MARITIME FORECAST TO 2050

Energy Transition Outlook 2020

SAFER, SMARTER, GREENER

MARITIME FORECAST TO 2050

Energy Transition Outlook 2020

FOREWORD

KNUT ØRBECK-NILSSEN

CEO
DNV GL – MARITIME

When we launched the first Maritime Forecast to 2050, it was hard to imagine a situation like we find ourselves in in 2020. The COVID-19 crisis has transformed the world, our behaviour and the maritime industry in a way that is unprecedented in modern history. For shipping, this has created a level of uncertainty in terms of energy use, ability to trade, and the safety of the assets and people working in our industry that could have long-lasting effects on the whole shipping sector.

Even in the face of the massive challenges brought on us by the virus, we can see that the maritime industry is still incredibly resilient. It is adapting, working to make the best of the situation, and innovating to keep delivering. The last few months have turbocharged the ongoing shift towards the wider use of data and models and remote services in shipping and this will surely result in overall gains in efficiency and productivity.

But even so, the ongoing challenge for this generation is finding a pathway towards decarbonization. There is still room for vessels to improve their efficiency, both operationally and in the technology onboard. But meeting this goal requires a new cooperative approach, and will require the systemic integration of technologies, fuels, and operational processes, within both vessels and the industry as a whole.

As we previously emphasized in the first Maritime Forecast publication, the biggest factor in decarbonization is the fuels that we use – and the fuel picture for shipping is becoming ever more complicated. Not only is the number of potential fuels expanding, but the availability, prices and policy measures that could enable or negatively impact each choice make the fuel decision much more difficult. Decarbonization is also becoming a motivating factor for stakeholders such as banks, investors, and customers further up in the supply chain, up to the end consumer – and they are now starting to act on it.

This complexity means that exploring a wide range of scenarios is essential. Helping to manage the risks when deciding on the ships we build and operate today lies at the core of the scenario-based modelling approach that we advocate in the Maritime Forecast.

Over the past year, the importance of certainty when it comes to making newbuilding decisions has become even more apparent. The significant boost in the uptake of LNG as fuel that has come with the finalization of the IGF code and the introduction of the global sulfur cap, shows that regulatory certainty is a critical factor that may drive the development and implementation of alternative fuels in the future.

With our Maritime Forecast, we are working to show that with foresight and a clear vision there can be a path through complexity. Because even in these extraordinary times, we must make practical and sound decisions today but still look ahead and find the innovations that will fuel our journey forward.

Knut

Knut Ørbeck-Nilssen,
CEO of DNV GL – Maritime

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THE PROJECT TEAM

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

Shipping's main challenge over the current decade is to prepare for and start on a decarbonization pathway. Alternative carbon-neutral fuels are essential for achieving International Maritime Organization (IMO) greenhouse gas (GHG) emissions reduction goals in 2050, and the only practical way for shipping to achieve the ultimate vision of full decarbonization as soon as possible before 2100.

WHAT WE DID

Forthcoming short-term policy measures and regulations under discussion at the IMO will already impact on business in 2023. In the longer term, large-scale development and deployment of carbon-neutral fuels are essential for achieving the 2050 GHG reduction goals and the ultimate vision of full decarbonization before 2100. Our report aims to enhance a shipowner's ability to navigate technological, regulatory and market uncertainty due to decarbonization – thus maintaining competitiveness, profitability and value over time.

Our updated scenario-based framework for assessing ship designs has two steps. First, we generate a library of scenarios, each describing a possible development of the future fleet composition, energy use and fuel mix, and carbon dioxide (CO_2) emissions to 2050. Second, we analyse how particular fuel-technology alternatives perform commercially in each of our scenarios using a new Panamax bulk carrier as a case study.

The scenarios cover three distinct decarbonization ambitions or pathways: '*No ambitions*' with no further decarbonization policies; '*IMO ambitions*' following the targets set in the Initial IMO GHG Strategy; and '*Decarbonization by 2040*' representing a future in which other stakeholders increasingly apply pressure on the industry with the result that the IMO adjusts its ambitions.

Within each pathway we explore uncertainty along three dimensions: regulatory policy measures, fuel prices, and seaborne trade demand. We have run 30 scenarios, giving an extensive library of possible decarbonization trajectories, each with a unique energy mix and technology uptake (Figure 1).

Our pathway modelling covers tank-to-wake CO_2 emissions. Although we have excluded non-CO_2 GHG emissions such as methane slip and nitrous oxides from the analysis, we anticipate that they will be addressed by regulations and reduced through technology development. We evaluate 16 different fuel types as well as 10 engine and fuel systems. The fuels originate from three primary energy sources: renewable electricity to produce electrofuels; sustainable biomass to make biofuels; and fossil fuels to make both conventional and blue fuels.[1]

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[1] Blue fuels are produced via reformed natural gas with carbon capture and storage.

HIGHLIGHTS

- This report aims to enhance a shipowner's ability to navigate technological, regulatory and market uncertainty due to decarbonization – thus maintaining competitiveness, profitability and value over time.
- We have developed a library of 30 scenarios projecting future fleet composition, energy use and fuel mix, and CO_2 emissions to 2050. We model 16 different fuel types and 10 fuel-technology systems. The fuels originate from three primary energy sources: renewable electricity to produce electrofuels; sustainable biomass to make biofuels; and fossil fuels to make both conventional fuels and blue fuels.
- Each of our scenarios belongs to one of three distinct decarbonization pathways: one in which no further regulations are imposed on shipping; a second, in which shipping achieves ambitions set in the Initial IMO GHG strategy; and a third, the most ambitious pathway, in which shipping aims to decarbonize the fleet by 2040.
- Regulatory policies and primary energy prices are key drivers for uptake of carbon-neutral fuels and the future fuel mix. Our library of 30 scenarios results in widely different outcomes for the fuel mix in the fleet in 2050:
    - Fossil VLSFO/MGO and LNG[2] are in rapid decline by mid-century, or even phased out in the most ambitious decarbonization scenarios. The uptake of carbon-neutral fuel picks up in the late 2030s or mid-2040s, reaching between 60% and 100% of the fuel mix in 2050.
    - It is hard to identify clear winners among the many different fuel options across all scenarios, but e-ammonia[3], blue ammonia and bio-methanol[4] are the most promising carbon-neutral fuels in the long run in a decarbonization trajectory.
    - Fossil LNG gains a significant share until regulations tighten in 2030 or 2040 depending on the decarbonization pathway, when we see bio-MGO, e-MGO, bio-LNG and e-LNG used as drop-in fuels for existing ships, and bio-methanol, blue ammonia or e-ammonia for newbuilds and some retrofits.
    - Although ammonia and methanol dominate the fuel mix in 2050, we also see that bio-LNG, e-LNG, bio-MGO and e-MGO have a limited but stable share for newbuilds, indicating that these fuels are not only transitional fuels but a viable alternative for some ships.
- Analysing how particular fuel-technology alternatives perform commercially in each of our scenarios using a newbuild Panamax bulk carrier as a case study shows that installing a dual-fuel LNG engine and fuel system is consistently the most robust choice.
- Picking the wrong solution can lead to a significant competitive disadvantage. Planning for fuel flexibility could ease the transition and minimize the risk of investing in stranded assets. A structured scenario-based approach to future-proofing vessels will help in managing the decarbonization risks.
- Uptake of carbon-neutral fuels will not happen until a clear and robust regulatory framework is put in place. To drive the development of new technologies, the framework must ensure global availability of large volumes of carbon-neutral fuels; enable their safe use; and, incentivize their uptake while retaining a level playing field.

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[2] VLSFO, very low sulfur fuel oil; MGO, marine gas oil; LNG, liquefied natural gas.

[3] e- indicates an electrofuel based on 'green'-hydrogen – from electrolysing water with renewable electricity – that can be synthesized with nitrogen or non-fossil carbon dioxide.

[4] Bio- indicates a biofuel derived from biomass.

WHAT WE FOUND

DECARBONIZATION PATHWAYS

Policy and regulation will be key among the many factors likely to impact the future decarbonization trajectory of shipping. Figure 1 shows the CO_2 emissions and carbon intensity (as grammes per deadweight-mile) trajectories for our 30 scenarios. We see that if no further policy measures than those already scheduled are implemented to regulate carbon emissions from shipping, absolute emissions could more than double, depending on seaborne transportation demand. In the most ambitious pathway, *Decarbonization by 2040*, emissions decrease rapidly to reach zero before 2040. For the intermediate decarbonization pathway – the *IMO ambitions* as prescribed by the Initial IMO GHG Strategy – all scenarios fulfil the 50% reduction in absolute emissions in 2050, and the carbon-intensity reduction target of 70%.

FUTURE ENERGY MIX

Regulatory policies and primary energy prices are key drivers for uptake of carbon-neutral fuels and the future fuel mix. The 30 scenarios result in widely different outcomes for the fuel mix in the fleet in 2050.

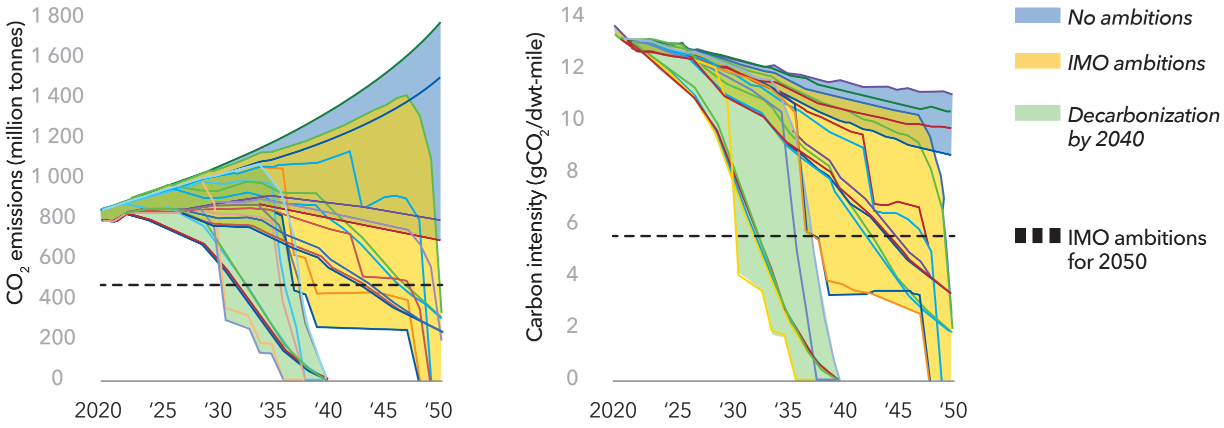
In the scenarios with no decarbonization ambitions fossil fuels such as very low sulfur fuel oil and marine gas oil (VLSFO/MGO) and LNG dominate the fuel mix, with their shares being determined by the primary energy prices of crude oil and gas.

In the decarbonization scenarios though, fossil VLSFO/MGO and LNG are in rapid decline by mid-century, or even phased out in the most ambitious scenarios. The uptake of carbon-neutral fuel picks up in the late 2030s or mid-2040s, reaching between 60% and 100% of the fuel mix in 2050 depending on the decarbonization pathway and corresponding policy measures (Figure 2). In the *Decarbonization by 2040* pathway, the uptake of carbon-neutral fuel increases rapidly, reaching up to 35% in 2030 and 100% by 2040, indicating that the fuel shift will happen during the lifetime of a vessel built today. In the *IMO ambitions* pathway, the shift takes place at least a decade later and fossil fuels are still an important part of the fuel mix in 2040.

It is hard to identify clear winners among the many different fuel options across all decarbonization

FIGURE 1

CO_2 emission (left) and carbon intensity (right) trajectories for the 30 scenarios modelled for the decarbonization pathways.



scenarios. Figure 3 shows the share of energy use in 2050 for each modelled fuel type across the 30 scenarios.

E-ammonia, blue ammonia and bio-methanol frequently appear with a high share of the energy-use mix in the scenarios. They are the most promising carbon-neutral fuels in the long run in a decarbonization trajectory. Most scenarios see substantial uptake of at least three or four different fuels in 2050. Fossil LNG gains a substantial share following the *IMO ambitions*. However, as regulations tighten in 2030 or 2040, depending on the decarbonization pathway, we see bio-LNG, e-LNG, bio-MGO and e-MGO used as drop-in fuel for existing ships, while bio-methanol, blue ammonia or e-ammonia are used for newbuilds and some retrofits. In the *Decarbonization by 2040* scenarios, instead of a transition via LNG, the fleet shifts directly to carbon-neutral methanol or ammonia, with bio-MGO and e-MGO as drop-in fuels for existing ships.

While ammonia and methanol dominate the fuel mix in 2050, bio-LNG, e-LNG, bio-MGO and e-MGO have a limited but stable share for newbuilds, indicating that these are not only transitional fuels but a viable alternative for some ships.

Though hydrogen as a fuel does not gain a significant uptake in the modelling, it is important to note that it still plays an integral role as a building block in the production of many carbon-neutral fuels (e.g. blue ammonia, e-ammonia and e-methanol).

FIGURE 2

Share of carbon-neutral fuels in shipping energy mix towards 2050 for the *IMO ambitions* and *Decarbonization by 2040* pathways. The range covers the minimum and maximum share per year across all scenarios for the particular pathway.

Units: Percentage (%)

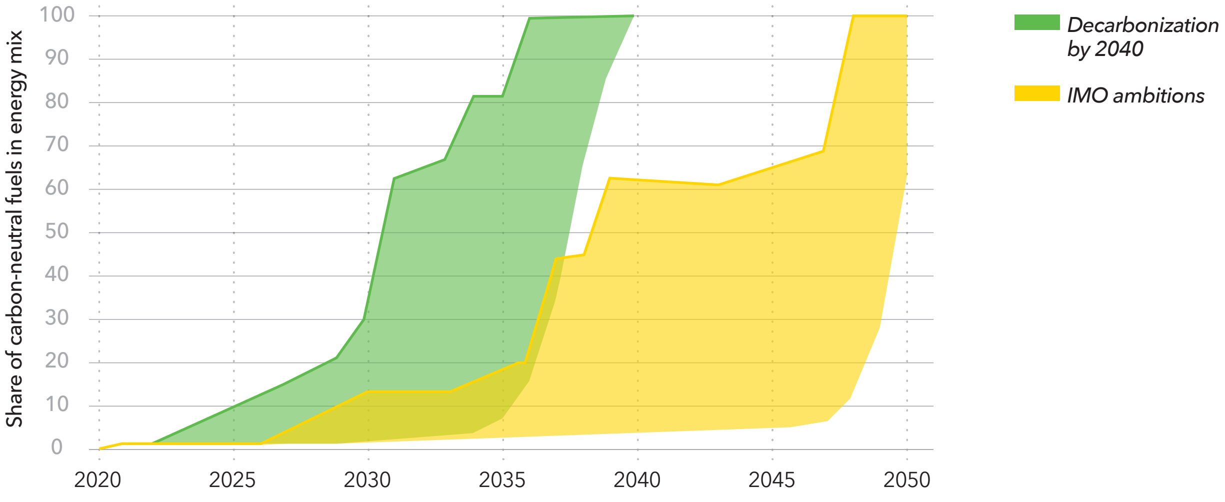


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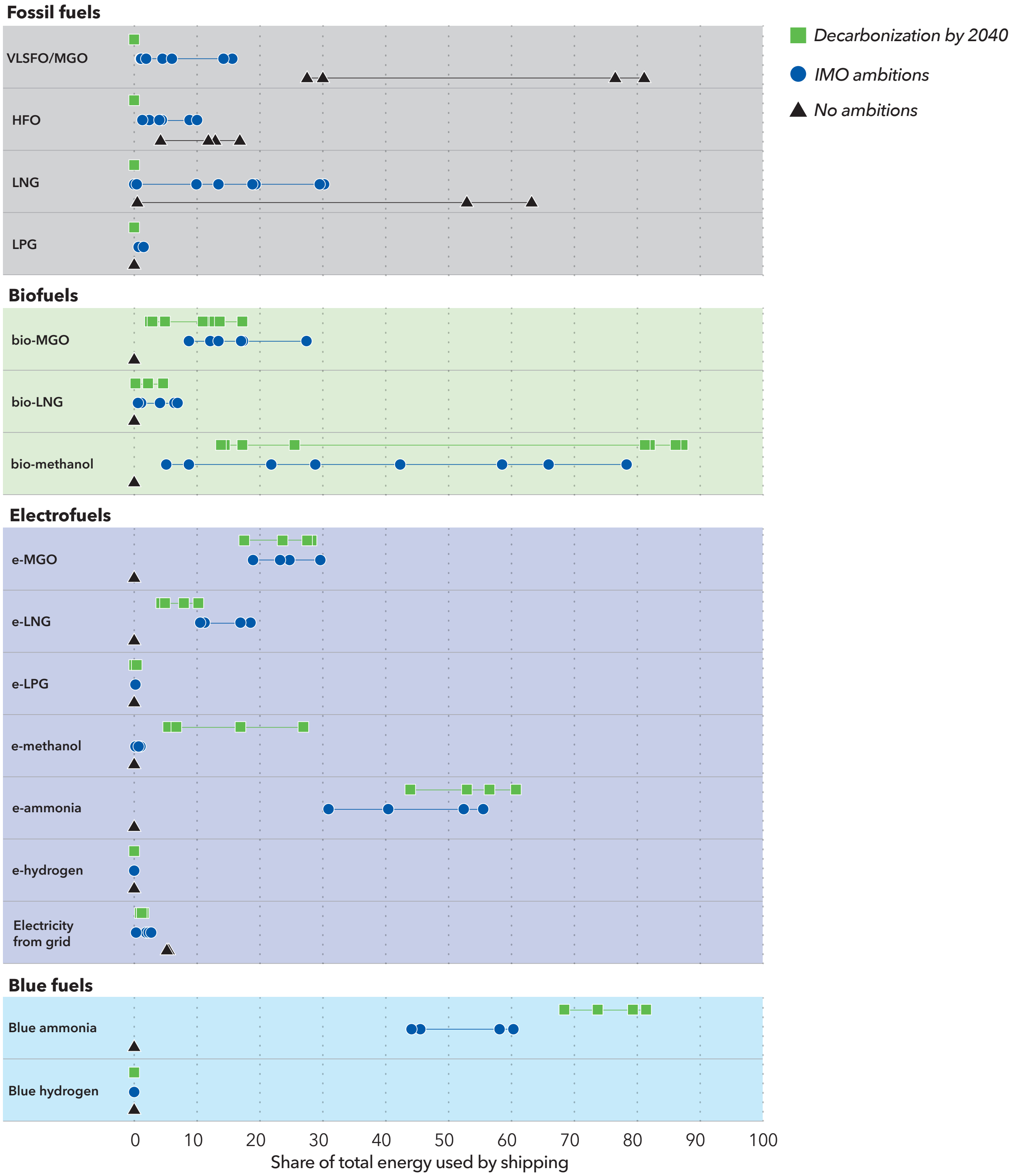
FIGURE 3

Share of total energy used by shipping in 2050 by fuel type. Lines show the minimum and maximum uptake of fuels for each decarbonization pathway represented by a geometric symbol. Note that the share is zero for many fuels in multiple scenarios.

Units: Percentage (%)



VLSFO, very low sulfur fuel oil; MGO, marine gas oil; HFO, heavy fuel oil; LNG, liquefied natural gas; LPG, liquefied petroleum gas

Note that the sensitivity of the results to the assumptions is high, as shown by the large variation in the fuel mix across scenarios. We find that regulatory policies and primary energy prices are key drivers of the future fuel mix in shipping. Changes to the input assumptions used in this study might result in very different outcomes. In addition, we have not limited the availability of carbon-neutral fuels, though this is likely to be a major constraint on achieving the decarbonization pathways. The constraints are both on the ship side – having available engines and fuel systems, the capacity to install them, and training crews to use them – and onshore, e.g. having the necessary and sustainable primary-energy production and distribution infrastructure.

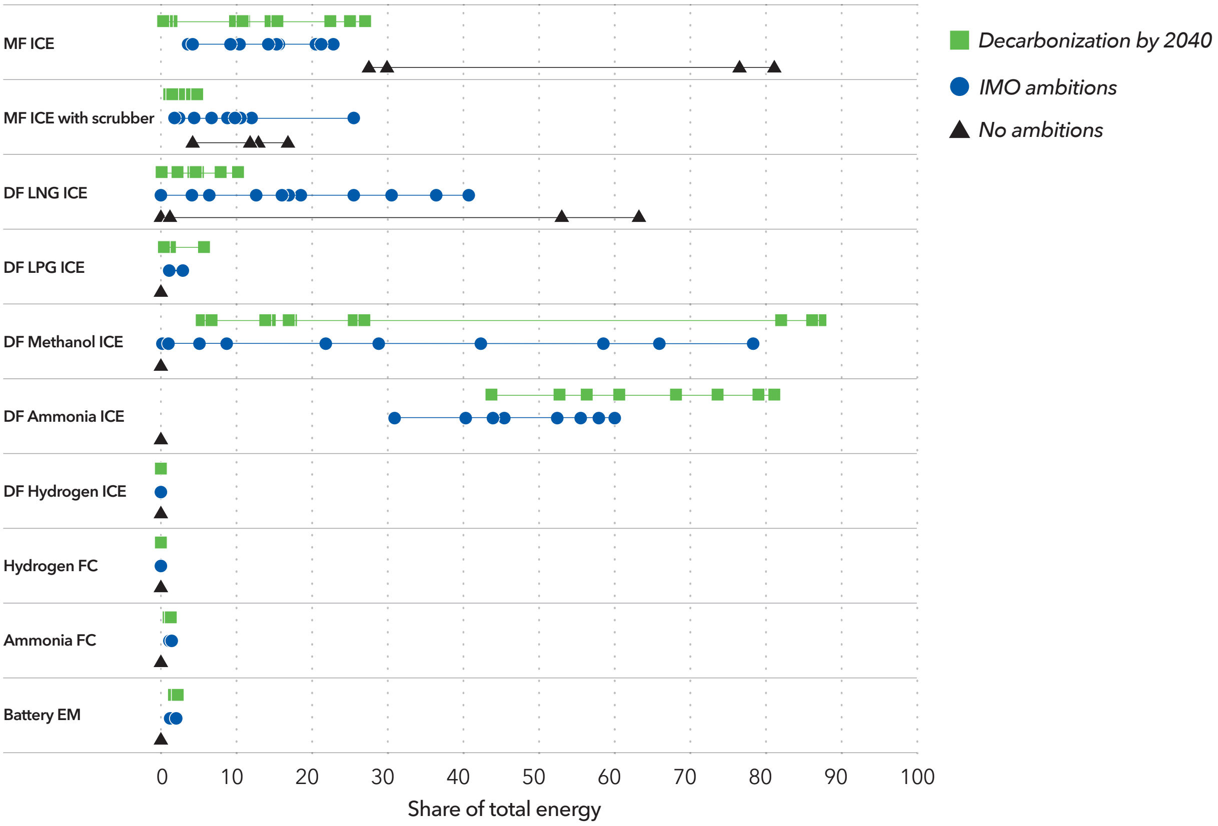
FUTURE FLEET-WIDE DISTRIBUTION OF ENGINE TECHNOLOGY SYSTEMS

Though alternative fuels may require specific onboard engine and storage technology, many of these fuel variants will be compatible with the same onboard technology. As shown by Figure 4, in our modelling of fleet-wide distribution of

FIGURE 4

Distribution of engine / fuel cell and fuel systems in terms of share of total energy use by shipping in 2050. Each geometric symbol represents a scenario.

Units: Percentage (%)



MF, mono fuel; ICE, internal combustion engine; DF, dual fuel; LNG, liquefied natural gas; LPG, liquefied petroleum gas; FC, fuel cell; EM, electric motor

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engine technology systems in the decarbonization scenarios (*IMO ambitions* and *Decarbonization by 2040*), dual-fuel methanol and ammonia engine and fuel systems (DF methanol ICE[5] and DF ammonia ICE) emerge as the most promising solutions towards 2050. Dual-fuel LNG engines gain a significant share in the *IMO ambitions* pathway with many ships retrofitting to methanol or ammonia engine and fuel systems towards mid-century.

The model prefers methanol and ammonia engine and fuel systems due to their assumed favourable fuel prices and investment costs for onboard implementation. Investment costs for onboard storage solutions for these fuels are lower than for others, such as hydrogen. However, ammonia engines and fuel systems are presently immature and significant technical and safety challenges need to be solved.

TRACKING RETROFIT TRANSITIONS FOR SELECTED SCENARIOS

The modelled fuel and technology mix for ships in 2050 will be a result of a development path where a ship is built to run on one fuel and later switch to a drop-in fuel or retrofit to another engine and fuel system. For instance, a significant share of ships expected to use methanol and ammonia in 2050 have in many scenarios been through a retrofit from dual-fuel LNG solutions. The pace of decarbonization plays a significant role. In the *Decarbonization by 2040* pathway, all fuels used must be carbon-neutral by 2040, and the transition must start almost immediately and accelerate from 2030. Instead of a transition via LNG, the fleet shifts directly to methanol or ammonia, with bio-MGO and e-MGO as drop-in fuels for existing ships.

To illustrate such paths, Figure 5 shows a stylized view of the engine and fuel system installed in the fleet, and key transitions each decade from 2020 to 2050, for two example scenarios. The first scenario (left panel, scenario 11) follows the *IMO ambitions* pathway with design and operational requirements, while the second scenario (right panel, scenario 19) follows the *Decarbonization by 2040* pathway using design and operational requirements. The development between 2020 and 2030 is very similar, with retrofitting of scrubbers and growth in the use of LNG on newbuilds. After 2030, a transition to methanol starts in the *Decarbonization by 2040* pathway, while for the *IMO ambitions* pathway, the uptake of LNG continues until 2040, when a transition to ammonia starts.

CASE STUDY: ASSESSING THE COMMERCIAL ROBUSTNESS OF A NEWBUILD PANAMAX BULK CARRIER

The fleet-wide distribution of engine technologies and fuel mix in the scenarios provides limited guidance for a shipowner investing in a particular vessel in a specific segment. As a case study, we have applied our future-proof framework to perform a commercial robustness assessment of different fuel technology alternatives on a Panamax bulk carrier built in 2020. A robust engine and fuel system should perform well in a high-growth economic scenario where shipping is decarbonized by 2040; in a low-growth economic scenario where decarbonization stretches beyond 2050; and, in other likely scenarios.

To measure the robustness and competitiveness of a design we use our key performance indicator (KPI), the Daily Cost Delta. This KPI is the difference between the technology break-even cost and the market benchmark rate for a specific segment and year, averaged over a 20-year period. Having a positive Daily Cost Delta means lower break-even costs than the market benchmark, and a higher margin.

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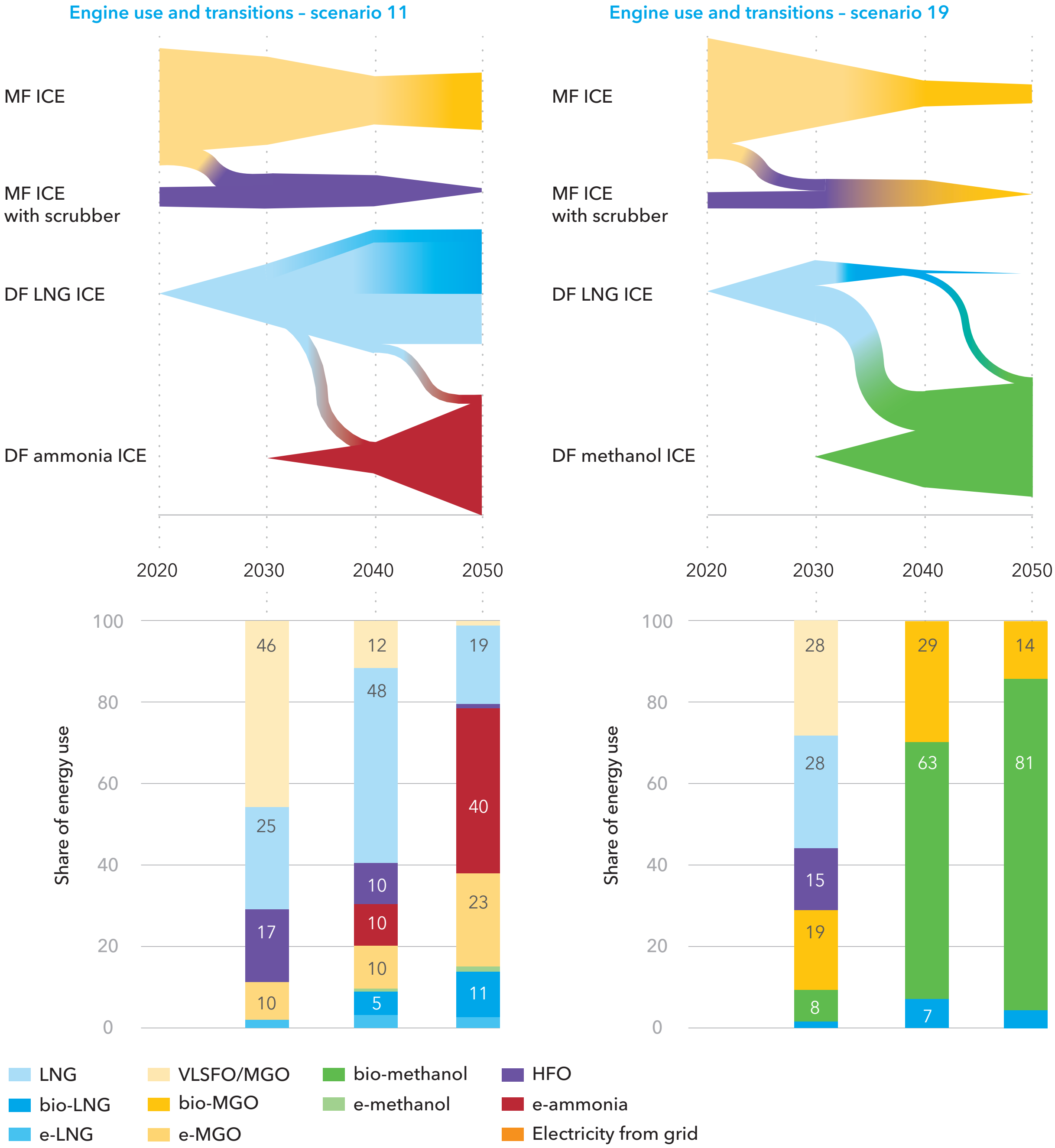
[5] ICE, internal combustion engine.

