol engines have been installed and tested on a Swedish pilot boat, GreenPilot.[13] Using methanol in fuel cells is also feasible; a test installation has been running on the Viking Line ferry MS Mariella since 2017.

The methanol industry spans the globe. Methanol is available in volume today, and will be over the next decades, but there is still a lack of related global infrastructure and bunkering facilities for shipping. Distributing methanol to ships can be by truck or bunker vessel. Stena Line has created a dedicated area in the Swedish port of Göteborg (Gothenburg) for bunkering the vessel Stena Germanica. In Germany, the first methanol infrastructure supply chain – from production using renewable energy, to trucking and ship bunkering through to consumption in a fuel-cell system on the inland passenger vessel MS Innogy – was launched in August 2017.

Today, methanol is generally produced using natural gas as a feedstock. It has attracted interest as an alternative, low-carbon fuel because it is also possible to produce with renewable feedstocks such as municipal and industrial waste, biomass, together with CO_2 and hydrogen (DNV GL, 2015a). The first commercial electrofuel plant was built in Iceland in 2012, with a capacity to produce more than five million litres of e-methanol per year. Iceland produces e-methanol using geothermal energy and CO_2 from the same source (Hansson and Grahn, 2016).

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[12] https://www.mandieselturbo.com/docs/default-source/shopwaredocuments/using-methanol-fuel-in-the-man-b-w-me-lgi-series.pdf
[13] https://news.cision.com/rise/r/new-methanol-engine-ready-for-the-marine-market,c2646904

3.2.3 DUAL-FUEL ENGINES BURNING AMMONIA

Safety and regulatory challenges as well as space/weight and cost considerations related to storing large quantities of H_2 on ships have generated interest in exploring alternative hydrogen-based energy carriers. Several studies have pointed to ammonia (NH_3) as a potential fuel for shipping (Maritime Knowledge Centre, TNO & TU delft, 2017; OECD, 2018). No marine engine currently on the market is capable of burning ammonia.

Development work on engines that can burn NH_3 is underway, and they are expected to be ready within the next few years.[14] Key challenges include ammonia's very high auto-ignition temperature, low flame speed, high heat of vaporization, narrow flammability limits, and toxicity (Brohi, 2014; Reiter & Kong, 2011; Gross & Kong, 2013), in addition to associated formation of NOx. Gross & Kong (2013) also reports that NH_3 is corrosive to copper, copper alloys, nickel and plastics, so that these materials must be avoided in ammonia-fuelled engines and fuel-supply systems. Ammonia is also relatively well-suited for deep-sea applications, as the energy density of the fuel is high compared with many of the alternatives (Figure 3.4).

Most NH_3 produced today is from the energy-intensive Haber–Bosch process, with natural gas as the starting point (Brohi, 2014; Päivi T. et al., 2018). Ammonia can be produced from renewable sources, utilizing electrolysis. This would result in a carbon-neutral fuel since the tank-to-propeller phase does not emit any carbon.

There is existing infrastructure for transporting and handling NH_3 because large quantities of it are used as agricultural fertilizer. However, the development of a bunkering infrastructure remains a barrier for its use as fuel.

Ammonia is expected by many to be an important maritime fuel in the future, provided that: carbon-free production of NH_3 is developed; necessary infrastructure is established; and promising onboard converters become available in the market. It should be noted that a ship operating with LPG as a fuel could in the future be relatively easily converted to run on ammonia, meaning that LPG could be a future-proof solution.

3.2.4 BATTERY ELECTRIC POWER SYSTEMS

A battery is an electrochemical system that can store electric power with very high responsiveness. In principle, batteries can serve all energy demands on a ship.

On a full-electric ship, the power system for propulsion and auxiliaries is based entirely on batteries charged from the onshore electric grid while at berth. If the electricity comes from a renewable energy source, a full-electric ship may be considered to emit no CO_2, NOx, PM and SOx. Depending on the propulsion arrangement, it may also produce no engine noise. A plug-in hybrid ship has batteries that can be charged using shore power, but also onboard conventional fuels and engines which may be used to charge the batteries. This is directly analogous to a plug-in hybrid car. The ship can operate on batteries alone on specific parts of the route; for example, when manoeuvring in port or during standby operations. It can also be 100%-electric for normal operation, with engines only for available backup or special circumstances. This is the case for the Norwegian ferry sector, where many ferries operate on a near full-electric basis, but are built as plug-in hybrid solutions with engines for backup use.

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[14] https://marine.man-es.com/docs/librariesprovider6/test/b-w-me-lgip-dual-fuel-engines-manpm-00-0497-preview.pdf?sfvrsn=6f26cba2_6

A battery hybrid ship uses batteries to optimize the engine and power systems and thereby reduce fuel consumption. The battery hybrid ship does not bunker electricity from shore, so the concept is not about changing to alternative fuel, but to improve the energy efficiency. The hybrid battery-electric configurations have significant potential for improving the energy efficiency which can be utilized in a variety of maritime applications and for a wide range of ship types.

Full-electric operation is currently relevant only for the short-sea shipping segment. Within this segment, ships on short routes, with regular schedules and long contracts, have the greatest potential of all for full electrification. Ships that operate on routes with frequent port calls, as well as harbour crafts, may also use more onshore electricity for charging batteries. Apart from electric shore power, deep-sea shipping looks unlikely to use a significant level of onshore power in the foreseeable future, but battery hybrid solutions can be of interest for parts of the power requirements such as auxiliary power. Deep-sea vessels can already install batteries for energy optimization, especially in harbour mode and during cargo handling there.

Today more than 320 hybrid/plug-in ships are in operation or on order. Limited shore-based infrastructure is available for charging (Figure 3.8), but progress is being made in certain regions,[15,16] (e.g. Ecofys, 2015). We expect that almost every newbuild vessel will use batteries in some way in the short near term.

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[15] First for Shore Power in India: http://www.maritime-executive.com/editorials/first-for-shore-power-in-india

[16] Shore power, Norway: http://www.tu.no/artikler/havner-vil-fa-hurtigruten-over-pa-landstrom/193818 and http://www.mynewsdesk.com/no/enova-sf/pressreleases/140-millioner-til-landstroem-1689508

FIGURE 3.8

Shore-based infrastructure for charging ship batteries

Source: AFI, DNV GL

We recently reviewed battery technologies for the maritime industry (DNV GL, 2019d). The most used battery type is lithium-ion. Lithium-ion batteries have the highest specific energy and highest energy density of commercially available batteries. Most of lithium-ion batteries currently available use carbon- or graphite-based anodes, but differ from each other in cathode chemistry. Figure 3.9 summarizes key technical characteristics for the three principal cell chemistries used in maritime lithium-ion batteries: nickel manganese cobalt oxide (NMC); lithium iron phosphate (LFP); and, lithium titanate oxide (LTO). NMC and LFP are two types of existing cathode chemistries, whereas LTO is an anode chemistry.

As the figure shows, batteries with NMC cathodes are the market leader in the maritime sector. Their design is flexible with respect to power and energy capabilities. The relative composition and quantities of NMC batteries can be tweaked to produce different properties with regard to power density, energy density, cost and safety. Tweaking can also customize the battery cells for certain applications or groups of applications. It depends on how the elements of nickel, cobalt and manganese are engineered.

FIGURE 3.9

Key characteristics of the three principal lithium-ion cell chemistries in maritime batteries

		NMC (Nickel Manganese Cobalt Oxide)	**LFP** (Lithium Iron Phosphate)	**LTO** (Lithium Titanate Oxide)
TECHNICAL CHARACTERISTICS	Typical application	Short-sea (all-electric) to deep-sea (hybrid)		
	Specific power	450–660 W/kg	1 000 W/kg	3 000–5 100 W/kg
	Specific energy density (Gravimetric)	150–220 Wh/kg	90–120 Wh/kg	50–80 Wh/kg
	Specific energy density (Volumetric)	350–580 Wh/L	300–350 Wh/L	110–140 Wh/L
	Thermal stability	Medium	Medium	High
	Flammability	High	Medium	Medium
	Toxicity	High	High	High
	Efficiency	85%–95%		
	Issues	Key properties equilibrium may be difficult to ensure for a stable lifespan	Relatively low specific energy; lower voltage; lower power capabilities	Relatively low specific energy; high initial cost
Potential reduction in emissions to air (GHG, SOx, NOx, PM)		100%		
Typical CAPEX		500–1 000 USD/kWh		1 000–2 000 USD/kWh
OPEX		Driven by electricity price		
Fuel flexibility		Feasible for most fuels with hybrid configuration		
CURRENT UPTAKE	Battery ships in operation	93	21	1
	Battery ships on order	79	9	7

Note that:
- The emission reduction assumes 100% battery power, charged from shore.
- The current uptake of ships with batteries is based on Maritime Battery Forum's ship register. There are other cell chemistries that can be used, and the total number of ships with batteries is larger.

Key: CAPEX, capital expense; GHG, greenhouse gas; kg, kilogram; kWh, kilowatt hours; L, litre; NOx, nitrogen oxides; OPEX, operational expense; PM, particulate matter; SOx, sulphur oxides; W, watts; Wh, watt hours

Source: The information is extracted mainly from DNV GL (2019d), but other sources are also considered.

Batteries with LFP cathodes differ significantly from most other cathode chemistries in terms of the structure, which is olivine rather than a layered metal oxide like in the case of NMC. The LFP chemistry is used in marine application because of its good thermal stability features. In addition to LFP batteries having higher safety characteristics, they are resilient to temperature fluctuations, and cathode doping is possible for higher power applications. LTO batteries have titanate in the anode, while the cathode can be other typical chemistries such as NMC. LTO batteries are suitable for applications that require fast charging, high power, or very large numbers of cycles. They have good safety characteristics, very high cycle life and high power capability.

The service life of a battery depends largely on controlling the cell temperature with air or liquid. Noise and vibrations are insignificant. Batteries are also expected to require far less maintenance than conventional combustion engines and turbines. The costs of installing battery systems onboard, including replacing them after typically eight to 10 years, is significantly higher than for traditional diesel engines. In addition, investment on shore infrastructure is needed provide electricity. Electricity production from hydropower is reported to be price-competitive with MGO (e.g. DNV GL, 2015c). However, considering uncertainty about future electricity prices and the large geographical variations, it is expected to be challenging for fully electric solutions to pay back investments through price differences alone.

DNV GL first issued class rules for the use of lithium-ion batteries on ships in 2012.[17] These rules cover fundamentals such as location, ventilation, fire-protection, and other key aspects for integrating a battery system on a ship. Specific testing requirements have also been developed to ensure the level of safety required in the maritime environment. We continue to increase the level of safety of these systems by leading the ongoing Maritime Battery Safety Joint Development Project in collaboration with representatives from the entire maritime battery-vessel value chain, including the relevant authorities.

Battery technology developments are mainly driven by the automotive, consumer electronics and power industries. These markets are pushing towards maximum energy density at minimum cost. Improvements in specific energy, energy density and specific power, often lead to structural changes to the electrodes, which affect both lifetime and safety – two important factors for maritime applications. Finding suitable trade-offs between these effects while simultaneously keeping production costs down are key challenges in battery technology development. The most interesting future technologies are solid-state batteries, preferably combined with metal-air. This combination dramatically improves specific energy, energy density and safety features. In 2020, Mercedes-Benz will deliver more than 40 buses with solid-state batteries, which are considered as safer and more energy dense than lithium-ion batteries with liquid electrolyte. The solid-state batteries to be installed on the buses are lithium metal polymer (LMP) batteries, which will increase the buses' range by 50% compared with equivalent vehicles with NMC batteries. The challenge is that the batteries used in the Mercedes-Benz project are specified to deliver only 16% of the power of batteries currently in use on ships.[18,19]

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[17] https://www.dnvgl.com/maritime/dnvglrules/innovate.html and https://rules.dnvgl.com/docs/pdf/DNVGL/RU-SHIP/2018-01/DNVGL-RU-SHIP-Pt6Ch2.pdf

[18] https://www.greencarcongress.com/2019/04/20190410-ecitaro.html

[19] https://blue-storage.com

3.2.5 FUEL CELLS

Fuel cells combined with alternative fuels can efficiently reduce and even eliminate emissions and noise, while energy efficiency can be increased as compared to combustion engines. Fuel cells can therefore be an important part of the solution towards complying with the new and stricter emission requirements that are being introduced. In simple terms, a fuel-cell power pack consists of the fuel being supplied from a fuel-storage reservoir (tank); a gas processing system; and, a fuel-cell stack that converts the chemical energy in the fuel to electric energy (and heat) through electrochemical reactions. The fuel cell produces electric energy, and the onboard power system must therefore be designed accordingly, allowing for the utilization of the electricity produced.

Some fuel cells can in principle run on several fuels, including well-established options such as LNG and MGO, as well as their bio-equivalents. This is predominantly the case for the high temperature fuel-cell types such as Solid Oxide and Molten Carbonate. Low temperature fuel cells such as Proton-Exchange Membrane need hydrogen as a fuel, but other fuels can be used if reformation of these is deployed to produce hydrogen. The direct use of hydrogen is possibly the most promising option for this technology, offering the highest total energy efficiency as well as three times more energy density on a weight basis than commonly used liquid hydrocarbon fuels (Figure 3.4). Using it on board will require storage capabilities, and there are challenges related to finding volume-efficient ways to achieve this. It is most commonly stored either as compressed gaseous H_2 (CGH_2) or as cryogenic liquefied H_2 (LH_2). For large quantities, it is possible to achieve lighter and more volume-efficient storage on board by using LH_2 rather than CGH_2, to which storage pressures of 350–700 bar are commonly applied; for example, in hydrogen cars. Due to reduced cargo space, these specialized tank arrangements will impact on the competitiveness of ships. Alternative arrangements and storage mediums for H_2, such as ammonia and LOHC, are needed to meet the energy need for large ships within the deep-sea fleet (e.g. MariGreen, 2018; Päivi et al., 2018; IRENA, 2018). In addition, hybrid solutions with other fuels in combination with H_2 may mitigate storage challenges for ships with high energy demand and long bunkering intervals.

Fuel cells have previously been mainly used for special purposes, such as in aerospace and submarines. The technology has matured and is in commercial use in applications such as forklifts, standby generators/uninterruptible power supply, and combined heat and power systems. Fuel cells have advanced to near commercial use for cars, buses, trucks and rail applications. Large-scale production of fuel cells for trucks and cars was announced in April 2019.[20]

Testing has been performed during the last decade for maritime applications, but use of fuel cells in shipping is still in its infancy. DNV GL (2017c) has previously identified a total of 23 fuel-cell projects in the sector. These included assessments of potential fuel-cell use, rule development, feasibility studies, concept design, and testing fuel cells in vessels.

Different fuel-cell types are available, and their names reflect the materials used in the electrolyte membrane. The properties of this membrane affect the permissible operating temperature and the ability to accommodate rapid load variations, the nature of electrochemical reactions, and fuel requirements. Depending on fuel-cell type, electrical efficiency of 50%–60% is expected, slightly higher than for marine diesel generators (DNV GL, 2017c). Some fuel-cell types operate at high temperatures, enabling heat recovery that can increase the overall system efficiency to more than 80%.

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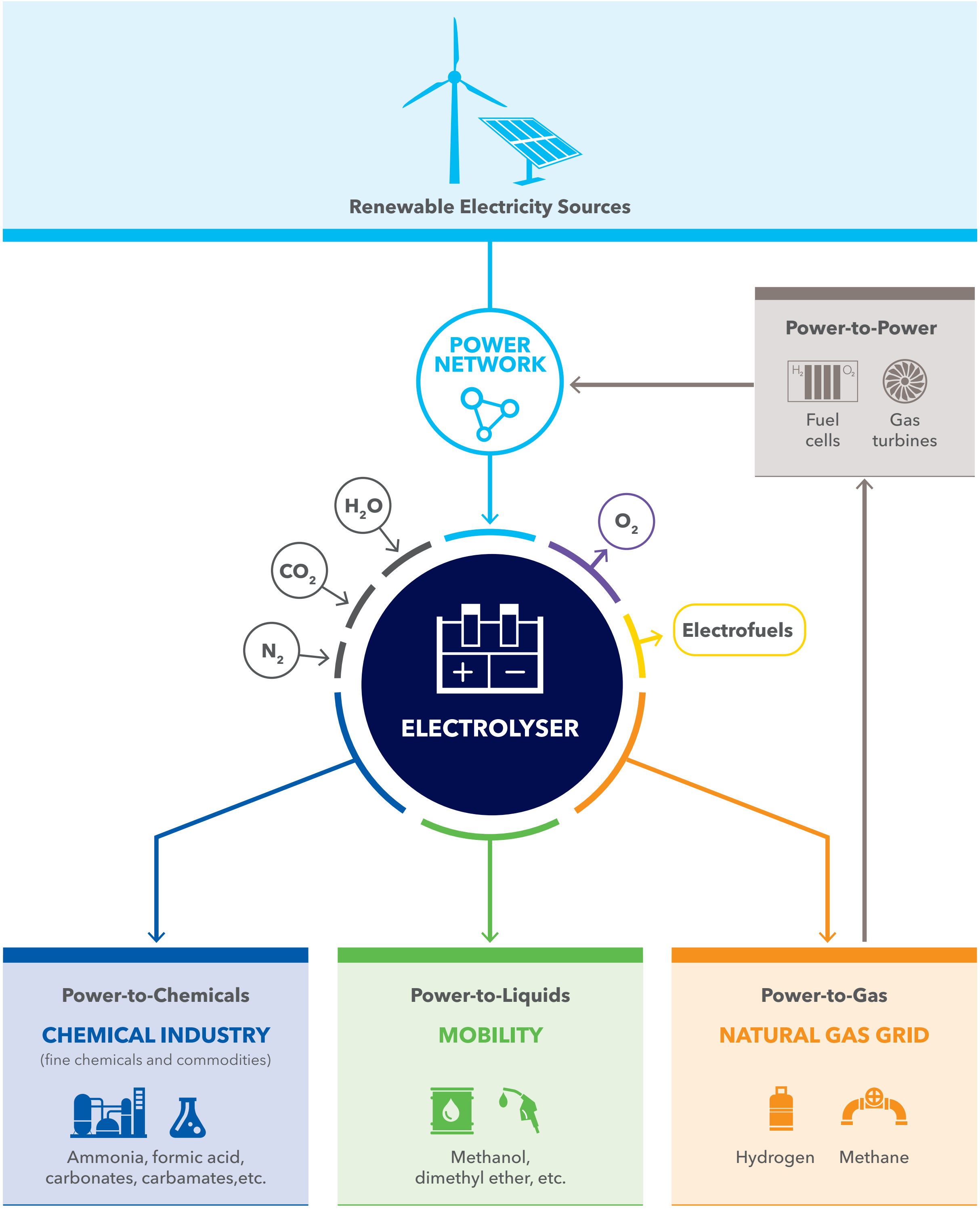
[20] https://www.bosch-presse.de/pressportal/de/en/bosch-to-cooperate-in-large-scale-production-of-fuel-cells-for-trucks-and-cars-188480.html



Electrofuel production, inspired by: A Case for Electrofuels, newsletter 2016

Fuel cells with low operational temperatures are more tolerant of dynamic load variations than high-temperature fuel cells. The lowest operational temperatures also require the purest H_2 (Shell, 2017). Noise and vibrations are insignificant, and fuel cells are also expected to require less maintenance than conventional combustion engines and turbines.

Figure 3.10 summarizes some key characteristics for three fuel-cell types relevant for shipping. The graphic builds on a recent European Maritime Safety Agency report (DNV GL, 2017c) on the screening of seven fuel-cell technologies. The report concluded that the solid-oxide fuel cell, the proton-exchange membrane (PEM) fuel cell, and the high-temperature PEM are the most promising for marine use. While there are many similarities between the assessed technologies, they also differ in important aspects such as complexity of installation, fuel options, tolerance for fuel impurity, and total efficiency including waste-heat recovery. More details about the fuel-cell types are given in the textbox on page 57.

Fuel cells are currently an expensive option compared with traditional energy converters. This is due to significantly higher capital costs. Operational costs may also be higher depending on the fuel used. Initial investment costs range from USD 2,000 per kilowatt (kW) to USD 6,000/kW (e.g. IEA, 2015; Biert, 2016; Sandia, 2016; Shell, 2017; Saito, 2018). A recent literature review presented estimates indicating PEM fuel-cell costs of around USD 1,500/kW to USD 2,860/kW, with an installation cost of USD 510,000. The SF-BREEZE project in the US examined the economic feasibility of a high-speed passenger ferry powered solely by H_2 fuel cells, where the cost of the PEM fuel cell was USD 2,500/kW (Sandia, 2016). Hydrogen infrastructure company Hydrogenic cited this as being in the upper range of expected fuel-cell costs for PEM cells today, based on a one-time order of a 5 MW capacity unit. The capital cost if the ship were to be built today was estimated to be 1.5 to 3.5 times higher than a comparable diesel ferry (Sandia, 2016). Operation and maintenance costs for the fuel-cell powered alternative were estimated to be two to eight times more than for a comparable diesel, due to the high current cost of stack replacement. Sandia (2016) also estimated that today’s fuel cost for the ferry operating on ultra-low sulphur would be three to five times higher in the case of non-renewable LH_2, and five to 16 times higher for a 100%-renewable LH_2 case.

Biert (2016) reported major cuts in the price of low-temperature PEM fuel cells for the automotive sector in recent years, though stack prices at current production volumes of 500 to 1,000 midsized fuel-cell vehicles per year, are typically still greater than USD 1,000/kW. A recent study has reported falling cost with increased land-based uptake of some fuel-cell technologies (residential PEM fuel cells in Asia), with price reductions of 16% and 21% for each doubling in production (Staffell et al., 2019). DNV GL analysis indicates that hydrogen fuel-cell electric vehicles will be competitive by 2030 for heavy vehicle segments such as heavy freight trucks and long-distance buses (DNV GL, 2019e).

The use of hydrogen use on ships requires purpose-designed storage tanks and bunkering systems. The cost of onboard fuel-storage systems can be significant, and formulas for estimating storage cost are reported (e.g. Saito, 2018; Raucci, 2017). Although LH_2 storage systems are being developed for ship use, there is very limited maritime experience with such systems. Storage tanks for LH_2 in ships are expected to be more expensive than LNG tanks, as liquefied hydrogen needs to be kept at a much lower temperature, leading to higher insulation and tank-system requirements.

Additional cost is incurred when replacing a cell stack. Raucci (2017) gives this as 60% of the capital cost of the fuel cell, while Wang (2018) reports about 50%. There is considerable variation in the available data indicating replacement intervals for cell stacks. Biert (2016) reports that most studies

FIGURE 3.10

Key characteristics: Proton-exchange membrane fuel cell (PEMFC); high-temperature PEMFC (HT-PEMFC); solid-oxide fuel cell (SOFC)

		PEMFC	HT-PEMFC	SOFC
TECHNICAL CHARACTERISTICS	Typical application	Short-sea / Auxiliary		
	Power/size	<400 kW	<30 kW	>100 kW
	Stack lifetime	Moderate	Unknown	Moderate
	Electrical efficiency	50%-60%		~60%
	Operation temperature	50-90°C	140-200°C	500-1 000°C
	Tolerance for load variations	High	Medium	Low
	Sensitivity of fuel impurities	High	Low	Low
	Maturity	High	Low	Moderate
	Energy density	High	High	Moderate
Air emissions reduction potential on hydrogen (GHG, SOx, NOx, PM)		100%		
Relative cost (among fuel cells)		Low	Moderate	High
FUEL FLEXIBILITY	Fossil	H_2 only	H_2/LNG/MGO/methanol	
	Non-fossil	H_2 only	H_2/LBG/biodiesel/biofuels	
CURRENT UPTAKE	Hydrogen ships on order	Four new ferries are planned to be delivered by 2021		

Note that the emission-reduction potential will change if the fuel cell is run on other fuel.
Key: GHG, greenhouse gas; H2, hydrogen; kW, kilowatts; LBG, liquefied biogas; LNG, liquefied natural gas; MGO, marine gas oil; NOx, nitrogen oxides; PM, particulate matter; SOx, sulphur oxides
Source: Information extracted mainly from DNV GL (2017c), but other sources are also considered.

assume a system lifecycle of 20 to 30 years, whereas stack lifetime is currently two to three years, and some manufacturers aspire to making this five to seven years. Raucci (2017) gives a range of 10,000–90,000 hours. Shell (2017) states that the life expectancy for the two most promising technologies is 60,000 hours for PEM fuel cells, and up to 90,000 hours for solid-oxide fuel cells.

The price of H_2 as fuel is today normally much higher than for available alternatives for shipping. Production and distribution costs for H_2 as fuel vary greatly depending on factors such as the value chain, the scale of production, and the cost of the energy source used. One benefit of H_2 production by electrolysis is that the technology is modular. This means that the H_2 might be produced at or close to the place of consumption, though its production cost remains closely related to the price of electricity. Due to the cost benefits of large-scale production, making hydrogen by steam methane reforming (SMR) is typically done at larger, centralized production plants. Here, the production cost is closely related to the price of gas and the scale of the production plant. In most cases, H_2 produced by SMR of natural gas, or as a by-product from industrial processes is expected to be cheaper than H_2 from electrolysis. For SMR of natural gas, the resulting carbon must be removed by carbon capture and storage (CCS) so that the H_2 produced has a low-carbon footprint.

The increased volume and weight of marine fuel cells compared to diesel engines has been a competitive disadvantage. New, innovative low-weight prototype fuel cells are significantly lighter in weight, and occupy less volume, than established fuel-cell systems. Even if the volume and weight of marine fuel cells were comparable to diesel engines, the high costs are still considered a bottleneck for uptake in shipping. In addition, development of, and investments in, a marine bunkering infrastructure are needed in parallel with the development of H_2 as a ship fuel. Also, fuel cells are not well suited for retrofitting, thus limiting the scaling potential for this technology.

Finally, regulatory and safety challenges need to be addressed for the use of H_2 and fuel cells. Specific requirements for these fuels and technologies are lacking. They are not currently included in the IGF Code.[21] According to Part A of this code, an alternative design approach must be carried out to demonstrate an equivalent level of safety. This will require an extensive and very costly design and approval process. DNV GL has issued class rules for fuel-cell installations.[22] These rules include requirements for the design and arrangement of fuel-cell power installations and the spaces containing such installations. They cover all aspects of the installation, from primary fuel supply up to, and including, the exhaust-gas system. The DNV GL rules do not directly cover other installation arrangements for using H_2 as fuel: i.e. H_2 fuel storage, and preparation and distribution of hydrogen. Existing class rules can ease the alternative design process, provided that the rules are acknowledged by the relevant administration. A summary of applicable rules for H_2 fuel-cell vessels in Norway has been prepared (DNV GL in cooperation with Norwegian Maritime Authority, 2018).

Experience with marine storage and use of H_2 is currently limited, but storage technologies available from land-based applications might be used. A key difference between fuel cells and batteries is that the former are based on continuous fuel (H_2) and air supply from a fuel-storage reservoir that can be located so that it is separated from the fuel cell. This means that, in case of a failure, the fuel and the energy converter can easily be isolated from each other.

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[21] The International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) entered into force on 1 January 2017. The IGF Code governs the use of low-flashpoint liquids and gaseous fuels, and is applicable for hydrogen

[22] https://rules.dnvgl.com/docs/pdf/DNV/rulesship/2011-07/ts623.pdf and https://rules.dnvgl.com/docs/pdf/dnvgl/ru-ship/2017-01/DNVGL-RU-SHIP-Pt6Ch2.pdf

FUEL CELLS WITH POTENTIAL FOR MARINE USE

DNV GL (2017c) reports the following fuel-cell types to be promising for marine use.

PROTON-EXCHANGE MEMBRANE FUEL CELL

The PEMFC uses platinum-based electrodes and the electrolyte is a humidified polymer membrane. It is an electric insulator, but is permeable to hydrogen ions. The operating temperature is low. Temperatures above 100°C are not feasible as the membrane needs to remain humid. A PEMFC has a high power-to-weight ratio (100–1,000 W/kg), and the low operating temperature allows for flexible operation and less stringent material requirements. This makes it a suitable and popular fuel cell for transport applications. The electrical efficiency of the PEMFC system is a moderate 50%–60%, and excess heat is of such a quality that heat recovery is not feasible. The low operational temperature means a complex system for water management is required. PEMFCs have been used extensively in many applications including in cars, buses, trucks and railway trains. Experience of their use in maritime includes the Alsterwasser passenger ship with a power output of 96 kW, and German Type 212A class submarines with each module ranging from 30–50 kW. PEMFC technology with power levels ranging from 12-60 kW has been used in other ships, and is dominating fuel-cell technology.

HIGH-TEMPERATURE PEMFC

The HT-PEMFC is less sensitive to poisoning by carbon monoxide (CO) and Sulphur compared with the PEMFC, and does not need a water management system. The HT-PEMFC can operate at temperatures up to 200°C by using a mineral acid electrolyte instead of the water-based system of a PEMFC. The reaction and fuel in the fuel cell are the same as for the PEMFC. The Pa-X-ell project demonstrated HT-PEMFC technology aboard the ferry MS Mariella with three stacks of 30 kW. The small port commuter ferry MF Vågen in Norway has demonstrated a 12 kW HT-PEMFC system. HT-PEMFC has lower power density than PEMFC, and cannot be cold-started. The electrical efficiency of a HT-PEMFC is similar or slightly better than the PEMFC's. However, there is potential to harvest more energy from heat recovery to increase the overall efficiency of HT-PEMFC systems.

SOLID-OXIDE FUEL CELL

The SOFC operates at temperatures in the range 500–1,000°C. Reforming to syngas (H_2+CO) occurs within it. The electrolyte is a porous ceramic material: yttria-stabilized zirconia is common. The SOFC uses a nickel alloy as the anode, and the cathode is normally composed of lanthanum strontium manganite, a material that has the required porosity and is compatible with the electrolyte. SOFCs are used mainly in land-based power plants and power supply, with electrical capacities up to 10 MW. The METHAPU, Felicitas, and SchIBZ projects, among others, have been looking into SOFCs for maritime use. The SOFC shows the same flexibility towards fuels as a molten carbonate fuel cell (MCFC), being able to use H_2 and hydrocarbons such as diesel, LNG and methanol.

HIGHLIGHTS

Flexibility in using fuels can assist shipowners to adapt to a gradual energy transition

Adopting a bridging philosophy can smooth the journey from relying on traditional fuels to using only carbon-neutral types.

Fuel flexibility in energy converters, onboard fuel-storage tanks and fuel systems, and in shore-side fuel infrastructure, are key to this bridging approach.

Deep-sea segment shipowners investing in the next five to 10 years should consider dual-fuel combustion engines.

Shipowners would also do well to assess energy optimization options beyond today's increasing focus on operational and traditional technical targets.

CHAPTER

4

FUEL FLEXIBILITY AS A BRIDGE TOWARDS LOW-CARBON SHIPPING

4 FUEL FLEXIBILITY AS A BRIDGE TOWARDS LOW-CARBON SHIPPING

This chapter introduces the concept of bridging technologies that can facilitate and ease the transition from traditional fuel oils, via fuels with lower-carbon footprints, to carbon-neutral fuels.

Several barriers complicate the introduction and implementation of carbon-neutral fuels. Overcoming them requires action along several axes and by many stakeholders. There is more on this in Chapter 5, but we first present an approach that could help to avoid disruption during the transition to carbon-neutral fuels.

We describe it as a bridging philosophy built on three flexibility pillars:

- Fuel-flexible energy converters.
- Fuel-flexible storage tanks and onboard systems allowing fuel switching.
- Flexible shore-side fuel infrastructure.

4.1 THE BRIDGING PHILOSOPHY

There are more than 110,000 ships in the world fleet,[23] most of them powered by diesel engines. It is not hard to see that a widespread adoption of carbon-neutral fuels could potentially take a long time. That is even without considering that some alternatives to diesel are not yet technically available for onboard use, or factoring in the time needed to properly develop low-carbon fuels, production capacity and infrastructure.

Facilitating a gradual phase-in of carbon-neutral fuels is one possible way to accelerate their introduction. Figure 4.1 illustrates this with two examples. Alternative 1 shows that a dual-fuel powered ship running on liquefied natural gas (LNG) could at some point in time blend in low-carbon drop-in fuels in the form of biogas and small amounts of hydrogen (H_2). Alternative 2 shows a liquefied petroleum gas (LPG) powered ship could shift fully to an alternative zero-carbon fuel such as ammonia (NH_3). This would require modifying and/or rebuilding storage arrangements, fuel lines and engines.

A gradual transition will require preparation on many fronts. These are summarized in this chapter as the bridging philosophy (Figure 4.2). It is a framework that could ease transition from traditional and lower-carbon fuels to carbon-neutral alternatives within the lifetime of a vessel, with limited investments and modifications along the way.

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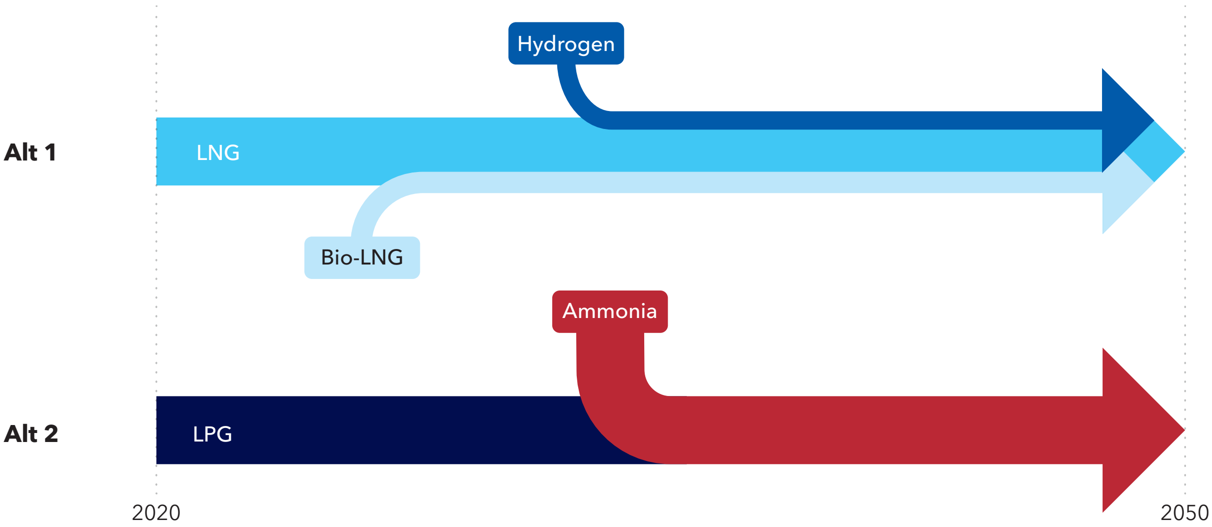
[23] Includes cargo ships, non-cargo ships and fishing vessels above 100 GT. Sources are: Equasis Statistics 'The World Fleet 2017', see http://www.emsa.europa.eu/equasis-statistics/items.html?cid=95&id=472; and, FAO Fishing Vessel Finder, see http://www.fao.org/figis/vrmf/finder/search/#.XREjd-QUng9

FIGURE 4.1

Examples of bridging with LNG (Alternative 1) and LPG (Alternative 2)



Note: These are for illustrative purposes only. There are many possible alternatives, and technical issues for the examples here could remain unsolved.

The bridging philosophy can also have significant benefits for policymakers tasked with delivering on high ambitions for rapid decarbonization of the shipping industry. Planning for gradual transitions, and incentivizing shipowners to invest in flexible ships, could give policymakers a larger toolbox for meeting the challenge.

Fuel-flexible energy converters are essential for bridging technologies. Such converters need to be competitive under different fuel scenarios and gradually tighter emission regulations. Flexible converters will need to provide optimal performance with different fuels and also under different operating profiles and speed regimes. Adopting a bridging philosophy may allow for continued use of internal combustion engines, but with a gradual shift to low-carbon fuel alternatives currently being developed and commercialized. As described in Chapter 3, some converters such as two-stroke dual-fuel engines have significant fuel flexibility and fairly high efficiency. With certain modifications to the engine and the fuel supply system, they can use several fuels such as ethanol, methanol and LPG, in addition to LNG and heavy fuel oil (HFO)/marine gas oil (MGO).[24] Sustainable biofuels are flexible alternatives because they can be blended with conventional fuels or used as drop-in fuels as full substitutes for conventional fossil fuels. Ongoing developing work is expected to lead to the availability in the next few years of combustion engines running on ammonia. Promising steam- and gas-turbine concepts, which would also be fuel flexible, are also being considered.

Fuel-flexible storage tanks and onboard systems are necessities for fuel switching. A flexible engine is of little use if onboard fuel storage and supply systems cannot handle the relevant fuels. For some

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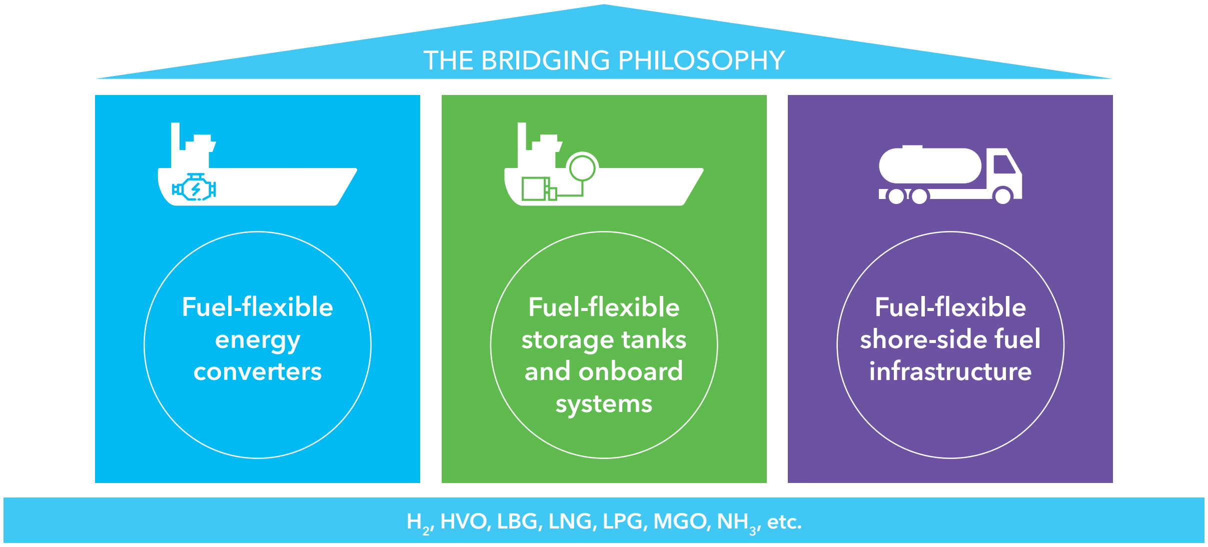
[24] https://marine.mandieselturbo.com/docs/librariesprovider6/technical-papers/the-man-b-amp-w-duel-fuel-engines-starting-a-new-era-in-shipping.pdf?sfvrsn=2

FIGURE 4.2

The three pillars of the bridging philosophy enabling use of alternative fuels



H_2, hydrogen; HVO, hydrotreated vegetable oil; LBG, liquid biogas; LNG, liquefied natural gas
LPG, liquefied petroleum gas; MGO, marine gas oil; NH_3, ammonia

fuel combinations, such as LNG and liquefied biogas, or hydrotreated vegetable oil (HVO; 'renewable diesel') and MGO, the relevant systems are compatible without alteration. For other fuels, such as H_2 and NH_3, the compatibility is more limited. This indicates that significant retrofits could be needed for these systems for some of the fuel alternatives. With this in mind, it is important when designing newbuildings to also consider including features that could ease retrofitting by installing what could be described as alternative fuel-ready solutions.

Flexible shore-side fuel infrastructure is needed to supply ships in port with alternative fuels. Some carbon-neutral fuels produced by electrofuel processes and bio-refining have potential to use existing infrastructure for marine fuels. For instance, the current investment in fossil-LNG bunkering infrastructure for ships can also be used in the future for synthetic- or bio-methane bunkering. Planning for flexibility could ease the transition and minimize the risk of investing in stranded assets.

> “Planning for gradual transitions, and incentivizing shipowners to invest in flexible ships, could give policymakers a larger toolbox for meeting the challenge.

4.2 DESIGNING FOR FUEL FLEXIBILITY

A key message of this report is that multiple alternative fuels, gaseous and liquid, are candidates for decarbonizing shipping in the future. Many are suitable for application with well-proven and energy-efficient engine technology, but all of them will be more expensive. No-one can say with certainty which alternative fuels will become most competitive and available for shipping. How then should shipowners make choices today and in the coming five to 10 years? Between 1,000 and 2,000 ships will be ordered every year up to the year 2030. How can their potential to reduce their greenhouse gas (GHG) emissions be maximized?

> “In other words, to decarbonize shipping, it is best to invest in the most decarbonization-flexible solutions.

We believe that the bridging philosophy can have significant benefits for shipowners. The key lies in the fact that shipowners do not invest in the fuel, they invest in energy converters (e.g. engines) and fuel-storage systems. Large-scale investments today are made in technologies which are already commercially available and competitive. We argue that investments should also be made in technologies offering the best hedge for adopting future alternative and lower- or zero-GHG fuels at minimum retrofit cost. In other words, to decarbonize shipping, it is best to invest in the most decarbonization-flexible solutions.

IMPLICATIONS FOR THE DEEP-SEA FLEET

Working through the logic of this for the deep-sea fleet, which accounts for the majority of shipping GHG emissions, we suggest that owners investing in the next five to 10 years should consider dual-fuel combustion engines. Facts supporting this strategy include:

- The technology is well proven, commercially available, and has up to 50% mechanical efficiency. GHG reductions up to about 20% can be achieved today using conventional LNG instead of fuel oil. LNG as fuel also significantly reduces or eliminates emissions of sulphur oxides, particulate matter and black carbon.

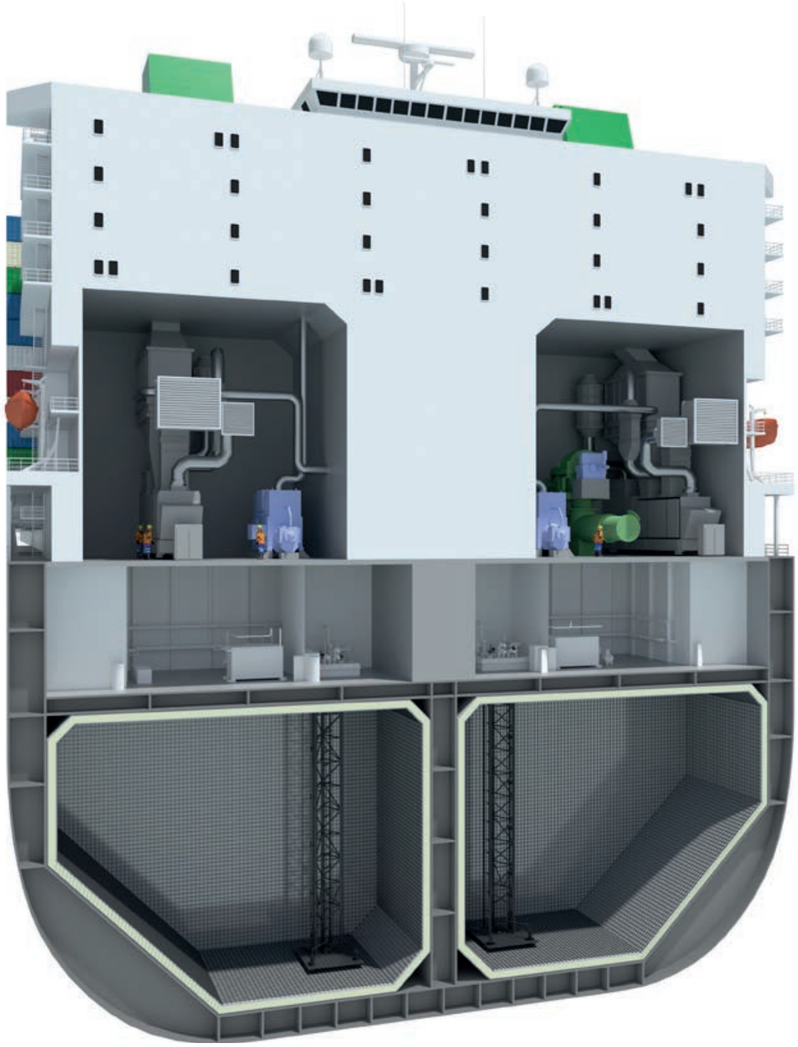
- The engines are flexible enough to burn a selection of liquid and gaseous potential alternative fuels with low/zero GHG footprints. These include biogas, biodiesel/HVO, e-diesel and e-methane (produced from renewables and CO_2 from the air).