FIGURE 5

Engine and fuel system, transition pathways and energy mix per decade to 2050 for scenario 11 (left panel) and scenario 19 (right panel). The width of the bars is approximately to scale, reflecting the energy use. The retrofit transitions are shown as a bar from one engine type to another. Not all engine types are shown, and only the most significant retrofit transitions are displayed.

Units: Percentage (%)



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We stress-test the performance of various engine and fuel-system options across the 30 scenarios, giving the results in Figure 6. Installing a dual-fuel LNG engine and fuel system is consistently the most robust choice in our case study, except in the low fossil-fuel price scenarios where the price difference between LNG and VLSFO/MGO is less. The financial performance of a conventional diesel engine with a scrubber (MF ICE with scrubber) and able to run on HFO is generally better than one without a scrubber (MF ICE).

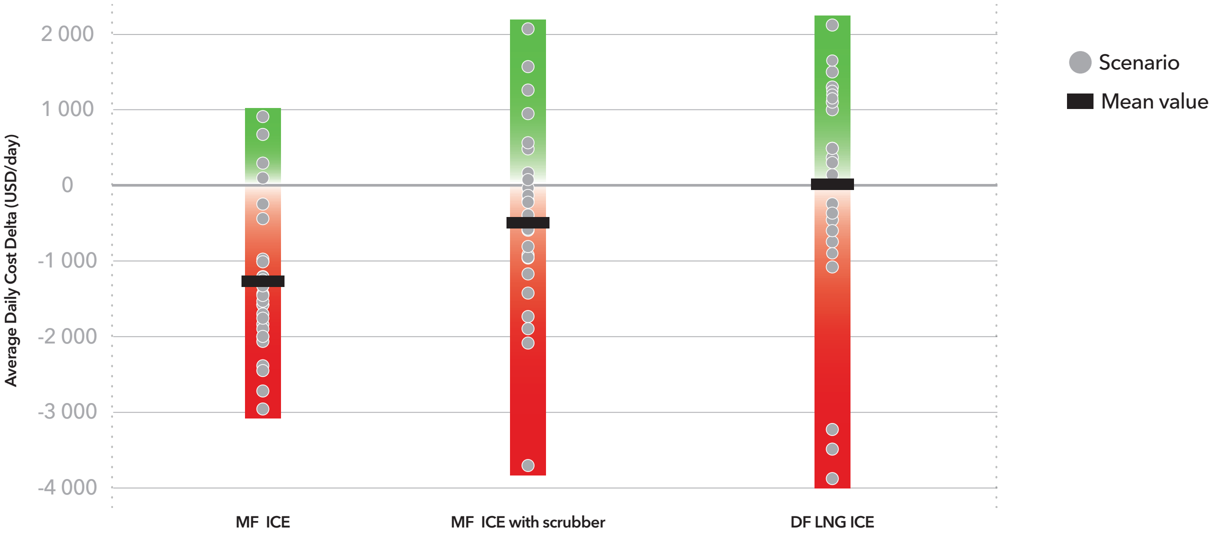
All three options generally perform worse in the *Decarbonization by 2040* scenarios where we expect that ships built today will have to switch to a carbon-neutral fuel sometime in the 2030s, and well within the lifetime of the ship. Regardless of the option selected today, the ship will be at a disadvantage to other ships in the segment with new technologies in the future, though dual-fuel LNG engines perform better than the other two options.

We see three main reasons for the higher comparative performance of the dual-fuel LNG engine: First and foremost, the dual-fuel LNG engine wins out because it can run on cheaper LNG. Second, ships equipped with LNG engines will have a 20% to 25% reduction in tank-to-wake CO_2 emissions, yielding a significant benefit when striving to comply with increasingly stringent regulations. Third, but also significant, the LNG engine and fuel system retains flexibility with regard to future decarbonization options including setting aside space for, and potentially reuse of, fuel storage tanks.

FIGURE 6

Average Daily Cost Delta over 20 years for engine and fuel options available for Panamax bulk carriers built in 2020. A positive Daily Cost Delta means lower break-even costs than the market benchmark. Each dot represents one of the 30 scenarios.

Engine and fuel-system robustness



MF, mono fuel; ICE, internal combustion engine; DF, dual fuel; LNG, liquefied natural gas

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CONCLUDING REMARKS

Our robustness assessment of various engine and fuel systems for a new Panamax bulk carrier shows that picking the wrong solution can lead to a significant competitive disadvantage. The wide variety in the fuel mix across the scenarios points to the high uncertainty of future policy measures, fuel availability, and prices. This represents a significant risk for today's newbuild decisions and should be on the radar for shipowners' asset value and balance sheet management. Planning for fuel flexibility could ease the transition and minimize the risk of investing in stranded assets. A structured, scenario-based approach to future-proofing will help in managing the decarbonization risks.

The scenario modelling shows that no uptake of carbon-neutral fuels will take place until a clear and robust regulatory framework is in place. The business case for developing and using new fuels and technologies must be clear. In addition, for a framework to drive the development of new technologies it must ensure global availability of large volumes of carbon-neutral fuels; enable their safe use; and, incentivize their uptake while retaining a level playing field.

Using very strict design requirements for newbuilds without corresponding operational requirements for all ships could severely disadvantage new ships, as they are forced to use a much more expensive fuel. This could again lead to older and less-efficient ships being kept in operation longer.

The speed of transition to carbon-neutral fuels will have major implications for the shipbuilding value chain and the land-based fuel supply chain. In practical terms, we need to start developing supply of carbon-neutral fuels in major ports, as well as developing the onboard solutions and corresponding regulations.

Starting with the current decade, we need to progress new-generation, carbon-neutral ships. This will require accelerated technology development, large-scale piloting for deep-sea vessels, and safety standards development. These are needed to overcome key barriers including technical maturity, cost of the required machinery and fuel-storage systems on vessels, fuel price, fuel availability and widespread/global bunkering infrastructure. Safety is also a primary concern for some fuels.

To further encourage developments, use of fuel-flexible or fuel-ready solutions onboard could help reduce shipowners' investment risk. Our modelling shows clearly the advantages of bridging technologies in the form of flexible solutions. This approach can also facilitate and ease the transition from conventional fossil fuels to carbon-neutral fuels. This must go together with greater energy efficiency of ships, requiring re-thinking both operationally and with an intensified uptake of proven energy-recovery and energy-efficiency technologies. The findings and observations above also place new and stronger emphasis on system-level thinking and integration of all available technologies.

CHAPTER

1

INTRODUCTION

1 INTRODUCTION

This publication is part of DNV GL's 2020 suite of Energy Transition Outlook (ETO) reports. This latest publication provides an independent outlook of the maritime energy future and examines how the energy transition will affect the industry – with focus on the decarbonization challenge. It significantly updates our 2019 analysis (DNV GL, 2019a).

Shipping is experiencing increasing pressure to decarbonize its operations and to reduce emissions to air. Most notably, in April 2018 the IMO adopted an ambitious GHG emissions-reduction strategy for international shipping. Increasingly, we also see key stakeholders such as banks and cargo owners focusing on decarbonization. All this points to a changing business environment for ships in the near future. It will shape the future fleet in important ways, particularly in the choice of fuels and technologies. This will likely impact costs, asset values and earning capacity more significantly than observed in the past.

In contrast to previous environmental requirements, meeting GHG targets requires fundamentally more challenging technological and operational changes for shipping. The challenges include a transition to new and alternative zero-carbon/carbon-neutral fuels and unconventional technologies. In addition, the energy efficiency of ships requires rethinking, with the uptake of proven energy-recovery and energy-efficiency technologies to be intensified. These challenges also place a new and stronger focus on system-level thinking and integration of all available technologies. While the industry has been discussing emissions reduction for many years, all the most likely solutions face challenges and barriers. Meanwhile, shipowners postpone investment in new ships for fear of ordering a vessel that will be unacceptable under future GHG regulations.

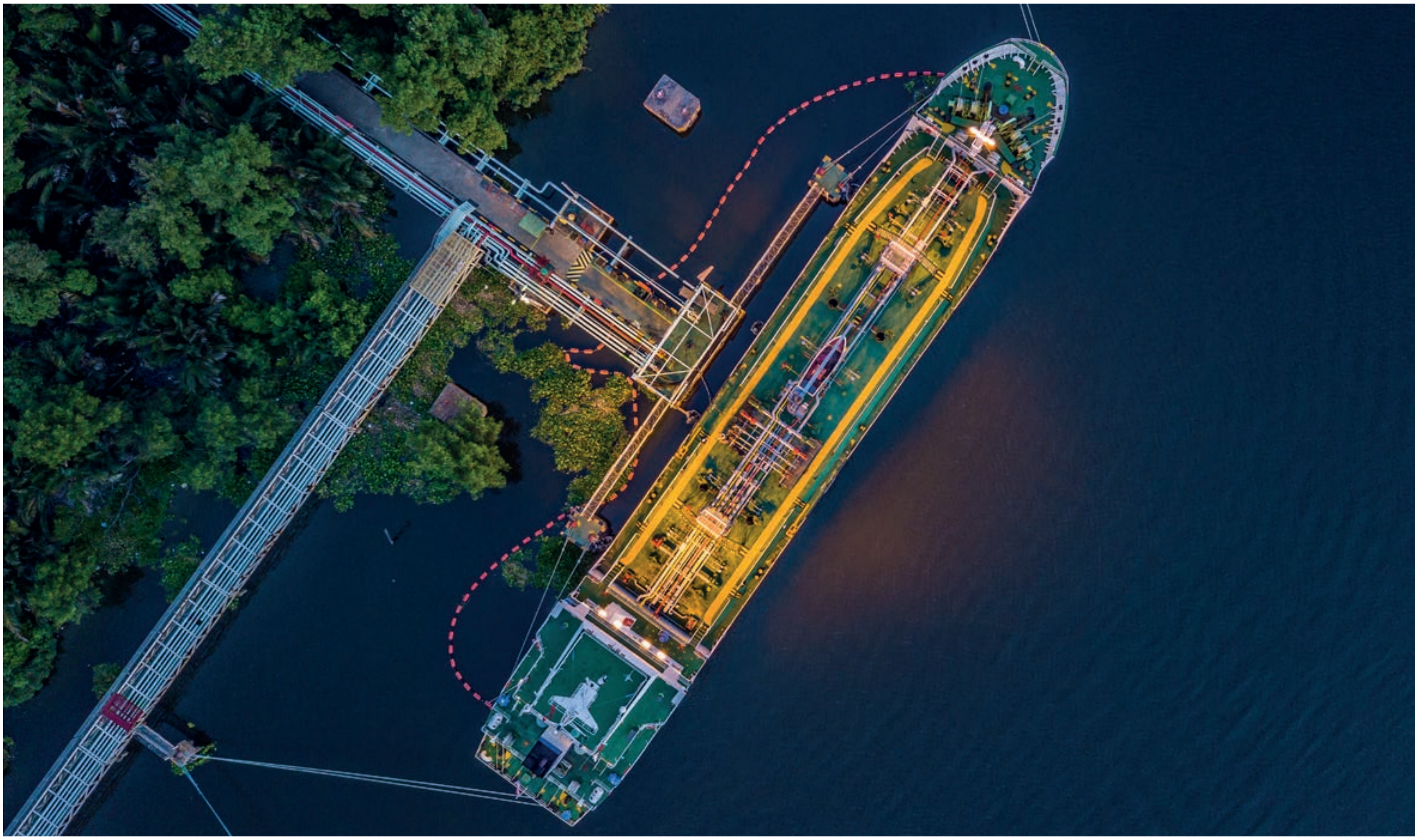
The decarbonization of shipping is part of a global transition across all industries towards greater use of renewable energy and less of fossil fuels. We have some ideas today on possible fuels for widespread adaptation in the decades to come, but cannot point to an entirely safe bet for the future. In our 2019 edition we demonstrated that carbon-neutral fuels need to supply around 40% of the total energy for international shipping in mid-century if the IMO's ambitions for reducing GHGs are to be achieved. The type and the pace of future regulations have an important role to play here, together with the future global energy mix, as well as fuel price and infrastructure development.

An increasing number of studies consider ways shipping could decarbonize, developing scenarios for the transition from conventional to zero-carbon or carbon-neutral fuels, along with technical and operational energy optimization. The zero-carbon/carbon-neutral fuels will need producing from three primary energy sources; sustainably provided biomass, renewable electricity, or fossil fuels with carbon capture and storage (CCS). Decarbonization could be especially challenging in the deep-sea segment, which generates 80% of the global fleet's CO_2 emissions.

The decarbonization issue poses challenges for a range of stakeholders, from policymakers and fuel suppliers, to yards, engine manufacturers and shipowners. For shipowners, key questions arise in relation to their ongoing newbuilding processes; how can they build ships today that are not outdated when new fuels are ready?

To help shipowners address this question, this study first discusses regulations and incentives for decarbonization (Chapter 2). We then apply a multiple-scenario approach to investigate possible fuel and converter options under different decarbonization pathways (Chapters 3, 4). Using a Panamax bulk carrier case, we stress-test engine and fuel systems to evaluate their commercial robustness under a range of scenarios (Chapter 5). Finally, we provide insights on how to bridge the emissions gap (Chapter 6).

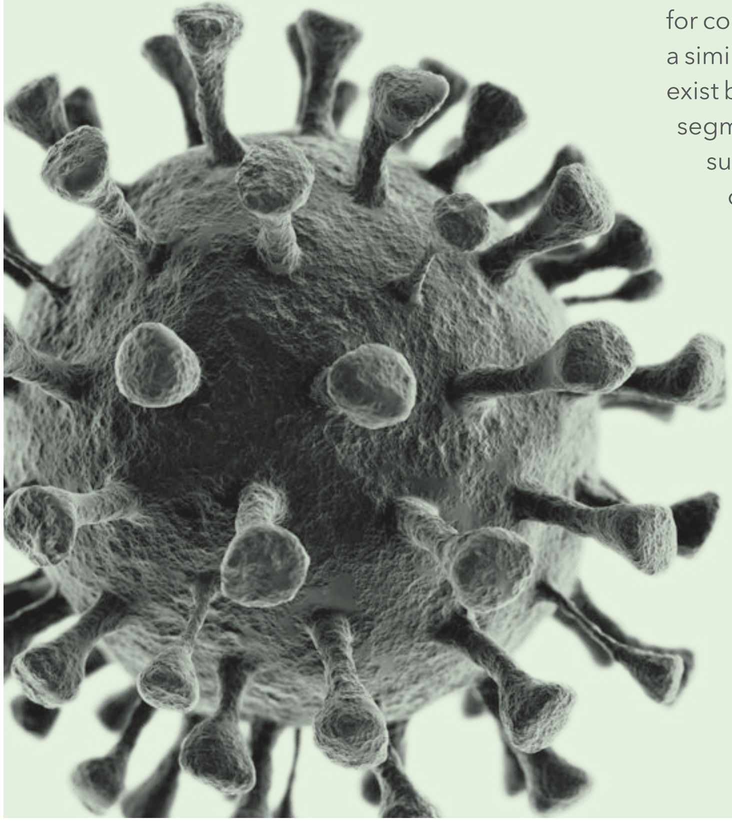
We stress that the coming decades towards 2050 hold significant uncertainties. These include, for example, economic development, future energy policies, human behaviour and reaction to policies, the pace of technological progress, pricing trends for existing and new technologies, and disruption of global supply chains (see text box next page). By applying both a structured and knowledge-based scenario approach supported by modelling tools, stakeholders can stay at the forefront of industry developments and remain competitive moving forward.



HOW HAS THE COVID-19 PANDEMIC IMPACTED SHIPPING ACTIVITY?

The maritime industry is playing a critical role in the response to the COVID-19 pandemic, keeping supply chains open and ensuring that essential goods such as food and medical products are delivered in a timely manner (UNCTAD, 2020a).

The World Trade Organization (WTO) goods barometer shows COVID-19 disrupted world trade from February to March 2020 (WTO, 2020). Output contractions due to COVID-19 in China in early 2020 were felt worldwide, reflecting the key and rising role China plays in global supply chains, travel, and commodity markets (OECD, 2020b). Subsequent outbreaks in other economies are having similar effects, albeit on a smaller scale (OECD, 2020b). Not all changes from 2019 to 2020 are due to COVID-19. The WTO barometer also shows world trade was already slowing in 2019 before the pandemic broke out. Higher tariffs on US-China bilateral trade over the past two years are important factors behind the weakening of global demand and trade (OECD, 2020b).



Global tracking data from the Automatic Identification System (AIS) indicate the impact on seaborne trade. While AIS data do not reveal the amount of cargo onboard vessels, they give a good picture of the distance sailed and transport capacity in deadweight-miles (dwt-miles). Figure 1.1 shows global AIS-tracking data from January to May 2020 compared with the same period in 2019. They reveal a decrease of around 6% in dwt-miles for container vessels. General cargo vessels show a similar trend. However, significant variations exist between different ship types and size-segments in the world fleet. Some segments, such as tankers, have shown an increase in dwt-miles compared with in 2019.

As our concern is with the long-term outlook for shipping, a key question is to what extent the changes in the first half of 2020 are temporary or will leave a permanent imprint on seaborne trade and shipping activities. It appears likely that the impact will be massive for 2020. The COVID-19 pandemic will significantly change projections for global economic growth for the period up to 2025. DNV GL's Energy Transition Outlook forecast is based on the International Monetary Fund's April GDP forecast

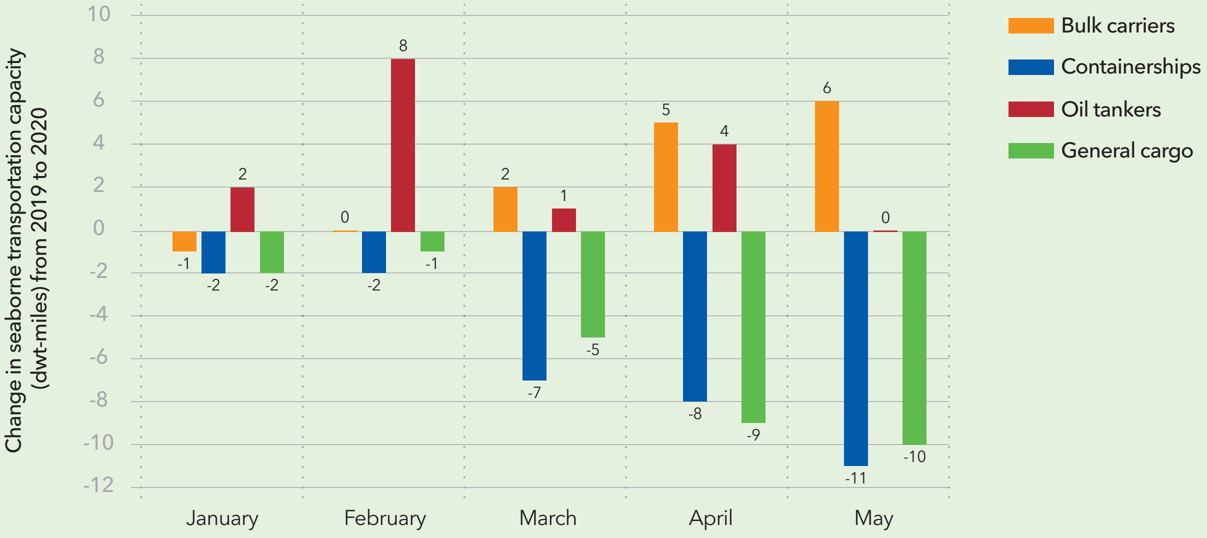
(DNV GL, 2020a). Depending on the region, the chosen scenario downgrades growth by 5% to 10% from pre-COVID projections for 2020, with pre-COVID growth rates slowly improving and only recovering fully by 2025.

For maritime trade, the negative effect varies between cargo types. Our estimates show total demand for seaborne transportation declining approximately 8% in 2020. The effect will differ depending on the given trade. A gradual recovery to the previous long-run norm for growth rates in seaborne transportation is assumed post-2020. Because manufacturing is typically more affected than the whole economy in an economic downturn, seaborne trade of manufactured products and base materials is usually at risk of greatest decline. Newbuilding of commercial and residential buildings as well as vehicle manufacture will see declines of almost a quarter in 2020; so, related shipping sectors will be hit hard. Some sectors will rebound to higher than former growth rates after 2020 before settling down later. For more details, consult Appendix B.3.

FIGURE 1.1

Changes in seaborne transportation capacity (dwt-miles) on a monthly basis, 2019 versus 2020. Statistics are based on individual tracking of all cargo ships with AIS (Automatic Identification System) in the world fleet.

Units: Percentage (%)



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HIGHLIGHTS

We provide a GHG regulatory and stakeholder outlook as the basis for developing decarbonization pathways used in our model:

- Forthcoming short-term policy measures and regulations under discussion at the IMO will already impact on business in 2023.
- In the longer term, large-scale development and deployment of carbon-neutral fuels are essential for achieving the 2050 GHG reduction goals and the ultimate vision of full decarbonization before 2100.
- Stakeholders other than the IMO can play an important role in driving decarbonization.

CHAPTER

2

REGULATIONS AND INCENTIVES FOR DECARBONIZATION

2 REGULATIONS AND INCENTIVES FOR DECARBONIZATION

This chapter discusses upcoming policy measures and regulations that will already impact on business in 2023, and their potential short- and long-term effects on the decarbonization trajectory. This is used as basis for developing the decarbonization pathways in Chapter 4.

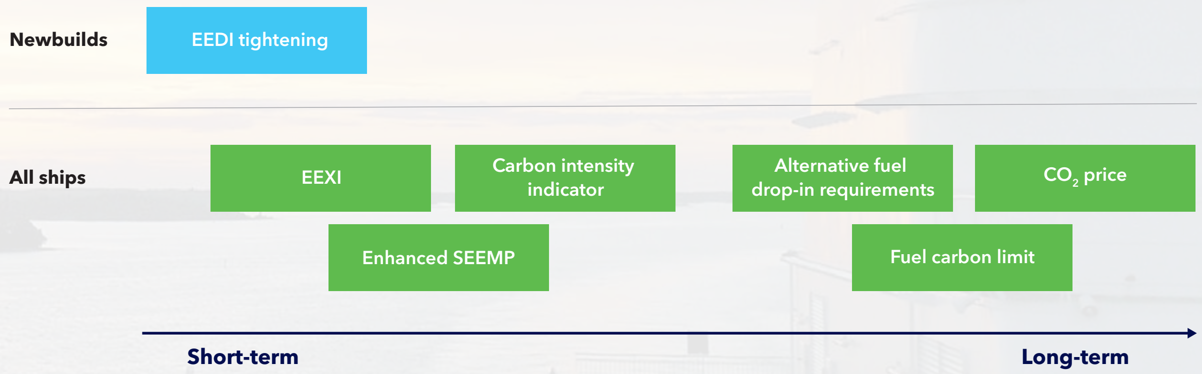
Policies and regulations are key drivers for decarbonization as the additional costs of using alternative fuels are too high to expect anything else. The Initial IMO GHG Strategy currently drives policy development within shipping. However, we also see regional regulations; market pull from charterers and banks; and private and public initiatives established to support and accelerate decarbonization. Such initiatives include, among others, Global Industry Alliance, Green Maritime Forum, Sustainable Shipping Initiative, Zero Emission Energy Distribution at Sea (ZEEDS), Getting to Zero Coalition and Green Shipping Programme.

The actual pace and form of the transformation ahead of us is still unknown. This is reflected in our modelling in Chapter 4, both in the varying decarbonization ambitions and the policy measures that may potentially be implemented. The Initial IMO GHG Strategy has an ambition to halve GHG emissions by 2050 and a vision to decarbonize shipping as soon as possible within this century. The proven ability of the IMO to design and implement industry-wide regulation to achieve the desired outcomes makes this a credible pathway. The Initial IMO GHG Strategy will be revised in 2023 and reviewed again every five years thereafter, which could result in more stringent targets. Our most ambitious pathway modelled, *Decarbonization by 2040*, goes beyond the current IMO GHG ambitions. This decarbonization pathway represents a future in which other stakeholders increasingly apply pressure on the industry, with the result that the IMO adjusts its ambitions.

New policy measures are constrained by two factors; political will and regulatory structures. Building on existing regulatory structures (conventions, codes, etc.) is much easier and faster than implementing new ones. The IMO often needs at least seven years from deciding to develop a new mandatory IMO convention – e.g. a market-based measure – until it enters into force. Amending an existing treaty (e.g. MARPOL) or adopting a new code with tacit or minimal ratification requirements is therefore significantly quicker. The IMO's two-tier approach to implementing decarbonization measures, focusing first on a limited set of short-term measures before embarking on more comprehensive long-term ones, reflects the fact that the different measures will require varying efforts and timelines for implementation (see Figure 2.1).

FIGURE 2.1

Indicative timeline for developing and implementing possible global policy measures – the list of measures is not exhaustive.



EEDI: Energy Efficiency Design Index
EEXI: Energy Efficiency Design Index for Existing Ships
SEEMP: Ship Energy Efficiency Management Plan

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2.1 SHORT-TERM EXPECTATIONS

Currently, measures addressing GHG emissions include only two mandatory requirements. One is the Energy Efficiency Design Index (EEDI) for newbuilds, mandating up to 30% improvement in design performance depending on ship type. The other is the Ship Energy Efficiency Management Plan (SEEMP) for all ships in operation, though it contains no explicit and mandatory performance requirements.

> “The IMO is on the verge of agreeing on and implementing the first tranche of additional GHG regulations, expected to enter into force in 2023.

The IMO is on the verge of agreeing on and implementing the first tranche of additional GHG regulations, expected to enter into force in 2023. We expect the centrepiece of this package will be a combination of design and operational regulations, supplemented with a suite of supporting non-regulatory measures. In combination with the upcoming EEDI Phase 3 and a possible Phase 4 later this decade, these measures will impact both newbuilds and existing ships and ensure that international shipping will meet the 2030 ambition of 40% reduction in carbon intensity.

The two key proposals for requirements for ships in operation being discussed in the IMO are: the application of the EEDI retroactively to all existing ships through the Energy Efficiency Design Index for Existing Ships (EEXI); and the Enhanced SEEMP, a strengthening of the SEEMP to include mandatory operational-efficiency improvement targets. The EEXI will impose requirements equivalent to EEDI Phase 2 or 3 to all existing ships, regardless of year of build. This also includes ships built to EEDI Phase 0 and 1 requirements, which do not currently meet EEDI Phase 2 or 3 requirements. It is intended as a one-off certification, but with a future strengthening of the EEDI we may also see a second EEXI phase to ensure that existing ships are not subject to less strict requirements than newbuilds, which might otherwise discourage fleet renewal.

The intention of the Enhanced SEEMP is to mandate year-on-year operational efficiency improvements using Carbon Intensity Indicators (CII). Examples of CIIs include the Annual Efficiency Ratio (AER) measured as gCO_2/dwt-mile, and the Energy Efficiency Operational Indicator (EEOI) expressed as gCO_2/tonne-mile.

Although these proposed measures are at different levels of maturity, both are built on established regulatory structures and can therefore be implemented quickly under the MARPOL tacit amendment procedures. We expect EEXI and Enhanced SEEMP to reach the first stage of agreement in 2020 as part of the short-term package, pending the IMO being able to conduct formal committee meetings this year in the wake of the COVID-19 pandemic. The consensus goal is to have these entering into force at the start of 2023.

2.2 LONG-TERM EXPECTATIONS

While the proposed short-term measures should be adequate in reaching the 2030 goals, further measures, or increased stringency of the short-term measures, are needed for achieving the 2050 ambitions. The IMO has made the large-scale development and deployment of carbon-neutral fuels a core part of its long-term strategy. This is driven by the understanding that not only are these fuels essential for achieving the 2050 reduction goals, they are also the only practical way for shipping to achieve the ultimate vision of full decarbonization before 2100.

At the IMO there is recognition that alternative fuels will be more expensive than conventional fuels and that a set of financial incentives could be necessary to make environmentally friendly solutions commercially attractive. We use the phrase carbon pricing to cover taxes, emission trading and levies. No form of carbon pricing scheme currently exists for international shipping, though national carbon taxes apply to domestic shipping in some countries.

Several options exist to achieve carbon pricing. While several governments (in particular, in the EU) are expected to prefer carbon pricing in the form of an emissions trading scheme, others lean towards a bunker levy. Neither option is inherently more effective than the other, and both create system-design challenges. Because the EU's Green Deal is expected to have shipping included in the EU Emissions Trading System (ETS) for GHG emissions, the IMO will be under strong political pressures to develop an international carbon pricing mechanism.

Carbon pricing could be expected to take time to be agreed and implemented. Unlike the options available for performance requirements for existing ships, any carbon pricing mechanism would most likely require a new convention to be adopted at the IMO and ratified by enough flag states. We assume that any form of carbon pricing scheme from the IMO cannot be implemented before the latter half of this decade due to the political and practical issues. An EU system could well be in place before this.

Using carbon prices as a policy tool for decarbonization could have a more uncertain outcome than using design and operational requirements. Our modelling shows that the carbon price must match or exceed the price differential between fossil and carbon-neutral fuels to incentivize a shift, but at this point the shift happens much faster than with design and regulatory requirements. If the carbon price is not high enough, no shift will take place.

With gradually stricter design and regulatory requirements a wider range of measures are applied in the modelled scenarios. In particular, we see more speed reduction. We also see prolonged use of fossil LNG because its lower CO_2 emissions gives it an advantage compared with VLSFO/MGO and HFO.

We also saw that using very strict design requirements for newbuilds without corresponding operational requirements for all ships could severely disadvantage new ships as they are forced to use a much more expensive fuel. This could again lead to older and less-efficient ships being kept in operation longer.

Although not modelled, combining carbon pricing with design and operational requirements would probably work well. The design and operational requirements are needed to force the change. The carbon price is effective in levelling the playing field, allowing some ships to run on fossil fuel in a transition period, and also avoiding distortion in the competition between new and existing ships.

Besides carbon pricing and performance requirements, other mechanisms that can potentially be applied to enforce uptake of alternative fuels include mandatory use of carbon-neutral fuels (similar to the fuel- sulfur limit). In the short term we also expect supporting measures intended to spur research, development and deployment of alternative fuels and the associated technologies and infrastructure. Developing what the IMO calls an 'implementation programme' for alternative fuels will be a key priority.

Standards based on lifecycle assessment will be needed to evaluate the carbon and GHG intensity and sustainability of the different fuels. 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.

2.3 REGULATORS AND STAKEHOLDERS BEYOND THE IMO

Our discussion until now has been IMO-centric. Clearly, other regularity entities, such as the EU, are also considering implementing regulations. This is not explicitly reflected in our modelling. This could have both regional and global impacts. Most notably, the EU has established general decarbonization goals suggesting a target of 80% below 1990 levels by 2050, with milestones to achieve a binding target of 40% emissions cuts by 2030 and, indicatively, 60% by 2040. All sectors are expected to contribute. For shipping this has, for example, led to the establishment of the EU system for Monitoring, Reporting and Verification (MRV) of CO_2 emissions, with its mandatory reporting obligations. The election of a new European Parliament and a new European Commission in 2019 has resulted in the new European Green Deal with its significantly higher ambitions. An overarching ambition of seeing a carbon-neutral Europe by 2050 is accompanied by an explicit inclusion of shipping in the Green Deal itself. While policy specifics and timelines are still work in progress, a clear mandate has been given to the European Commission to include shipping in the EU ETS for GHG emissions. Regulating access to EU ports for the most polluting ships, as well as obliging docked ships to use shore-side electricity are additional examples of Green Deal policy proposals that may very likely become regulatory measures.

We are also seeing the proliferation of domestic and local regulations. This is not only driven top-down by authorities recognizing the need to impose stricter requirements, but also bottom-up by local communities demanding action from their political representatives. This opens the way for a broad range of uniquely local requirements on ships' environmental performance. There is a rising likelihood of this also happening with GHG-related regulations. The increased focus on reducing GHG emissions, and the growing number of ports worldwide applying differentiating port fees, could strengthen rebate schemes for environmental technologies and make the business case for alternative fuels more attractive (e.g. COGEA, 2017; Mjelde et al., 2019).

Furthermore, and irrespective of the regulatory environment, companies and the public sector are attempting increasingly to 'green' their value chains, reducing their carbon footprints. This is driven by factors such as consumer preferences and pressure from investors, non-governmental organizations, politicians, and the general public. The pressure to reduce shipping GHG emissions is exemplified by the recent Poseidon Principles[6], a framework signed by major shipping banks for assessing the climate alignment of ship-finance portfolios. In addition, cargo owners and charterers have started addressing GHG emissions when selecting shipping vendors. In 2017, for example, nearly 25% of the dry bulk and wet bulk market used the RightShip A to G rating of GHG emissions as policy when choosing which vessels to charter. As a result, many of these companies are actively not sending their cargoes on vessels rated F or G, the most inefficient in the fleet (Rehmatulla et al., 2017). Consequently, a vessel's GHG performance is set to become an additional rate and contract differentiator.

The policies and incentives established by the different stakeholders will be interdependent and dynamic. We believe that IMO will be able to put in place regulations to meet their ambitions. While other stakeholders may contribute significantly to incentivizing decarbonization in the shipping industry, we maintain that the IMO is the single most influential stakeholder, with a pivotal role to play. However, it remains to be seen if the pace will be satisfactory for other key stakeholders. If not, more stringent requirements by other stakeholders are to be expected.

In the following chapters we use the presented regulatory outlook for GHG as the basis for developing the decarbonization pathways and scenario modelling.

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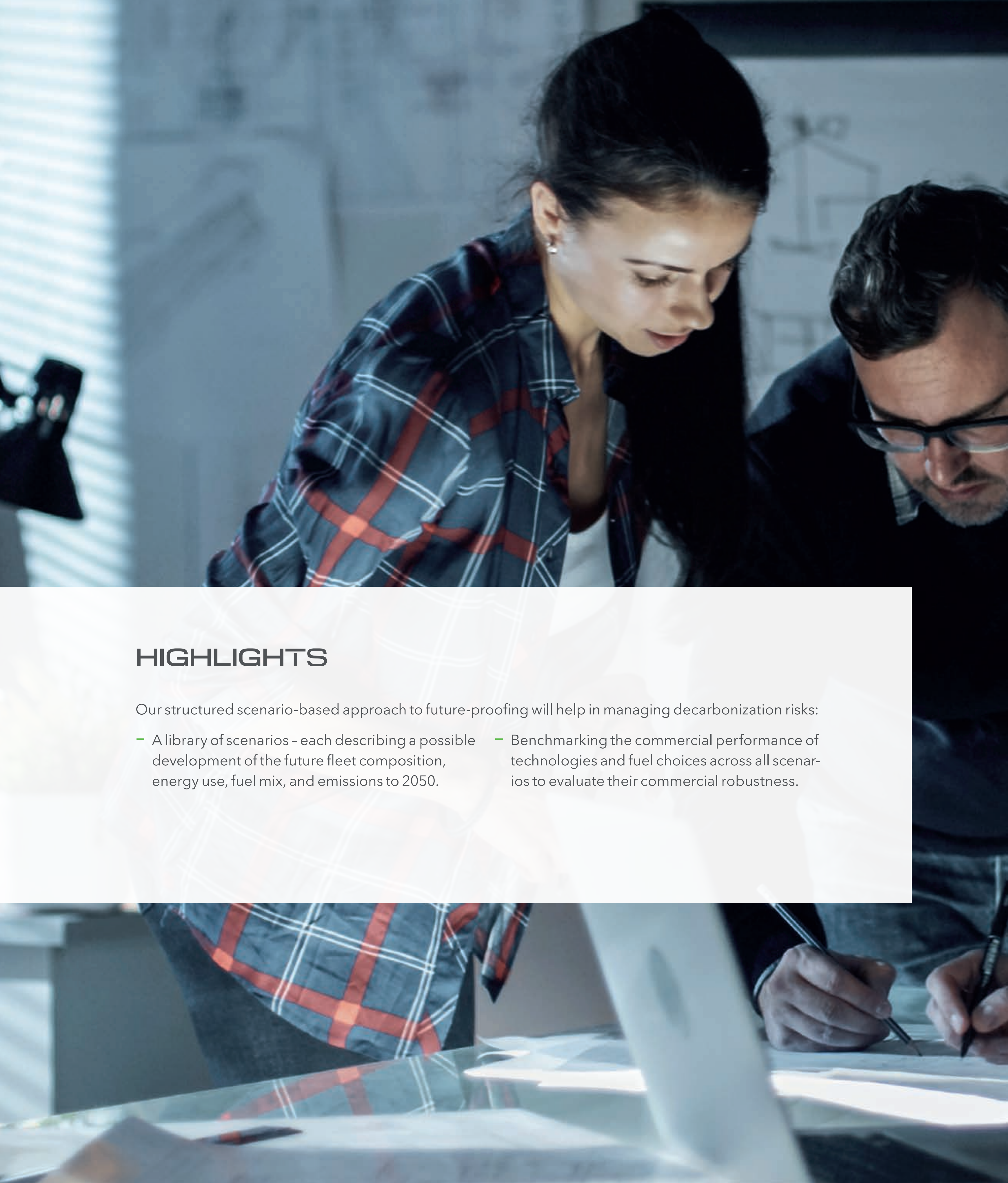
[6] 'Poseidon Principles: A global framework for responsible ship finance'. Poseidon Principles, Copenhagen, Denmark, Version 2.0, May 2020. www.poseidonprinciples.org/wp-content/uploads/2019/07/Poseidon_Principles.pdf



HIGHLIGHTS

Our structured scenario-based approach to future-proofing will help in managing decarbonization risks:

- A library of scenarios – each describing a possible development of the future fleet composition, energy use, fuel mix, and emissions to 2050.
- Benchmarking the commercial performance of technologies and fuel choices across all scenarios to evaluate their commercial robustness.

CHAPTER 3

OUR SCENARIO-BASED FRAMEWORK

3 OUR SCENARIO-BASED FRAMEWORK

The uncertainties around future decarbonization pathways are challenging for a shipowner that considers investing in new ships. In this chapter, we describe our scenario-based framework for enhancing a shipowner's ability to navigate technological, regulatory and market uncertainty to maintain competitiveness, profitability and value over time. This framework is used to develop decarbonization pathways in Chapter 4 and for the commercial robustness assessment in Chapter 5.

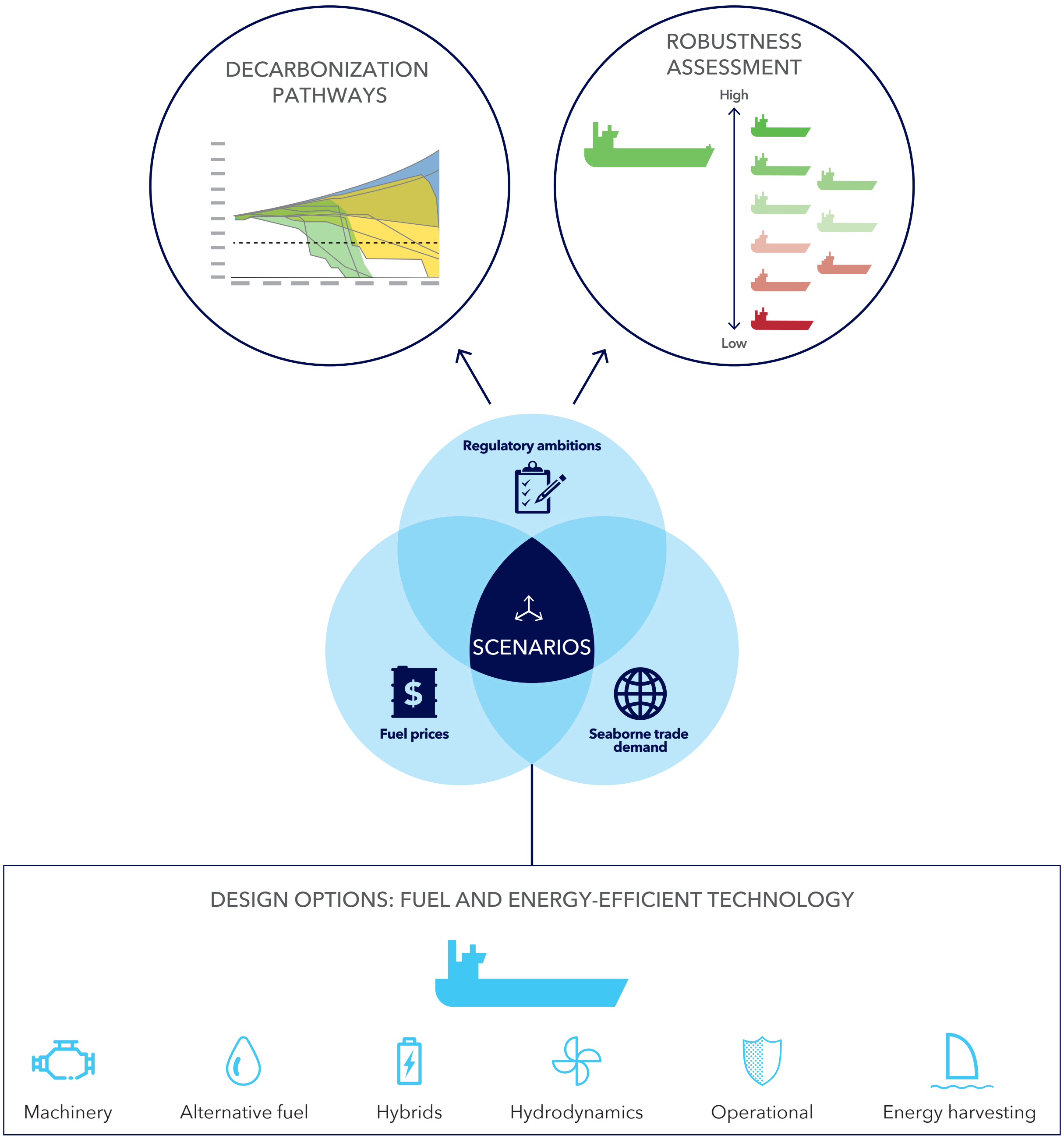
DNV GL has in previous editions of our Maritime Forecast to 2050 presented the GHG Pathway Model and Carbon-Robust Model, and our framework for future-proofing ship designs (DNV GL, 2018a; 2019a). Our updated approach for scenario-based assessment of ship designs has two analytical steps:

1. First, we generate a library of scenarios – each describing a possible development of the future fleet composition, energy use and fuel mix, and emissions to 2050 (Figure 3.1, top left). The scenarios cover three decarbonization ambition levels, spanning uncertainties about regulations, fleet growth and energy cost.
2. Second, we analyse how particular ship-design choices and technology alternatives perform in each of our scenarios. We benchmark the commercial performance of technologies and fuel choices across all scenarios to evaluate their robustness (Figure 3.1, top right). A robust investment strategy should select options that perform well in a high economic growth scenario where shipping is decarbonized by 2040; in a low economic growth scenario where the decarbonization stretches beyond 2050; and, in other likely scenarios' pathways.

In the following sub-chapters, we further describe these two steps.

FIGURE 3.1

Illustration of the scenario-based framework for generation of different decarbonization pathways and assessment of commercially robust ship designs.



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3.1 DEVELOPING A LIBRARY OF DECARBONIZATION SCENARIOS – ALTERNATIVE PATHWAYS TOWARDS 2050

Significant uncertainties around several factors influence our projected energy transition from conventional to carbon-neutral fuels when establishing long-term decarbonization pathways for shipping. This study explicitly reflects on these uncertainties, applying a scenario-based framework. A scenario describes a path of development under anticipated frame conditions, leading to a particular outcome. It is not intended to represent a full description of the future, but instead intends to highlight central elements of a possible future and to draw attention to the key factors that will drive the future developments. Scenarios are hypothetical constructs well suited to explicitly assess uncertainty in the results; they are neither forecasts, nor predictions or sensitivity analyses.

Considering the uncertainty that lies ahead, scenario analysis is a well-established method that can provide valuable input to strategic newbuilding plans and enhance fleet flexibility and resiliency to a range of possible futures related to regulatory and technology landscapes. Several studies have applied scenarios, or more advanced probabilistic techniques, to understand future developments in regard to shipping emissions and decarbonization pathways (e.g. Corbett et al., 2003; Eyring et al., 2008; Eide et al., 2013; Faber et al., 2020; Smith et al., 2014; UMAS, 2016; UMAS/Lloyd's Register, 2019; DNV GL, 2017b, 2018a, 2019a). An increasing number of recent studies have considered how shipping could decarbonize, developing scenarios for the transition from conventional to zero-carbon / carbon-neutral fuels (e.g. UMAS, 2016; UMAS / Lloyd's Register, 2019; DNV GL, 2017b, 2018a, 2019a). Our previous work has shown how different scenarios lead to very different robustness for a ship design (DNV GL, 2018a, 2019a). This study provides a much larger set of scenarios, reflecting a large span of different futures.

Our scenario library explores three distinct decarbonization pathways: '*No ambitions*' where no further decarbonization takes place; '*IMO ambitions*' of at least a 50% reduction in GHG emissions by 2050; and '*Decarbonization by 2040*'. Within each decarbonization pathway we explore three uncertainties (Figure 3.1).

- First, we explore regulatory policy measures. The IMO has come far in developing the initial regulations, but uncertainty remains over the pace, form and type of regulatory measures the organization will implement to invoke the desired change. The main variants are technical and operational measures and carbon pricing.

- Second, fuel and energy prices are key drivers of the future energy mix, as previous work has exemplified (e.g. Acciaro et al., 2012; Eide et al., 2013; DNV GL, 2019a). We use our Marine Fuel Price Mapper to explore the impact of price variations in three main inputs: fossil fuels (crude oil and gas), renewable electricity, and biomass.

- Third, we look at seaborne trade demand to reflect the large uncertainty in transportation demand. Studies have reported that international world maritime trade could grow between 25% and 250% by 2050 (Smith et al., 2014; ITF/OECD, 2019; DNV GL, 2020a), while the Fourth IMO GHG study projects between 40% and 115% growth (Faber et al., 2020).

Because regulatory ambitions, fuel prices, and seaborne trade demand have the highest uncertainty in the decades to come, we selected them as the main dimensions of our scenario constructs. Their impact on scenario outcomes are very high. Details of the modelling approach, assumptions, and the resulting scenario library are described in Chapter 4 and Appendices A and B.

The global potential of supplying sufficient amounts of primary energy for production of carbon-neutral fuels, including sustainable biomass for production of biofuels, is well-documented in literature (e.g. Delft, 2020; Ash et al., 2019; DNV GL, 2020b). We have not put any constraints on the availability of any of the fuels considered in the GHG Pathway Model. In a transition, we can expect that the initial supply is limited before production and distribution can be scaled. The scaling also depends on having available primary energy, such as sustainable biomass and renewable electricity. This approach is useful for providing an estimate of the amount of fuel needed, and when, in order to map the need for production and infrastructure.

Our pathway modelling covers tank-to-wake CO_2 emissions, which is by far the most significant for shipping from a 100-year Global Warming Potential (GWP) perspective accounting for 98% of GHG emissions in 2018 if not including black carbon (Faber et al., 2020). Other GHGs such as methane and nitrous oxides may have an increasing impact on total GHG emissions with introduction of new technologies and fuels such as LNG and ammonia. We anticipate that non-CO_2 GHG emissions will be addressed by regulation and reduced through technology development.

The same applies for well-to-tank emissions – extraction, production and transportation of new fuels will contribute to global GHG emissions. Our focus is on the ship, and we assume that what are referred to as carbon-neutral fuels in this study, and applied in our modelling, are produced by renewable electricity, from sustainably provided biomass, or from fossil sources with CCS. GHG emissions from extraction and production of fuels should be accounted for in national GHG-emissions inventories. Of course, shipping must also consider the total lifecycle impact and climate effect of the future fuels it uses.

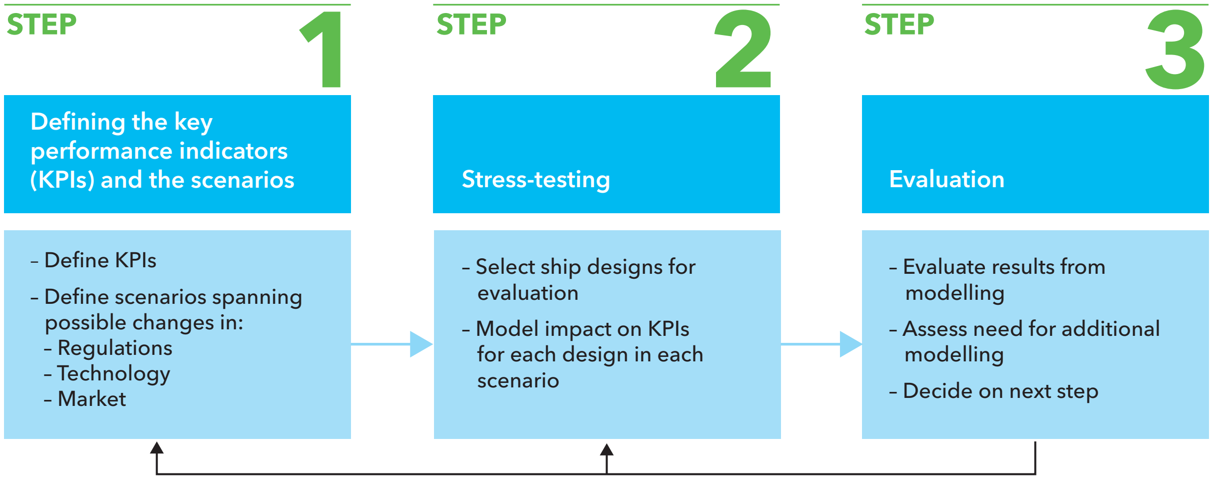
3.2 ASSESSMENT OF DESIGN ROBUSTNESS

Recent studies have addressed the importance of robust future ship designs able to meet the energy transition over the operational lifespan of a vessel (e.g. Gaspar et al., 2015; Pettersen & Erikstad, 2017; Raucci et al., 2017; DNV GL, 2018a; 2019a). In previous editions of the Maritime Forecast to 2050 we presented our three-step framework for future-proofing a ship (see Figure 3.2) and the Carbon-Robust Model enabling quantitative assessment of the future competitiveness of different design options in terms of environmental and financial performance (DNV GL, 2018a; 2019a). In the evaluation, we identified that a multi-scenario approach would help build resilience and readiness and provide valuable insight into a newbuild strategy process.

The aim of the analysis in this study is to identify designs that are resilient to future changes and perform well under a range of scenarios. By developing a library of scenarios (sub-chapter 3.1), we can analyse the effect of assumptions such as a decarbonization pathway or trade growth. Shipowners can choose to focus on scenarios that fit their future expectations when analysing the results and applying them to their strategic considerations.

FIGURE 3.2

A framework for future-proofing ships.



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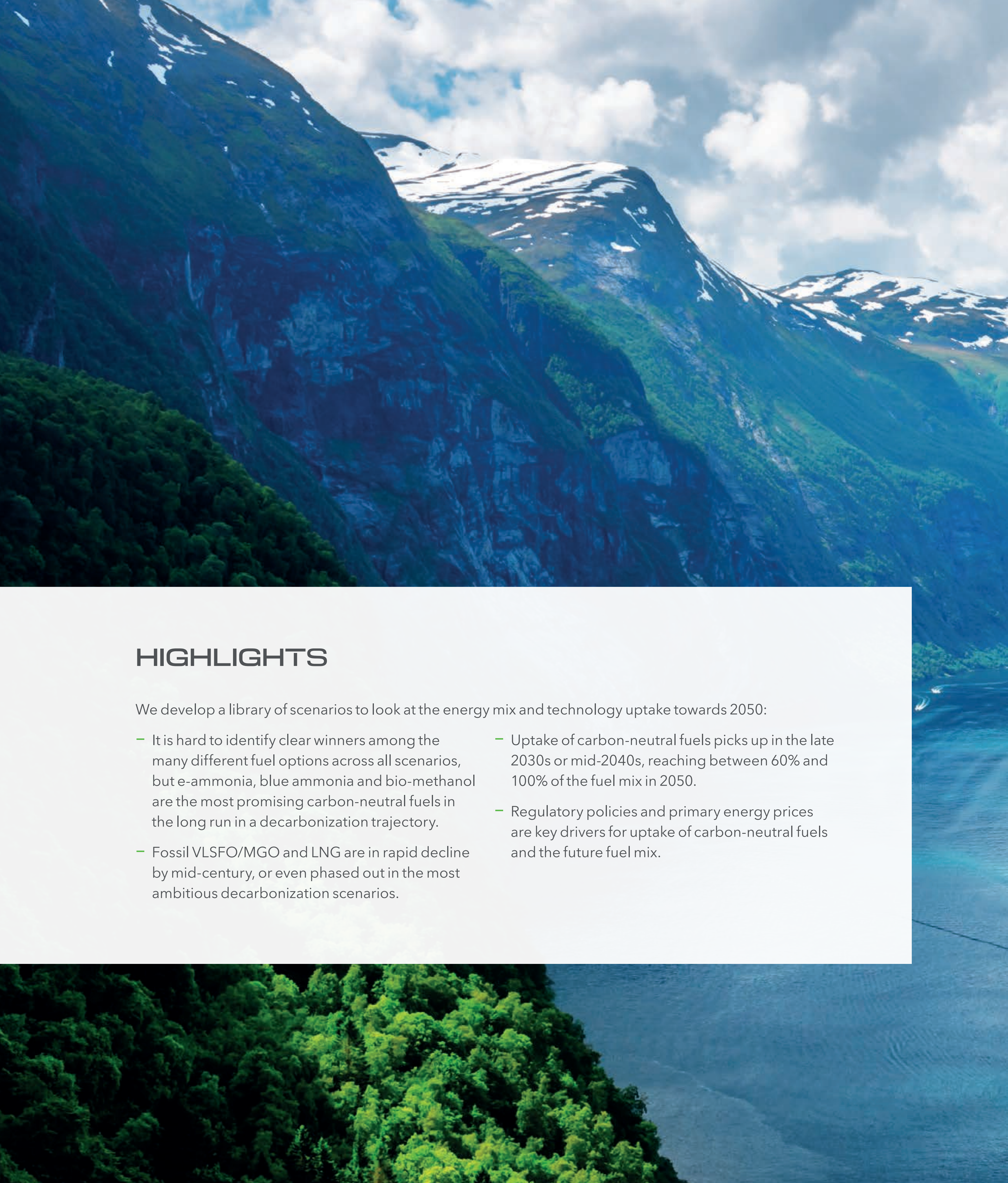
In this edition, we have expanded the number of scenarios and now have a unique opportunity to stress-test and evaluate choices across a wide span of possible futures. The GHG Pathway Model used to develop the scenarios provides ship-specific year-by-year modelling, allowing us to track the financial performance of individual technologies and fuels and benchmark them to the segment's performance.

Given the uncertainty over what type/s of alternative fuels will be available in the future, the choice of energy converter / engine technology and onboard fuel storage is one of the most critical decisions a shipowner needs to take today. From the shipowner's perspective, the robustness assessment centres on a single ship segment (we use Panamax bulk carriers as an illustrative case study) and evaluates which engine and fuel-storage technologies are the most financially robust. Details of the modelling approach and the resulting robustness assessment are described in Chapter 5.

> “Given the uncertainty over what type/s of alternative fuels will be available in the future, the choice of energy converter / engine technology and onboard fuel storage is one of the most critical decisions a shipowner needs to take today.



HIGHLIGHTS

We develop a library of scenarios to look at the energy mix and technology uptake towards 2050:

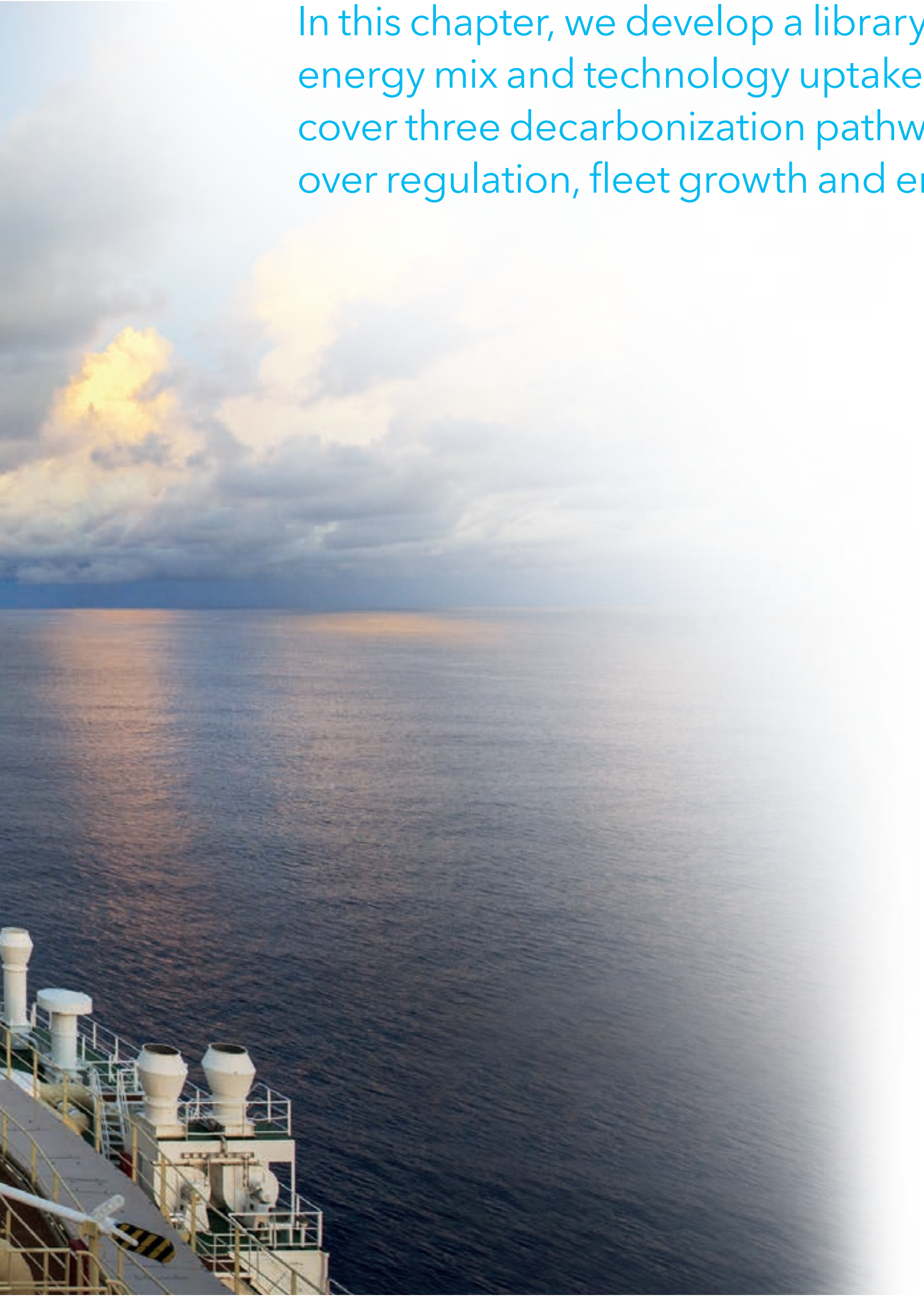
- It is hard to identify clear winners among the many different fuel options across all scenarios, but e-ammonia, blue ammonia and bio-methanol are the most promising carbon-neutral fuels in the long run in a decarbonization trajectory.
- Fossil VLSFO/MGO and LNG are in rapid decline by mid-century, or even phased out in the most ambitious decarbonization scenarios.
- Uptake of carbon-neutral fuels picks up in the late 2030s or mid-2040s, reaching between 60% and 100% of the fuel mix in 2050.
- Regulatory policies and primary energy prices are key drivers for uptake of carbon-neutral fuels and the future fuel mix.