- The engines may be converted for burning methanol and NH_3 (from fossil or renewable sources), and fuels mixed with hydrogen.

- Other alternative fuel-technology pathways based largely on batteries or fuel cells in deep-sea shipping are either technically unrealistic (batteries) or unavailable commercially due to immature and expensive technology (fuel cells) and high fuel price (H_2).

It must be said that future shifts will not be straightforward for some alternative fuels, even if they are commercially available and the dual-fuel engine involved is quite fuel flexible. This note of caution applies especially to potentially significant retrofits of onboard storage and fuel-supply systems for some of the alternatives, such as for H_2 and ammonia. Nevertheless, switching is still regarded as possible, particularly if alternative fuel-ready solutions are introduced in the ship design phase.

Shipowners would also do well to investigate opportunities for further optimizing energy efficiency. In doing so, it would be best not to be limited to today's increasing focus on operational (speed, logistics etc.) and traditional technical (hull shapes, propellers etc.) targets for optimization. Take, for example, the introduction of electric power-transmission systems, batteries, Power Take In (PTI) technology, and hybrid electric solutions. They can also improve the overall efficiency of deep-sea vessels and enable increased incorporation of waste energy (e.g. heat) and, potentially, different types of renewable sources from the vessel's surroundings (wind, solar, waves etc.). The large number of embedded components will increase system complexity and require careful design, performance monitoring, and power management. For all these solutions, software and controls become an increasingly important aspect and challenge.



A possible arrangement of tanks, fuel-gas handling room and power plant under the deckhouse of a container vessel from the Perfect II project.

HIGHLIGHTS

Shipowners choosing technology and fuels are influenced by a wide range of stakeholders

Understanding the roles of influencers can help to drive uptake of alternative fuels and thereby support commercialization.

Our in-depth analysis of the development and commercialization of liquefied natural gas (LNG) as ship fuel reveals the principal stakeholders in the LNG ecosystem and their roles.

Our Alternative Fuel Barrier Dashboard indicates the current status of key barriers to using such fuels for maritime applications.

The public sector can play a key role as it can take on risk from a longer-term strategic perspective based on societal rather than purely financial gain.

CHAPTER 5

AN ECOSYSTEM APPROACH TO BRIDGE THE EMISSIONS GAP

5 AN ECOSYSTEM APPROACH TO BRIDGE THE EMISSIONS GAP

Drawing on the case of LNG as ship fuel, this chapter explains why key actors in the shipping ecosystem must collaborate to gradually cut greenhouse gas (GHG) emissions from ships. We also introduce the Alternative Fuel Barrier Dashboard mapping the current status of key barriers to implementation.

Understanding the roles of various stakeholders in this system is instrumental to driving growth of alternative fuel in the marine market, to raising customer and policymaker awareness, and to supporting product commercialization.

Shipowners make the decision to deploy new, improved technologies and fuels, but are part of an ecosystem of stakeholders influencing this decision. This influence is often paramount. The ecosystem includes cargo owners, charterers, ports, yards, equipment and service suppliers, fuel suppliers, regulators such as the IMO, EU and national states, classification societies, investors, banks and other financial institutions, and others. The interaction between stakeholders holds the power to decide on investing in new fuels. They each play essential roles, for instance in creating cost-effective and sustainable logistic solutions, shaping business cases for shipowners, providing green funding and new fuel infrastructure.

Cargo owners, the actual users of the ships and services, are striving to make their value chains greener and reduce their carbon footprints, and have the power to heavily influence shipowners in this regard.

Phasing in low- and zero-carbon emission fuels with associated infrastructure will require substantial investment across the value chain by both private companies and authorities. The public sector and national governments have key roles to play due to their unique ability to take risk and adopt long-term strategic perspectives from a societal rather than strictly financial point of view (UNEP, 2018).

MF Glutra, the first ferry fuelled by LNG, illustrates the public sector playing an important enabling role in phasing in new low-emission technology in shipping. Commissioned by the Norwegian Public Roads Administration, Glutra entered into service in 2000.[25] It was followed in 2015 by Ampere, the first full-electric car ferry.[26] 70 electrical car ferries have so far been contracted for public ferry routes in Norway, having been commissioned at the county level of government. The country's national road authorities will also put two new hydrogen-fuelled ferries into service in 2021.[27] In addition, one hydrogen-

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[25] http://docplayer.me/12229867-Miljoutfordringer-bakteppe-verdens-forste-gassdrevne-ferje-et-lite-historisk-tilbakeblikk-m-f-glutra-gassferjer.html
[26] http://www.tu.no/artikler/denne-fergen-er-revolusjonerende-men-passasjerene-merker-det-knapt/222522
[27] https://www.sjofartsdir.no/en/news/news-from-the-nma/breaking-new-ground-in-hydrogen-ferry-project

powered ferry will be built in Scotland[28] and another in California,[29] both with public-sector funding. Public-private partnerships such as the Green Shipping Programme[30] could also play an important role, as they combine the potential agility of private-sector actors with the regulatory capacity of public actors. Studies have highlighted the importance of identifying key challenges along the entire value chain and proposing measures to overcome them (e.g. IRENA, 2018; UNEP, 2018; DNV GL, 2017d; WLPGA, 2017).

To better understand the many stakeholders, and the roles they need to play in driving growth of alternative fuels in the marine market, we draw on the relatively mature but still recent case of LNG. In the following section, we outline the principal stakeholders in the LNG ecosystem and identify their roles.

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[28] https://www.passengership.info/news/view,hyseas-iii-hydrogen-ferry-project-meets-major-milestone_57671.htm
[29] https://www.electrive.com/2018/11/22/construction-begins-for-usas-first-hydrogen-ferry
[30] https://www.dnvgl.com/maritime/green-shipping-programme/index.html

5.1 THE LNG CASE: STAKEHOLDERS AND BARRIERS

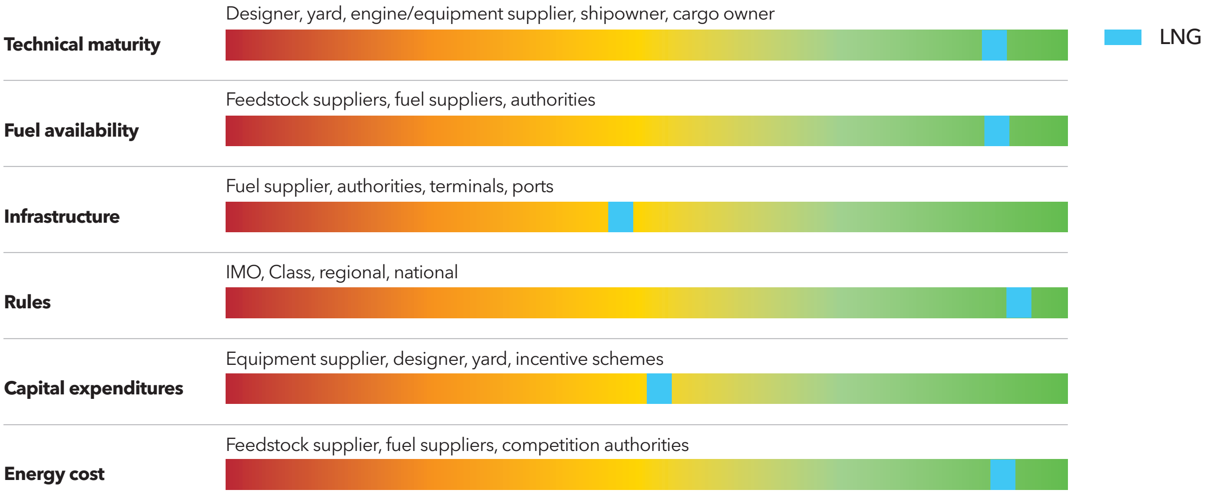
Among the low-emission fuel alternatives to marine bunker oil, LNG is the most prolific. It fuels about 300 ships operating or on order, and is used in shipping around the globe as well as in most ship segments. LNG is currently the only green fuel that is scalable commercially and globally for long-distance transport at sea.

Figure 5.1 reflects the current status of some key barriers to using LNG as ship fuel. It also identifies the key players who have traditionally driven its development and can further reduce barriers to LNG as fuel. Many of the barriers exist at the intersections between different stakeholders. Understanding the ecosystem's maturity is essential, as one player cannot succeed alone.

In short, the LNG ecosystem has matured as LNG is now available globally and in large volumes. However, bunkering infrastructure is limited, and must be expanded before widespread uptake of LNG ship fuel can take place. Regulations and technical rules for safe design and use are in place. However, investment in the technology is still more

FIGURE 5.1

LNG as fuel: Indicative status of key barriers, and key players who have traditionally driven its development and can further reduce barriers to LNG as fuel



Technical maturity – refers to the level of engine technology and systems.
Fuel availability – applies to LNG ship fuel, future production plans, and long-term availability.
Infrastructure – refers to infrastructure for LNG bunkering.
Rules – refers to rules and guidelines for design and safety requirements for the ship and onboard systems.
Capital expenditures – refers to the capital costs of the LNG engine and fuel system over and above a baseline cost for conventional fuel-oil system.
Energy cost – reflects fuel competitiveness compared with marine gas oil (MGO), taking into account conversion efficiency.

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expensive than the alternatives, and the capital costs should be reduced to improve competitiveness. The price of LNG fuel is variable, and a transparent market is still not in place.

Reaching the current state of maturity for LNG has involved many stakeholders over a long time. Almost 20 years have passed since the first LNG-fuelled ship was delivered. Introducing new energy carriers takes time. In the case of LNG, there was already significant industry know-how, safety standards and operational experience from decades of using it as fuel onboard LNG carriers before it entered the market as a marine fuel for other segments. We elaborate below on this timeline.

A TIMELINE OF LIQUEFIED NATURAL GAS AS SHIP FUEL

For more than 50 years, LNG carriers have been capable of burning boil-off gas from their LNG cargos as a secondary fuel (IMO, 2016). Steam turbines consuming natural boil-off-gas were the preferred propulsion system until dual-fuel engines were introduced in the early 2000s. This technology breakthrough enabled large fuel savings over the traditional steam turbines.[31]
A new era began when LNG was used as a primary fuel by the Norwegian car and passenger ferry MF Glutra, as discussed above. Several Norwegian ferries and offshore service vessels have since then adopted LNG as fuel. The first movers were vessels that operated in Norwegian waters, and within relatively fixed geographical areas. Over the following years, LNG-fuelled ships entered service outside Norway (AFI data; Sharples, 2019). Some of the milestones in this journey include:

2013-14

21 additional LNG-fuelled vessels were launched, with the first few vessels deployed outside Norway and Europe. Of these 21, all except two were passenger or offshore service ships. By the end of 2014, only 18% of LNG-fuelled ships worldwide were based outside Norway.

2015-16

40 LNG-fuelled vessels were launched. Many were offshore vessels, but the list also included the first LNG-fuelled icebreaker, bulk carriers, car carriers, container ships, roll-on/roll-off (ro-ro) cargo ships, and oil/chemical tankers. By the end of 2016, 42% of LNG-fuelled ships were based outside Norway.

2017-18

47 more LNG-fuelled vessels were launched, bringing the total in operation worldwide to 143. These new vessels included the world's first LNG-fuelled dredgers and cruise ship. By the end of 2018, 57% of LNG-fuelled ships were based outside Norway.

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[31] https://www.wartsila.com/twentyfour7/in-detail/back-to-the-future-steam-turbine-to-dfde-conversion-for-lng-carriers

These developments reflect how LNG uptake has progressed by geographic area and ship segments, also highlighted in Figure 5.2. Environmental regulation, primarily aimed at sulphur and nitrogen oxides (SOx and NOx), has stimulated uptake of LNG. A large majority (83%; 118 out of 143) of LNG-fuelled vessels were operating in a SOx or NOx emission control area (ECA) in January 2019 (Sharples, 2019). The breakdown was 95 vessels in North Sea/Baltic Sea ECAs, 19 in North American/US Caribbean ECAs, and four in the Chinese (non-IMO) ECA.

Fevre (2018) finds experience showing that adoption of LNG ship fuel is most likely where: vessels operate primarily or exclusively in areas subject to strict SOx and NOx limits; journey patterns are mainly regular and predictable; ships follow routes that allow easy access to LNG-fuelling facilities; vessels are owner-operated; vessels are large and fuel costs are a high proportion of operating costs; and, where there are high levels of government support for new investment favouring LNG etc.

We now look in more depth at the roles of different actors in the development of LNG as a ship fuel, structuring our analysis around the key barriers based on the ranking of LNG in Figure 5.1 on Page 70.

TECHNICAL MATURITY

The gas engine is a development of the marine diesel engine, which has been around for more than 100 years. Through research and development efforts starting in the 1980s, gas engine technology was developed, and the first steps on the maturity ladder taken. Engine manufacturers and R&D institutions were key actors in this phase.

The LNG-fuelled ferry Glutra that entered into service in 2000 was commissioned by Norway's Public Roads Administration. It was initiated as a development project, with the ambition of achieving emissions reductions then and over the next 10 to 15 years, with local pollution as a focus, and using Norwegian natural gas.[32] The government's willingness to drive the development, and the willingness of ferry owners to take risk, were key factors for success. This development accelerated the maturity of the technology by increasing its exposure to real-world conditions.

Later, forward-looking shipowners in the offshore market were instrumental in expanding the use of LNG to other segments. This development was largely boosted after 2007 when the Norwegian NOx Fund was established. It stimulated LNG uptake by covering up to 80% of the extra investment costs for commissioning LNG-operated ships, and by reducing tax on their NOx emissions. By 2012, 35 LNG-fuelled vessels were in operation, all based in Norway. Further development outside Norway was driven by the International Maritime Organization (IMO) tightening restrictions on SOx emissions in the North Sea and Baltic Sea ECAs, and the entry into force of the North American/US Caribbean NOx ECA in 2016 (Sharples, 2019). Throughout this phase, providers of the necessary engines and storage tanks have invested in developing an immature market, improving and maturing the technology.

Today, gas-powered ferries in Norway have all used single-fuel (lean burn) medium- or high-speed gas engines. Dual-fuel medium-speed gas engines have dominated the offshore and cargo ship segments (Stenersen and Thonstad, 2017). Slow-speed, two-stroke dual-fuel gas engines for larger cargo ships have recently entered the market. LNG storage tanks of different types and LNG process equipment are also available commercially. The ranking in Figure 5.1 indicates that most gas engines have been used for some time and are today considered to be proven technology.

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[32] http://docplayer.me/12229867-Miljoutfordringer-bakteppe-verdens-forste-gassdrevne-ferje-et-lite-historisk-tilbakeblikk-m-f-glutra-gassferjer.html

RULES AND REGULATIONS

In year 2000, there were no regulations or technical rules for using LNG as primary marine fuel. A risk-based approach was used instead, resulting in the issuing of special Norwegian permits by the Norwegian Maritime Directorate. DNV GL issued the first technical class rules in 2001 for gas-fuelled ships. These rules were used as input for the IMO Interim Guidelines on Safety for Natural Gas-fuelled Engines (IMO, 2016). Issued in 2009, this IMO document included rules and guidelines related to the design and safety requirements for the gas-fuelled ship and onboard systems. In addition to ship rules, classification societies were developing guidelines and standards related to the bunkering operation and personnel certification. The IMO International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) for LNG and compressed natural gas (CNG) came into force on 1 January 2017, establishing an international regulatory basis for the design and construction of LNG-fuelled ships. This recent development is reflected in the high rank on the ‘rules’ barrier category in Figure 5.1. The presented timeline for the development of LNG rules shows that more than 15 years were needed for establishing the IMO rules. Although a formal framework for approval of LNG existed for many years, our impression is that it was not until the IGF Code was finalized that widespread interest in LNG as a fuel was observed.

FUEL AVAILABILITY

> “A future fuel must be available to the market in sufficient quantity.

A future fuel must be available to the market in sufficient quantity. The LNG-fuelled vessels, and LNG carriers using boil-off, represent the maritime demand side for LNG. Recent estimates indicate marine LNG consumption of 6.5 million tonnes per year (Mt/yr), with LNG-fuelled vessels accounting for 1.5 Mt/yr (ICCT, 2017; Sharples, 2019). The shipowners with LNG-fuelled vessels commonly ensure a long-term contract for regular bunkering operations with a reliable supplier (Sharples, 2019). This is highly relevant for larger ships such as container and cruise ships, with high annual fuel consumption. For example, CMA CGM signed a contract with Total for the provision of 300,000 t/yr of LNG as a bunker fuel for container vessels, for 10 years from 2020.[33]

LNG consumption will increase significantly over the next years due to phasing in of new LNG-fuelled ships, as well as the introduction of larger vessels such as container and cruise ships. The question is what would happen if a fuel alternative were to become so attractive that a large number of operators would want to adopt it for their ships within a short period of time? In theory, a switchover for a major part of the global fleet to LNG is not unrealistic, given current and planned production capacity and the size of the global gas market and available gas resources. LNG has a share of approximately 10% in the global natural gas market. LNG production capacity is set to increase significantly over the next five years. For the foreseeable future, there are no main limitations to production capacities that could limit the availability of LNG as ship fuel. Figure 5.1 therefore assigns a high score to fuel availability.

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[33] https://www.total.com/en/media/news/press-releases/Strategic-Agreement-between-Total-and-CMA-CGM-on-Liquefied-Natural-Gas-Fuel-Supply-for-CMA-CGM-New-Build-Container-Ships

INFRASTRUCTURE

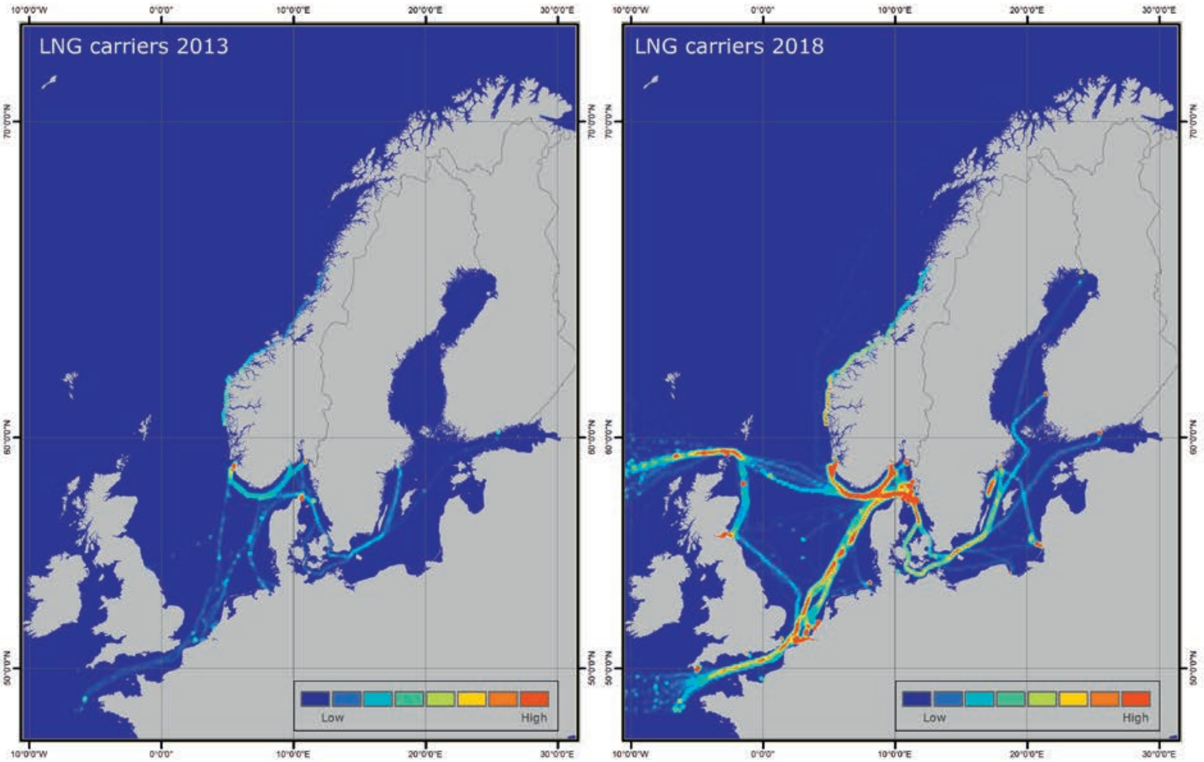
The supply side represented by regional LNG bunkering infrastructure such as LNG terminals, truck-loading facilities and LNG bunker vessels for refuelling seagoing ships, is also expanding. Infrastructure was first developed locally from around 2005 in Norwegian waters, then regionally into the Baltic/North Sea. Gasnor and Skangas, key actors in the early phases, made LNG available dockside by truck delivery.

Infrastructure outside Norway has only been substantially developed in the last five to seven years. Figure 5.2 reflects the development from 2013 to 2018 of small-scale transport by LNG carriers and bunker vessels of less than 25,000 gross tonnage (GT) tracked by AIS. As shown, small-scale distribution increased significantly over this period, particularly in Northwest Europe and Baltic waters.