CHAPTER 4

CONSTRUCTING POSSIBLE WAYS FORWARD – ALTERNATIVE DECARBONIZATION SCENARIOS

4 CONSTRUCTING POSSIBLE WAYS FORWARD – ALTERNATIVE DECARBONIZATION SCENARIOS

In this chapter, we develop a library of scenarios to look at the energy mix and technology uptake towards 2050. The scenarios cover three decarbonization pathways, spanning uncertainties over regulation, fleet growth and energy cost.



Applying DNV GL's GHG Pathway Model, our previous work has demonstrated that the future energy mix and demand for carbon-neutral fuels will be heavily dependent on the specific design of the GHG regulations, and on how energy prices develop towards 2050. The decarbonization pathways will also depend strongly on the level of growth in seaborne trade.

We use a scenario-based framework to explore three main uncertainties; regulatory policy measures, fuel prices and seaborne-trade demand. The GHG Pathway Model is used to develop each scenario describing a path leading to a quantified description of the future fleet composition, emissions, energy use, fuel mix and costs.

In the following, we describe the GHG Pathway Model, the input data and modelling assumptions applied, and the resulting scenarios. More details on inputs to the GHG Pathway Model may also be found in Appendices A and B.

4.1 THE GHG PATHWAY MODEL

DNV GL's GHG Pathway Model is a flexible modelling tool for assessing alternatives for maritime decarbonization (Eide et al., 2011, 2013; DNV GL, 2012, 2017a, 2018a, 2019a). The model has been further developed and enhanced since our previous Maritime Forecasts to 2050, though its basic structure remains as described last year (DNV GL, 2019a). It comprises the following two core evaluation modules (Figure 4.1):

- The fleet development module in which the future fleet is simulated by adding and removing ships year-by-year. The objective is to provide the fleet supply capacity corresponding to the seaborne-trade demand projections used as input. The starting point for the fleet development is the current fleet for the base year 2019, with associated ship activity deriving from actual ship movement data from the AIS tracking data.
- The abatement uptake module in which the model evaluates available solutions for CO_2 emission reduction on all existing vessels and newbuilds for each year, including alternative fuels, energy-efficiency measures and speed reduction. The ships are fitted with the most cost-effective feasible combinations of measures that fulfil regulatory requirements imposed as input. Possible fuel transitions achieved through drop-in fuels or retrofit of engine and fuel system are added to the model input.

The model includes two feedback loops: 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 a second feedback loop, uptake of technical measures and fuels results in year-by-year technology learning, which reduces the costs for future installations.

The output of the model is vessel specific and provides an overview of energy use, uptake of measures, associated costs and other activity data, such as sailed distance, that can be used to calculate carbon-intensity indicators. At the fleet and segment levels, the output provides projections of the future fleet, fuel mix, CO_2 emissions and abatement cost towards 2050. The model also provides output on financial parameters such as capital and operational expenses that are used in the robustness evaluation in Chapter 5. The model does not capture market cycles in shipping, and the intention is to focus on the long-term trajectories.

The input to the model is described in Appendices A (emission abatement input) and B (scenario assumptions). Since carbon-neutral fuels are critical to the decarbonization effort, we next highlight the input on engine and fuel systems, and on fuel prices.

4.1.1 FUEL AND ENGINE OPTIONS

Details of all CO_2-emission abatement measures can be found in Appendix A, including energy-efficiency measures, speed reduction and logistics. Since the focus in this year's edition is to dive deeper into the fuel selection and which engines / fuel cells and fuel system[7] to install onboard, we highlight here the main options used in the model for the engine and fuel systems, including possible drop-in and retrofit paths.

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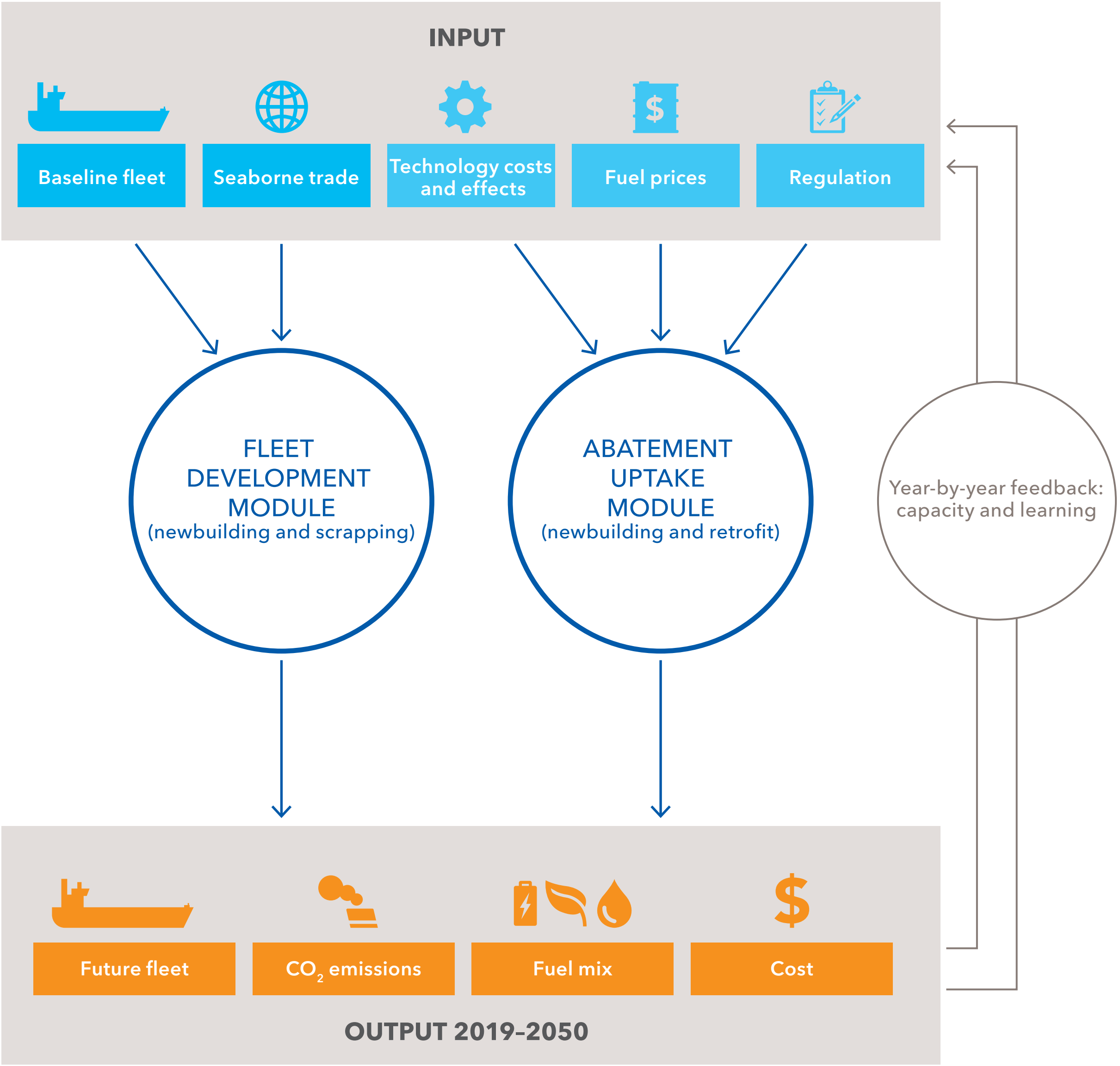
[7] Fuel systems include the fuel supply and storage system (e.g. tanks).

FIGURE 4.1

Overview of the GHG Pathway Model



The world fleet today is powered mainly by internal combustion diesel engines fuelled by VLSFO, MGO, and HFO in conjunction with a scrubber. Some 120 ships have dual-fuel gas engines burning LNG, 10 vessels are running on methanol and around 120 car/passenger ships are powered by batteries.[8]

The modelling includes 10 options for power generation including fuel systems. The main types are mono-fuel (MF) and dual-fuel (DF) internal combustion engines (ICE), which include both two-stroke and four-stroke engines in combination with diesel-electric or diesel-mechanical propulsion systems, fuel cells with electric motors, and batteries with electric motors.

Different technologies are assumed to reach a level of maturity sufficient for commercial application at different times; for example, in 2030 for hydrogen fuel cells. As a simplification, all ICEs running on ammonia, hydrogen, LNG, liquefied petroleum gas (LPG) or methanol are assumed to be dual-fuel, i.e. capable of running on VLSFO/MGO as well. Technologies such as battery-hybrid solutions, waste-heat recovery and direct current (DC) grid are considered as possible energy-efficiency measures (see Appendix A for details).

The two different types of fuel cells considered in the model are Proton Exchange Membrane (PEM) and Solid Oxide Fuel Cell (SOFC), which are modelled to run on hydrogen and ammonia respectively. Use of other fuels in combination with a reformer is also possible, but has not been evaluated. For more information on different fuel-cell types and internal combustion engines running on alternative fuels, please refer to the 2019 edition of this report (DNV GL, 2019a).

To analyse the transition to carbon-neutral fuels from various primary energy sources, the model considers the uptake of:

- Biofuels (from sustainable biomass sources);
- Electrofuels (from renewable electricity, and non-fossil carbon);
- Blue fuel alternatives (from reformed natural gas with CCS); and
- Fossil fuels (from fossil sources).

All biofuels referred to in this report are given the prefix 'bio' (e.g. bio-methanol); electrofuels take the prefix 'e-' (e.g. e-methanol), and fuel alternatives produced via reformed natural gas with CCS are designated as 'blue' (e.g. blue ammonia). We do not consider any fuel blends.

We have assumed that all biofuels, electrofuels and blue fuel alternatives in the modelling are carbon-neutral in a tank-to-wake perspective. However, the production of fuels and the emissions from well-to-tank are also important to consider. Getting to a fully carbon-neutral production process will take time and may not be fully possible for all processes, such as CCS. Production of grid electricity and advanced biofuels also result in CO_2 emissions today (e.g. DNV GL, 2019b, 2020b, and ICCT, 2017).

We have not included any limitation on the availability of carbon-neutral fuels, which is likely to be a major constraint on achieving the decarbonization pathways. Constraints on the ship side include having available engines and fuel systems, the capacity to install them, and training crews to use them. Constraints onshore include the availability of a necessary primary-energy production and distribution infrastructure. As such, the modelling

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[8] Source: Alternative Fuels Insight platform (AFI), afi.dnvgl.com

results should be read as showing the demand for alternative fuels at a given time. Detailed discussion on barriers to alternative fuel is provided in sub-chapter 6.1.

The allowed engine / fuel cell and fuel-system options, compatible fuels and retrofit options are summarized in Figure 4.2. Drop-in fuels are those that can be used in an engine or fuel cell without any additional retrofit capital expenditure (CAPEX). Thus, for a dual-fuel methanol engine, drop-in fuels include bio-methanol, e-methanol, bio-MGO, e-MGO and VLSFO/MGO. We also allow for retrofits from certain engine options to another. In such cases, this will incur extra CAPEX for required modifications to the engine and/or to the tanks and fuel system.

Allowed retrofit pathways have been determined on the basis of the technical feasibility, with focus on the implied conversion of fuel-storage systems and engines to each given retrofit fuel. Options that involve a change in the engine type – e.g. from an ICE to an electric motor – have been deemed to be technically unfeasible for the general fleet, so have not been allowed in the GHG Pathway Model. Retrofits from one fuel to another have also been disregarded where they would involve great differences in volumetric energy density; for example, VLSFO/MGO to hydrogen. Finally, retrofits of vessels fuelled by carbon-neutral variants of ammonia, hydrogen, and methanol to use other fuels have been disallowed altogether.

FIGURE 4.2

Conventional and carbon-neutral fuels by primary-energy source and mapping of allowed fuel-transition routes in the GHG Pathway Model.

ENGINE / FUEL CELL AND FUEL SYSTEM						Blue ammonia	Blue hydrogen	
		e-MGO	e-LNG	e-LPG	e-methanol	e-ammonia	e-hydrogen	Electricity from grid
		bio-MGO	bio-LNG		bio-methanol			
	HFO	VLSFO/MGO	LNG	LPG				
MF ICE	⚙	✓	⚙	⚙	⚙			
MF ICE with scrubber	✓	✓	⚙	⚙	⚙			
DF LNG ICE		✓	✓		⚙	⚙		
DF LPG ICE		✓		✓	⚙	⚙		
DF methanol ICE		✓			✓			
DF ammonia ICE		✓				✓		
DF hydrogen ICE		✓					✓	
Hydrogen FC							✓	
Ammonia FC						✓		
Battery EM								✓

⚙ Retrofit ✓ Drop-in

MF, mono fuel; DF, dual fuel; ICE, internal combustion engine; FC, fuel cell; EM, electric motor; HFO, heavy fuel oil; VLSFO, very low sulfur fuel oil; MGO, marine gas oil; LNG, liquefied natural gas; LPG, liquefied petroleum gas

Investment costs are different for each engine / fuel cell and fuel system shown in Figure 4.2. They are divided into: cost of engine and fuel-supply system; and, cost of fuel-storage system. The former cost is proportional to the installed power on the vessel, and the latter to the fuel-storage capacity. As an example, engines running on LNG are assumed to be more expensive than those running on methanol. Likewise, storing methanol as a fuel onboard a vessel is assumed to be cheaper than storing LNG. For retrofits, incurred investment costs were estimated based on the assumption that energy-storage capacity onboard the vessel must be the same, i.e. additional tank volume-capacity is needed in case of a switch from a fuel with high volumetric energy density to one with a lower density. Estimated cost-data are based on an extensive review of literature (e.g. de Vries, 2019; Taljegard et al., 2014; FCBI, 2015), and communication with industry actors.

4.1.2 FUEL PRICES

In this study, we have developed a Marine Fuel Price Mapper, estimating current and future fuel prices until 2050. For carbon-neutral fuels, levelized cost of production and distribution has been used as a proxy for fuel price, an approach based on DNV GL's ExplEnergy[9] tool, which allows analysis of different energy value chains (DNV GL, 2018b). The two-step method for calculating carbon-neutral fuel-price trajectories is described below and illustrated in Figure 4.3.

1. Deduction of production costs: Based on a literature review we have mapped the relationship between the cost of fuel production and the price of primary-energy sources. The cost of producing biofuels, electrofuels, and blue fuels is assumed to be directly influenced by the price of biomass, renewable electricity and fossil energy respectively. For carbon-based electrofuels, the cost of capturing and utilizing non-fossil CO_2

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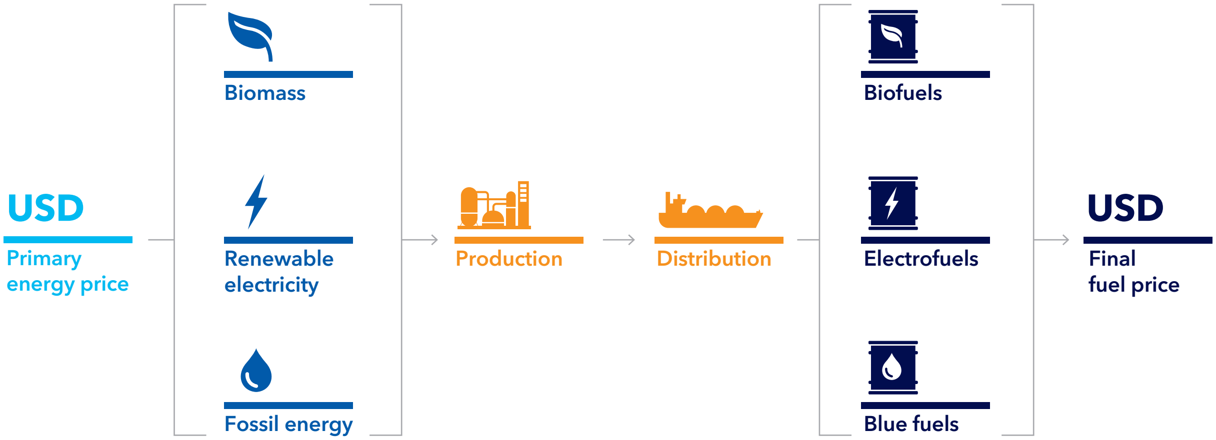
[9] https://www.dnvgl.com/oilgas/contact/explenergy-2019-register-user.html

FIGURE 4.3

Illustration of the method used for calculation of future carbon-neutral fuel prices to 2050. For conventional fossil fuels, a different approach has been used.



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(CCU) for fuel production is included. Similarly, the cost of CCS for blue fuel alternatives has also been included. For fuels with immature production processes (e.g. e-MGO), a gradual decrease in future production cost is assumed due to technological developments. Where required (e.g. for e-LNG), the cost of additional processes such as liquefaction has been included in the fuel production cost. A variety of information sources (e.g. H21, 2018; Brynolf et al., 2018) have been used as a basis.

2. Calculation of distribution and bunkering costs: Depending on the storage conditions of each fuel product, there will be different costs associated with distribution. For example, distribution of liquefied hydrogen at -253°C will likely face higher distribution costs than e-MGO which is kept as a liquid in ambient conditions. A review of available literature has been conducted to estimate distribution costs for different fuels (e.g. Delft, 2020; IEA, 2019b).

For calculating future bunkering prices for conventional fuels (e.g. LNG and HFO), we have used the historical relationship between bunkering prices and crude oil and natural gas prices. For LNG, a distribution cost has been added to the hub price given in the Alternative Fuels Insight (AFI) platform.[10]

Three different price scenarios have been constructed and applied in the GHG Pathway Model, primarily by changing the underlying primary-energy price assumptions. The price scenarios address the sensitivity between different fuel families, for example biofuels and electrofuels. The price difference between fuels with the same primary-energy source, e.g. bio-methanol and bio-MGO, are included through cost estimates of the process steps to produce the fuels, but the sensitivity has not been evaluated through the price scenarios. Further details on fuel-price modelling are provided in Appendix B, including the high and low prices used in the scenarios for 2050.

[10] Source: Alternative Fuels Insight platform (AFI), afi.dnvgl.com

4.2 DECARBONIZATION PATHWAYS EXPLORED

The IMO's decarbonization ambitions in its Initial GHG Strategy are to at least halve total emissions from shipping by 2050, and to reduce the average carbon intensity 40% by 2030 and 70% by 2050, compared with levels in 2008. This trajectory is not the only possible pathway. While the IMO GHG Strategy is currently driving policy development in shipping, we also see national and regional regulations, market incentives from charterers and others, and public pressure for shipping to contribute its fair share to limiting average global warming to 1.5°C (see Chapter 2 for a detailed discussion on regulations and incentives for decarbonization). This could mean faster decarbonization. We should also not rule out the possibility that the IMO and shipping will fail to deliver a decarbonization path.

To reflect these possibilities, we explore three decarbonization pathways: one in which no further regulations are imposed on shipping; a second, in which shipping achieves ambitions set in the IMO GHG Strategy; and a third, in which the ambition is to decarbonize the fleet by 2040.

These pathways are defined in Table 4.1. and illustrated in Figure 4.4. For each, we have defined sets of regulations that drive shipping towards the 2050 ambitions. As this study focuses on the long-term reduction and fuel shift, we have not added policies to ensure achievement of the ambitions for carbon intensity in 2030 and for emissions to peak as soon as possible.

Many circumstances are likely to impact the future decarbonization trajectory of shipping. Even if regulations are designed to limit ship CO_2 emissions towards the set ambitions, decarbonization trajectories will depend on future demand for seaborne transportation, fuel prices and the given policy measure, among other factors. For each of the three decarbonization pathways we construct scenarios where input varies along these three key dimensions.

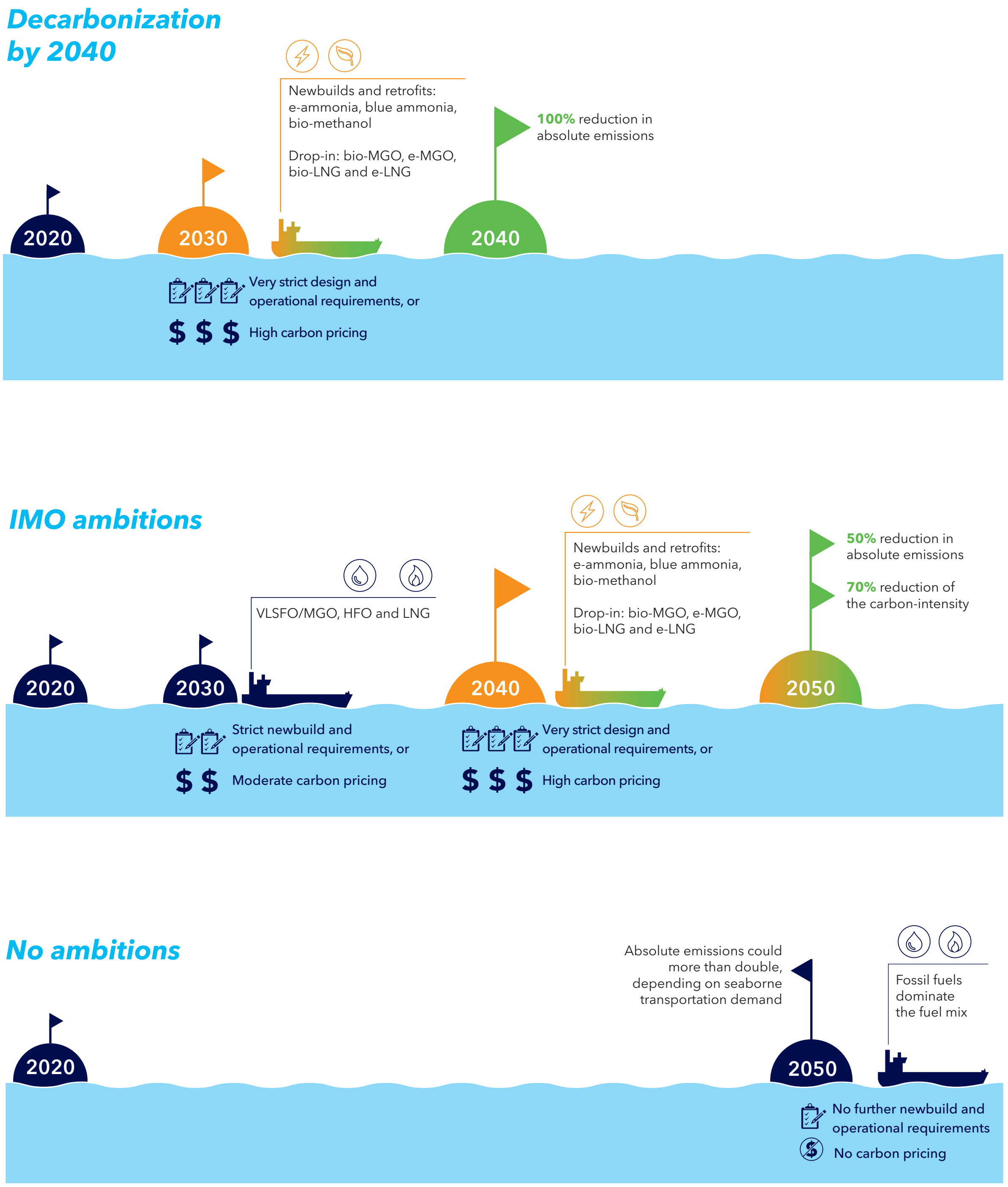
TABLE 4.1

Description of decarbonization pathways evaluated in the GHG Pathway Model.

PATHWAY	Assumptions
No ambitions	No further policies
IMO ambitions	At least 70% lower carbon intensity in 2050 compared with in 2008 At least 50% less absolute emissions in 2050 compared with in 2008
Decarbonization by 2040	At least 95% less absolute emissions in 2040 compared with in 2008

FIGURE 4.4

Decarbonization pathways: Timelines for implementing decarbonization measures and achieving targets.



> “While the IMO GHG Strategy is currently driving policy development in shipping, we also see national and regional regulations, market incentives from charterers and others, and public pressure for shipping to contribute its fair share to limiting average global warming to 1.5°C.

To reflect the large range of projections for seaborne trade, this study has applied two – 25% and 180% total growth between 2020 and 2050 – representing low and high seaborne-trade demand growth.

The IMO has come far in developing the first regulations to support its ambitions in the short term. However, uncertainty remains over the pace, form and type of regulatory measures the organization will implement to invoke the desired change towards 2050. To cover this uncertainty, we look at two principal ways to incentivize change. One is to set technical or operational emission limits on individual ships, at design stage or in operation. The other is a carbon price.

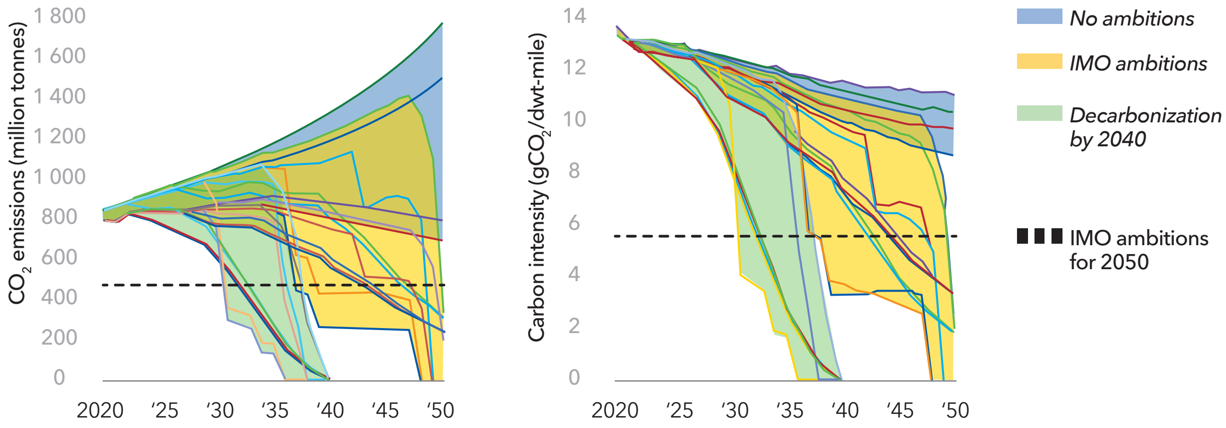
The assumptions on fuel prices are elaborated in sub-chapter 4.1.2. More details on the assumptions for seaborne trade, fuel prices and policy measures are given in Appendix B.

Table 4.2 summarizes the 30 resulting scenarios. Note that we have only six scenarios for the *No ambitions* pathway because we are not exploring variations in regulations. We have 12 scenarios each for the other two decarbonization pathways.

Applying input as described above, the GHG Pathway Model produces the CO_2 emissions and carbon-intensity trajectories shown in Figure 4.5 for the 30 scenarios in our library. The blue-coloured areas, giving the range of results from

FIGURE 4.5

CO_2 emission (left) and carbon intensity (right) trajectories for the 30 scenarios modelled for the decarbonization pathways.



the *No ambitions* scenarios with no further decarbonization policies, show a large spread of CO_2 emissions towards 2050 due to variations in demand for transportation. We still see that the carbon intensity decreases due to more energy-efficient ships in the fleet, and uptake of LNG. In the high-growth scenarios, the fleet renewal is faster, resulting in lower carbon intensity overall.

The scenarios following the *IMO ambitions* decarbonization pathway are shown in the yellow areas. All fulfil the 50% absolute emissions reduction in 2050; but, due to demand growth, achieving this requires a reduction greater than the 70% in carbon intensity prescribed by the *IMO ambitions*.

We see a similar pattern for the *Decarbonization by 2040* scenarios shown in the green areas. To achieve this ambition, the shipping fleet needs to start deploying alternative fuels by 2030. Another observation is that with carbon prices we can expect very abrupt transitions, assuming alternative fuels are available for all segments and geographies.

We apply the same regulation measures – carbon prices or design/operational requirements – across all scenarios in a decarbonization pathway (e.g. *IMO ambitions* or *Decarbonization by 2040*). This results in some scenarios where the targets are met earlier and exceeded, and other scenarios where the shift is delayed until the last moment and targets are only just met. For example, in the low biomass-price scenario the difference in cost between fossil and carbon-neutral fuels is much lower than in scenarios with low renewable electricity prices. Thus, the same carbon price would give a very different selection of fuels. In some *IMO ambitions* pathway scenarios this results in the fleet being decarbonized before 2050.

In the *IMO ambitions* pathway, we assume a carbon price of USD 50/t in 2030, increasing to USD 200/t in 2040 and USD 400/t in 2050. For the *Decarbonization by 2040* pathway, the carbon prices had to be set to USD 700/t in 2040 to incentivize a complete shift to carbon-neutral fuels, but we also saw that USD 500/t would be sufficient to reduce CO_2 emissions by more than 95% in most scenarios.

We have applied stylized representations of three types of possible IMO regulations: mandatory design requirements applicable at the newbuilding stage; operational requirements applicable to all ships in operation (which also includes design requirements for existing ships, e.g. the EEXI); and carbon pricing. They are not intended to accurately represent the exact nature of upcoming regulations, but instead to mimic the expected outcome function of such measures. For instance, an operational requirement may take many forms on how to measure carbon intensity or emissions (e.g. AER, EEXI, EEOI, or any other carbon-intensity indicator) and the compliance scope (e.g. individual ship, fleet or time averaging) of the requirements. See Chapter 2 for more details on the possible policy measures.

The current EEDI requirements will ensure that ships with greater energy efficiency keep entering the fleet, though without additional requirements we see that the 2030 ambitions will not be met. In the *IMO ambitions* pathway scenarios, in addition to the current EEDI design requirements for newbuilds, we have modelled a proxy for the EEXI and Enhanced SEEMP. This proxy is an operational requirement starting with a 5% reduction in GHG emissions (relative to an average ship built before 2013) in 2023, increasing to 40% in 2030. The effect of the operational requirements can be seen from 2027 with improved operations and greater speed reduction for existing ships – either because of the EEXI and lower power allowed in use and/or an operational requirement. For newbuilds, we anticipate a higher uptake of LNG and greater energy-efficiency designs.

In the following sub-chapter we explore the energy mix and onboard technologies associated with the 30 different CO_2 trajectories.

TABLE 4.2

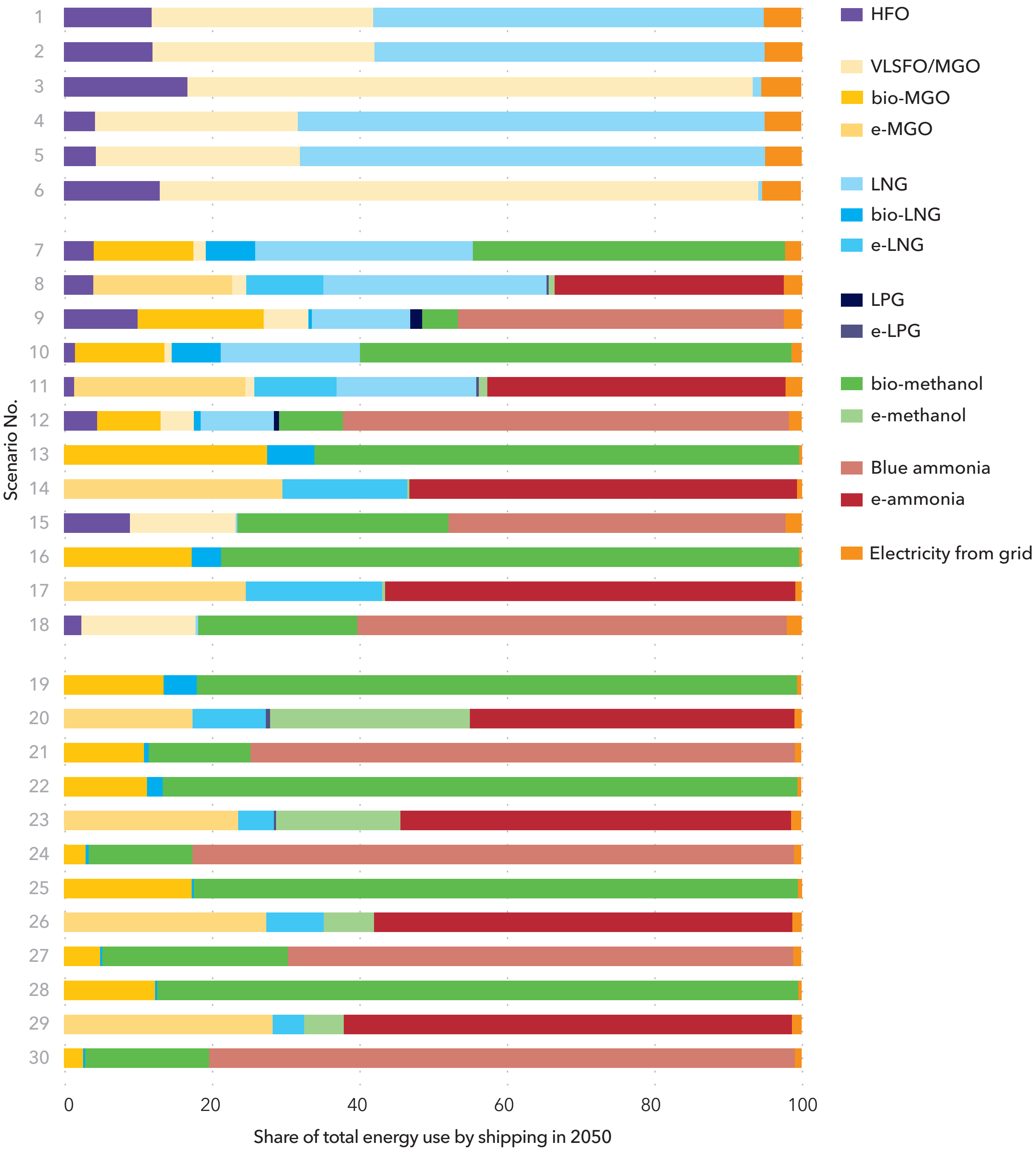
List of scenarios explored in this study.

DECARBONIZATION PATHWAY	REGULATIONS	FLEET GROWTH	FUEL PRICES	SCENARIO
No ambitions	**Current design requirements**	Low growth	Low biomass price	1
			Low electricity price	2
			Low blue and fossil price	3
		High growth	Low biomass price	4
			Low electricity price	5
			Low blue and fossil price	6
IMO ambitions	**Design and operational requirements**	Low growth	Low biomass price	7
			Low electricity price	8
			Low blue and fossil price	9
		High growth	Low biomass price	10
			Low electricity price	11
			Low blue and fossil price	12
	Carbon price	Low growth	Low biomass price	13
			Low electricity price	14
			Low blue and fossil price	15
		High growth	Low biomass price	16
			Low electricity price	17
			Low blue and fossil price	18
Decarbonization by 2040	**Design and operational requirements**	Low growth	Low biomass price	19
			Low electricity price	20
			Low blue and fossil price	21
		High growth	Low biomass price	22
			Low electricity price	23
			Low blue and fossil price	24
	Carbon price	Low growth	Low biomass price	25
			Low electricity price	26
			Low blue and fossil price	27
		High growth	Low biomass price	28
			Low electricity price	29
			Low blue and fossil price	30

FIGURE 4.6

Percentage share of total energy use by shipping for each scenario in 2050.

Units: Percentage (%)



4.3 FUTURE ENERGY MIX, ENGINES AND FUEL SYSTEMS

4.3.1 FUTURE ENERGY MIX

Figure 4.6 shows the share of shipping energy usage in 2050 for each modelled fuel type in each of the 30 scenarios described in sub-chapter 4.2. Demand for seaborne trade will drive the energy required. The total annual energy need in mid-century in the low-growth scenarios is between 10.5 exajoules (EJ) and 11 EJ (251 to 263 million tonnes of oil equivalent, Mtoe) and 23.5 EJ to 24.6 EJ (561 to 588 Mtoe) in the high-growth scenarios.

The figure shows large differences in the fuel mix between the six *No ambition* scenarios, and the 24 other scenarios. Also, while the figure shows very large variation between the 24 decarbonization scenarios, these follow a discernible pattern. In the scenarios where a favourable biomass cost is assumed, bio-methanol plays a dominant role. In the other scenarios, ammonia plays the dominant role, though the sourcing of the ammonia depends on whether we assume favourable prices for either fossil fuel (with CCS) or renewable electricity. The difference between the *IMO ambitions* and *Decarbonization by 2040* scenarios lies mainly in how far the decarbonization and fuel transition has come, with higher uptake of the carbon-neutral fuels in the latter. In the *Decarbonization by 2040* scenarios, the situation in 2050 is close to a stable end state, although we still see some transitional fuels being phased out as new ships enter the fleet. In the *IMO ambitions* scenarios, the transition is still very much underway in 2050.

The same difference can be seen between high and low-growth scenarios. In the high-growth scenarios where the newbuild rate is greater, we see a larger relative share of fuels requiring new engine and fuel system technologies like ammonia and methanol, and less of the carbon-neutral drop-in fuels for VLSFO/MGO and LNG, which are more applicable to existing ships.

Compared with our 2019 edition (ETO, 2019a), which considered the *IMO ambitions* pathway, we have a significant uptake of methanol in particular in the low biomass-price scenarios where biofuels are more attractive than electrofuels and blue fuel alternatives.

An alternative view of the results is presented in Figure 4.7, which shows the share of energy use in 2050 for each modelled fuel type across the 30 scenarios.

In the scenarios with no decarbonization ambitions, fossil fuels such as VLSFO/MGO and LNG dominate the fuel mix with their individual shares determined by the primary energy prices of crude oil and gas. In the decarbonization scenarios though, fossil VLSFO/MGO and LNG are phased out, or on the way to being phased out, by 2050.

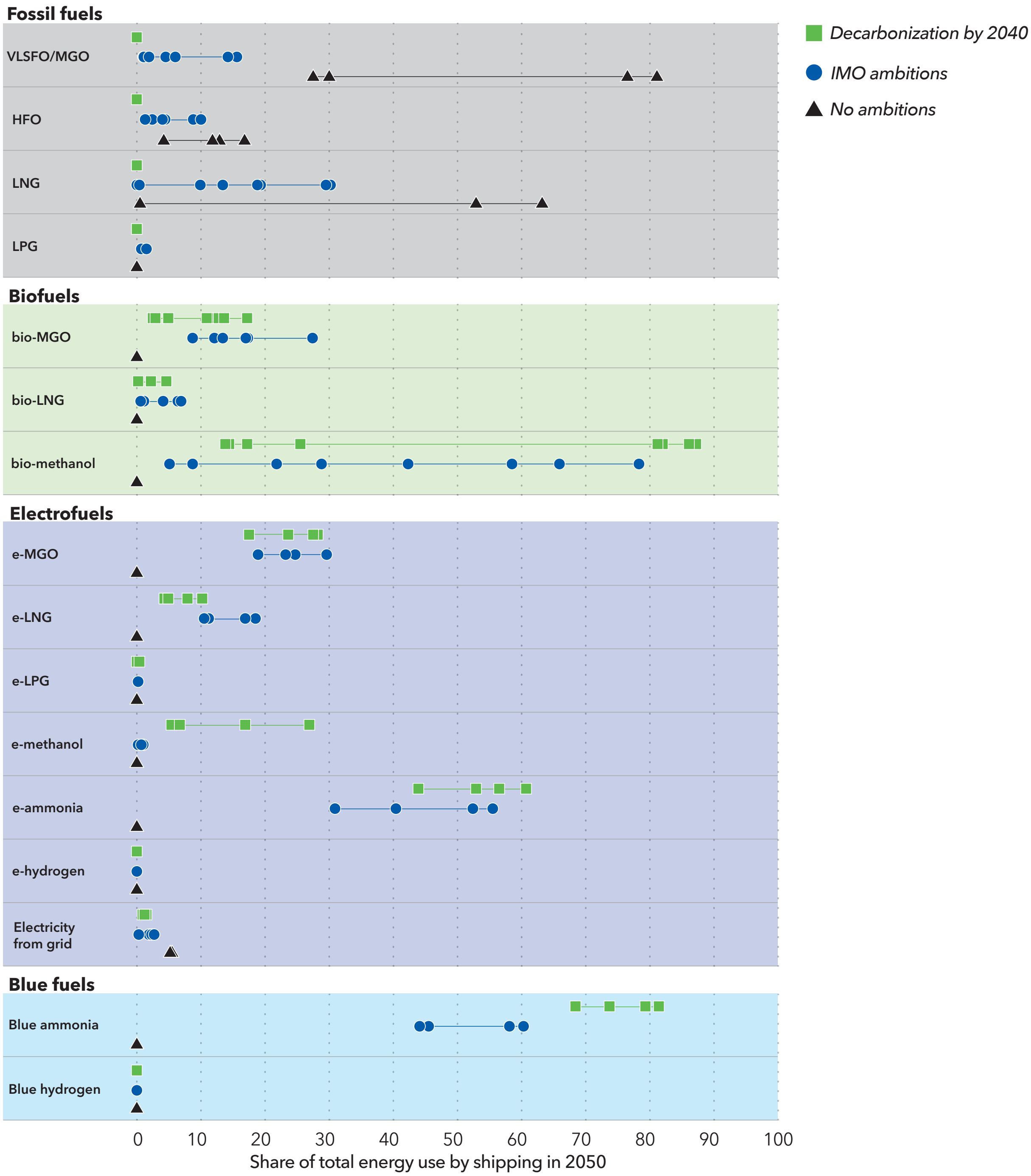
In our modelling, e-ammonia, blue ammonia and bio-methanol are the most promising carbon-neutral fuels in the long run in a decarbonization trajectory, with uptake in some scenarios reaching as high as 61%, 81%, and 87% respectively in 2050. In many scenarios, however, there is far lower uptake of these fuels and a single winner cannot be determined.

Most scenarios see significant uptake of at least three or four different fuels in 2050. Fuels like bio-MGO and e-MGO have a limited but stable share in the *Decarbonization by 2040* scenarios, while in the *IMO ambitions* scenarios, bio-LNG and e-LNG also have a small share. This indicates that these are not only transitional fuels but a viable alternative for ammonia and methanol for some ships. Hydrogen and LPG see limited uptake across all scenarios (see separate text box page 63).

FIGURE 4.7

Share of total shipping energy usage in 2050 for each fuel type. The lines show the minimum and maximum uptake of a fuel for each decarbonization pathway. Each geometric symbol represents a scenario. For many fuels, the share is zero in multiple scenarios.

Units: Percentage (%)



VLSFO, very low sulfur fuel oil; MGO, marine gas oil; HFO, heavy fuel oil; LNG, liquefied natural gas; LPG, liquefied petroleum gas

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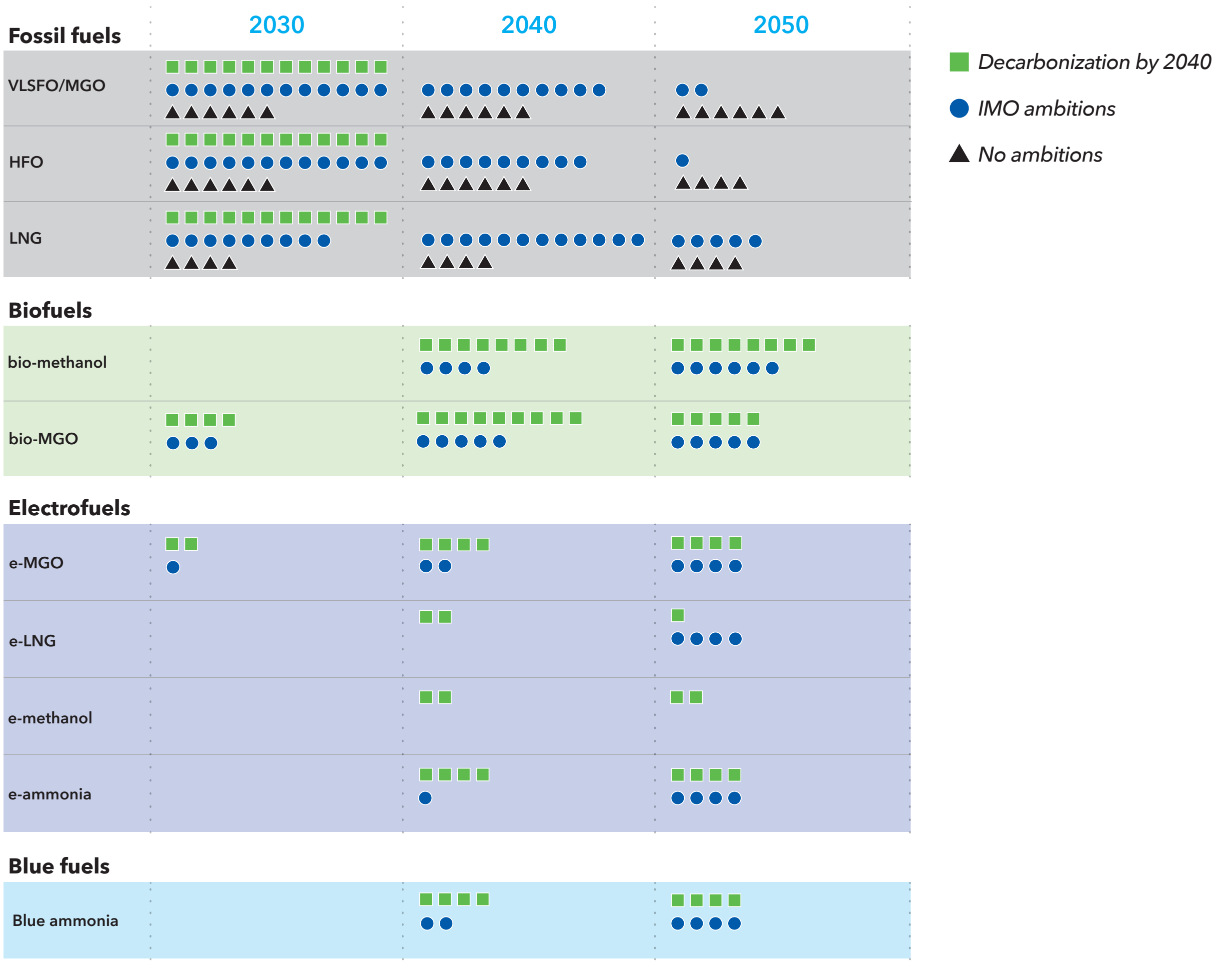
To also consider the time dimension, Figure 4.8 shows the number of scenarios where a fuel has more than 10% uptake in the shipping energy mix in 2030, 2040 and 2050. The energy mix is still dominated by fossil fuels in 2030 across all scenarios. In the *No ambition* pathway (black triangles), the use of fossil fuels lasts to 2050 and beyond, with a shift to LNG in 2040, except in scenarios with low fossil-fuel prices. Unless regulations and other incentives are put in place to encourage and enforce uptake of the more expensive carbon-neutral fuels, economics will remain the main deal-breaker for uptake.

FIGURE 4.8

Number of scenarios where a fuel is modelled to reach more than 10% uptake in the energy mix in 2030, 2040 and 2050. Each symbol represents a scenario. Fuels modelled to have less than 10% uptake in all scenarios are not shown.



VLSFO, very low sulfur fuel oil; MGO, marine gas oil; HFO, heavy fuel oil; LNG, liquefied natural gas

Following the *IMO ambitions* pathway (blue dots), we already see the same shift to LNG by 2030, driven by increasingly stricter regulation of CO_2 emissions. The transition to carbon-neutral fuels accelerates after 2040 to reach the 50% reduction in 2050, with drop-in fuels for existing ships and bio-methanol, blue ammonia or e-ammonia for newbuilds and retrofits. In some scenarios we see that fossil LNG still has a significant market share in 2050.

In the *Decarbonization by 2040* pathway (green squares), the fuel shift has to take place between 2030 and 2040. Instead of a transition via LNG, the fleet shifts directly to methanol or ammonia, with bio-MGO and e-MGO as drop-in fuels for existing ships, depending on the fundamental price drivers for biomass, renewable electricity and fossil fuels. Bio-methanol, blue ammonia, e-MGO and e-ammonia emerge as the most prolific carbon-neutral fuels in 2050.

Note that the 10% threshold used in Figure 4.8 leaves out bio-LNG which has a non-negligible uptake in 2050 (as seen in Figure 4.7).

Figures 4.6, 4.7 and 4.8 show that it is hard to identify clear winners among the many different fuel options across all scenarios. In most scenarios, however, fossil options are gradually replaced by carbon-neutral alternatives.

Figure 4.9 shows the share of carbon-neutral fuels in the shipping energy mix towards 2050 for the *IMO ambitions* and *Decarbonization by 2040* pathways. In the ambitious *Decarbonization by 2040* pathway, all fuels used must be carbon-neutral by 2040, and the transition must start almost immediately and accelerate from 2030.

For the less-progressive *IMO ambitions* pathway, the fuel shift starts later and accelerates slower. Depending on the scenario, the uptake of carbon-neutral fuel picks up in the late 2030s or mid-2040s, reaching between 60% and 100% in 2050, depending on policy measures, fuel prices, and seaborne-trade demand growth.

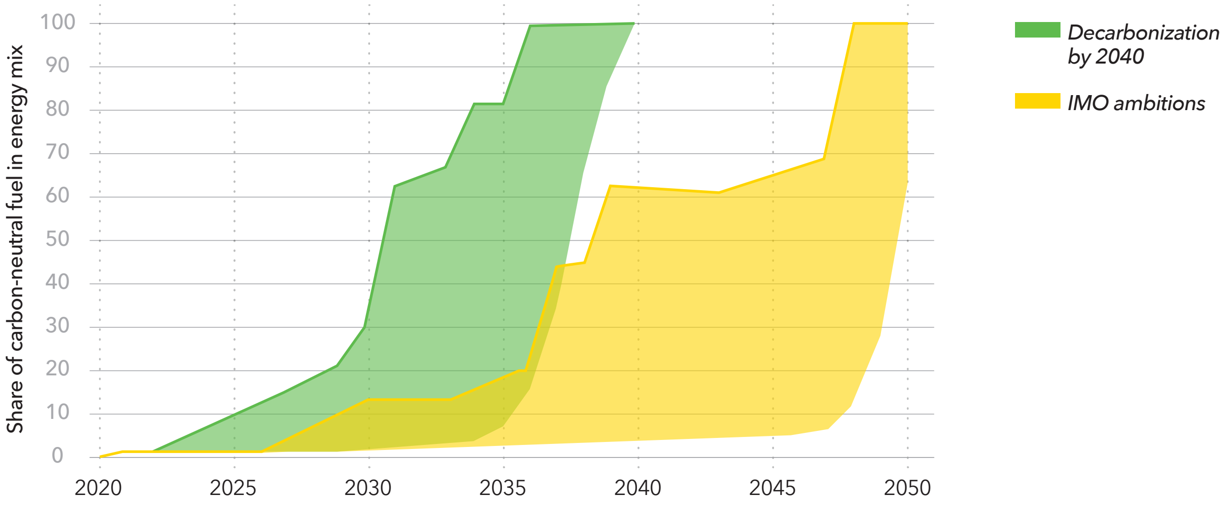
The sensitivity of the results to the assumptions is high. Changes to the input assumptions used in this study might result in very different outcomes, in particular for fuel uptake. Thus, our results should be used with caution. The modelling results should be read as showing the demand for carbon-neutral fuels at a given time, and to indicate the timeline and the necessary speed of the fuel shift, rather than concluding that a particular fuel will be a winner in the future mix.

The fuel mix varies significantly between scenarios, even with minor changes in the input assumptions on fuel prices. Uptake of alternative fuels in the GHG Pathway Model is determined based on applying the most cost-effective feasible combination of measures which fulfil the regulatory requirements per ship per year (see Abatement uptake module in sub-chapter 4.1). As a result, our assumed investment costs for implementing engines and fuel systems and fuel-price projections have a major impact on the energy mix for each scenario.

FIGURE 4.9

Share of carbon-neutral fuels in shipping energy mix towards 2050 for the *IMO ambitions* and *Decarbonization by 2040* pathways. The range covers the minimum and maximum share per year across all scenarios for the particular pathway.

Units: Percentage (%)



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Through our Marine Fuel Price Mapper (see sub-chapter 4.1.2) we have analysed the value chain of each carbon-neutral fuel evaluated in this report. Based on our analysis, we do not anticipate that carbon-neutral fuels will reach price-parity with traditional fossil fuels unless a carbon price is imposed. However, among our carbon-neutral fuel alternatives, some options were identified as having a relatively low value-chain cost. For example, e-ammonia was found to have a more favourable price than e-hydrogen in all scenarios. The reason for this lies in the differences in distribution cost. Even though production costs of e-hydrogen and e-ammonia are at a very similar level, the distribution cost for liquefied hydrogen was found to be significantly higher than that for ammonia. Hence, e-ammonia ended up with a more favourable bunkering price than e-hydrogen.

It is important to note that each fuel-price scenario evaluated has been designed to reflect different price trajectories between the main cost drivers for each fuel family (i.e. price of primary-energy sources like biomass and renewable energy). Consequently, the relative price differences between fuels within a family remain at a similar level across all fuel-price scenarios. This should be the subject of further investigation.

FUELS WITH LOW UPTAKE

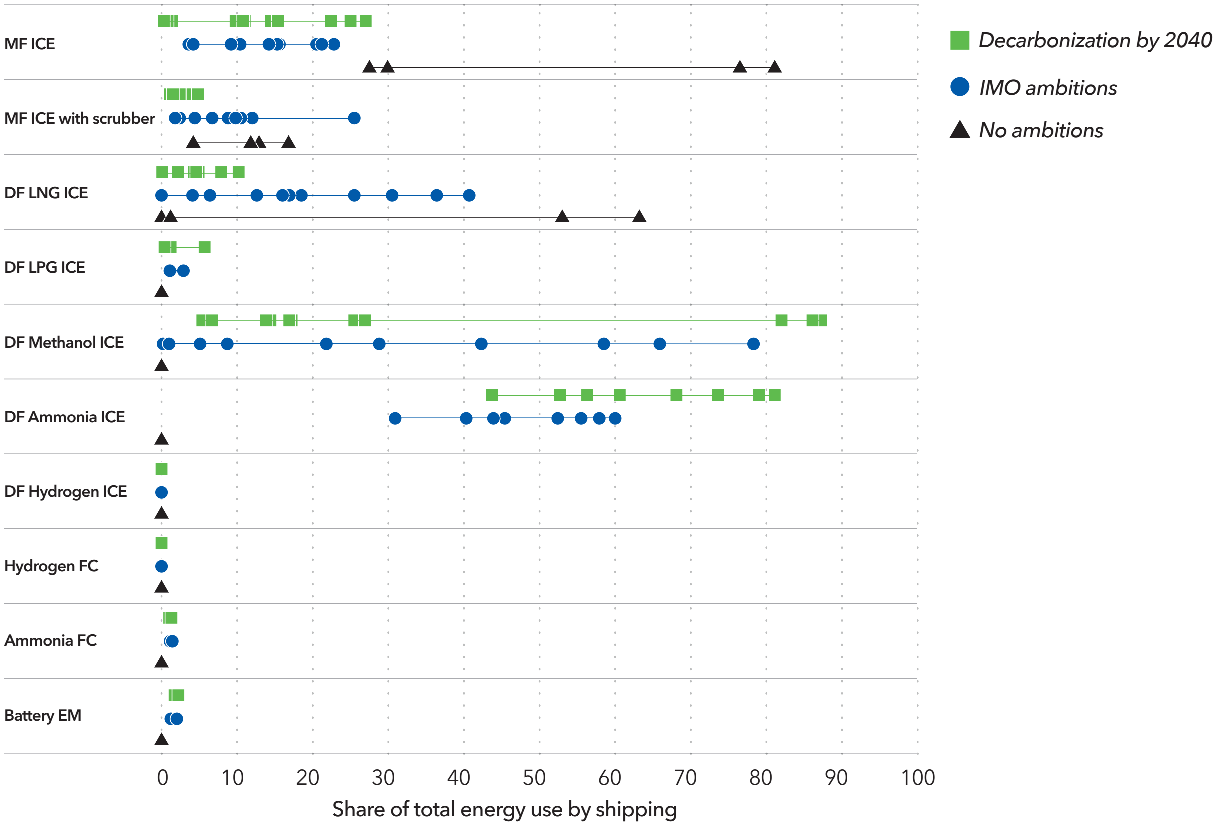
Our results show a very limited uptake of liquefied hydrogen (e-hydrogen and blue hydrogen), as well as LPG and e-LPG, across all scenarios evaluated. The reason for this is the assumed fuel prices based on our Marine Fuel Price Mapper (see sub-chapter 3.1.2), and the CAPEX for the engines / fuel cells and fuel systems. Expenditure on fuel is the most significant cost component, and cheaper fuels are available for all hydrogen and LPG variants considered. In addition, assumed investment costs for each engine / fuel cell and fuel system plays a role, together with the storage of liquefied hydrogen significantly increasing the investment cost of all considered hydrogen-fuelled ship designs. However, this does not mean that we cannot see use of these fuels in niche applications and geographies, such as hydrogen-fuelled ferries and cruise vessels, and LPG carriers. Incentivization schemes could boost the uptake of hydrogen in the short-to-medium term. The GHG Pathway Model does not capture such aspects. Neither does it consider ship designs with compressed-hydrogen storage, an option that may be more cost-efficient for some short-sea segments than vessels running on liquefied hydrogen.

Even though hydrogen as a fuel does not gain a significant uptake in the model, it is important to note that it still plays an integral role as a building block in the production of several carbon-neutral fuels such as e-ammonia, blue ammonia and e-methanol.

FIGURE 4.10

Distribution of engine / fuel cell and fuel systems in terms of share of total energy use in 2050. Each dot represents a scenario. If several scenarios have the same share, only one dot will be shown.

Units: Percentage (%)



MF, mono fuel; ICE, internal combustion engine; DF, dual fuel; LNG, liquefied natural gas; LPG, liquefied petroleum gas; FC, fuel cell; EM, electric motor

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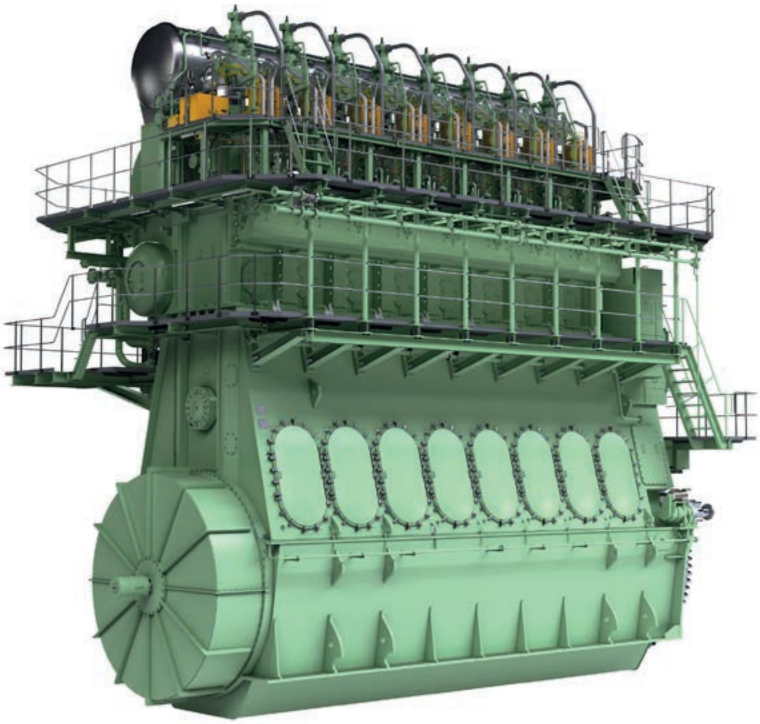
4.3.2 FUTURE ENGINE AND FUEL SYSTEMS

There is a large variety of possible fuels but fewer compatible engine and fuel-storage systems, because many engine types can run on several fuel types. Take for example the conventional mono-fuel internal combustion engine (MF ICE) which may be fuelled by HFO (if scrubber-fitted) and VLSFO/MGO, bio-MGO or e-MGO. It may also be retrofitted into a dual-fuel LNG (DF LNG ICE) or methanol engine. Such flexibility is key to handling the uncertainty of the future fuel mix (see sub-chapter 6.1 for more information about fuel flexibility). However, even if an engine may run on several alternative fuels (sometimes dependent on moderate retrofits), the bigger challenge will typically be differing requirements for onboard fuel storage and supply systems for different fuels.