Several LNG bunker vessels were delivered in 2017 and 2018 for operation in key locations such as the Amsterdam, Rotterdam, Antwerp (ARA) region, the North Sea, the Baltic Sea, and on the coast of Florida, US. Bunker vessels for other key locations such as the Western Mediterranean, the Gulf of Mexico, the Middle East, Singapore, China, South Korea and Japan have recently been ordered, or are under development and will likely materialize in parallel with significant orders for LNG-fuelled deep-sea ships within the next years. We also expect to see a focus on developing LNG bunker vessels for refuelling seagoing ships in the near

FIGURE 5.2

Ship traffic density as fuel consumption by LNG carriers below 25 000 gross tonnage in 2013 and 2018



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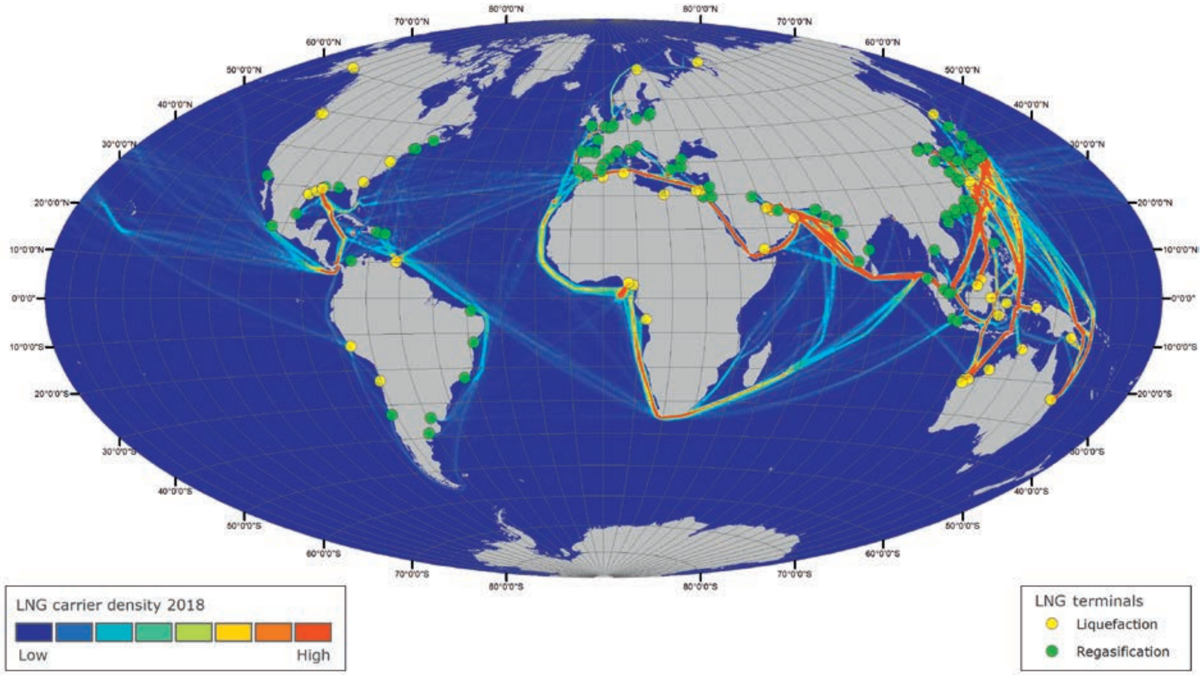
future. Bunkering by truck and permanent local depots will also continue to grow for certain trades and segments. Dual-fuel engine technology may also offer some flexibility and redundancy as the LNG bunkering network for the deep-sea fleet evolves. The infrastructure rank in Figure 5.1 reflects the fact that the LNG bunkering infrastructure is still regional and limited.

National governments and the EU have pushed infrastructure development, through financial support and requirements. For information on LNG bunkering infrastructure, please visit DNV GL's Alternative Fuels Insight (AFI) online portal (afi.dnvgl.com).

As highlighted by Sharples (2019), the existing regional LNG market infrastructure in Northern Europe provided a base upon which the 'last mile' of LNG bunkering infrastructure was developed, making the fuel available quayside. There are several regions, as in the North Sea/Baltic Sea, where similar 'last mile' development could occur. Figure 5.3 shows global gas-liquefaction plants, export and import. As of March 2018, total liquefication capacity was almost 370 Mt/yr (IGU, 2018). It has seen significant growth in recent years, with 92 Mt/yr capacity being under construction. Australia and the US have been the primary drivers of this phase of capacity growth (IGU, 2018).

FIGURE 5.3

Global liquefaction plants[34] (export/import), regasification plants (import/distribution), and LNG carrier traffic density represented by fuel consumption in 2018



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[34] https://knoema.com/mcuutn/liquefied-natural-gas-multibillion-dollar-investments-at-risk

CAPITAL EXPENDITURE

LNG as ship fuel is rapidly approaching the status of a fully developed technology, with various technology suppliers active in the market. As applications increase and competition between suppliers heats up, we can observe that capital expenditure (capex) for additional investment in ship systems and equipment is decreasing. This can be attributed to suppliers of engines and storage tanks competing in a growing market where the players also include shipyards, which for newbuild projects usually determine the final total additional price.

Capex for LNG systems are, and will continue to be, higher than those associated with diesel/heavy fuel oil (HFO) systems that include emission-reduction technologies to meet strict limits on sulphur and nitrogen oxides, SOx and NOx respectively. Increased uptake of LNG systems is expected due to the tightening of global SOx regulations in January 2020, restrictions on NOx emissions in the North Sea/Baltic Sea ECAs from January 2021, and the possible introduction of both new IMO and non-IMO ECAs.

The extra investment needs to be compensated for in operations and will consequently depend on oil and gas prices. Based on recent experience, the newbuilding cost of LNG-fuelled ships is about 10%–30% higher than for equivalent diesel-fuelled ships, depending on ship type (Æsoy et al., 2011; DNV GL, 2015b). Also, LNG fuel tanks typically require at least three times as much space as oil tanks with the same energy content, when also factoring in the shape of the tank when it is relevant.

> “ LNG appears to have reached what is, historically, the most competitive feedstock price level among all alternative fuels.

As indicated above, LNG as fuel has been attractive to shipowners investing in newbuild vessels that will operate in ECAs, but there has also been increased uptake for ships operating outside ECAs. The capital investment required has limited retrofitting of existing vessels. The low ranking against capex in Figure 5.1 reflects these barriers. Note that it applies only to capex related to the ship; additional capex will be needed for related bunkering facilities (e.g. PwC, 2017), which will be reflected in the fuel price.

ENERGY COST

LNG appears to have reached what is, historically, the most competitive feedstock price level among all alternative fuels. However, logistics costs for LNG are substantial, adding a significant penalty to the delivered price. Distribution-related costs have fallen because of a growing market, increased asset utilization, and increasing competition. Currently, the price level is competitive with marine gas oil (MGO), but direct competition with HFO may be difficult. From 2020, high-sulphur HFO will not be permitted without a scrubber system being installed, and the price of the new low-sulphur fuel oil (LSFO) reference fuel is expected to be higher than for HFO. Furthermore, LNG is expected to be price-competitive with the low-sulphur HFO. LNG also has the potential to compete with the combination of high-sulphur HFO and scrubbers. Figure 5.1 therefore assigns a high score to energy cost.

Key actors influencing fuel prices include oil and gas majors producing and liquefying natural gas; fuel suppliers responsible for distribution and bunkering; LNG terminal operators setting loading tariffs for bunker vessels and trucks; and governments, deciding taxation of fuels.

5.2 BOOSTING UPTAKE OF LOW- AND ZERO-CARBON EMISSION FUELS

Alternative fuels for shipping all face challenges and barriers to their uptake (e.g. DNV GL 2014b, 2015b, 2017d; Brynolf, 2014). Key barriers include the cost of the required machinery and fuel storage on vessels, fuel price expectations, availability, and widespread/global bunkering infrastructure. Safety will also be a primary concern for some fuels. This can be translated into monetary terms once a design has been established and the necessary safety measures are identified. Uncertainty regarding long-term availability of a specific fuel is also a concern. In addition, storage of most alternative fuels will require more space onboard compared with traditional fuels, due to reduced energy density and/or space required for high pressure/low temperature storage systems. For many ship types, this fact translates to loss of cargo carrying capacity, i.e. potential loss of income. Land-based demand and infrastructure development are also critical for the success of introducing alternative fuels in shipping.

The Alternative Fuel Barrier Dashboard in Figure 5.4 overleaf indicates the current status of key barriers to LNG, ammonia, hydrogen, biofuel (hydrotreated vegetable oil, HVO) and battery electric power. Moving the markers in this figure rapidly to the right will be of very great importance for the shipping industry to achieve the IMO ambitions on GHG emissions reduction. Such a development relies not only on shipowners' willingness to start using alternative energy sources, but also on contributions and incentives from charters/cargo owners (e.g. via contracts), proactive regulators, procurement policies, incentive schemes, and international cooperation.

Shipowners have traditionally gravitated towards solutions that are cheaper, more reliable, more efficient and needing less space onboard. Going forward, owners will still favour such solutions. The challenge is that solutions to societal needs are typically more expensive, less mature, less efficient and require more space onboard.

So what will motivate shipowners to move in the right direction and subsequently activate sufficient parts of the maritime ecosystem to drive uptake of an alternative fuel? Creating appropriate incentives while also driving change through regulation are two of the answers.

Shipping does not operate in a vacuum. Ship operators will work with other sectors to ensure availability of zero- and low-carbon fuels, infrastructure for bunkering and cold ironing facilities, appropriate logistics, and technical solutions. Experience and technology transfer from other sectors is also useful and necessary for achieving emission-reduction targets at least cost. Lessons can be learned from the case of LNG, and recommendations can be made to accelerate uptake of low- and zero-carbon emission fuels for shipping.

As the previous chapter illustrated, the introduction of LNG in the world fleet has taken place both locally and regionally at a very slow initial pace as gas engines, tank technology, rules and infrastructure become available. Introduction of LNG has happened first in regions focused on stringent environmental requirements whilst offering financial incentives (e.g. the Norwegian NOx Fund).[35] In these regions, LNG is already available from existing large-scale terminals and from the

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[35] The NOx Fund's primary objective is to reduce NOx emission. The fund is a cooperative effort in which participant companies pay according to the scale of their emissions and may apply for financial support for NOx-reducing measures. https://www.nho.no/samarbeid/nox-fondet/the-nox-fund/articles/about-the-nox-fund

investments being made in small-scale liquefaction plants. LNG has been criticized as being a dead-end fuel technology for shipping. Our work shows that this might not be the case, because bridging is possible.

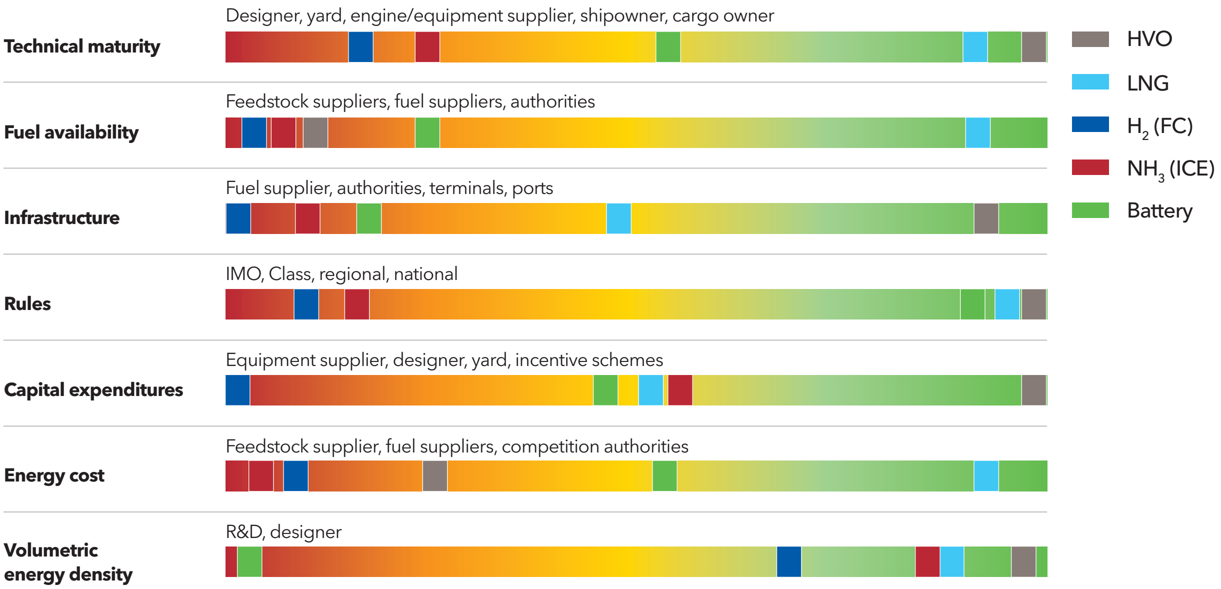
Common effort and cooperation will be needed among the key players in the ecosystem. Based on the mapping carried out in this study, there will be a need to reduce all the key barriers. This is reflected in the illustration below, analysing the status of some promising alternative zero-carbon fuels. As shown, all the zero-carbon candidate fuels that we have assessed score low for infrastructure and availability. Even if they can be made available, expected fuel-price levels are also very challenging.

Economics will be the main driver of fuel shifts in shipping in the future, though environmental regulations will also have a significant impact on choices of fuel and energy. Regulators should be mindful of the complex maritime ecosystem when considering new regulations or incentives. Identifying and stimulating the right parties to reduce key barriers is essential. Focusing solely on the shipowners will not work.

Figure 5.4 is another illustration of the fact that the cost of the alternative fuel and the associated ship

FIGURE 5.4

The Alternative Fuel Barrier Dashboard: Indicative status of key barriers for selected alternative fuels



Technical maturity – refers to technical maturity level for engine technology and systems.
Fuel availability – refers to today's availability of the fuel, future production plans and long-term availability.
Infrastructure – refers to available infrastructure for bunkering.
Rules – refers to rules and guidelines related to the design and safety requirements for the ship and onboard systems.
Capital expenditures (capex) – Cost above baseline (conventional fuel oil system) for LNG and carbon-neutral fuels, i.e. engine and fuel system cost.
Energy cost – reflects fuel competitiveness compared to MGO, taking into account conversion efficiency.
Volumetric energy density – refers to amount of energy stored per volume unit compared to MGO, taking into account the volume of the storage solution.

HVO, hydrotreated vegetable oil; LNG, liquefied natural gas; H_2 (FC), hydrogen in fuel cells;
NH_3 (ICE), ammonia burned in internal combustion engines; Battery, full-electric with batteries

systems will be key barriers. Ways of stimulating the accelerated uptake of costly technologies should be developed and promoted by public and private actors in partnership. Possible sources of inspiration include the Norwegian NOx Fund and the Green Shipping Programme. Governmental green permits and concessions are examples that could help bring carbon-neutral fuels into use. Long-term contracts that promote low/zero-emission shipping, and logistics optimization, are other examples that could help.

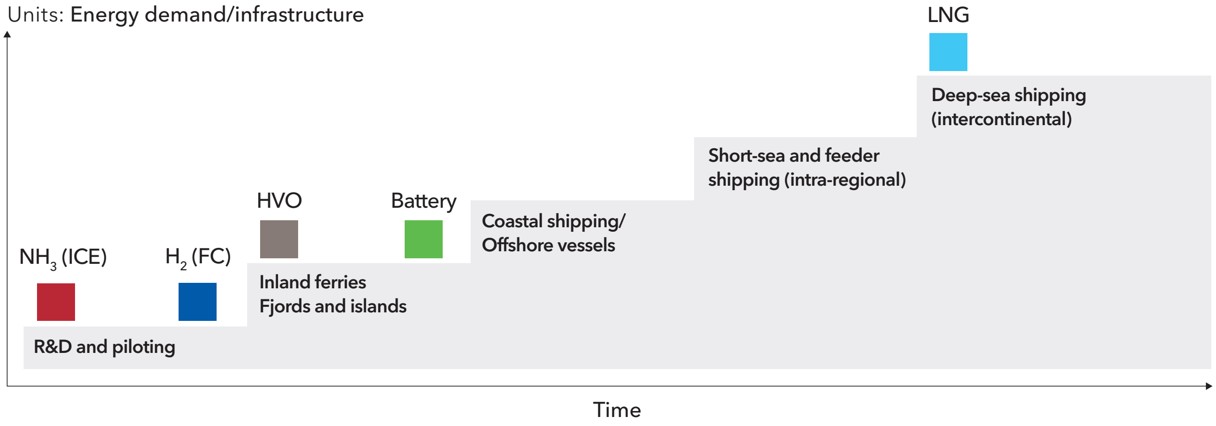
As illustrated in our modelling of the world fleet's CO_2 emission towards 2050 (Chapter 6), the use of low- and/or zero-carbon fuels and technologies (Section 3.2) will be critical for meeting IMO GHG ambitions. Uptake of such fuels in significant amounts will happen only when they become economically competitive, or when they are required by cargo owners. In reality, the most competitive alternatives within a given set of environmental restrictions will dominate.

The high additional costs associated with promising low- and zero- carbon fuels mean significant regulatory changes must be enforced before any real change in uptake of the fuels will occur.

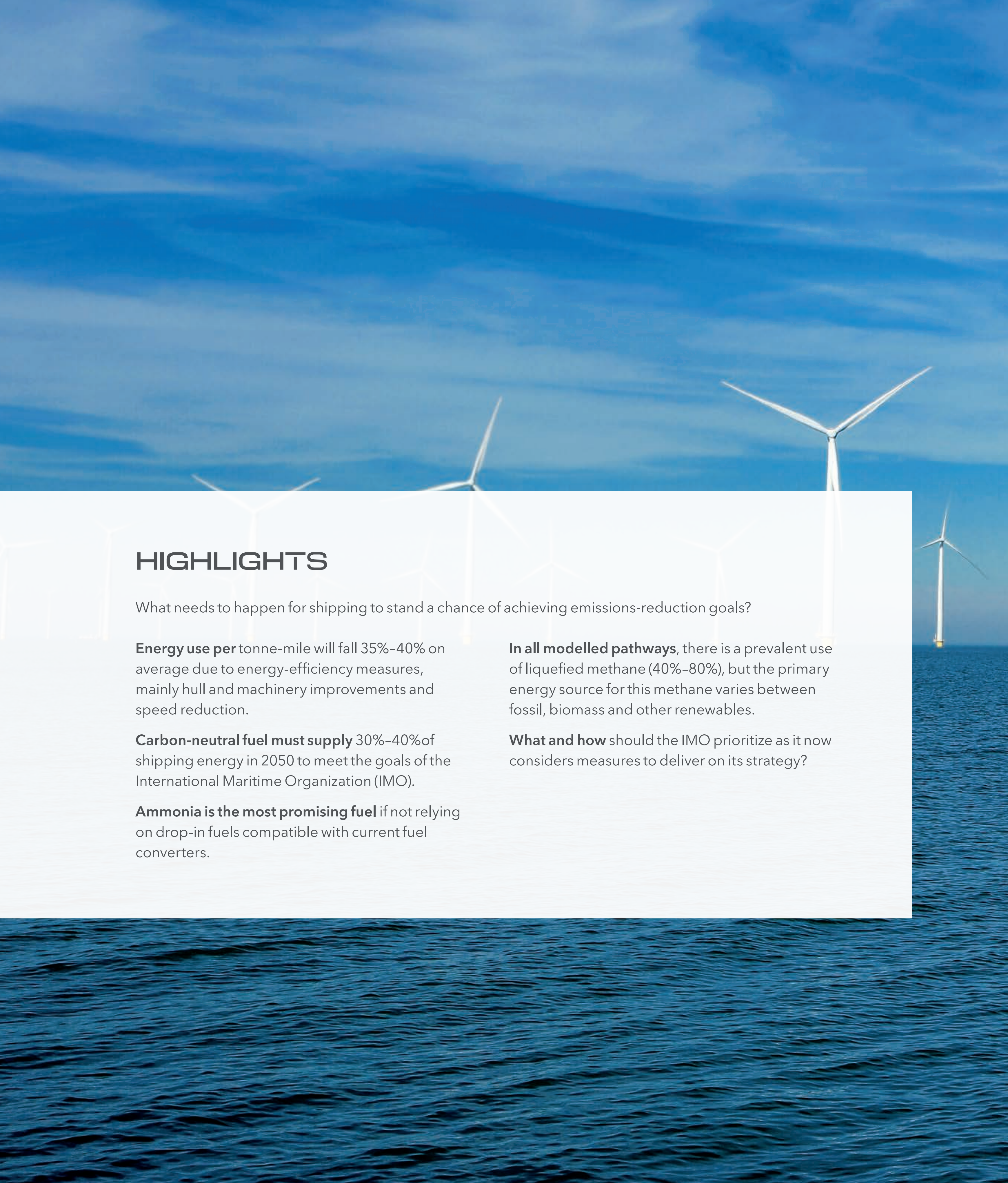
Figure 5.5 below is another way of representing development steps for alternative fuels. It illustrates how LNG has evolved through several stages since 2000, as discussed in detail earlier. Research and development including the piloting of technology are elements of the history of LNG-fuelling of vessels in Norway, described in more detail in Section 5.1. To recap briefly, knowledge has been accumulating from the very first use of LNG in the Norwegian ferry fleet from year 2000, then in coastal and short-sea shipping, and most recently in deep-sea shipping. We assume that this ‘fuel evolution stairway’ – from smaller vessels over short distances, then larger ships and longer journeys as technology, fuel infrastructure and market uptake develop – is largely valid for other alternative fuels. Not all the options have the potential to reach the deep-sea stage, due to limited energy densities, as Figure 5.4 indicates. Hydrogen and ammonia are still on the first steps of the stairway, while HVO and battery electric power have seen their first commercial short-sea applications. Furthermore, each alternative fuel must overcome different barriers to advance up the ladder, as Figure 5.4 illustrates.

FIGURE 5.5

Current development stage for selected alternative fuels



NH_3 (ICE), ammonia burned in internal combustion engines; H_2 (FC), hydrogen in fuel cells; HVO, hydrotreated vegetable oil; Battery, full electric with batteries; LNG, liquefied natural gas



HIGHLIGHTS

What needs to happen for shipping to stand a chance of achieving emissions-reduction goals?

Energy use per tonne-mile will fall 35%–40% on average due to energy-efficiency measures, mainly hull and machinery improvements and speed reduction.

Carbon-neutral fuel must supply 30%–40%of shipping energy in 2050 to meet the goals of the International Maritime Organization (IMO).

Ammonia is the most promising fuel if not relying on drop-in fuels compatible with current fuel converters.

In all modelled pathways, there is a prevalent use of liquefied methane (40%–80%), but the primary energy source for this methane varies between fossil, biomass and other renewables.

What and how should the IMO prioritize as it now considers measures to deliver on its strategy?

CHAPTER 6

WORLD FLEET CO$_2$ OUTLOOK

6 WORLD FLEET CO_2 OUTLOOK

This chapter provides an outlook for the world fleet, focusing on how shipping may meet the International Maritime Organization (IMO) ambitions to cut greenhouse gases (GHGs) given potential developments in energy efficiency, logistics and alternative fuels.

Applying DNV GL's GHG Pathway Model, we project possible pathways for the world fleet size, fuel mix and carbon dioxide (CO_2) emissions towards 2050, based on expected transport demand. The approach focuses on the long-term developments; we do not model short-term cycles.

In the 2018 edition of this report we estimated that 39% of the energy used by the world fleet should be carbon-neutral by 2050 if the IMO GHG-reduction ambitions are to be met. But we did not specify what types of fuels will be involved. Using an updated model, we now explore this question.

We find that the 2050 fuel mix will be heavily dependent on the specific design of the GHG regulations, and on how fuel prices develop towards 2050. Even minor changes to the underlying assumptions can significantly alter the outcome of our modelling. Consequently, our outlook is an exploration of some potential pathways among many, rather than establishing one main projection.