Figure 4.10 shows the distribution of engine and fuel systems in terms of share of energy in 2050, where each scenario represents one sample. The figure reveals a large spread in the uptake of various combinations of onboard engine and fuel system.



MAN B&W ME-LGI 2-stroke diesel dual-fuel engine

In the *No ambition* pathway, the only engine and fuel systems in the fleet are: MF ICE and MF ICE with scrubber, all running on VLSFO/MGO or HFO; and DF LNG ICE, for which uptake varies between near-zero and above 60 % in 2050, reflecting uncertainty over the relationship between oil and gas prices.

> “If an engine may run on several alternative fuels (sometimes dependent on moderate retrofits), the bigger challenge will typically be differing requirements for onboard fuel storage and supply systems for different fuels.

In the *IMO ambitions* pathway, we see a significantly reduced role for the MF ICE (with or without scrubber), and dual-fuel methanol engines and dual-fuel ammonia engines (DF methanol ICE and DF ammonia ICE) emerge as the strongest contenders in this pathway, reaching possible uptakes close to 80% and 60% respectively in the most favourable scenarios. The share of DF LNG ICE engine and fuel systems could be as high as 40% in the most favourable scenario. That said, uptake rates are significantly lower in most scenarios. The median uptake rate for DF LNG ICE is 16%, 15% for DF methanol ICE and 38% for DF ammonia ICE.

In the *Decarbonization by 2040* pathway, the pattern with increased use of DF methanol ICE and DF ammonia ICE is amplified as the decarbonization is completed at this point, though the fuel transition is ongoing as old vessels are replaced with newbuilds with DF methanol ICE and DF ammonia ICE. The median uptake rates are 2% for DF LNG ICE, 21% for DF methanol ICE, and 55% for DF ammonia ICE.

Note that Figure 4.10 is only a snapshot of the situation in 2050, not the path leading up to it. For instance, it does not reveal if the engine and fuel systems result from installations on newbuilds or from retrofitting in place of other engine and fuel systems – for example, from DF LNG ICE to DF ammonia ICE. Each scenario will have its distinct technology path. To illustrate such paths, Figure 4.11 shows a stylized view of the engine and fuel system installed in the fleet, and key transitions in each decade from 2020 to 2050, for two example scenarios.

The first scenario (left panel, scenario 11) follows the *IMO ambitions* pathway with design and operational requirements, low renewable electricity prices, and high seaborne-trade growth. During the decade to 2030, we see growing LNG use in newbuilds, and some retrofit to scrubbers. In the 2030s, there is significant growth in LNG, but still only on newbuilds. Regulations start to have an effect with some retrofits from DF LNG ICE to DF ammonia ICE. After 2040, we see most newbuilds being built with an ammonia-fuelled propulsion system.

The second scenario (right panel, scenario 19) follows the *Decarbonization by 2040* pathway using design and operational requirements, low biomass prices, and low growth; and we see an entirely different technology path. The development between 2020 and 2030 is very similar to scenario 11, with retrofitting of scrubbers and growth in the use of LNG on newbuilds. After 2030, with new regulations coming into place, and with use of biofuels being the most economically feasible way to decarbonize, we see a quick transition to bio-methanol in 2040, including a high share of retrofits from LNG. LNG as a fuel is almost phased out, while we see some use of bio-MGO in part of the fleet in 2050.

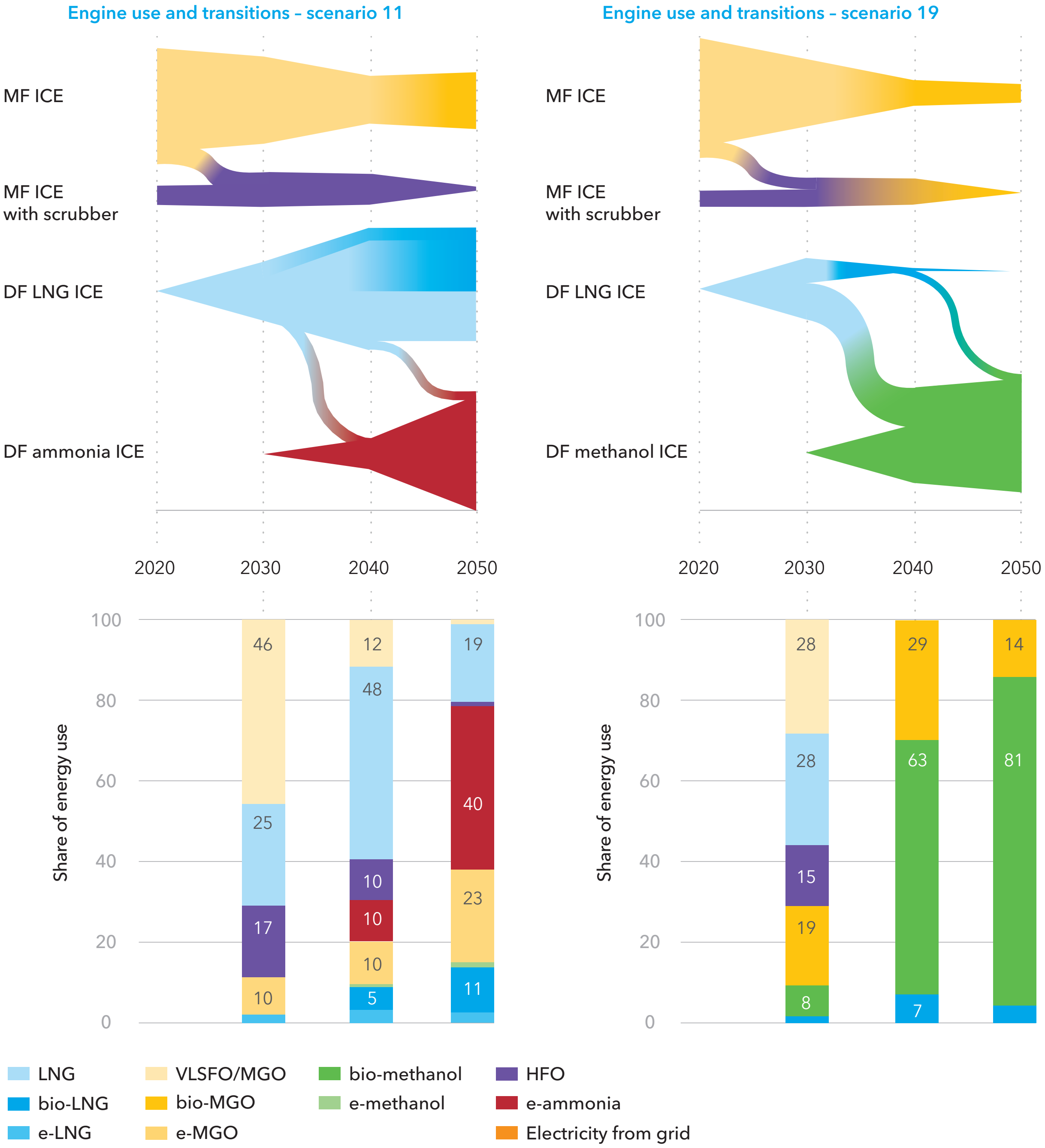
ON THE UPTAKE OF FUEL CELLS

Our modelling shows limited uptake of fuel cells. Predicting the future development of fuel cells is challenging. The technology is not currently mature enough for large-scale application, though we have seen several large-scale demonstration projects and new hydrogen-fuelled ferries are expected to enter into service in 2021. In addition to technology maturation, a significant cost reduction is needed for fuel cells to become commercially viable. In our modelling we have assumed high power efficiency and a cost reduction of 25% in 2030 compared with today, but we see limited uptake and the combustion engine remains the dominant energy converter-technology across all scenarios evaluated. The tables may turn in the future if fuel cells become much cheaper.

FIGURE 4.11

Engine and fuel system, transition pathways, and share of total energy use by shipping per decade to 2050 for scenario 11 (left) and scenario 19 (right). The width of the bars is approximately in scale, reflecting the energy use. The retrofit transitions are shown as a bar from one engine type to another. Not all engine types are shown, and only the most significant retrofit transitions.

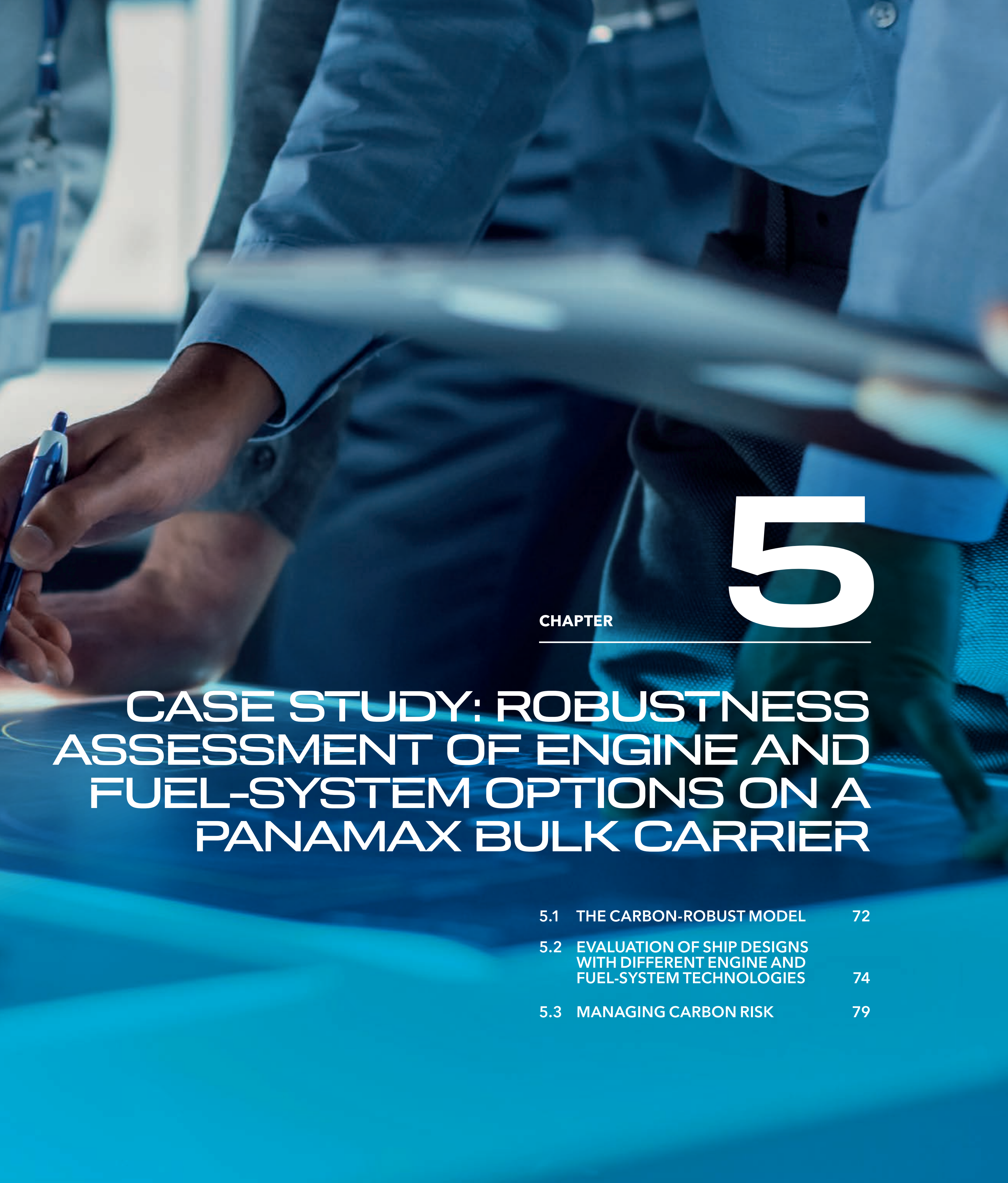
Units: Percentage (%)



HIGHLIGHTS

We have applied our future-proofing framework in evaluating the commercial robustness of design:

- A newbuild Panamax bulk carrier as a case study shows that installing a dual-fuel LNG engine and fuel system is consistently the most robust choice.
- Picking the wrong solution can lead to a significant competitive disadvantage.
- Planning for fuel flexibility could ease the transition and minimize the risk of investing in stranded assets.



CHAPTER

5

CASE STUDY: ROBUSTNESS ASSESSMENT OF ENGINE AND FUEL-SYSTEM OPTIONS ON A PANAMAX BULK CARRIER

5 CASE STUDY: ROBUSTNESS ASSESSMENT OF ENGINE AND FUEL-SYSTEM OPTIONS ON A PANAMAX BULK CARRIER

In this chapter, we use our scenario library reflecting possible pathways for the maritime energy mix to identify commercially robust choices for engine and fuel systems for a new Panamax bulk carrier as a case study.

Sub-chapter 4.3 discussed the fleet-wide distribution of fuel types and engine technologies in the modelled scenarios, most of which are also relevant for the Panamax bulk carrier segment. However, these findings provide limited guidance for a shipowner investing in a ship today.

A robust engine and fuel system should ensure that the ship remains compliant and competitive over its lifespan, either as is or taking into consideration a future retrofit. While many aspects need considering in a newbuild strategy, we will focus on the choice of engine and fuel systems identified in Chapter 4 as a critical issue with high uncertainty. The library of scenarios developed in Chapter 4 enables us to stress-test the options across a wide range of possible futures.

> “A robust engine and fuel system should ensure that the ship remains compliant and competitive over its lifespan, either as is or taking into consideration a future retrofit.

In the following sub-chapters, we apply the future-proofing framework and evaluate the commercial robustness of various design options for a new Panamax bulk carrier as a case study, starting with a brief description of the updated Carbon-Robust Model. Similar robustness analyses could be performed for any segment in the world fleet.

5.1 THE CARBON-ROBUST MODEL

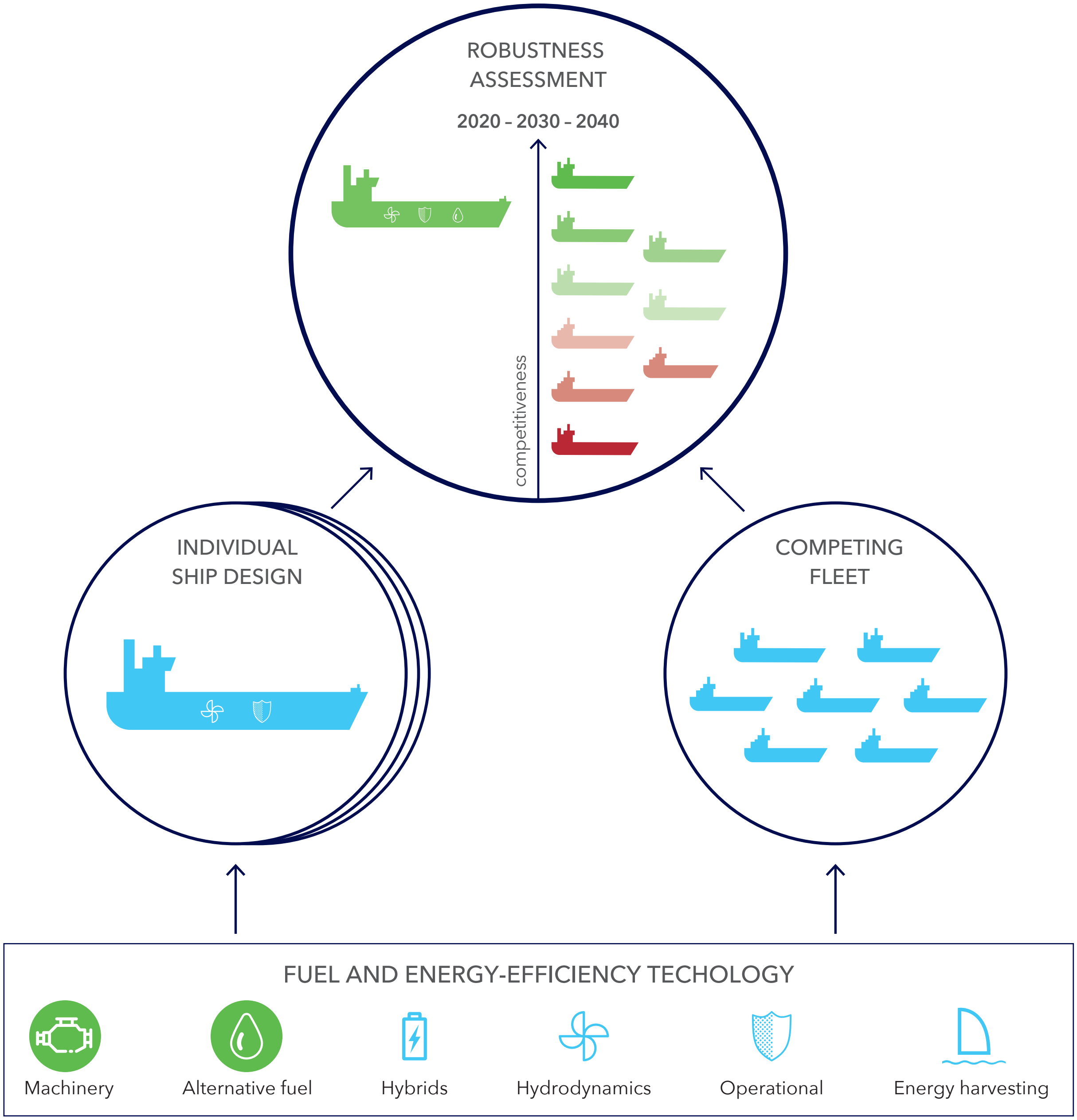
The essence of our future-proof framework described in the 2019 edition of this report is to compare the financial performance of design choices against a competing fleet of ships as it develops over time. For this we have developed the Carbon-Robust Model (Figure 5.1) (DNV GL, 2018a; 2019a). Through such a comparison, robust choices can be identified – i.e. designs that perform favourably across a wide range of scenarios. In this year's study we have further developed the Carbon-Robust Model and integrated it more closely with the GHG Pathway Model (sub-chapter 4.1) to exploit the scenario library and follow the different design options towards 2050.

To measure the robustness and competitiveness of a design we introduce a new key performance indicator (KPI) – the Daily Cost Delta – which is the difference between the technology break-even cost and the market benchmark rate for a specific segment and year, averaged over a 20-year period.

The technology break-even cost is the total cost of the vessel, including all capital and operational expenses (including fuel), annualized and divided into a daily cost. As a proxy for the market rate, which is the potential income for the ship, we have opted for the lowest technology break-even cost for a technology with at least 15% market share. With more than 15% market share, a charterer should have a reasonable selection of ships with this technology, and the technology break-even cost serves as a market benchmark rate for the segment. Having a positive Daily Cost Delta means lower break-even costs than the market benchmark, and thus a higher profit margin. See Appendix C for more details on the calculation.

FIGURE 5.1

Outline of the Carbon-Robust Model. The commercial robustness of selected individual ship designs is evaluated against a competing fleet of ships at a given point in time (e.g. 2030) using defined key performance indicators as measures. Alternative fuels and machinery are the main technology focus in this year's modelling.



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

5.2 EVALUATION OF SHIP DESIGNS WITH DIFFERENT ENGINE AND FUEL-SYSTEM TECHNOLOGIES

The three relevant engine and fuel systems for a newbuild Panamax bulk carrier commercially available today are a mono-fuel diesel engine running on VLSFO/MGO; a mono-fuel diesel engine running on HFO with a scrubber fitted; or a dual-fuel LNG engine capable of running on LNG and VLSFO/MGO. In the future, as carbon-neutral fuels become available, we also expect that dual-fuel methanol and dual-fuel ammonia engines will be relevant options. These are not considered mature options for a newbuild today, but the ship can retrofit to some of these options at a later stage. Due to limited uptake in the modelled scenarios we have excluded ICEs running on LPG and hydrogen, as well as fuel cells, while batteries with electric motors are impossible to apply in this segment.

The average Daily Cost Delta over 20 years for the three currently available technology options for a Panamax bulk carrier built in 2020 is shown in Figure 5.2 for all 30 scenarios developed in Chapter 4. The market benchmark rate, including fuel costs, for this segment is currently about USD 20,000–25,000 per day (/d), but this changes over time depending on the scenario, reaching USD 40,000–50,000/d in the aggressive decarbonization scenarios owing to the additional cost of carbon-neutral fuels. The Daily Cost Delta shows the deviation from this benchmark rate for the engine and fuel-system options under consideration over a 20-year period from 2020 to 2040. A positive Daily Cost Delta means lower break-even costs than the market benchmark, which should result in higher profit margins.

Figure 5.2 shows that the mean value of the Daily Cost Delta is higher for the dual-fuel LNG engine and fuel system than the other options. Also, while the spread in values between scenarios is similar for the LNG engine and the scrubber-fitted diesel engine, most scenarios are clustered at a higher level for the LNG-option. This indicates that installing a dual-fuel LNG engine that can run on either VLSFO/MGO or LNG, or can potentially retrofit to methanol or ammonia in the future, consistently yields a better margin between the market benchmark rate and the break-even cost. It should thus be considered the most commercially robust choice. The only exceptions are the low fossil-fuel price scenarios where the price difference between LNG and MGO is less. The performance of a conventional diesel engine with a scrubber (MF ICE with scrubber) and able to run on HFO is generally better than one without a scrubber (MF ICE).

In Figure 5.3, we look at the performance of the engine and fuel-system options for each decarbonization pathway. We see that all options generally perform worse in the *Decarbonization by 2040* scenarios in which we expect that ships built today will have to switch to a carbon-neutral fuel sometime in the 2030s, and well within the lifetime of the ship. Regardless of the option selected today, the ship will be at a disadvantage to other ships in the segment with new technologies in the future, although dual-fuel LNG engines perform better than the other two.

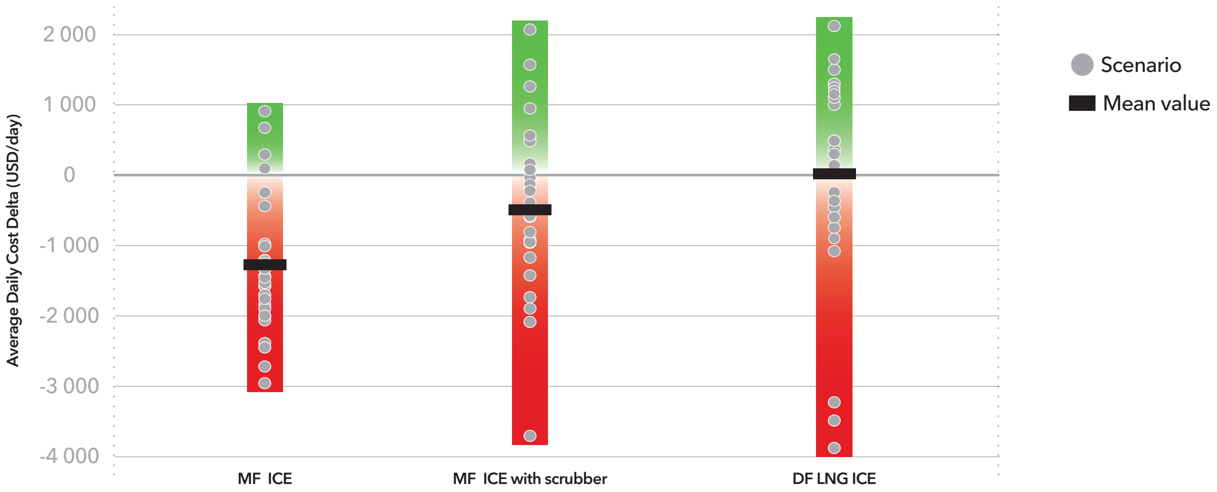
We see three main reasons for the higher comparative performance of the dual-fuel LNG engine. First and foremost, the dual-fuel LNG engine wins out because it can run on cheaper LNG.

Second, ships equipped with LNG engines will have a 20% to 25% reduction in tank-to-wake CO_2 emissions, yielding a significant benefit when

FIGURE 5.2

Average Daily Cost Delta over 20 years for engine and fuel-system options available for Panamax bulk carriers built in 2020. A positive Cost Delta means lower break-even costs than the market benchmark. Each dot represents one of the 30 scenarios developed.

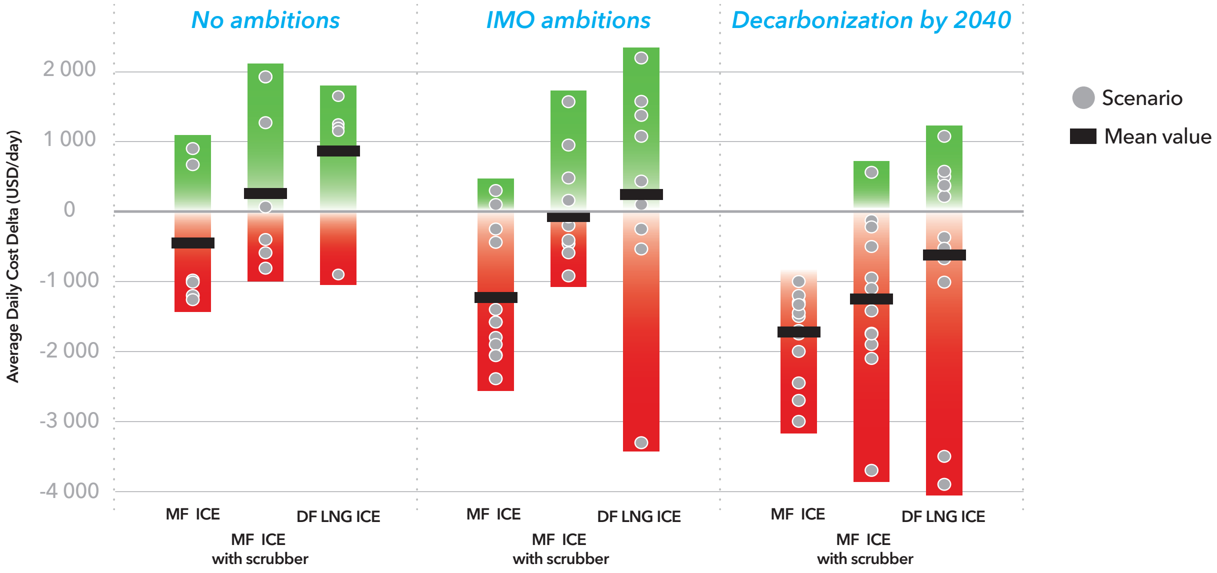
Engine and fuel-system robustness



MF, mono fuel; ICE, internal combustion engine; DF, dual fuel; LNG, liquefied natural gas

FIGURE 5.3

Average Daily Cost Delta over 20 years for engine and fuel-system options available for Panamax bulk carriers built in 2020, per decarbonization pathway. A positive Cost Delta means lower break-even costs than the market benchmark. Each dot represents a scenario.



MF, mono fuel; ICE, internal combustion engine; DF, dual fuel; LNG, liquefied natural gas striving to comply with increasingly stringent regulations (it is assumed that methane slip is eliminated). This means that under gradually stricter operational requirements adressing tank-to-wake CO_2 emissions, a ship with an LNG engine can continue to run on fossil LNG. However, ships on conventional MGO engines will need to apply speed reduction or other costly energy-efficiency measures in order to stay compliant. Applying these options puts the ship with the conventional engine at a disadvantage. This effect is less pronouced in scenarios with carbon pricing included.

Third, but also significant, the LNG engine and fuel system retains flexibility with regard to future decarbonization options including setting aside space for storage tanks. Recall from Chapter 4 that a range of fuels can be used as drop-in fuels or require a retrofit. For the three relevant engine options evaluated in this chapter, Figure 5.4 shows the main retrofit and drop-in fuel options available. As the figure shows, the dual-fuel LNG engine and fuel system enables using the cheapest fuels available today. The engine also has the possibility of using a wider range of drop-in carbon-neutral fuels at the end of its lifetime, or to retrofit to either an ammonia or methanol engine and fuel system. As we saw in Figure 4.11, a large number of ships retrofit from LNG to methanol in scenario 19. We see a similar pattern for all *Decarbonization by 2040* scenarios

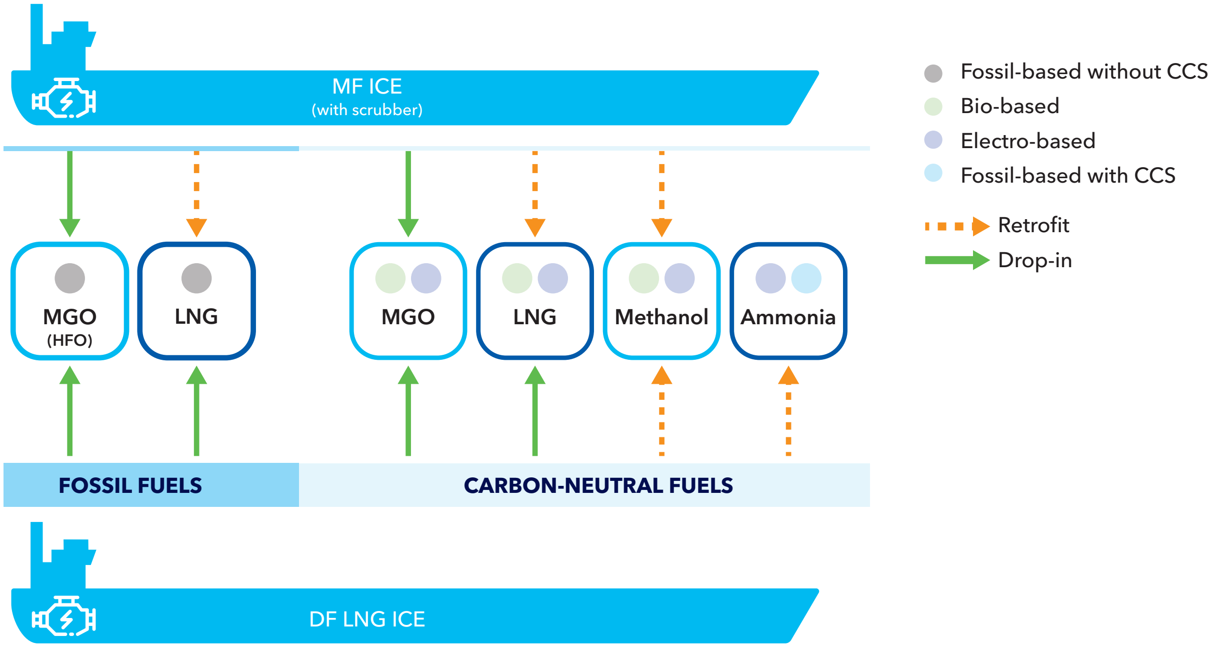
where ships with LNG engines and fuel systems retrofit to either methanol or ammonia engines and fuel systems. Of course, the conventional diesel engine is not without flexibility, as it can retrofit, for example, to a dual-fuel methanol engine, or it can switch to bio-MGO or e-MGO. However, the flexibility is less than for the dual-fuel engine, and the retrofits are mostly costly.

Besides the robustness of today's engine and fuel-system options, we observed in the design and operational requirements scenarios that applying a very strict design requirement for newbuilds forces them to run on carbon-neutral fuels. If the requirements for existing ships in operation do not follow suit, the competetiveness of newbuilds is severely distorted, and we risk old ships being retained in the fleet for a long time. In Figure 4.11 we see that in scenario 11 a fifth (20%) of the energy use comes from fossil LNG, while all newbuilds from 2040 are required to run on carbon-neutral fuels.

The analysis underpins the need for clear and long-term regulatory signals before we can expect any changes to ship technologies and fuels. In shaping regulations, policymakers need to be careful not to distort competition and to avoid creating unintended incentives, for example for older ships. These aspects are discussed in more detail in Chapter 2.

FIGURE 5.4

Main retrofit and drop-in fuel options available for a Panamax bulk carrier today and in the future if fitted with different engine and fuel systems; MF ICE (top) and DF LNG ICE (bottom).



MGO, marine gas oil; LNG, liquefied natural gas; HFO, heavy fuel oil; MF, mono fuel; DF, dual fuel; ICE, internal combustion engine


METHANOL

5.3 MANAGING CARBON RISK

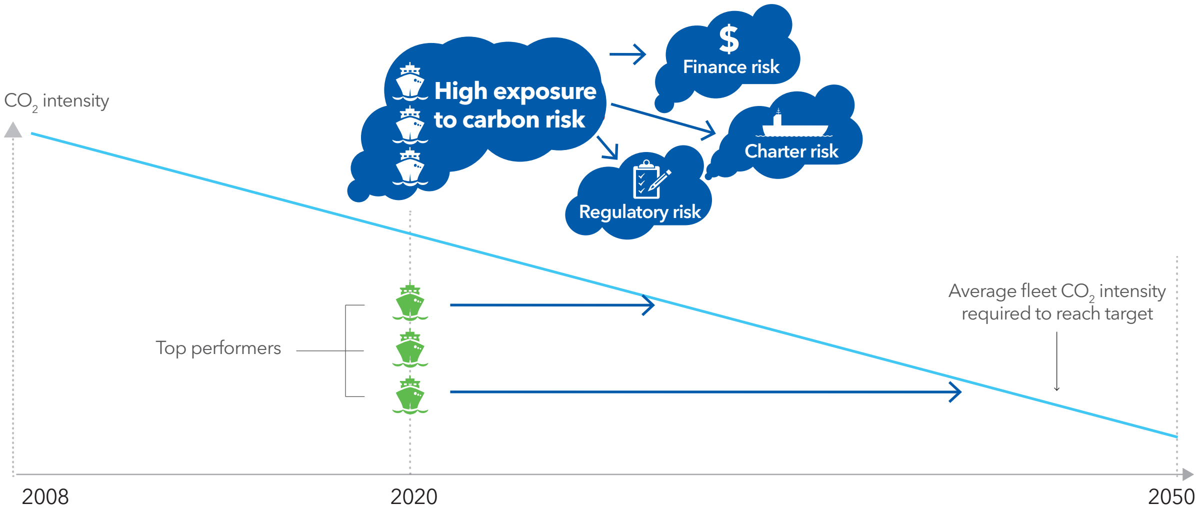
The robustness assessment shows that picking the wrong solution can lead to a significant competitive disadvantage. The high uncertainty of future policy measures and fuel availability and prices represents a significant risk for today's newbuild decisions and should be on the radar for shipowners' asset value and balance sheet management. Planning for flexibility could ease the transition and minimize the risk of investing in stranded assets. A structured approach to future-proofing will help in managing the risks.

While regulation is a key factor in assessing carbon risk, other factors could be important, such as finance risk and charterer risk (see Figure 5.5). A complete carbon-risk evaluation for a ship design needs to consider all these factors. The current analyis centres on IMO policy measures, and we have not considered incentives from other stakeholder and charter/financial risks (see sub-chapter 2.3 for a discussion on stakeholders beyond the IMO). These stakeholders can require transparent and comparable disclosure of a ship's GHG performance as a prerequisite for their financing/chartering, thus creating incentives for shipowners to improve the GHG performance of their vessels. Pressure from regulators, financiers and charterers will thus push shipowners to ensure that their ships stick to an acceptable GHG emission trajectory.

> “The high uncertainty of future policy measures and fuel availability and prices represents a significant risk for today's newbuild decisions and should be on the radar for shipowners' asset value and balance sheet management.

FIGURE 5.5

Conceptual illustration of potential exposure to carbon risk.



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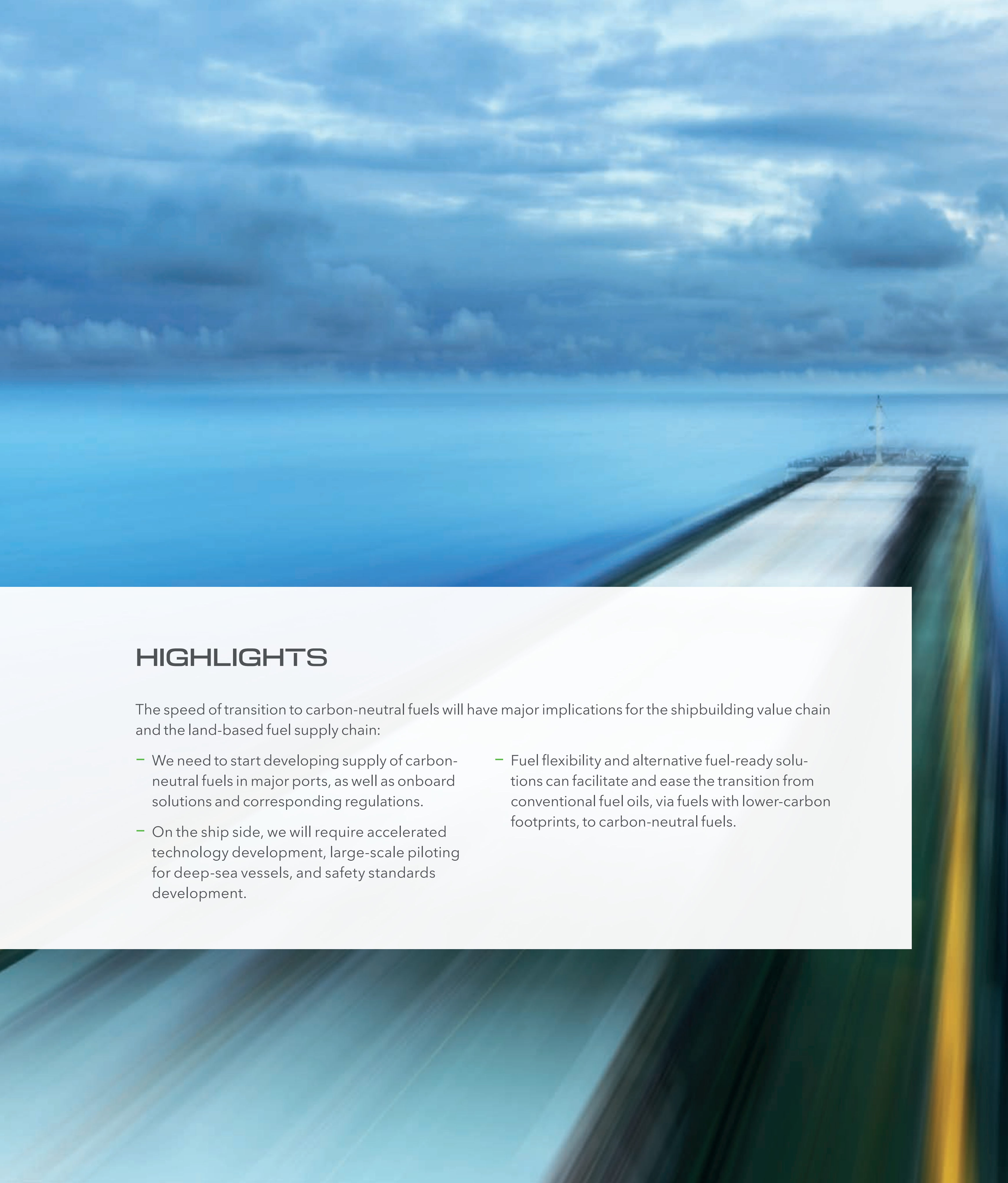


HIGHLIGHTS

The speed of transition to carbon-neutral fuels will have major implications for the shipbuilding value chain and the land-based fuel supply chain:

- We need to start developing supply of carbon-neutral fuels in major ports, as well as onboard solutions and corresponding regulations.
- On the ship side, we will require accelerated technology development, large-scale piloting for deep-sea vessels, and safety standards development.
- Fuel flexibility and alternative fuel-ready solutions can facilitate and ease the transition from conventional fuel oils, via fuels with lower-carbon footprints, to carbon-neutral fuels.

CHAPTER 6

ACCELERATING CHANGE TO BRIDGE THE EMISSION GAP

6 ACCELERATING CHANGE TO BRIDGE THE EMISSION GAP

Decarbonizing shipping requires new fuels and technologies to enter the fleet. Drawing on an updated Alternative Fuel Barrier Dashboard, which maps key barriers to implementation, this chapter explains how an ecosystem of stakeholders can positively impact a shipowner's business case for alternative fuels – and thus accelerate change.

Decarbonization cannot be achieved only by energy-efficiency and speed-reduction measures. The decarbonization pathways described in Chapter 4 point to the need for a massive scale-up and implementation of low-carbon technologies and fuels. To achieve decarbonization pathways, our results demonstrate the need for accelerated implementation of regulatory measures and incentives, and uptake of new technologies and large volumes of carbon-neutral fuels with global availability. To cover the future demand for shipping, the supply of zero-carbon/carbon-neutral fuels needs to be scaled up exponentially, along with accelerated maturation and cost reduction to commercialize technologies and fuels.

Importantly, for the 2050 targets to be reached ships ready for carbon-neutral fuels should start to enter the fleet from 2030 – using either drop-in fuels with existing engine and fuel-system technologies or with new technologies such as ammonia engines. In this decade, we must prepare the ground for this initial introduction, developing the supply of relevant fuels in major ports, and the onboard solutions and corresponding regulations. In this context, it is also important to consider the typical lag of three to five years from concept to ship on water. Recall, for instance, that it took 20 years from the appearance of LNG as fuel on ships other than gas carriers to its proliferation into most geographies and segments that we see today, including deep-sea shipping. The pace must be significantly accelerated for the uptake of new carbon-neutral fuels.

In light of the short timeline available, the question is how to accelerate developments. What are the key barriers hindering the creation of sustainable markets for ships using carbon-neutral fuels? What will motivate shipowners to move in the right direction and thereby activate sufficient parts of the maritime ecosystem to drive uptake of carbon-neutral fuels? This chapter addresses these aspects from the shipowner perspective. We analyse the following two sets of challenges.

- **Maturing low-carbon solutions and fuels:** The practicalities of applying a new fuel include considering engine and storage-system design, safe application, availably of fuel, port infrastructure etc. A shipowner needs to be confident that the ship will not break down or be left without fuel.
- **Ensure demand for ships with low-carbon footprints:** A shipowner needs to be confident that the additional investment, challenge and effort that goes into using a new fuel or technology will leave the owner well positioned in the market both today and in the future.

6.1 MATURING LOW-CARBON SOLUTIONS AND FUELS

Emission-reducing technologies and fuels exist but are not ready for large-scale implementation, as indicated in our Alternative Fuel Barrier Dashboard (DNV GL, 2019a). Key barriers mapped include technical maturity, cost of the required machinery and fuel-storage systems on vessels, fuel price, fuel availability and widespread/global bunkering infrastructure. Safety will also be a primary concern for some fuels.

The updated Alternative Fuel Barrier Dashboard in Figure 6.1, which now includes LPG and methanol, indicates the current status of key barriers to fossil fuels like LNG and LPG, and the carbon-neutral alternatives – ammonia, battery-electric power, biofuel (hydrotreated vegetable oil, HVO), hydrogen, and methanol.

As an example, the LNG ecosystem has matured as LNG is now available globally and in large volumes. Still, bunkering infrastructure is limited, and must be expanded before widespread uptake of LNG ship fuel can happen. Regulations and technical rules for safe design and use are in place. However, investment in the technology is still far more expensive than the conventional alternatives, and the capital costs should be reduced to improve competitiveness. The price of LNG fuel is not a significant barrier, but it is variable, and a transparent global market is still not in place.

For the other fuels, our dashboard reflects that various large barriers and challenges exist. For example, the current availability of carbon-neutral fuels is limited and none of the alternatives could today replace conventional fossil fuels.

Even if we can solve the cost, maturity and volumetric barriers, a fuel shift will not happen without scaling up volume and developing infrastructure, nor will it occur without having applicable rules for onboard use. Our pathway modelling shows that carbon-neutral fuels need to supply more than 60% of the total energy for international shipping in mid-century if the IMO’s ambitions for reducing GHG emissions are to be achieved.

Developing the necessary infrastructure and production capacity will take time, be costly, and involve many stakeholders in the land-based supply chain. New infrastructure and additional production capacity will only be developed if there is an emerging market for the expected ‘winners’, and if fuels have scale-up potential and long-term availability. Recently, we have seen bunkering-infrastructure built up using regions as stepping stones towards global availability of fuels (e.g. LNG, charging of batteries).

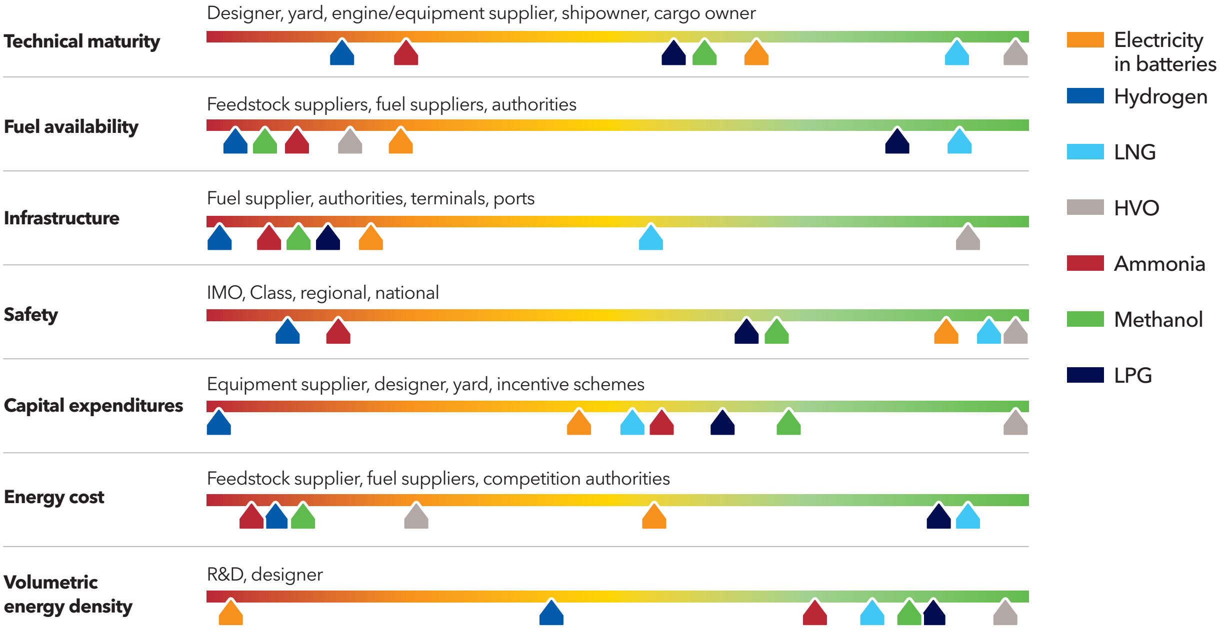
In the following pages, we address in some detail the safety challenges related to the introduction of new fuels and technologies. These challenges are reflected in the status of the key barriers technical maturity and safety for selected alternative fuels in Figure 6.1. Because the task of resolving all the barriers will take a long time, we also point out advantages of fuel-flexible options building on the bridging philosophy (DNV GL, 2019a).

6.1.1 SAFETY CHALLENGES

Most new and alternative fuels have properties posing different safety challenges from those of conventional fuel oils. This requires the development of regulations and technical rules for safe design and use onboard ships in parallel with the technological progress needed for their uptake. As Figure 6.1 indicates, alternative fuels have reached different levels of technical and regulatory maturity.

FIGURE 6.1

The Alternative Fuel Barrier Dashboard – indicative status of key barriers for selected alternative fuels in 2020.



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.
Safety – refers to rules and guidelines related to the design and safety requirements for the ship and onboard systems.
Capital expenditures – 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 with MGO, taking into account conversion efficiency.
Volumetric energy density – refers to amount of energy stored per volume unit compared with MGO, taking into account the volume of the storage solution.

HVO – hydrotreated vegetable oil;
LNG – liquefied natural gas;
LPG – liquefied petroleum gas;
Hydrogen – carbon-neutral liquefied hydrogen consumed in fuel cells;
Ammonia – carbon-neutral ammonia burned in internal combustion engines;
Electricity in batteries – full-electric with batteries;
Methanol – carbon-neutral methanol burned in internal combustion engines.

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The IMO has developed the International Code of Safety for Ships Using Gases and Other Low-Flashpoint Fuels (IGF Code, 'the Code'), providing an international regulatory framework (see text box). Currently, the IGF Code has detailed technical regulations only for LNG. For other types of gases and low-flashpoint fuels, approval will be based on first-principle analysis demonstrating that the design complies with the basic functional requirements of the Code. This risk-based approval process is referred to as the 'alternative design' approach, where an equivalent level of safety needs to be demonstrated.

The alternative design approach can be a time-consuming process with potentially higher business risk than the prescriptive experience-based rules that the maritime industry is used to working with. This must be considered as a barrier against uptake of alternative fuels in the industry. Reducing this barrier will require a learning process involving many stakeholders, in which development of the regulatory framework is continued, ships are designed and built, operational experience is gained, and the new and modified design is implemented.

The IMO is continuing its efforts in developing more detailed provisions for alternative fuels, but the process of developing statutory regulations is lengthy. Work on the IGF Code began in 2004, and the Code entered into force in 2017 after more than a decade of discussion and extensive work in the IMO. While interim guidelines for methanol and ethanol as fuel are agreed and due for approval, detailed provisions for fuel cells and LPG fuel are under discussion. There is currently no initiative in the IMO related to introduction of more detailed provisions for hydrogen as fuel, while an initial information paper on ammonia as fuel was submitted to the IMO in July 2020.

Classification Societies develop rules more quickly, and these rules may be used to simplify the alternative design approach mandated by the IGF Code if agreed by the Flag Administration. DNV GL has issued class rules for the use of methanol, ethanol and LPG as fuel in addition to LNG. There is also ongoing development work for ammonia and hydrogen, and DNV GL is working with industry partners on removing barriers. For example, we have initiated the MARHYSAFE joint development project (JDP) designed to advance maritime hydrogen-specific competence. The JDP aims to combine the alternative design approach for generic hydrogen vessels, available R&D results, and industry experiences to provide preliminary recommendations for safe and effective introduction of hydrogen as a marine fuel.

6.1.2 FUEL FLEXIBILITY OR WAIT AND SEE?

Resolving all the barriers will take a long time, even with accelerated efforts. Waiting for all barriers to be reduced to acceptable levels could mean that the time window available to implement mature solutions will be too narrow to reach the stated decarbonization goals – or that the rate at which the solutions must be implemented is unrealistically high. The 2019 edition of this report therefore promoted the concept of bridging technologies that can facilitate and ease the transition from conventional fuel oils, via fuels with lower-carbon footprints, to carbon-neutral fuels.

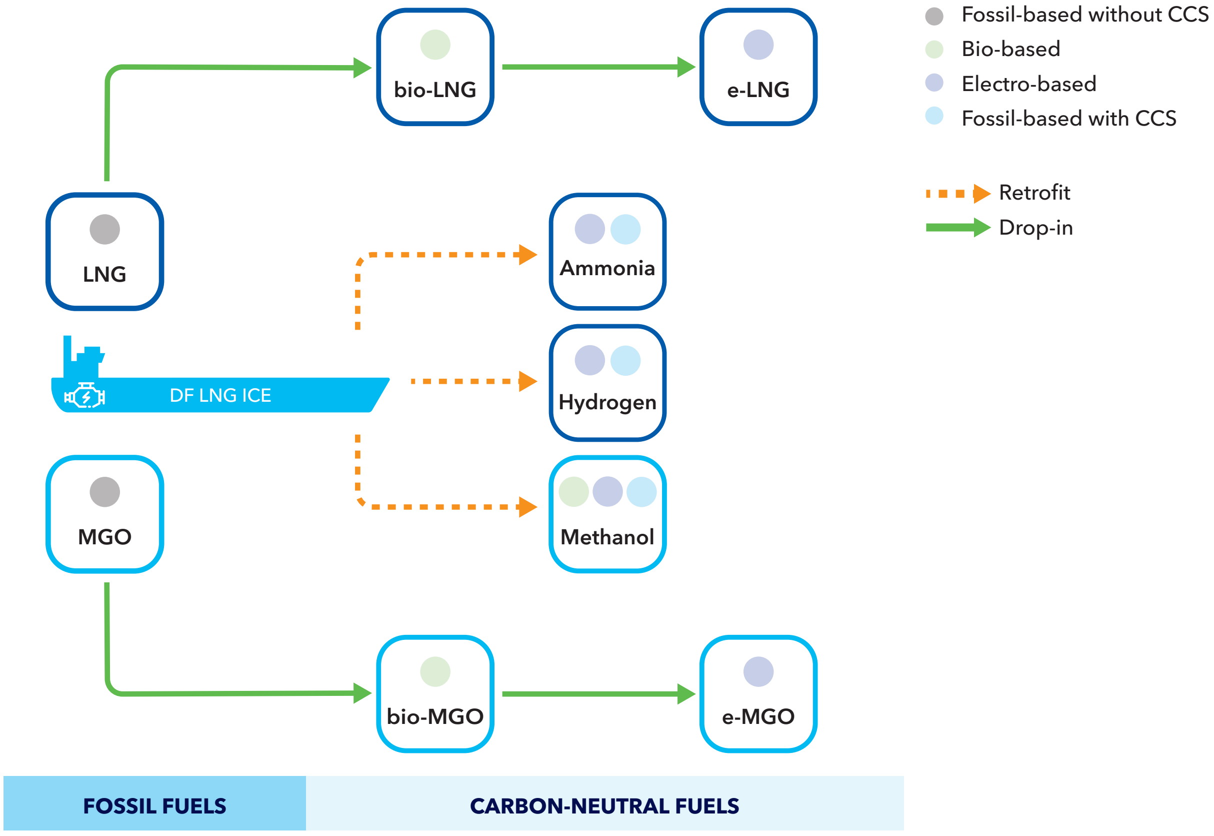
An example of fuel flexibility building on the bridging philosophy is illustrated in Figure 6.2. A vessel powered by dual-fuel ICEs that can burn LNG and MGO has different options for fuel shifts, allowing for a gradual transition to carbon-neutral fuel alternatives as they are developed and commercialized. Bio-based and, later on, electro-based LNG and MGO are flexible alternatives. They may be blended with conventional fossil fuels, or used as full drop-in substitutes for these conventional fuels without modifications onboard. For other fuels such as ammonia, hydrogen, or methanol the compatibility is more limited and retrofits are required for engines, storage tanks and fuel-supply systems. By considering fuel flexibility based on the bridging philosophy when designing newbuilds, features like fuel-flexible converters and arrangements could ease retrofitting at a later stage. Our case study results in Chapter 5 indicate the advantages of dual-fuel ICEs that can burn both LNG and MGO.

In addition, the dual-fuel solutions analysed in Chapter 5 could be improved to further bolster their robustness. This could be achieved by applying alternative fuel-ready solutions, which

> “ The highest possible level of energy efficiency will under any circumstances ease a future fuel shift.

FIGURE 6.2

A vessel with dual-fuel engine capable of burning LNG and MGO illustrates fuel flexibility, building on the bridging philosophy.[11, 12]



MGO, marine gas oil; LNG, liquefied natural gas

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[11] bio-LNG and bio-MGO are terms used in this report to denote bio-based liquefied methane and bio-based diesel respectively.

[12] e-MGO, e-LNG and e-LPG are terms used to denote (respectively) electro-based diesel, electro-based liquefied methane, and electro-based propane.

implies building the vessel with conventional fuel technology but preparing it to allow a less-costly conversion later. Relevant preparations for an alternative fuel-ready design could be designated space for the future fuel installation, fuel-flexible converters, or documentation of structural preparations needed to allow for future fuel-storage tanks. The highest possible level of energy efficiency will under any circumstances ease a future fuel shift. With an alternative fuel-ready design at hand, an assessment can be made to evaluate which preparations would be beneficial to incorporate in the newbuild and which could be left for the alternative-fuel retrofit at a later stage.

SAFETY CONSIDERATIONS FOR ALTERNATIVE FUELS

Fire is a major hazard onboard a ship, and handling flammable fuels in spaces with ignition sources and hot surfaces is one of the risk factors.

Fuel vapour may ignite spontaneously without any secondary ignition source if it is heated up to its auto-ignition temperature. Leaking oil coming into contact with high-temperature surfaces is by far the most common reason for engine-room fires.

With an ignition source present, fuel vapours may also be ignited when the fuel is heated to a temperature at which the fuel will give off enough flammable vapour to be ignited. This temperature is referred to as the flashpoint of the fuel. The flashpoint, the amount of energy required to ignite the vapour mixture (minimum ignition energy) and the ratio of air to fuel vapour (flammability range) are specific to each fuel type. To limit the risk of tank explosions and vapours being ignited, IMO has generally prohibited the use of fuel oils with a flashpoint below 60°C.

Most alternative fuels are gases or liquids with a significantly lower flashpoint than conventional fuel oils and will, unlike conventional fuel oils, create an explosive gas atmosphere in an enclosed space unless properly contained. Some alternative fuels are also toxic to humans in small quantities and in low concentrations, and some are stored at very low temperatures, adding to the challenge of integrating a safe storage and distribution system. On the positive side, many have a substantially higher auto-ignition temperature than fuel oils.

Storage of gaseous fuels in liquefied form will require control of temperature and/or pressure in the storage tanks. Due to the high energy content, damage to storage tanks can have potentially catastrophic consequences.

The differences in properties and associated hazards for alternative fuels require additional safety barriers to maintain the safety level when compared with conventional oil fuel. Each alternative fuel has its unique properties and associated hazards requiring special consideration. The safety concept of DNV GL's current rules for LNG is summarized in the figure below. We anticipate that the same principles can be applied to other alternative fuels in the development of prescriptive fuel-specific class rules.