TABLE 6.1

Description of our three pathways' assumptions on regulations for reducing GHG emissions

	TWO PATHWAYS TO ACHIEVE IMO AMBITIONS		**A THIRD PATHWAY**
	Focus on design requirements[a] (DR)	**Focus on operational requirements[a] (OR)**	**Keep current policies (CP)**
Design requirements for newbuildings	Currently adopted EEDI requirements until 2035 From 2035: 60% reduction From 2040: 90% reduction, starting with short-sea, then deep-sea vessels.	Currently adopted EEDI requirements	Currently adopted EEDI requirements
Operational requirements for all ships	Gradually increasing to 45% reduction in 2040	Gradually increasing to 60% reduction in 2050	No requirements

[a] The design and operational requirements are carbon-intensity requirements set relative to an average ship in 2015, which is close to the reference lines used in the Energy Efficiency Design Index (EEDI) framework.

6.1 PATHWAYS EXPLORED

The IMO's 2018 strategy for achieving specific GHG-reduction targets needs to be implemented through regulatory and other policy measures which are still under discussion. See Section 2.2.1 for a discussion on what type of regulations can be expected in the short and long term. Whether, and how, we can expect these targets to be met remain key questions for the projections in this study, as they will impact on the uptake of new technologies and fuels.

We explore three different projections for the world fleet (see Table 6.1), where the uptake of energy-efficiency measures, speed reduction, and alternative fuels are simulated based on costs and on current and imminent regulatory measures. The first two pathways are to meet the IMO ambitions: a 50 % GHG-reduction and 70% carbon-intensity reduction in 2050 compared with 2008. In both these pathways, we make the assumption that regulations will be in place on individual ships to incentivize the necessary emissions reduction, but the specifics of the regulations differ.

In the first of these pathways, the regulatory emphasis is on design requirements, i.e. the requirements placed on the performance of newbuilds. This projection assumes that current ships and those built in the next 20 years will not make a major shift to alternative, carbon-neutral fuels. This will require a complete fuel shift on newbuildings from 2040 to reach the IMO targets. In such a pathway, shipping does not have to consider retrofits and fuels compatible with current converters, and can design newbuildings for the most relevant fuel.

In the second pathway for achieving IMO GHG ambitions, the regulatory emphasis is on the operational requirements, and we explore how a more gradual introduction of alternative fuels on ships in operation could impact differently on the fleet and fuel mix. In this pathway, drop-in fuels such as advanced biodiesel and liquefied biogas (LBG) are preferred to avoid costly retrofits.

The third pathway projects what would happen without any further regulations beyond the currently adopted Energy Efficiency Design Index (EEDI) requirements. In this pathway, solutions not mandated by the current EEDI requirements would only be applied if they were cost effective. This pathway is used in the world fleet CO_2 Barometer to indicate if the IMO ambitions can be met by the application of current technologies and solutions (see Chapter 2).

> “The IMO's 2018 strategy for achieving specific GHG-reduction targets needs to be implemented through regulatory and other policy measures which are still under discussion.

6.2 GHG PATHWAY MODEL

Our GHG Pathway Model is a flexible modelling tool for assessing alternative futures, and can handle various scenarios including regulatory developments, fuel-price assumptions, and energy-efficiency technologies. It significantly enhances the model first developed by Eide et al. (2011), extended in our 'Shipping 2020' study (DNV GL, 2012) and 'Low-Carbon Shipping' project (Eide et al., 2013), and amended in the 'Low Carbon Shipping towards 2050' study (DNV GL, 2017b). Moreover, the model was last enhanced and applied in the 2018 edition of this publication projecting future energy mix and CO_2 emissions for the world fleet (DNV GL, 2018a).

The model outlined in Figure 6.1 projects the future fleet, fuel mix, CO_2 emissions and abatement cost towards 2050. The inputs are seaborne trade forecasts, costs and the effects of abatement options, fuel prices, and regulations.

Abatement options cover technical and operational energy-efficiency options including speed reduction and alternative fuels. Regulations relate to requirements for limiting energy-intensity/emission-intensity in operation and newbuild phases, as well as explicit speed limits and pricing CO_2.

The model illustrated in Figure 6.1 has two core elements. One we call the Fleet Development Module. The other is described as the Abatement Uptake Module.

In the Fleet Development Module, the future fleet is simulated by adding and removing ships year-by-year, with the aim of balancing the fleet supply capacity against the seaborne trade demand projections given as input. The starting point for the fleet development is the current fleet for the base year 2018 with associated activity data. The model treats every ship in the fleet individually. Each active ship has a set of characteristics based on various technical databases; an operational profile based on AIS tracking data, such as distance sailed, time at sea and port, fuel consumption and CO_2 emissions; and, a ship-owner risk profile which determines the time horizon for the financial evaluation of options for abatement.

In the Abatement Uptake Module, the model evaluates the available measures on all existing ships and newbuilds for each year. The ships are fitted with the most cost-effective measures – that is the highest net present value (NPV) – which fulfil the regulatory requirements imposed as input. Since the model evaluates all options annually, all possible fuel transitions – either by drop-in fuel or retrofit of the converter – are simulated for all ships. The model takes into account measures already implemented since the base year.

It also includes two feedback loops. In the first, if speed reductions are adopted by a ship, thereby reducing the trading capacity of the fleet, the Fleet Development Module ensures that additional ships are built to replace the lost capacity. In the second feedback loop, uptake of technical measures and fuels in the fleet result in year-by-year reduction in the cost for future installations, due to technology and the market effects of its maturation.

FIGURE 6.1

DNV GL's GHG Pathway Model and its Fleet Development and Abatement Uptake modules

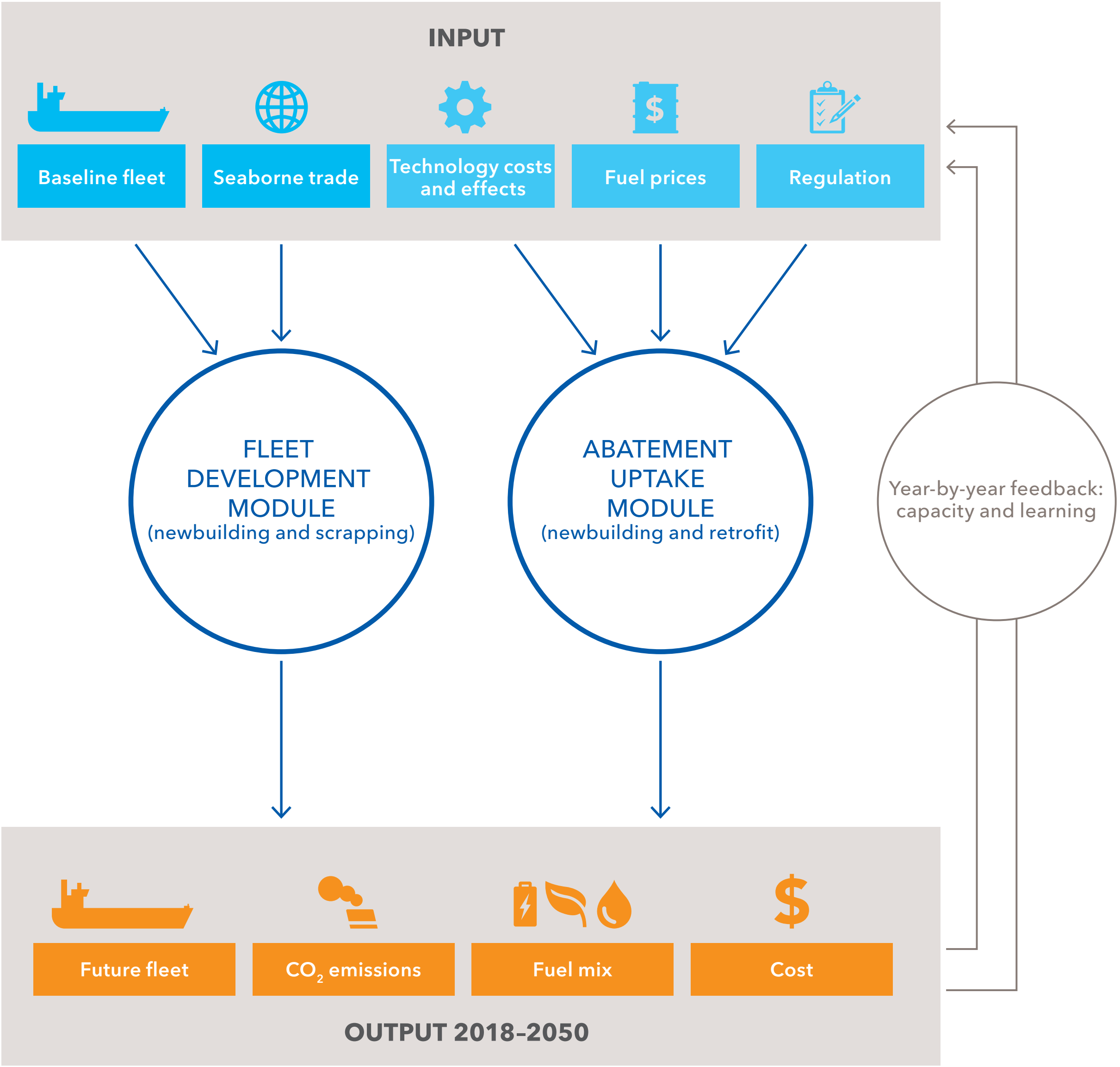
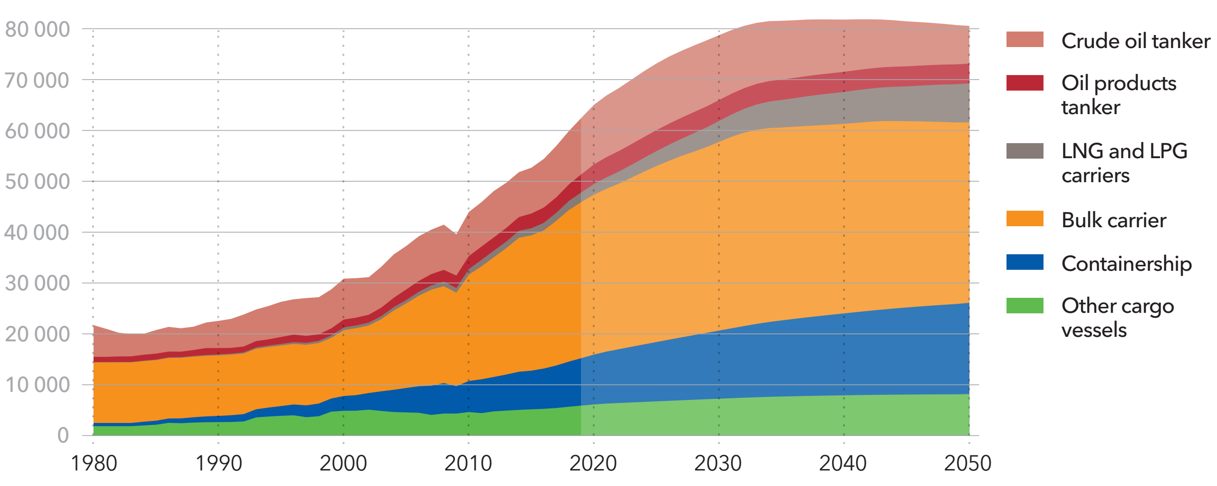


FIGURE 6.2

World seaborne trade in tonne-miles by vessel type



Historical data source: Clarksons Research (2019)

TABLE 6.2

Historic and predicted average annual percentage growth in tonne-mileage of seaborne trade

	Average annual percentage growth		
Type of trade	**2010-2018**	**2018-2030**	**2030-2050**
Crude oil	2.3%	1.5%	-2.1%
Oil products	2.4%	2.9%	0.0%
Natural gas	6.1%	7.2%	3.2%
Bulk	4.3%	1.7%	-0.1%
Container	2.4%	3.6%	1.5%
Other cargo	2.4%	2.2%	0.6%
Average	**3.7%**	**2.3%**	**0.3%**

6.2.1 MODEL INPUT

The starting point for the fleet development is the current fleet for the base year 2018 with associated activity data based on AIS (see Chapter 2). The baseline includes the effect on emissions from already implemented energy-efficiency and speed-reduction measures, and the current uptake of LNG and scrubbers based on data from DNV GL's Alternative Fuels Insight portal. The estimated CO_2 emission level in 2018 is about 870 million tonnes.

We forecast global maritime transport, as measured in tonne-miles, to increase by 39% towards 2050 compared to 2018, as shown in Figure 6.2 (DNV GL, 2019a). Most of the growth will come before 2030, at a forecast average annual growth rate of 2.3%/yr (Table 6.2). After that, global seaborne trade will stabilize. Growth in certain segments, especially gas and container trade, will outpace the average rate (Table 6.2). However, as the global demand for coal and oil peak, their trade will also peak, reducing their seaborne trade by more than two thirds and one third, respectively.

Technologies and solutions to reduce energy use and CO_2 emissions are grouped into four main categories: alternative fuels; fuel converters; energy-efficiency measures; and logistics.

ALTERNATIVE FUELS

The fuel properties that the model primarily considers are price, CO_2 emission factors, and compatibility with different converters (engines). Projecting fuel prices is difficult; many of these fuels are not available for the shipping market today, lacking infrastructure and, in many cases, fuel converters. The most important element in projecting uptake is to estimate the relative price difference between fuels.

The following assumptions are applied for fuel prices:

- For fossil fuels, today's average price is used for 2018. Projected prices towards 2050 are based on the updated projections for oil and gas prices in the main report (DNV GL, 2019a); the oil price increases slightly through the period to 2050, while gas prices fall about 15%.
- A literature review for the biofuels advanced biodiesel and LBG indicates representative price levels today about double those of their fossil equivalents. Our modelling assumes this relative difference is maintained towards 2050.
- For hydrogen (H_2), the prices from the main report (DNV GL, 2019a) are used. Whereas the electricity price remains fairly constant towards 2050, the production cost of H_2 reduces greatly due to two factors. First, lower investment costs for electrolysers. Second, carbon capture and storage (CCS) for H_2 produced from natural gas by steam methane reforming (note that the captured carbon for fossil gas cannot be used to produce carbon-based electrofuels, but has to be stored). The cost of ammonia (NH_3) is assumed as a fixed mark-up of the H_2 price.
- The cost for carbon-based electrofuels (e.g. diesel, methane and methanol) is based on reviewing literature on standard processing methods (e.g. Fischer-Tropsch) of H_2 and carbon.

For calculating CO_2 emissions, we categorize these as carbon-neutral fuels: advanced biodiesel, LBG, H_2, carbon-based electrofuels, and NH_3. Although the carbon neutrality of biofuels is debated, those used in the future will be different from today. Third- and fourth-generation biofuels will likely be closely examined to see if they can be approved for use and labelled as carbon-neutral and sustainable (see DNV GL 2017e, p. 141, for a more detailed discussion on this topic). Making carbon-neutral H_2 and NH_3 requires using renewable energy, or CCS in the case of production from fossil energy sources.

In line with the Intergovernmental Panel on Climate Change and GHG accounting procedures, this study assumes that combustion of biofuels and electrofuels, and use of electricity, is carbon-neutral. Any emissions due to production are accounted for elsewhere in our ETO analysis and are not double-counted in this maritime outlook. The IMO has yet to decide how such fuels will be accounted for when measuring progress towards each of its GHG-reduction targets and, on individual ships, for complying with regulations such as EEDI.

For liquefied natural gas (LNG), we assume a 20% reduction of CO_2 emissions compared with marine fuel oils. As we show in Section 3.2, due to methane slip, the overall GHG-reduction depends significantly on the engine type. For gas engines typically used for deep-sea vessels, which emit most of the world fleet's global emissions, methane slip is low. We also expect methane slip to be reduced for smaller vessels in the future.

FUEL CONVERTERS

The modelling is based on three main types of fuel converters, with each being able to use one or more compatible fuels. Shifting between fuels for the same converter can in some cases be done without additional capex (i.e. drop-in fuels). In other cases, it will incur capex for required modifications to the engine and/or energy-storage system. Each converter has a projected development on conversion efficiency – i.e. how much of the fuel energy can be utilized for propulsion and other purposes onboard.

The three principal converters and compatible fuels per variant are:

- **Internal combustion engine (liquid, gas or dual fuel)**
    - Low-sulphur fuel oil (LSFO) or marine gas oil (MGO), advanced biodiesel, synthetic diesel (electrofuel)
    - LNG, LBG, synthetic methane (electrofuel)
    - Synthetic methanol (electrofuel)
    - Heavy fuel oil (HFO) and scrubber
    - Liquefied petroleum gas (LPG)
    - NH_3
    - H_2
- **Fuel cells**
    - NH_3
    - H_2
- **Electric motors**
    - Electricity from grid

ENERGY-EFFICIENCY MEASURES

The impact of energy-efficiency measures is mostly based on the numbers used in the 2018 edition of the Maritime Forecast to 2050. The main update in this edition is the introduction of different speed reduction levels – from 0% to 50% – and associated fuel-consumption reduction levels.

DNV GL has its own abatement database for different ship types. It covers costs and emission-reduction potential for many technical and operational measures allocated into predefined ship categories. Data on costs and reduction effects for operational and technical measures are based mainly on data from available literature; more than 30 three-phased energy management projects; fuel-consumption data from ship reports; DNV GL's Technology Outlook activities, and COSSMOS[36] modelling and simulation projects.

Our model does not evaluate the uptake of each single measure (e.g. waste-heat recovery, air-cavity lubrication). Interactions between the measures are complex to model. We instead compile the energy efficiency (EE) measures into internally consistent packages as follows:

- **Baseline:** Average energy efficiency of a vessel built before 2015. Includes basic operational measures.
- **Basic EE:** Average energy efficiency of a vessel built after 2015. Includes hull optimization, basic

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[36] DNV GL COSSMOS: Computer platform for modelling, simulation, and optimization of complex ship energy systems

machinery improvements, cargo handling gear and advanced operational improvements.

- **Enhanced EE:** Energy-efficiency measures expected to be mature in five years. Includes Basic EE and advanced machinery improvements (e.g. hybridization, waste-heat recovery, and auxiliary power optimization).
- **Advanced EE:** Energy-efficiency measures expected to be mature in 10 years. Includes Advanced EE and air-cavity lubrication, wind power (e.g. fixed sails, Flettner rotors).

SPEED REDUCTION

The model applies five different levels of speed reduction: 0% (sailing at 75%–80% of maximum continuous rating, MCR),[37] 10%, 20%, 30% and 50%. The resulting reductions in main-engine power for an individual vessel are estimated based on reported fuel-consumption data. Percentage power reduction is larger at 10% and 20% lower speeds than at 30% and 50% where the resistance from wind and waves becomes more prominent. Up to 30%–35% less fuel is used when speed is reduced by 20%, and 60%–67% less when the speed reduction is 50%. Speed reduction comes at a cost. As the transport capacity of the vessel is reduced, its earning capacity declines. More vessels would have to be built to cover for the lost capacity. In addition, the cargo owner has increased costs due to capital being tied up through longer sailing times. This is reflected in the modelling, where the cost of speed reduction is based on the charter rate of the vessel type. The model factors in the applied speed reduction and builds more vessels to fully make up for the reduced transport capacity.

The fleet sailing in 2018 would already have implemented some of the energy efficiency and speed reduction measures. We have assumed that all vessels built after 2015 will have the Basic EE package, for example. In addition, the average speed from the AIS data is used to set an already implemented speed reduction on the baseline fleet in 2018. The model evaluates all combinations of EE packages and speed reductions and selects the combination with the highest NPV.

LOGISTICS

Toward 2050 we expect gradual improvements in the supply chain to increase vessel utilization by about 25% for deep-sea trades except bulk; approximately 5% for deep-sea bulk; and, by some 20% for short-sea trades. We expect average ship sizes to increase by 40% for LNG tankers, 30% for container ships and 10% for bulkers. The sizes of other types of ship will remain as today.

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[37] The MCR is the maximum power output from an engine operating continuously within safety limits and conditions

6.3 CO_2 EMISSIONS TOWARDS 2050

Shipping emitted 921 megatonnes of carbon dioxide ($MtCO_2$) in 2008, according to Smith et al. (2014); we estimate 870 $MtCO_2$ for 2018 (Chapter 2). If emissions per tonne-mile remain the same, baseline emissions in 2050 would be 1,210 $MtCO_2$ based on the 39% projected demand growth for seaborne trade (Figure 6.2).

The impact of energy-efficiency measures and speed reduction can be achieved to full effect early in the period up to 2035, as they can be implemented without renewing the fleet. We project that emissions will peak in mid-2020. Beyond 2035, we will see the full impact of gradually improving the energy efficiency of new ships, and of the shift to carbon-neutral fuels for the pathways to achieve IMO ambitions (see Table 6.1).

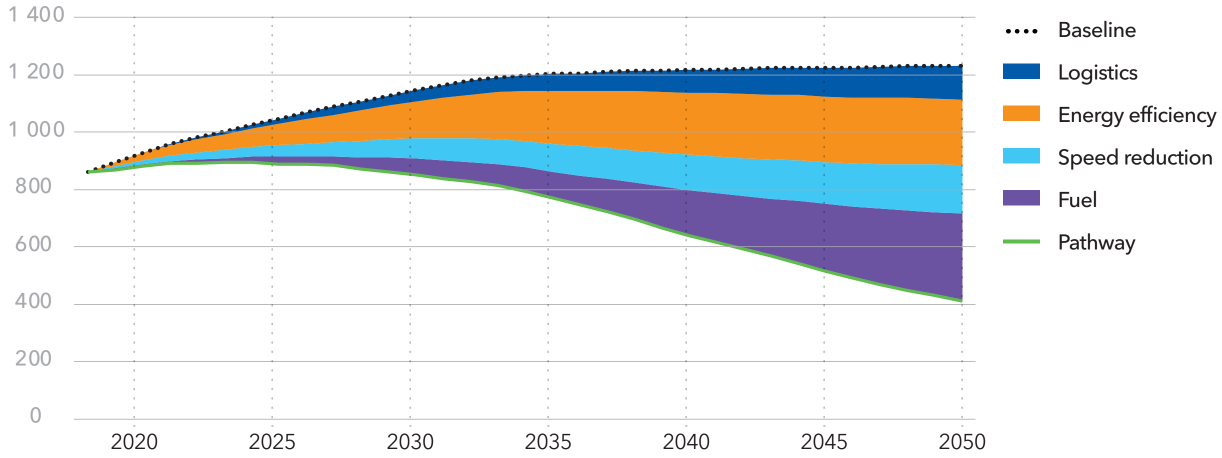
In these two pathways, carbon emissions from international shipping will be around 410 $MtCO_2$ in 2050. Figure 6.3 shows how various measures contribute to the emissions reduction for the 'design requirements' pathway (see Section 6.1). A tenth (10%) of the emission reduction will be due to logistical improvements in the supply chain; 18% from technical and operational energy-efficiency measures; 14% from speed reduction, taking into account the additional ships needed to cover the transport work; and, a further 22% because of carbon-neutral fuels.

Without further regulation, we do not expect uptake of alternative fuels to be sufficient to reach the IMO GHG targets. For the 'current policies' pathway (see Table 6.1), we project 670 $MtCO_2$

FIGURE 6.3

Shipping emissions reduction by measure (2018–2050) for the 'design requirements' (DR) pathway (see Table 6.1)

Units: Megatonnes of carbon dioxide ($MtCO_2$)



emissions in 2050, little more than a quarter (27%) below levels in 2008.

The IMO GHG strategy also aims to reduce the carbon intensity (CO_2 emissions per transport work) of international shipping by 40% in 2030 and 70% in 2050, relative to 2008. The Fourth IMO GHG study to be completed in 2020 will establish an official carbon-intensity baseline for 2008.

In the 'design requirements' and 'operational requirements' pathways (see Table 6.1), we project a carbon intensity of 5.6 grams (g) of CO_2/tonne-mile in 2050, three quarters (74%) less than in 2008. In the 'current policies' pathway, the carbon intensity ends on 8.2 gCO_2/tonne-mile, 62% less than in 2008. The results indicate that even if growth of seaborne trade is moderate to low, the IMO's 50% absolute reduction ambition is stricter than the carbon-intensity reduction ambition.

6.4 WORLD FLEET ENERGY MIX

We predict that total energy use in international shipping will rise from about 10.6 exajoules (EJ) in 2018 to peak at 11.6 EJ in 2025 and then decrease to some 9.0–9.5 EJ in 2050. This is despite a projected increase of about 39% in demand for seaborne trade (Figure 6.2). The total energy use in 2050 equates to about 210 Mt of oil equivalent (Mtoe). The container (23%), bulk (16%) and tank (13%) segments will account for the largest shares of total shipping energy use in 2050.

The total energy use does not vary much between the pathways modelled, but there are significant differences in the energy mix. To recap (see Table 6.1), we are talking here about two pathways to achieve IMO ambitions, one based on design requirements (DR) and the other on operational requirements (OR), and a third pathway based on current policies (CP).

In all three pathways modelled, liquefied methane ends up dominating the fuel mix (40%–80% in 2050), but the primary energy source of the methane varies between fossil, biomass and other renewables. Carbon-neutral fuels need to supply 30%–40% of the total energy for international shipping in mid-century if the IMO's ambitions for reducing GHGs are to be achieved.

In the IMO ambitions OR pathway, our modelling sees LNG initially capturing a large share of the fuel mix for international shipping, due to gradually stricter operational requirements on GHG emissions. From 2040, use of LBG or synthetic methane (electrofuel) starts to grow, so that the mix by 2050 is 70% fossil LNG, 13% carbon-neutral methane and 17% other carbon-neutral fuels. Liquid fossil fuels are almost completely removed from the mix as the sector progressively becomes decarbonized.

In the IMO ambitions DR pathway (Figure 6.4 and 6.5), the strictest requirements are enforced at a later stage. Initial transition is slower, with lower uptake of LNG. In 2050, the LNG share ends up at more than 40%, with no transition to carbon-neutral methane (Figure 6.5). Instead, due to the stricter newbuild requirements from 2040, the newbuilds run on ammonia (NH_3), which in 2050 results in a 25% share of NH_3 in the energy mix. Almost 20% of the energy for international shipping in mid-century will come from liquid fossil fuels. The preference for NH_3 is due to the lower cost of the converter and storage compared with H_2, and the lower price compared with other bio- or electrofuels. Uptake of H_2 is limited to a small number of smaller ships; this is due to high investment costs and technical constraints.

This is nevertheless subject to some significant uncertainties on costs and availability of NH_3 relative to other fuels. The availability of new fuels will experience the same chicken-and-egg problem that we have seen with LNG. Without any infrastructure and distribution, it is difficult for shipowners to commit to a new fuel, but suppliers will not develop the infrastructure before they are certain of demand.

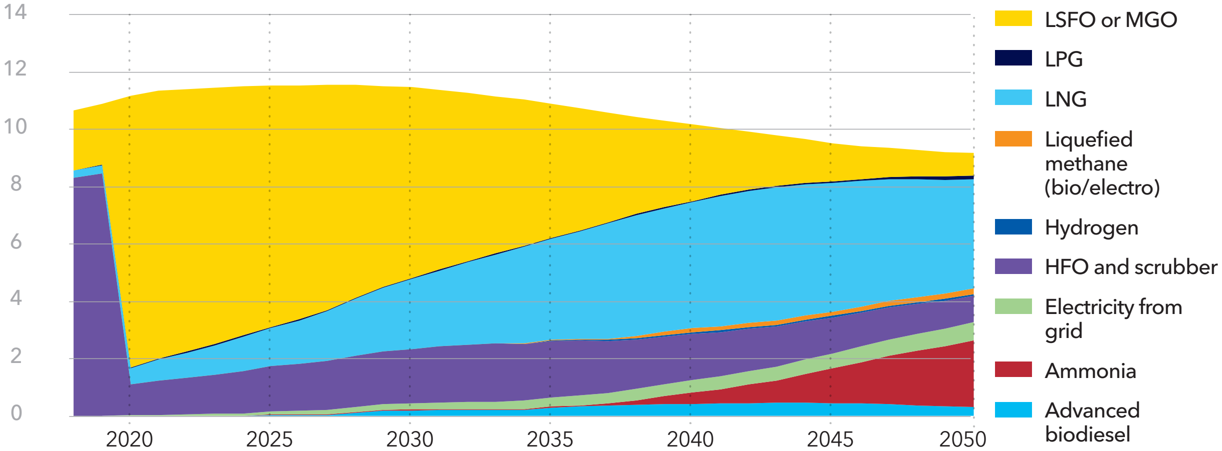
In the CP pathway, where no further policies are put in place, there will be limited transition to other fuels. The energy mix in 2050 will be 93% based on fossil fuels (50% LNG and 43% liquid fuels).

It should be mentioned that the high uptake of LNG in all three pathways is largely driven by the gas fuel price, which reduces towards 2050. As a sensitivity test, running the DR pathway with 20 % higher gas price leads to LNG uptake being more than halved, consequently giving higher uptake of other fuel alternatives. This exemplifies the high impact of fuel prices on the future energy mix.

FIGURE 6.4

Energy use and projected fuel mix 2018-2050 for the simulated IMO ambitions pathway with main focus on design requirements

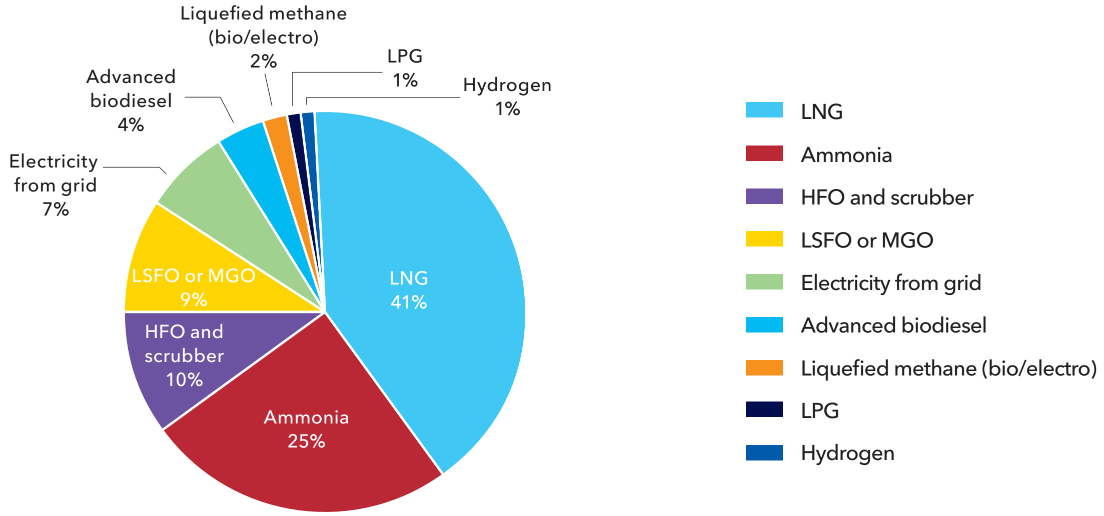
Units: EJ/yr



LSFO, low-sulphur fuel oil; MGO, marine gas oil; LPG, liquefied petroleum gas;
LNG, liquefied natural gas; HFO, heavy fuel oil;
Advanced biodiesel, produced by advanced processes from non-food feedstocks

FIGURE 6.5

Energy use in 2050 by fuel type for the simulated IMO ambitions DR pathway with main focus on design requirements



LSFO, low-sulphur fuel oil; MGO, marine gas oil; LPG, liquefied petroleum gas;
LNG, liquefied natural gas; HFO, heavy fuel oil
Advanced biodiesel, produced by advanced processes from non-food feedstocks

Shore-based electricity will in all pathways provide about 5%–7% of the total energy for shipping through batteries and cold ironing (i.e. shore-to-ship power), amounting to 150–170 terawatt hours (TWh) of electricity.[38] The service and passenger segments will have the highest share of electricity with almost 18% of the energy need provided by grid electricity.

The use of scrubbers and HFO is mainly dependent on the price differential between HFO, LSFO/MGO and LNG. In our three pathways, the price favours HFO with scrubbers, which even in the IMO ambitions DR pathway has a 10% share of the energy mix in 2050, mainly in the deep-sea segment. In the IMO ambitions OR pathway, the use of scrubbers is eliminated due to stricter operational requirements, while in the CP pathway the share is 17%. The cost and availability of HFO is further discussed in Chapter 7.

6.4.1 IMPACTS ON NEWBUILDINGS

Behind the gradual changes in the energy mix, there are two distinct differences between the two IMO ambitions pathways. In the DR pathway focusing on design requirements, the shift in fuel and fuel-converter technology on newbuildings is very abrupt (Figure 6.6). The delayed implementation of LNG leads to the need to shift almost all newbuildings to ammonia from 2040 to 2045.

In the OR pathway focusing on operational requirements, the uptake of ammonia is limited and more gradual, and the fossil LNG is replaced by carbon-neutral LBG or synthetic methane (electrofuel) as a drop-in fuel (Figure 6.7). Such an abrupt transition could prove very challenging when considering, for example, the need to build up infrastructure and yard capacity. This should be taken into account when considering policy.

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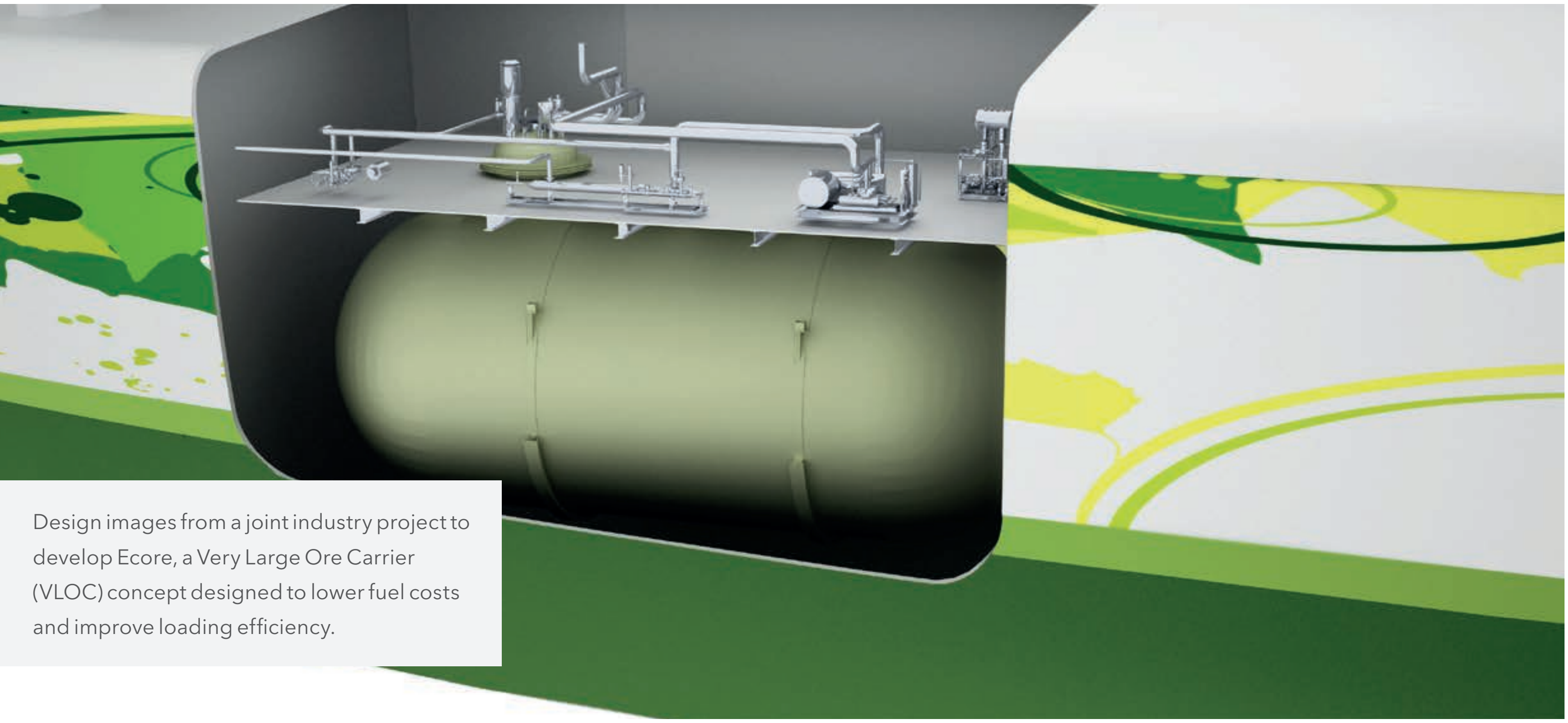
[38] 1 EJ = 23.9 Mtoe = 278 TWh

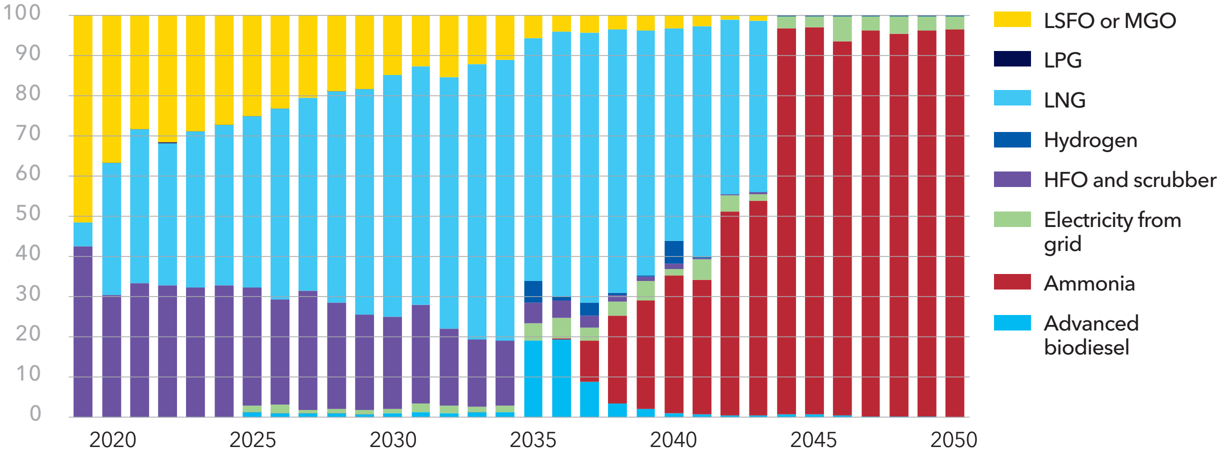


Design images from a joint industry project to develop Ecore, a Very Large Ore Carrier (VLOC) concept designed to lower fuel costs and improve loading efficiency.

FIGURE 6.6

Share of fuels (% of energy bunkered) for newbuildings for the IMO ambitions DR pathway (2018–2050) with main focus on design requirements

Units: Percentage (%)

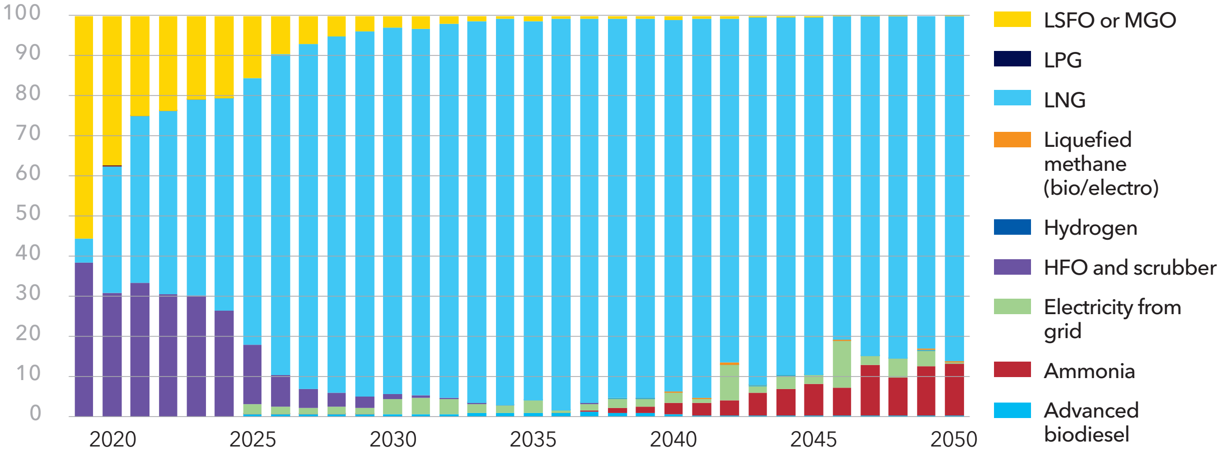


LSFO, low-sulphur fuel oil; MGO, marine gas oil; LPG, liquefied petroleum gas;
LNG, liquefied natural gas; HFO, heavy fuel oil
Advanced biodiesel, produced by advanced processes from non-food feedstocks

FIGURE 6.7

Share of fuels (% of energy bunkered) for newbuildings for the IMO ambitions OR pathway (2018–2050) with main focus on operational requirements

Units: Percentage (%)



LSFO, low-sulphur fuel oil; MGO, marine gas oil; LPG, liquefied petroleum gas;
LNG, liquefied natural gas; HFO, heavy fuel oil
Advanced biodiesel, produced by advanced processes from non-food feedstocks

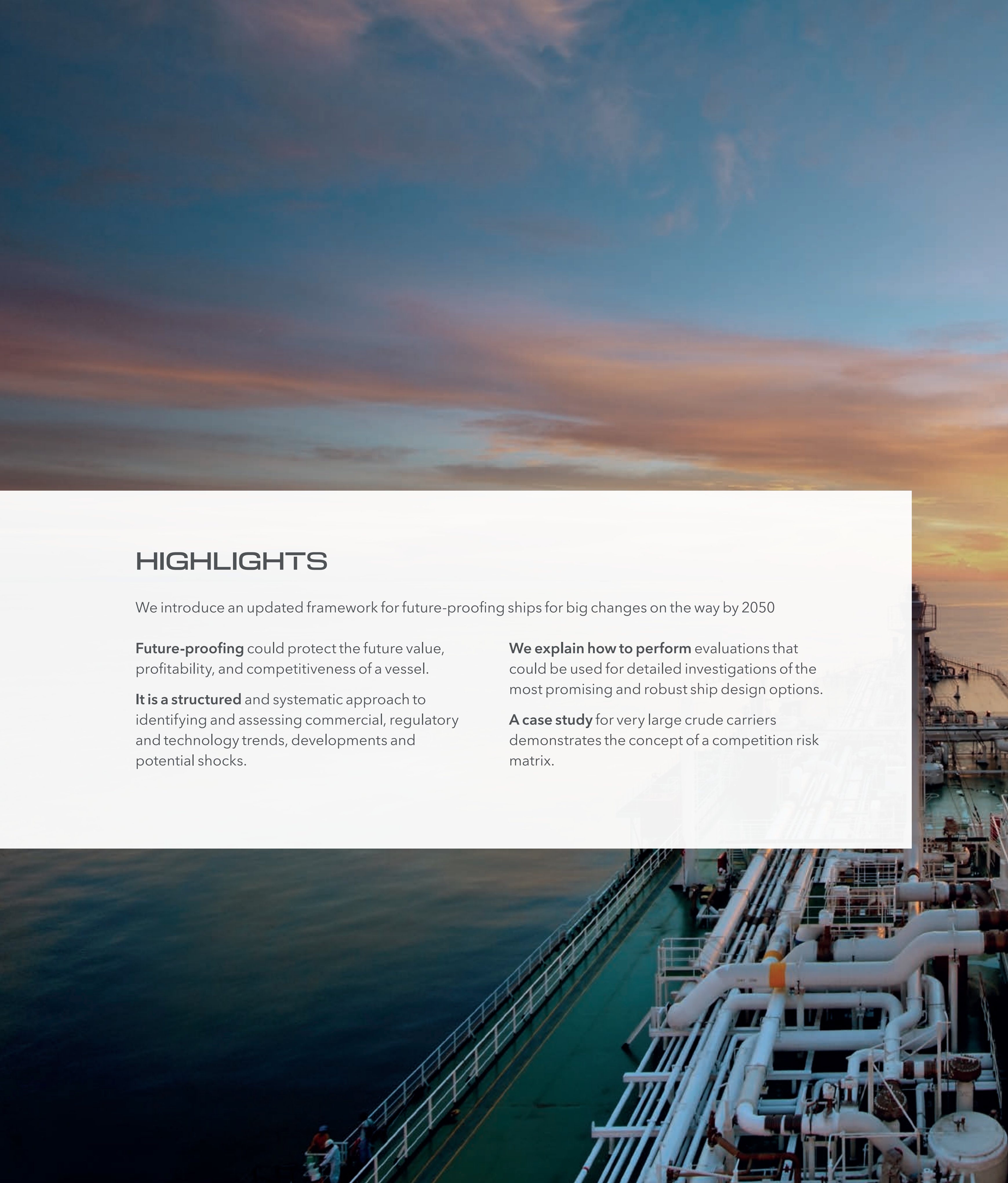
6.5 DISCUSSION

We acknowledge that in taking a long-term perspective, there are significant uncertainties in a number of factors influencing our projections as our modelling attempts to explore the impact of specific GHG regulations.

Our results demonstrate that reaching the IMO GHG-reduction targets is possible but is also challenging. Unless prices for alternative fuels move to the same level as those for fossil fuels, introducing policy measures is a key to addressing GHG emissions in shipping. Without further incentives for alternative fuels, the current fuel mix will prevail, but with LNG taking a greater share of it.

In addition to future maritime policies, the cost and availability of carbon-neutral fuels are the key uncertainties that will impact on the energy mix in 2050. In this work, we have explored the impact of changes in the regulatory framework on CO_2 emissions and fuel mix. Further analysis is needed to fully explore the impact of changes to fuel-price assumptions. This is supported by the sensitivity tests we have carried out, and by previous work (e.g. Acciaro et al., 2012; Eide et al., 2013). Impacts from developments in production and distribution infrastructure, as well as technology development in other sectors such as aviation and road transport should be further analysed.

The work presented in this chapter shows the great need for alternative fuels, and the time it takes for a transition to have a significant impact on emissions. In scenarios with higher growth in shipping demand, the need for alternative fuels becomes even greater. Further modelling can be useful for policymakers and the maritime industry to anticipate the need for scaling up the supply of alternative fuels to satisfy the demand generated by new regulations. The results also highlight a need for new polices to address the barriers identified in Chapter 5 in a timely manner to enable this scaling up.



HIGHLIGHTS

We introduce an updated framework for future-proofing ships for big changes on the way by 2050

Future-proofing could protect the future value, profitability, and competitiveness of a vessel.

It is a structured and systematic approach to identifying and assessing commercial, regulatory and technology trends, developments and potential shocks.

We explain how to perform evaluations that could be used for detailed investigations of the most promising and robust ship design options.

A case study for very large crude carriers demonstrates the concept of a competition risk matrix.

CHAPTER 7

FUTURE-PROOF SHIPS

7 FUTURE-PROOF SHIPS

In this chapter, we enhance our framework for optimizing a ship or fleet's ability to navigate technological, regulatory and market uncertainty to maintain competitiveness, profitability and value.

A shipowner investing in tonnage must consider the increasing uncertainty in the maritime industry concerning regulatory developments, technological progress, alternative fuels and charter requirements. A vessel's operating lifetime can span several decades, meaning a ship built today will most likely see significant developments in all these regards. This includes digitalization and decarbonization, which are currently the most transformative forces in shipping. They will have a large impact on how ships are designed and operated. Subsequently, all the factors mentioned above will have a significant effect on both the competitiveness and value of vessels.

> “A shipowner investing in tonnage must consider the increasing uncertainty in the maritime industry concerning regulatory developments, technological progress, alternative fuels and charter requirements.

To help navigate this future and manage the uncertainty we have previously proposed a carbon-robust ship concept (DNV GL, 2017a). We followed this with the Carbon-Robust Model (DNV GL, 2018a). This model allows for a quantitative assessment of the future competitiveness of different design options. However, as we noted in last year's publication, the model should be used in a structured way to explore a range of scenarios and designs in order to reach firm conclusions. To properly manage the risk of the vessel becoming a stranded asset, more scenarios should be explored, including varying trade volumes and fleet growth rates. In this chapter, we present a further updated framework for future-proofing ships. A case study building on 144 simulations for the very large crude carrier (VLCC) segment is also presented, demonstrating the concept of a competition risk matrix.

7.1 THE CONCEPT OF FUTURE-PROOF SHIPS

Increasing uncertainty makes it more important than ever to examine and understand regulatory and technological challenges and opportunities for future scenarios as we head towards 2050. Our approach to future-proofing ships can ensure the long-term competitiveness of both the existing fleet and newbuildings.[39]

Future-proofing implies preparing for changes that will affect the value and competitiveness of the ship being invested in. The strategy aims at minimizing the risk of an asset becoming obsolete or losing value. When building a new ship, the technology choices and level of system flexibility will thus be crucial. For example, should space be set aside for retrofit opportunities or is it wise to invest in a fuel-flexible energy converter? In this context, 'future-proof ships' refer to either a ship or fleet that can maintain short- and long-term profitability, competitiveness and value under different scenarios.

Large-scale investments today will only be made in technologies that are currently commercially available and competitive. However, a robust investment strategy should also include the available technologies offering the best hedge for adopting future alternative fuels emitting lower or no greenhouse gases (GHGs) at minimum retrofit costs. Figure 7.1 outlines our proposed future-proofing approach. The impact of all relevant factors should be explored. They include external factors such as trade growth and fuel prices, and internal ones like a ship's design features. As indicated by the bottom line, the approach can be re-applied with adjusted scenarios or designs for evaluation.

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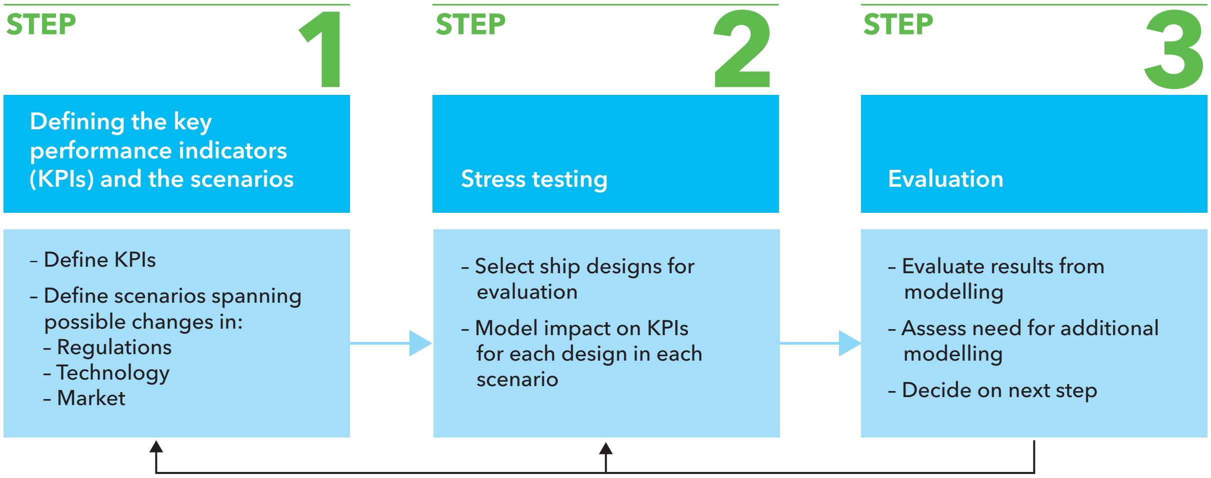
[39] DNV GL (2018). 'Energy transition offers innovators a competitive edge through 'carbon robust' ship designs', DNV GL press release, 10 September 2018, view at dnvgl.com

FIGURE 7.1

A framework for future-proofing ships



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The approach has the following three steps:

7.1.1 STEP ONE: DEFINING THE KEY PERFORMANCE INDICATORS (KPIs) AND THE SCENARIOS

In principle, any indicator related to the profitability, competitiveness and value of the vessel could be applied. DNV GL (2018a) applied two KPIs: break-even rates relative to the competing fleet; and, carbon dioxide (CO_2) emissions relative to the competing fleet. To recap, the break-even rate is the minimum rate that a ship must secure to cover all costs. Rates above the break-even cost will leave the shipowner with a profit. The break-even rate is composed of three cost elements: capital, voyage and operational.

These KPIs were combined and used to assess the degree of commercial and carbon robustness of different vessel designs.

After defining KPIs, the next task is to identify the most important external factors likely to impact them. In other words, what are the major risk and opportunity drivers beyond the control of the shipowner? Drivers depend on the ship segment, but would typically relate to relevant technologies in the fleet, regulatory developments, stakeholders, and market trends and development. The focus should be on drivers with high impact and large uncertainty. As fuel cost can represent up to 50%–60% of the total running cost, depending on ship type and size, the selection of fuel and technologies will have a large impact on ship competitiveness and profitability in the short and long term. The choices will also affect the vessel's appeal in the second-hand market and the possibility of operating it in different geographical regions, including Emission Control Areas (ECAs). Technologies impacting on the need for crew could also have a substantial impact.

Once key drivers have been identified, the range of possible outcomes for each should be defined. This leads on to the generation of a manageable set of scenarios. Extreme scenarios can be set up to evaluate the limits of the opportunity space, and scenarios in between can be used to assess more probable futures. The scenarios can be assigned different weights. This allows the user to specify the degree to which the results for a given scenario should be considered.

7.1.2 STEP TWO: STRESS TESTING

In this step, the impact of the defined scenarios on the selected performance indicators is modelled to assess how a ship design will respond to varying assumptions about future developments. In principle, any technology or design feature could be modelled, thereby exploring the impact of the most important factors directly influenced by the shipowner. Energy efficiency and alternative fuels are examples of relevant design options. Other technologies that could be assessed might relate to the vessel's ability to include the digital transformation in ship design and operation. Another set of design features could be linked to a ship's flexibility to transport different cargo types to adapt to changes in market demand and improve its utilization.

The currently applied model allows for combining different fuel and technology configurations. Figure 7.2 outlines how the model works. The core feature of the Carbon-Robust Model lies in evaluating different fuel and technology options by comparing a design's break-even cost – the minimum rate a ship must secure to cover all costs – to that of the competing fleet of ships in different future scenarios.[40]

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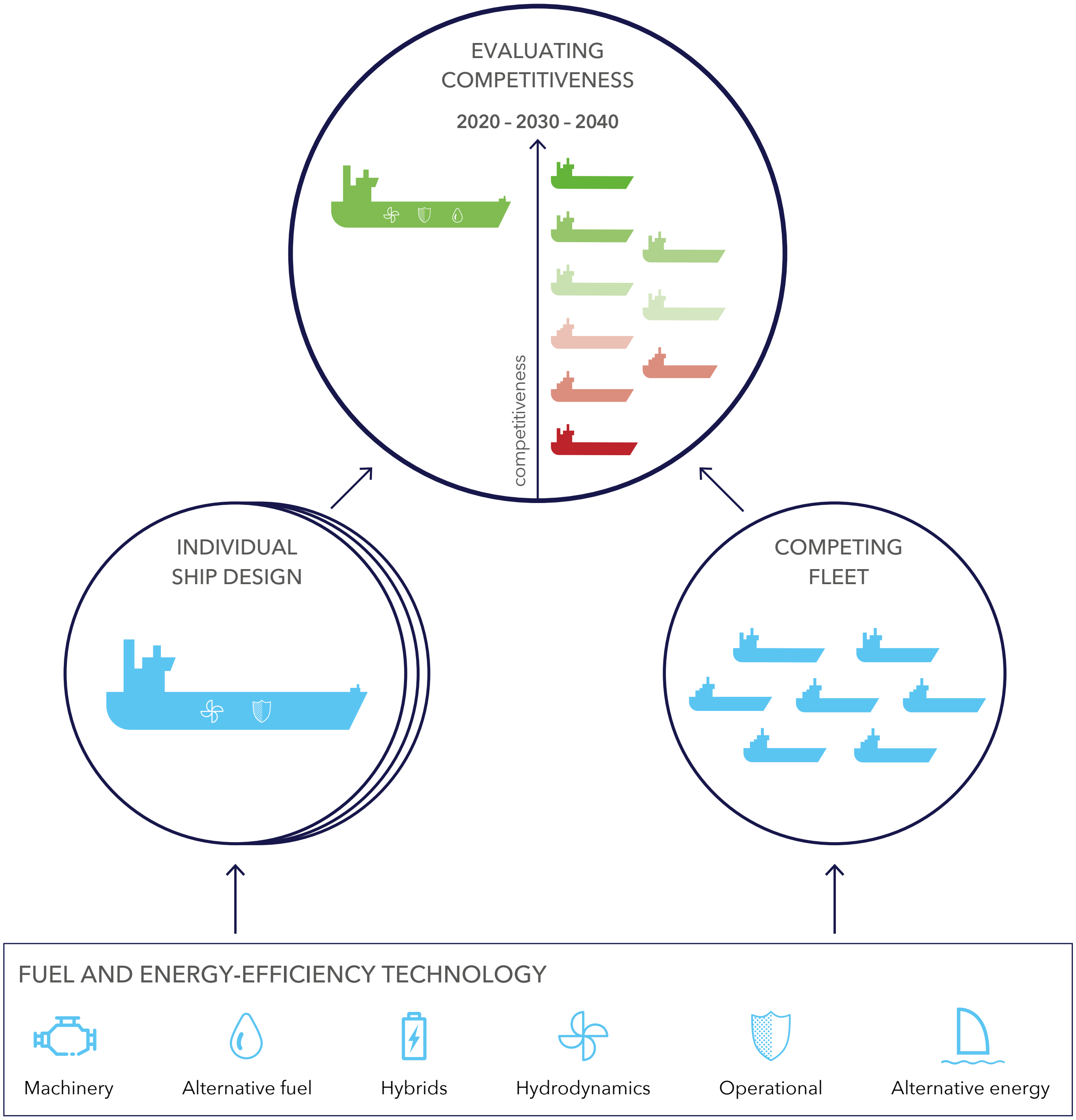
[40] DNV GL (2018). 'Putting yourself ahead of the pack with the carbon-robust ship', Ø Endresen, DNV GL, 4 March 2019 [online], view at www.dnvgl.com

FIGURE 7.2

Outline of the Carbon-Robust Model

Competitiveness of selected individual ship designs is evaluated against the competing fleet of ships at a given point in time (e.g. 2030 or 2040) using the break-even cost or CO_2 emissions as a measure. The user can draw on a pool of fuel and technology options in creating the individual ship designs. For the competing fleet, fuel and technology uptake are governed by pre-set scenarios.



Source: Energy Transition Outlook 2018: Maritime Forecast to 2050, DNV GL

To assess the degree of commercial and carbon robustness of a vessel, DNV GL (2018a) developed and used the Carbon-Robust Model (for a bulk carrier). To learn more about how this model is set up, and its features, please see DNV GL (2018a). The model should cover the high-level options available to the shipowner, including fuel and energy-efficiency options. While scenarios selected in step one of the future-proofing framework reflect external variability, the ship designs should cover the variability controlled by the shipowner/designer.

7.1.3 STEP THREE: EVALUATION

Here, the results of step two are assessed, examining the KPI outcomes in various scenarios, to make an overall evaluation of how future-proof the design in question is. If the result is unsatisfactory, design changes should be implemented. The modelling in step two should then be repeated until a satisfactory number of designs have been evaluated to determine the best course of action. The outcome of the evaluation could also be to investigate the most promising design options in further detail.

In the next section, we apply the future-proofing framework to a case study evaluating the future competitiveness of different VLCC configurations using DNV GL's Carbon-Robust Model. We demonstrate the applicability of our competitiveness risk matrix, allowing performance evaluations of specific VLCC designs in a range of realistic commercial, regulatory and technology scenarios.

7.2 FUTURE-PROOF VLCC: A CASE STUDY

To showcase the future-proof concept, we select the VLCC tanker segment and consider a ship to be delivered in 2020. We define the VLCC segment as oil tankers between 300,000 and 320,000 deadweight tonnage (DWT), with an estimated fleet of 850 vessels in 2020.

7.2.1 STEP 1: DEFINING THE KPIs AND THE SCENARIOS

To assess the competitiveness of the VLCC carrier we select two KPIs: first, the break-even rate relative to the competing fleet; second, CO_2 emissions relative to the competing fleet (for LNG-powered vessels a CO_2 reduction of 20% has been applied, accounting for methane slip).

The two KPIs are coupled by the application of different fuels, energy-efficiency measures and through the introduction of a CO_2 tax.

Further, a set of scenarios to span a realistic commercial, technology and regulatory opportunity space must be established. Fleet growth rates, technology and fuel uptake in the fleet, and fuel prices are all associated with high uncertainty and impact greatly on the future competitiveness of a ship design.

FLEET GROWTH RATES

Two fleet growth rates are selected to capture the high uncertainty of the oil trade over the next decades:

- **Stagnation and decline;** the VLCC fleet grows moderately until 2030; during the following decade, the segment experiences negative growth rates, where fewer new ships enter the fleet and do not compensate for the loss created by tonnage sold for scrapping; this projection is in line with the oil trade projections used in Chapter 6.
- **Moderate growth;** the VLCC fleet grows steadily over the next 30 years; such a situation could reflect a more positive outlook for the tanker fleet in general, or stronger growth in the VLCC segment than in other tanker segments.

TECHNOLOGY AND FUEL UPTAKE IN THE VLCC FLEET

The extent to which energy-efficiency technologies and alternative fuels will be deployed in the VLCC fleet in the coming decades is highly uncertain. Developments will likely be driven primarily by international regulations, but other drivers, such as charter requirements, may also impact the technology and fuel mix significantly. Two alternatives[41] for fuel and technology uptakes are selected:

- **Business-as-usual;** in this situation, energy efficiency uptake is sufficient for compliance with regulations currently in place, meaning the Energy Efficiency Design Index (EEDI) requirements; alternative fuels, here in the form of LNG, are applied to a limited degree, mostly after 2030.
- **Green ambition;** in this situation, new regulations enter into force to ensure implementation of the agreed IMO ambitions on GHG reductions; energy efficiency and alternative fuel uptake comply with the new, more stringent regulations; advanced energy-efficiency options are deployed at large scale; post-2030 almost all vessels are built with LNG as fuel; towards 2050, biofuels are used in moderate amounts; a CO_2 tax of USD 50/tCO_2 is applied from 2030.

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[41] Note that these alternatives are based on the 'current policies' and 'IMO ambition' scenarios described in Chapter 6, though with modifications. For instance, the Carbon-Robust Model is not set up to handle speed reductions on a fleet level, which is a major feature of scenarios in Chapter 6

FUEL PRICES

The fuel price development is highly uncertain, even short term. Fuel prices, and most importantly the spread between fuel alternatives, are a decisive factor in our modelling. For this segment we consider three main options beyond 2020: LSFO (low-sulphur fuel oil), compliant with the IMO's 0.5% sulphur cap;[42] HFO (heavy fuel oil), which requires scrubbers for compliance; and, LNG. Four fuel-price spread options[43] are selected, and held constant over time:

- **Reference;** this option approximates the current price picture, with LSFO at USD 550 /t, LNG at USD 500/t, and HFO at USD 400/t. All prices are given in metric tonnes.
- **High;** this option reflects a high price level for all fuels, with LSFO at USD 750/t, LNG at USD 700/t, and HFO at USD 600/t.
- **Cheap LNG;** this option reflects a situation with relatively cheap LNG, with LSFO at USD 750/t, LNG at USD 400/t, and HFO at USD 350/t.
- **Expensive LNG;** this option reflects a situation with relatively expensive LNG, with LSFO at USD 750/t, LNG at USD 700/t, and HFO at USD 350/t.

Combining the variables – fleet growth rates, technology and fuel uptake in the fleet, and fuel prices – results in 16 distinct scenarios as discussed in the following section.

7.2.2 STEP 2: STRESS TESTING

We apply the Carbon-Robust Model to assess how the KPIs will change for a selected ship design in the 16 scenarios representing external future variability. A range of alternative ship specifications are tested to identify the most robust design choices. We want to explore the following designs:

- **Three different fuel types;** LSFO, HFO with scrubber, and LNG.
- **Three different levels of energy efficiency;** baseline, enhanced, and advanced – where each level represents a combination of various measures. The baseline grouping includes all energy-efficiency technologies expected to be standard on a VLCC newbuild in 2020. The enhanced level of energy efficiency includes low-hanging fruits which are technologically mature, but beyond standard on a VLCC in 2020. The advanced category consists of measures which are more immature, complicated or costly to implement.

The nine VLCC design combinations are shown in Table 7.1:

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[42] For Emission Control Area operation, switching to 0.1% sulphur-compliant marine gas oil is assumed, but not included in calculations

[43] Note that fuel prices are not coupled with technology and fuel uptake. The fuel-price spreads are kept constant throughout the modelling period

TABLE 7.1

Applied numbering of the nine VLCC design combinations

Fuel type	Baseline energy efficiency	Enhanced energy efficiency	Advanced energy efficiency
Low-sulphur fuel oil (LSFO)	1	2	3
Heavy fuel oil (HFO) + scrubber	4	5	6
Liquefied natural gas (LNG)	7	8	9

7.2.3 STEP 3: EVALUATION

Running the model with nine selected design combinations for all 16 scenarios results in a 16 by 9 matrix (144 simulations) for each year of interest, and for each KPI. We call this the competition risk matrix, which provides a schematic overview showing the competitiveness of ship designs within a set of scenarios spanning the commercial, regulatory and technology opportunity space. Thus, the competition risk matrix is meant to illustrate the degree of commercial robustness of a ship design in any given year.

This risk matrix is meant as a knowledge-based, structured and systematic best-practice method to evaluate commercial and carbon robustness of a new ship. We believe it can help shipowners manage uncertainty. Supported by modelling tools and expert assessment, it enables stakeholders to stay ahead of industry developments and remain competitive moving forward.

Table 7.2 shows a selection of the modelling results, illustrating competitiveness on break-even rate for 2030 for all 9 designs in all 16 scenarios. The colour coding illustrates competitiveness compared with the rest of the fleet. The colours represent the following threshold values:

- **Green;** top 10% performer.
- **Yellow;** performing in the 10%–30% range.
- **Red;** bottom 70% performer.

For example, in a fleet of 850 vessels, being a top 10% performer on break-even rate implies that no more than 85 ships have a lower break-even rate.

In the matrix in Table 7.2, each row shows the resulting competitiveness for a given design, across all the 16 scenarios. A clear distinction is observed between scenarios 1–8 (business-as-usual setting) and scenarios 9–16 (green ambition setting).

Table 7.2 also shows differences between ship specification 1-3, which are variations of the LSFO

TABLE 7.2

Break-even rate competitiveness in 2030

Ship specifications		**Scenarios***															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
LSFO, baseline energy efficiency	1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
LSFO, enhanced energy efficiency	2	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
LSFO, advanced energy efficiency	3	🟥	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
HFO + scrubber, baseline energy efficiency	4	🟨	🟨	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
HFO + scrubber, enhanced energy efficiency	5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
HFO + scrubber, advanced energy efficiency	6	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LNG, baseline energy efficiency	7	🟥	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟩	🟨
LNG, enhanced energy efficiency	8	🟨	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟨
LNG, advanced energy efficiency	9	🟨	🟩	🟩	🟨	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟨

* Green = top 10% performer; yellow = performing in the 10%–30% range; red = bottom 70% performer.
Scenarios 1–8 are commercial, technology and regulatory opportunity space combinations in the business-as-usual setting and scenarios 9–16 constitute the same combinations in the green ambition setting (see Section 7.2.1).
Key: HFO, heavy fuel oil; LNG, liquefied natural gas; LSFO, low-sulphur fuel oil

vessel, specification 4–6 (HFO vessel), and 7–9 (LNG-powered). With the fuel-price spread used in this example, the vessels with HFO and scrubber (4–6) perform relatively better than the other alternatives. Also, improved competitiveness is observed for increasing levels of energy efficiency.

However, these results only portray economic competitiveness in one year of the vessels' lifetimes (year 2030); performance in other years and on different KPIs should also be considered. To support decision making, we therefore present the modelling results in the aggregated format below, in the form of a robustness score (R).

The robustness score represents the proportion of scenarios in which the ship designs perform better than a defined KPI competitiveness threshold. The threshold should reflect a shipowner's desired market position. The score is presented for each KPI in the years 2020, 2030 and 2040.

If the selected threshold is 10%, the robustness score (R_{10}) shows the proportion of scenarios in which the ship design is a top 10% performer.

$$R_{10} = \frac{\text{Number of scenarios where the ship design is a top 10\% performer}}{\text{16 scenarios}}$$

A similar score can be calculated for any threshold level. In the following case study, we apply 10% and 30% thresholds.

Table 7.3 shows the results for break-even rate competitiveness. For example, in 2020, LSFO with enhanced energy efficiency exhibits 0% achieving the 10% threshold (R10) and 100% achieving the 30% threshold (R30) for break-even rate competitiveness. This means that the ship specification does not compete in the top 10% in any of the scenarios, but it does compete within the top 30% in all scenarios – implying that in all scenarios, the ship specification competes in the 10%–30% range in 2020. Table 7.4 shows the corresponding results for CO_2 competitiveness.

7.2.4 CASE RESULTS

The key takeaways from the simulations of the different designs are (Table 7.3 and Table 7.4):

- **Designs with LSFO** exhibit relatively poor economic performance, especially long term, and require investment in energy-efficiency measures to compete. Competitiveness on CO_2 emissions worsens throughout the vessels' operating lifetime, with considerable carbon risk in 2040.
- **Designs with HFO and scrubber** perform very well economically in both the short and long term. Improving the energy efficiency further increases their competitiveness. There are, however, some uncertainty factors: HFO may not be available in all ports in the future; there is ongoing discussion on the impact of scrubber wash-water on the environment in ports and closed waters; and the additional energy required for scrubber can be an issue under future carbon policies. Competitiveness on CO_2 emissions worsens throughout the vessels' operating lifetime, with the highest carbon risk in 2040, among the fuels assessed.
- **Designs with LNG and baseline energy efficiency** perform worse than HFO with scrubber in 2020 to a large degree due to higher capex, which is predominantly driven by the cost of cryogenic tanks. Similarly as for the other fuels, investing in energy efficiency improves the economic competitiveness throughout the LNG vessels' lifetimes. LNG competes well on CO_2 emissions in 2020 and 2030, but could face competitive alternatives in 2040.

The challenge is to be robust both on financial and environmental KPIs in the short and long term. To remain competitive throughout the operating lifetime of a vessel, investing in energy efficiency is paramount. This is because a VLCC built today will compete with vessels built in five, 10, 15 years' time, and must consider future standards to remain competitive.

TABLE 7.3

Robustness score for the break-even rates, showing the proportion of scenarios in which the ship specifications succeed on break-even rate competitiveness criteria in 2020, 2030 and 2040 for the 10% (R_{10}) and 30% (R_{30}) thresholds

			R_{10}			R_{30}		
			2020	**2030**	**2040**	**2020**	**2030**	**2040**
Ship specifications	LSFO, baseline EE	1	0%	0%	0%	0%	0%	0%
	LSFO, enhanced EE	2	0%	0%	0%	100%	0%	0%
	LSFO, advanced EE	3	0%	0%	0%	100%	88%	0%
	HFO + scrubber, baseline EE	4	100%	25%	31%	100%	100%	88%
	HFO + scrubber, enhanced EE	5	100%	100%	88%	100%	100%	100%
	HFO + scrubber, advanced EE	6	100%	100%	100%	100%	100%	100%
	LNG, baseline EE	7	0%	13%	25%	100%	88%	63%
	LNG, enhanced EE	8	50%	63%	69%	100%	100%	100%
	LNG, advanced EE	9	50%	63%	75%	100%	100%	100%

Key: EE, energy efficiency; HFO, heavy fuel oil; LNG, liquefied natural gas; LSFO, low-sulphur fuel oil

TABLE 7.4

Robustness score for the CO_2 emissions, showing the proportion of scenarios in which the ship specifications succeed on CO_2 emission competitiveness criteria in 2020, 2030 and 2040 for the 10% (R_{10}) and 30% (R_{30}) thresholds

			R_{10}			R_{30}		
			2020	**2030**	**2040**	**2020**	**2030**	**2040**
Ship specifications	LSFO, baseline EE	1	50%	0%	0%	100%	50%	0%
	LSFO, enhanced EE	2	100%	50%	50%	100%	100%	50%
	LSFO, advanced EE	3	100%	50%	50%	100%	100%	50%
	HFO w/scrubber, baseline EE	4	0%	0%	0%	0%	0%	0%
	HFO w/scrubber, enhanced EE	5	50%	0%	0%	100%	50%	25%
	HFO w/scrubber, advanced EE	6	100%	50%	50%	100%	100%	50%
	LNG, baseline EE	7	100%	50%	50%	100%	100%	50%
	LNG, enhanced EE	8	100%	100%	50%	100%	100%	100%
	LNG, advanced EE	9	100%	100%	50%	100%	100%	100%

Key: EE, energy efficiency; HFO, heavy fuel oil; LNG, liquefied natural gas; LSFO, low-sulphur fuel oil

Poor competitiveness on CO_2 emissions – as shown by a low robustness score (low R_{10} and R_{30} value) – indicates that a vessel is exposed to a high carbon risk (Figure 7.3). While this carbon risk is not easily quantified, it is possible to understand the key aspects of the two parameters which jointly constitute the risk: consequence and likelihood.

Starting with the consequence aspect, a high-emitting ship could fall out of favour with both banks and charterers. This could mean reduced access to capital and higher capex cost, or reduced charter rates - or even revoked license to operate in the market. New CO_2 requirements could be placed on existing ships in the future by regulators such as the IMO, e.g. in the form of a mandatory operational CO_2-index level. Such requirements could force high-emitting ships to reduce speed, invest in new fuels or technologies, or otherwise reduce emissions.

The likelihood of such consequences is hard to assess. However, it is not unlikely that the IMO will impose requirements as discussed above, and there are several examples of environmental requirements with impact on existing ships including the 2020 Sulphur requirements. Similarly, it is not unlikely that banks and charters will favour 'green' ships. Forward-leaning charterers have already started down that road (see example where an energy efficient VLCC receives close to a 20% premium rate compared with a standard VLCC).[44] In the future, CO_2 emissions could become an additional rate differentiator. Banks and other lenders are also increasing their focus on CO_2 emissions. Recently, major shipping banks representing 20% of the global shipping portfolio signed[45] up to the Poseidon Principles; they have pledged to scrutinize their investments in ships to gauge the environmental performance of the assets they finance.[46]

While our modelling does not quantify the carbon risk, it provides shipowners with the possibility to carefully consider the balance between short-term cost reduction and long-term carbon-risk exposure for the various designs. This is particularly evident for the designs with HFO and scrubber.

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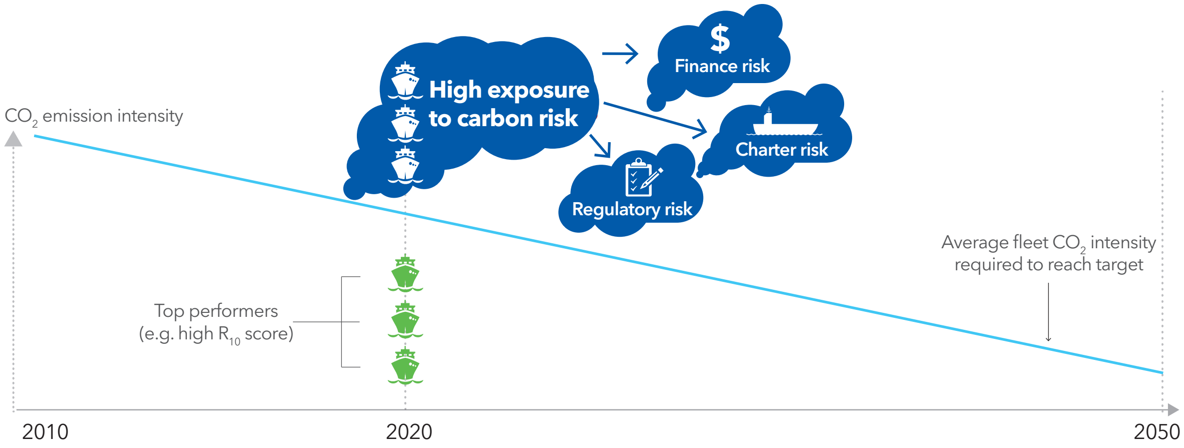
[44] Compass Maritime weekly market report, 14 June 2014, viewed at www.compassmar.com
[45] TU (2019) (in Norwegian), https://www.tu.no/artikler/storbank-bygger-kompetanse-innen-baerekraftig-shipping-og-havbruk/468920
[46] See www.poseidonprinciples.org

FIGURE 7.3

Conceptual illustration of the exposure to carbon risk. For a given year, the CO_2 performance of all ships in the fleet is plotted against a benchmark. The benchmark shows the average CO_2 performance required to reach a given emission target (e.g. the IMO targets). Ships with poor competitiveness on CO_2 emissions fall above the benchmark and will be exposed to carbon risk relating to finance, charterers, and to regulations.



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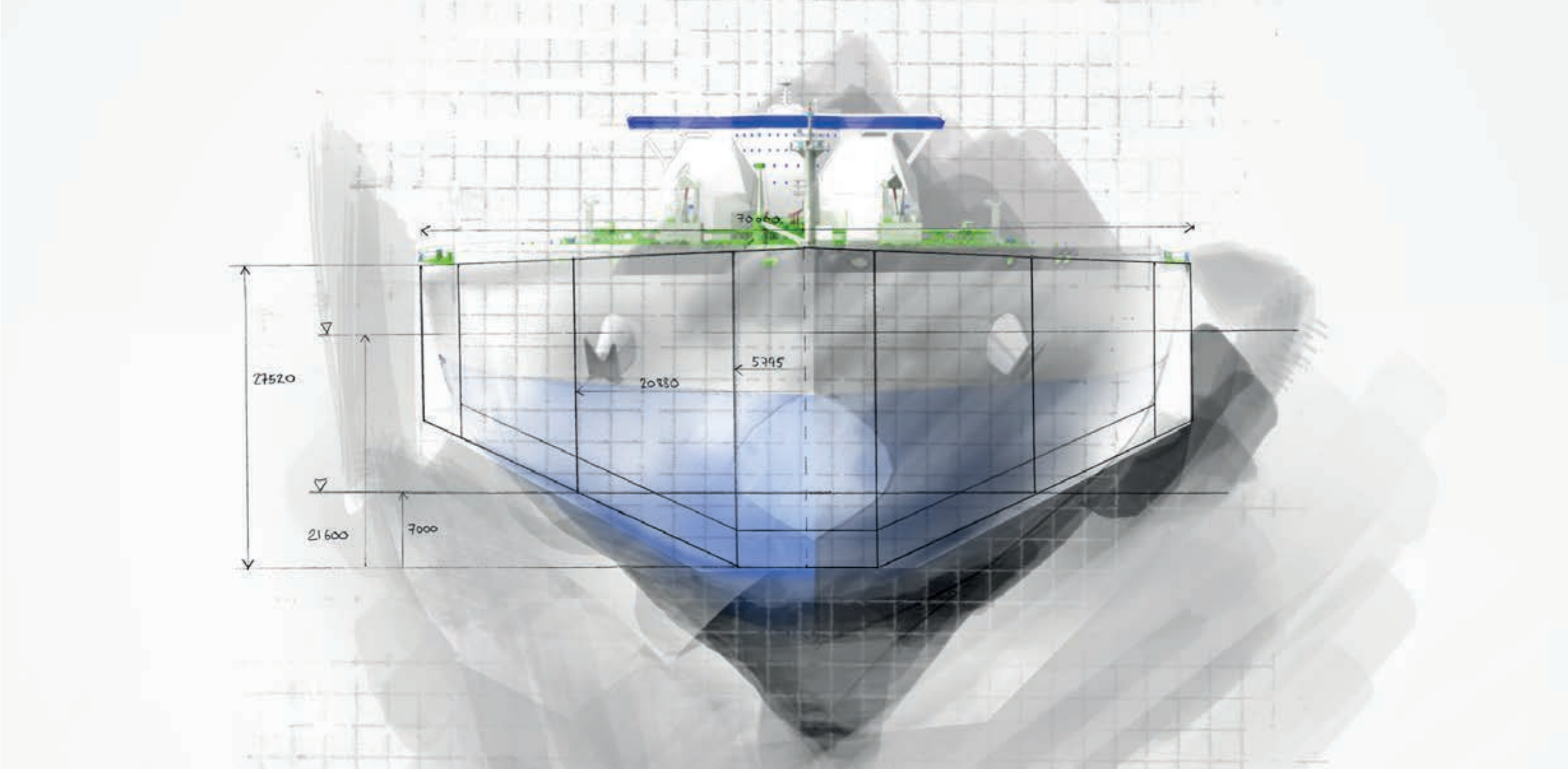
7.3 DISCUSSION OF THE FUTURE-PROOF CONCEPT

Considering the uncertain future that lies ahead, failing to go through a future-proofing process in the newbuilding phase could lead eventually to a devastating fate for the asset.

There is a significant risk that for a vessel built in 2020, the most competitive fuel in the ship's early life will not necessarily be the same as when it is scrapped. Keeping the bridging philosophy in mind (see Chapter 4) when designing a vessel, allowing for flexibility to switch to another fuel during the operating lifetime, would be vital to lower the risk of becoming a stranded asset.

Any modelling results must be understood in a wider context. For instance, fuel availability and bunkering infrastructure are issues to consider carefully. In the short term, LNG may not be available in all relevant trades. Similarly, HFO availability could be limited in the long term, which could also impact on the fuel-price spread.

The introduction of a multi-scenario approach will help build resilience and readiness, and provide input to a robust newbuilding strategy. However, it is worth re-emphasizing that the scenarios described are limited in complexity and variability, and that additional parameters could be included to gain even more insight for making informed business or policy decisions.



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HISTORICAL DATA

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Published by DNV GL – Maritime
Design Fiete Deichgraph/SDG/Drive McCann/Wildfire/Infogr8
Print 07 Media AS
Paper Arctic Volume White 115/200gr.
Images Damir Cvetojevic (4), Shutterstock (8, 18, 22, 29, 31, 32, 58, 63, 80, 91), Wilhelmsen/Moss Maritime (15), Making Waves (17), Energy Observer (38), HSHI Co. Ltd (41), Wärtsilä (43, 60), Color Line AS (49), DNV GL (65, 104,111), Adobe Stock (66, 96), Fiskerstrand (69), Ecore design concept JIP (94), Getty images (98).

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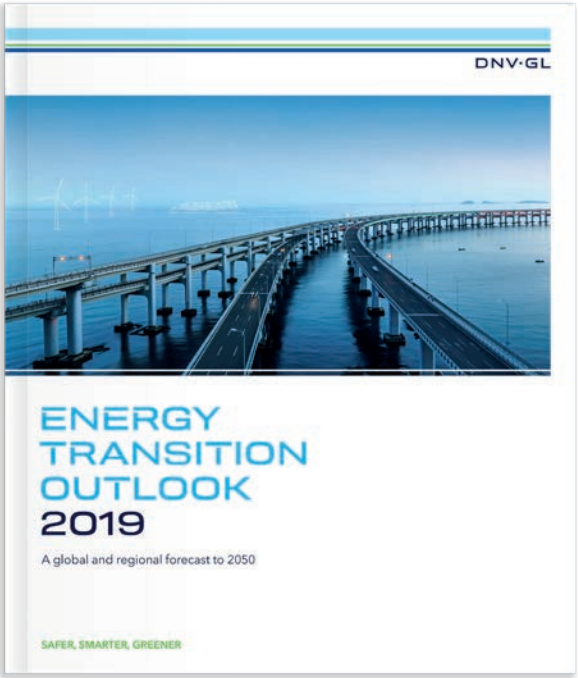

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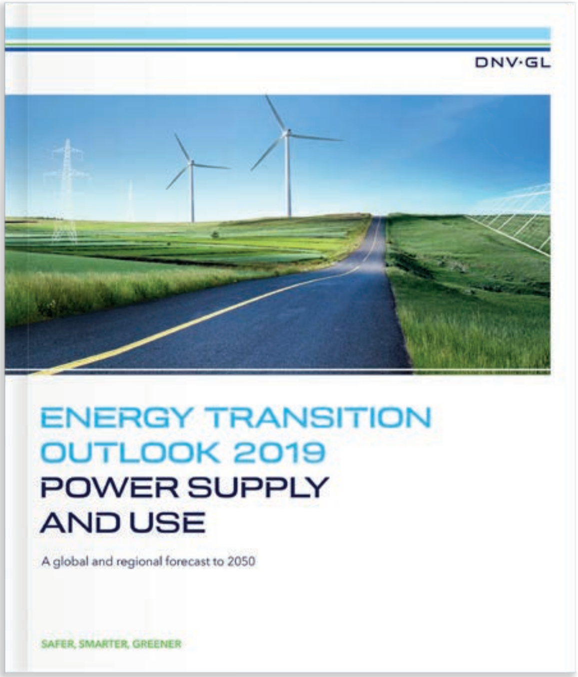

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A global and regional forecast to 2050

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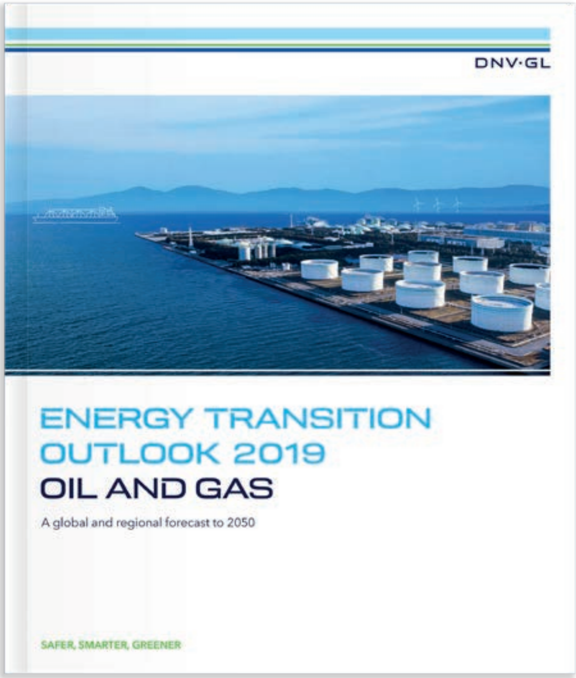
- The global energy demand for transport, buildings and manufacturing, the changing energy mix, energy efficiency and expenditures
- Detailed regional energy outlooks
- The climate implications of our outlook and an assessment of how to close the gap to well below 2°C

POWER SUPPLY AND USE

This report presents implications of our energy forecast to 2050 for key stakeholders involved in electricity generation, including renewables; electricity transmission and distribution; and energy use. Amidst electricity use increasing rapidly and production becoming dominated by renewables, the report details important industry implications. These include:

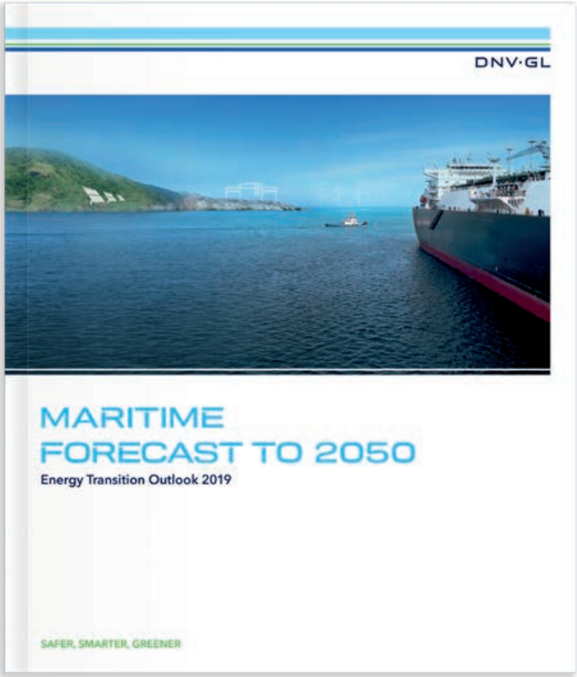
- Substantial opportunities for those parties involved in solar and wind generation
- Massive expansion and reinforcement of transmission and distribution networks
- Further need for implementation of energy efficiency technology
- Acceleration of the electric vehicle revolution
- The energy transition is fast, but not fast enough to meet the goals of the Paris Agreement



OIL AND GAS

Our Oil and Gas report discusses how these hydrocarbons remain key to the secure supply of affordable energy up to 2050. Key features include:

- Gas becomes the primary energy source from the mid-2020s as oil and gas companies decarbonize portfolios and gas increasingly complements variable renewables
- Gas demand growth plateaus in 2033 but it remains the dominant primary energy source, supplying 29% in mid-century. New sources of gas (e.g. biogas, hydrogen and synthetic methane) are will be introduced to domestic and commercial energy systems, helping to decarbonize gas consumption
- Oil supplies 17% of primary energy in 2050, despite oil demand peaking in the mid-2020s
- A need for greater efficiency and investment in new oil and gas production are indicated



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- Uptake and characteristics of relevant technologies, i.e. dual-fuel engines, fuel cells, and battery electric power
- How fuel flexibility and bridging technologies can smooth transition from traditional fuels
- CO_2 emissions and which fuels are likely to be in the mix towards 2050
- A new multi-scenario approach for robust newbuilding strategy based on our expanded concept of future-proof ships

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