Segregation Protect fuel installation from external events	**Double barriers** Protect the ship against leakages
Leakage detection Give warning and enable automatic safety actions	**Automatic isolation of leakages** Reduce consequences of a leakage

6.2 ENSURE DEMAND FOR LOW-CARBON SHIPPING

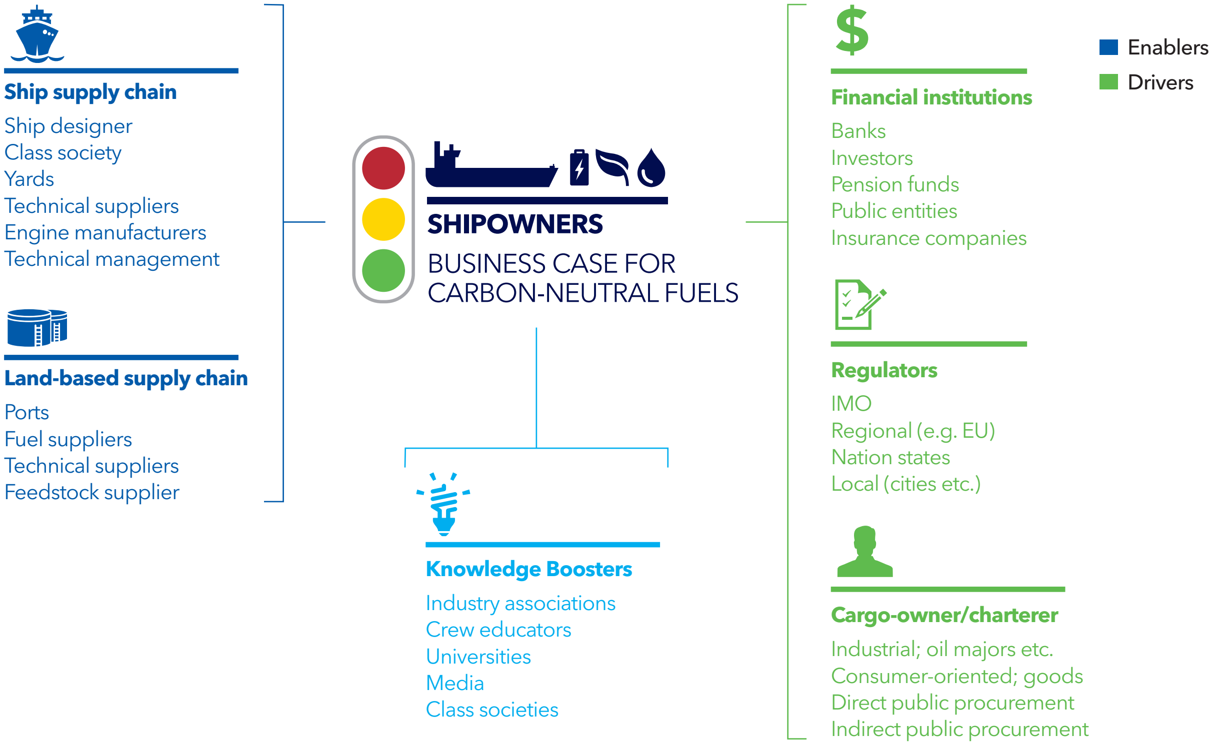
Shipowners have conventionally gravitated towards solutions that are cheaper, more reliable, more efficient, and which demand less space onboard. Going forward, owners will still favour such solutions. The challenge is that solutions to reduce global maritime GHG emissions are typically more expensive, less mature, less efficient and require more space onboard.

Without a development that moves the status markers significantly to the right in the Alternative Fuel Barrier Dashboard (see Figure 6.1), shipowners making the decision to deploy new, improved technologies and fuels will not risk investing in immature solutions. This is just one aspect of the challenge: demand and willingness to pay for shipping services with low-carbon footprints are equally essential for sustainable business.

As Figure 6.3 indicates, the shipowner business case is influenced by an ecosystem of stakeholders. The interaction between stakeholders holds

FIGURE 6.3

The ecosystem of stakeholders influencing the shipowner business case for carbon-neutral fuels. Inspired by DNV GL (2019c).



> “Shipowners making the decision to deploy new, improved technologies and fuels will not risk investing in immature solutions.

the power to make investing in new fuels worthwhile or not. The shipowner-centric system presented in Figure 6.3, includes both anticipated drivers and enablers for future fuel shifts. Enablers are responsible for developing solutions for carbon-neutral shipping – breaking down the barriers identified in sub-chapter 6.1 – but will not do so unless incentivized by stakeholders characterized as drivers. The business case for developing and using new fuels and technologies must be clear.

A number of actions can help to ensure demand for shipping powered by carbon-neutral fuels, thereby reducing market and regulatory risks and accelerating uptake of the fuel:

- International, regional, national and local (e.g. city) regulations will be key drivers to incentivize uptake of new solutions. This covers both technical requirements and pricing mechanisms. Our analysis underpins the need for clear and long-term regulatory signals before we can expect any changes to ship technologies and fuels.
- Supportive green procurement policies from both public and private cargo-owners, combined with long-term contracts, will enable investments in ships powered by carbon-neutral fuels.
- Schemes providing favourable, long-term financing to green ships.
- Risk-sharing mechanisms to reduce the risk for first movers.

Importantly, the timeline is an important parameter to achieve the decarbonization pathways, and there is a range of critical development steps. Starting with the decade ahead, we need to progress new generation carbon-neutral ships. This will require accelerated technology development, large-scale piloting for deep-sea vessels, and safety standards development.

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HISTORICAL DATA

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For energy related charts, historical (up to and including 2018) numerical data is mainly based on IEA data from World Energy Balances © OECD/IEA 2019, www.iea.org/statistics, License: www.iea. org/t&c; as modified by DNV GL.

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APPENDIX A – EMISSIONS ABATEMENT INPUT

In the following sub-chapters we provide details on all CO_2 emission abatement measures used in our scenario modelling.

A.1 ENERGY-EFFICIENCY MEASURES

DNV GL has its own abatement database for different ship types, utilized as input to the GHG Pathway Model. The abatement database 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, COSMOS[13] 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 as presented in Table A.1. The measures included in the different EE packages will depend on the applicability for the ship type in question. This study allocates the EE measures in packages for six main ship segments.

TABLE A.1

Defining the energy-efficiency packages

EE group	Maturity	Explanation
Baseline EE	–2015	Average energy efficiency of a vessel built before 2015. Includes basic operational measures, as well as standard hull cleaning, propeller polishing, engine auto-tuning and optimization of cargo handling systems.
Basic EE	2015–2020	Average energy efficiency of a vessel built after 2015 and until 2020. Includes hull form optimization, basic machinery improvements, variable frequency drives, shaft motor/generator, and measures to improve hydrodynamic propulsion, such as devices before the propeller and high-efficiency propellers and rudders.
Enhanced EE	2020–2025	Energy-efficiency measures expected to be mature within five years. Includes waste-heat recovery systems, bow shapes optimized for real sea states, variable engine speed and improved steam-plant operation.
Advanced EE	2025–2030	Energy-efficiency measures expected to be mature within 10 years. Includes, among other measures, hard sails, solar panels, next-generation waste-heat recovery systems, and reduced-ballast design.
Cutting-edge EE	2030–	Measures expected to mature in more than 10 years are placed in the cutting-edge package, including digital twins and onboard wind turbines.

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

A.2 SPEED REDUCTION

The model applies five different levels of speed reduction: 0% (sailing at 75%–80% of maximum continuous rating, MCR[14]), 10%, 20%, 30% and 50%. The resulting reductions in main-engine power for an individual vessel are estimated based on reported fuel-consumption data from more than 2,000 vessels. Percentage main-power reduction is larger at 10% and 20% speed reduction 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 also 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 and included when considering the most cost-effective measure to apply. The model factors in the applied speed reduction and adds more vessels to make up for the reduced transport capacity.

The fleet sailing in 2019 would have already implemented some of the energy-efficiency and speed-reduction measures. We have assumed that all vessels built before 2015 will have the Baseline EE package, while those built from 2015 will have the Basic EE package. The difference in efficiency can be observed in the MRV data for 2018 published by the European Commission (European Commission, 2020). In addition, the average speed from the AIS data is used to set an already implemented speed reduction on the baseline fleet in 2019. The model evaluates all combinations of EE packages and speed reductions, and selects the combination with the highest net present value.

A.3 LOGISTICS

Towards 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 containerships and 10% for bulk carriers. The sizes of other ship types will remain as today.

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

APPENDIX B – SCENARIO ASSUMPTIONS

In the following sub-chapters we provide details on the assumptions made in the 30 scenarios developed in Chapter 4.

B.1 REGULATIONS

The IMO has come far in developing the first regulations to support its GHG ambitions in the short term. However, uncertainty remains over the pace, form and type of regulatory measures the organization will implement to achieve the desired change towards 2050. To cover this uncertainty, we look at principal ways to incentivize a change (see Table B.1) – newbuild design requirements and operational emission limits to individual ships, and a carbon price. The design requirements are given as percentage reductions from an EEDI reference line, and the operational requirements as percentage reductions compared with a pre-2013 average ship.

Variations in fuel prices and fleet growth mean different levels of requirements and carbon prices will be needed in each scenario to achieve the desired reduction in GHG emissions. To simplify things, we apply the level needed in the most extreme scenarios – those with high growth and the largest spread between fossil and carbon-neutral fuels – to all scenarios with the same ambition.

In all scenarios we assume that the currently adopted EEDI regulations will apply.

TABLE B.1

Assumptions on regulatory measures and percentage reduction in GHG emissions.

Ambitions	Regulations	Newbuild requirements	Operational requirements (gradually increasing)	Carbon price (gradually increasing)
No ambitions	Current design requirements	Currently adopted EEDI requirements: up to 30% reduction depending on ship type	None	None
IMO ambitions	Newbuild and operational requirements	Currently adopted EEDI requirements: up to 30% reduction depending on ship type From 2035: 50%–80% reduction depending on ship type From 2040: 90% reduction	2030: 40% reduction 2040: 60% reduction 2050: 70% reduction	None
	Carbon price	Design requirements: Currently adopted EEDI requirements: up to 30% reduction depending on ship type	None	2030: 50 USD/tCO_2 2040: 200 USD/tCO_2 2050: 400 USD/tCO_2
Decarbonization by 2040	Newbuild and operational requirements	Currently adopted EEDI requirements: up to 30% reduction depending on ship type From 2030: 90% reduction	2025: 35% reduction 2030: 55% reduction 2040: 100% reduction	None
	Carbon price	Currently adopted EEDI requirements: up to 30% reduction depending on ship type	None	2030: 150 USD/t CO_2 2040: 700 USD/t CO_2

B.2 FUEL PRICES

The overall method for calculating fuel prices has been given in sub-chapter 4.1.2. We have developed a Marine Fuel Price Mapper using levelized cost of production and distribution as a proxy for fuel price. This approach is based on DNV GL's ExplEnergy tool, which allows analysis of different energy value chains (DNV GL, 2018b).

To address the high uncertainty related to future price-differences between the main families of alternative fuels, three different fuel-price scenarios have been constructed. Each of these scenarios is characterized by the cost of primary energy as shown in Table B.2.

Table B.3 below shows the assumed price trajectories of primary energy sources used as input in fuel-price calculations. Due to the long time-perspective of the GHG Pathway Model, recent declines in the natural gas and crude oil prices have not been included in the modelling.

It is important to note that the price scenarios outlined in Table B.2 are designed to address uncertainties between different fuel families, not price differences of fuels within a particular fuel family. Figure B.1 shows estimated high and low prices for fuels in 2050, used as input in the model. The GHG Pathway Model does not distinguish between VLSFO and MGO, hence they are named VLSFO/MGO. However, the price of VLSFO/MGO reflects the price of VLSFO, rather than MGO.

FIGURE B.1

Assumed high and low prices for fuels in 2050. The prices include both production and distribution costs. Fossil-fuel prices are shown without any carbon tax, which is imposed as a regulatory measure of decarbonization in some scenarios.

Units: USD/GJ

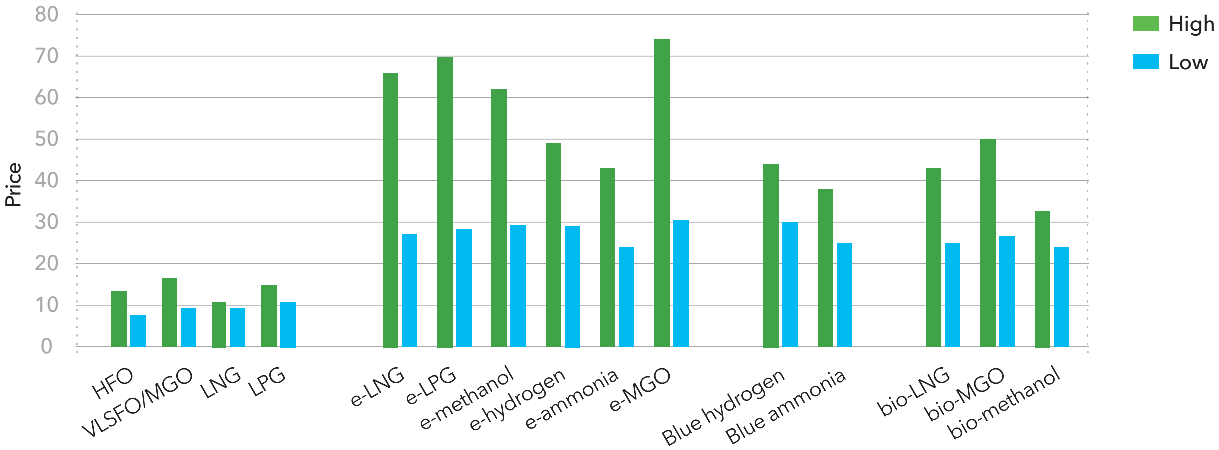

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TABLE B.2

Fuel-price scenarios evaluated in the GHG Pathway Model.

	Price of primary energy source		
Scenario name	**Renewable electricity price**	**Fossil-fuel price (including blue fuels)**	**Biomass price**
Low renewable- electricity price	Low	High	High
Low fossil-energy price[15]	High	Low	High
Low biomass price	High	High	Low

TABLE B.3

Assumed primary energy costs by price scenario. Based on current costs and projections for future cost of primary-energy sources (e.g. IEA, 2019a; IRENA, 2019).

Primary energy source	Scenario	2020	2030	2040	2050	Unit
Electricity from renewables[16]	High	183.1	114.0	95.0	76.0	USD/MWh
	Low	48.2	30.0	25.0	21.0	
Biomass[17]	High	1.0	1.7	2.0	2.0	No unit
	Low	1.0	1.2	1.3	1.3	
Natural gas	High	7.7	8.9	9.9	9.9	USD/MMBtu
	Low	7.7	7.5	7.5	7.5	
Crude oil	High	70	89.9	105.2	105.2	USD/barrel
	Low	70	63.3	60.3	60.3	

MWh, megawatt hours; MMBtu, million British thermal units

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[15] Includes both natural gas and crude oil prices.

[16] Based on estimated levelized cost of renewable energy production: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf and https://www.irena.org/publications/2019/Oct/Future-of-wind.

[17] Cost of biomass given as a factor relative to the cost of biomass in 2020. Different biomass sources are used for production of different biofuels, and an average value is shown in the table.

B.3 SEABORNE-TRADE DEMAND

Studies have reported that international world maritime trade could grow between 25% and 250% by 2050 (Smith et al., 2014; ITF/OECD, 2019; DNV GL, 2019a, 2020a). The Fourth IMO GHG study projects between 40% and 115% growth (Faber et al., 2020). The wide span of projections indicates large uncertainty, which is reflected in our choice of scenarios. This study has used low- and high-growth scenarios (Table B.4 and Figure B.2).

For the **low-growth scenarios**, we use DNV GL's own updated projection with 25 % growth between 2019 and 2050 (DNV GL, 2020a). This is less than any scenarios used in the Third and Fourth IMO GHG Studies. Most of the growth will come before 2030. After that, global seaborne trade will stabilize. Growth in certain segments, especially gas and container trade, will outpace the average rate. However, as the global demand for coal and oil peak, their trade will also top out, reducing their seaborne trade by more than two thirds and one third, respectively in 2050. The projection also takes into account the effect of the COVID-19 pandemic.

TABLE B.4

Seaborne-trade demand growth assumptions for the low- and high-growth scenarios.

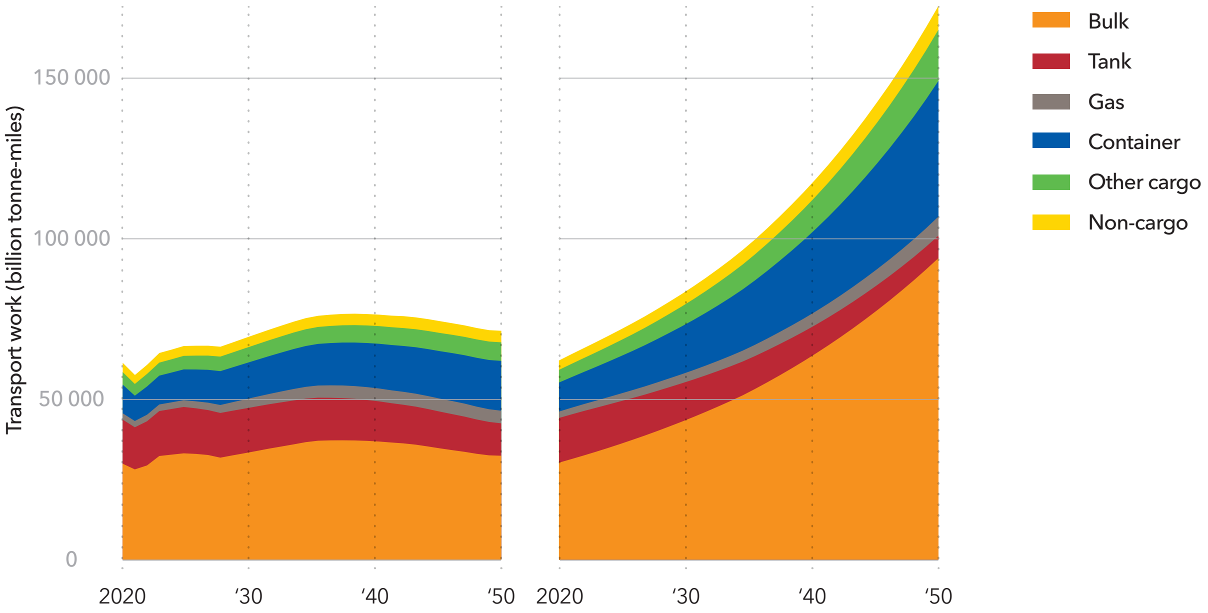
Scenario	Assumptions	Annual change			Total change
		2020-2030	2031-2040	2041-2050	2020-2050
Low-growth DNV GL ETO	Tank	-0.6%	-0.7%	-1.4%	-21.8%
	Bulk	1.3%	0.9%	-1.4%	8.3%
	Container	2.5%	2.2%	1.2%	73.4%
	Gas	7.5%	5.8%	2.5%	327.6%
	Other cargo	1.3%	1.0%	0.3%	28.7%
	Non-cargo	2.6%	2.6%	2.1%	94.7%
	Total growth	**1.4%**	**1.2%**	**-0.3%**	**24.9%**
High-growth RCP2.6, SSP 4	Tank	-3.6%	-3.2%	0.0%	-52%
	Bulk	3.6%	3.7%	3.9%	211%
	Container	5.1%	5.1%	5.1%	367%
	Gas	3.6%	3.6%	3.6%	198%
	Other cargo	4.2%	4.2%	4.2%	258%
	Non-cargo	3.6%	3.6%	3.6%	198%
	Total growth	**2.6%**	**3.5%**	**4.0%**	**179%**

RCP, Representative Concentration Pathways; SSP, Shared Socioeconomic Pathways

For the **high-growth scenarios**, we use scenario 16 from the Third IMO GHG Study (Smith et al., 2014) which is based on RCP2.6 for demand for transport of fossil energy (crude oil and coal) and SSP4 (inequality) for other cargoes. Since the actual transport demand in the baseline used in 2019 for this study is higher than predicted in this scenario from 2014, this study uses the growth between 2019 and 2050, which results in a slightly higher transport demand in 2050 than in the original scenario. For segments not explicitly described in the Third IMO GHG study, we have used the following: non-cargo, chemical tankers and gas tanker have the same demand growth as the average for all other segments. Other dry bulk is assumed to have the same growth as for non-coal bulk. See Table B.4 and Figure B.2 for details.

FIGURE B.2

Transport work in the low-growth (left) and high-growth (right) scenarios.



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APPENDIX C – CALCULATING THE DAILY COST DELTA

The following input and definitions are used in the robustness assessment in Chapter 5.

Vessel break-even cost: the total daily cost of the ship including all capital, operational and fuel expenses.

- **Capital expenses** include the basic newbuild cost and the additional cost of energy-efficiency, engine and fuel-storage costs. It also includes the capital expenses of a retrofit. The basic newbuild cost is the average newbuild cost for the segment over the last five years from Clarksons (2020). The annualized capital expense is converted into a daily expense based on loan with an interest of 4% over 20 years, and a residual value of 30% after 20 years. The cost includes the interest costs and a fixed instalment of the loan less the residual value per year, and is divided by 350 days.
- **Operational expenses** include all costs of running the vessel, such as crew, maintenance and so on, based on Drewry (2020). It also includes any additional costs of running energy-efficiency technologies.
- **Fuel expenses** include all fuel and carbon-price costs.

Technology break-even cost: For each year and ship segment, we calculate a vessel break-even cost for each engine technology. This is calculated as the average break-even cost of all vessels with that technology. To compare the break-even costs of ships with varying degree of speed reduction, we apply a cost correction to account for the fact that a ship going slower needs to be hired in for more days to do the same transport work. For example, a ship with 20% speed reduction has a correction multiplier of 1/(1 – 20%) = 1.25.

Market benchmark rate: For a segment and year, this rate is determined as the lowest technology break-even cost of the technologies with more than 15% market share. This reflects that technologies with less market share are assumed to be unable to impact the market price, and the real choice for a charterer is from technologies with more than 15% market share. This is a simplification. For example, for many segments, the fuel cost is not included in the charter rate and is paid by the charterer. However, we believe that an informed charterer will take the potential fuel cost of a vessel into account.

Delta between technology break-even cost and the market benchmark rate: The financial performance of a technology is defined as the market benchmark rate minus the technology break-even cost of a ship with that technology. The idea is that a ship with a technology costing less that the market benchmark rate would give a larger margin than one with a technology that costs more.

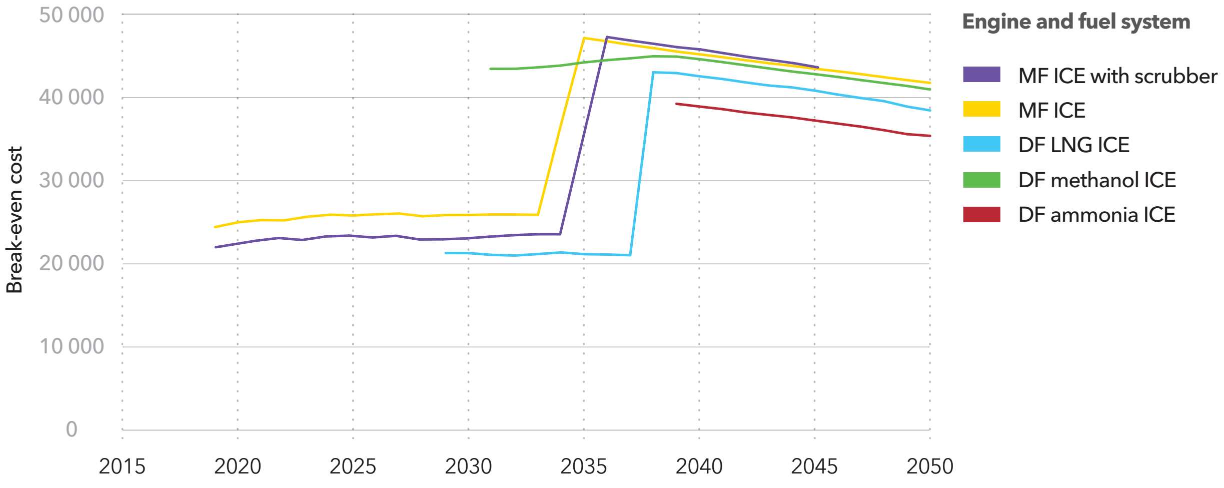
Daily Cost Delta – average delta rate over a period: The Delta rate should be seen over a relevant time span. A ship built today is expected to stay in operation until at least 2040. In the *Decarbonization by 2040* pathway, this ship will, towards the end of its lifetime, be likely to have to run on carbon-neutral fuel and compete with newbuilds built for this purpose. A ship built in 2025 and later will start to spend a significant part of its lifetime under stringent decarbonization policies. In order to make comparisons across a period, we calculate an average delta rate over 20 years.

Figure C.1 shows an example of technology break-even costs for the Panamax bulk carrier segment for scenario 20 (see description in Appendix B) targeting decarbonization by 2040 by meeting design and operational requirements. The lowest line at any point is the market benchmark rate for that year. Until 2030, ships running on MGO/LSFO or HFO are the dominant technologies, with ships fitted with scrubbers having the lowest break-even and setting the market benchmark rate. Around 2030, ships with dual-fuel gas engines have sufficient market share to impact market rates and, for a short period, are compliant with sharply increasing operational requirements, whereas ships using other fuels need to shift to a more expensive carbon-neutral fuel, thereby increasing rates by a third. Towards 2040, dual-fuel ammonia engines start to pick up.

FIGURE C.1

Break-even costs by engine technology for Panamax bulk carrier for scenario 20 with *Decarbonization by 2040* design and operational requirements, low growth, and low renewable electricity prices. The lowest line at any time is the market benchmark rate for that segment and year, and the Daily Cost Delta is the average difference between the benchmark rate and break-even cost over a 20-year period.

Units: USD/day



MF, mono fuel; ICE, internal combustion engine; DF, dual fuel; LNG, liquefied natural gas

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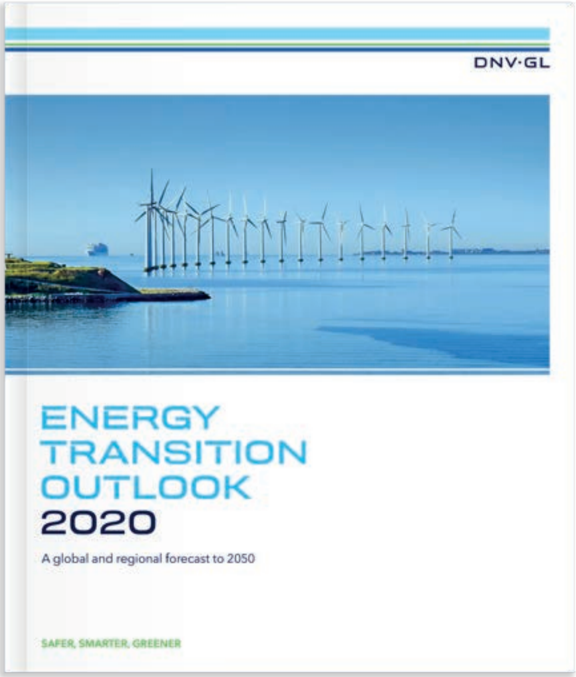

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- The climate implications of our forecast and solutions for closing the gap to well below 2°C.

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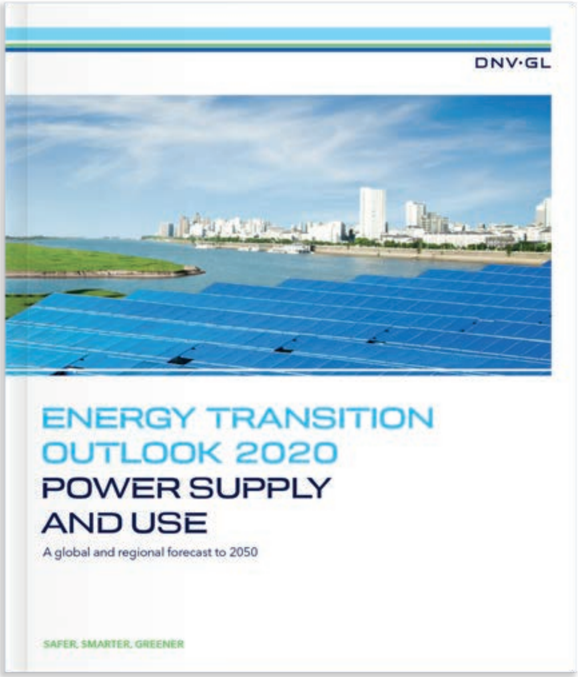

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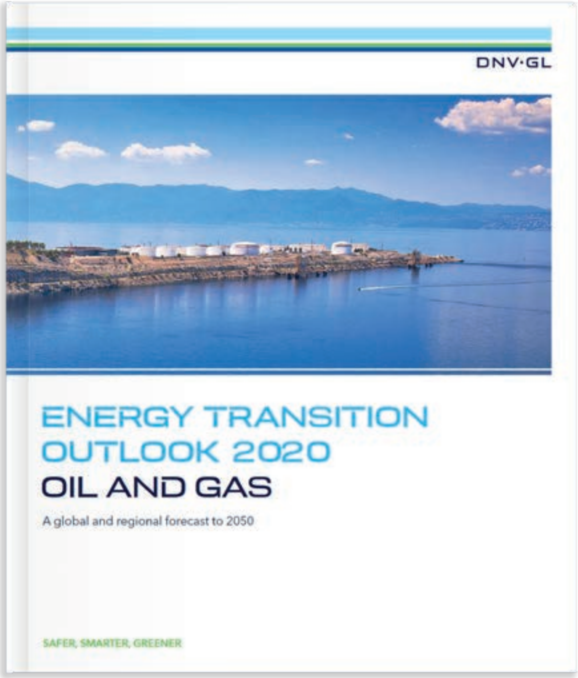
POWER SUPPLY AND USE

This report presents implications of our energy forecast to 2050 for key stakeholders involved in electricity generation, 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, reinforcement and upgrading of transmission and distribution networks
- Further need for implementation of energy-efficiency measures
- Acceleration of the electric vehicle revolution
- Digitalization enabling process improvements and smarter operations
- The energy transition is fast, but not fast enough to meet the goals of the Paris Agreement.



ENERGY TRANSITION OUTLOOK 2020
OIL AND GAS
A global and regional forecast to 2050

OIL AND GAS

This report provides the demand, supply, and investment forecast for hydrocarbons to 2050, with commentary on key trends:

- The world is moving from more oil to cheapest oil as demand declines
- LNG is set to thrive in a strong gas market
- We forecast multiple energy transitions, from coal and oil to natural gas; and fossil fuels to renewables and decarbonized gas.
- Further, we focus on decarbonizing the oil and gas industry:
- Pressure is mounting as emissions are set to remain stubbornly high until mid-2030s
- Industry and governments are driving decarbonization, but not at the pace or depth required to meet the goals of the Paris Agreement
- Hydrogen and CCS have the potential to transform the industry.

MARITIME FORECAST TO 2050
Energy Transition Outlook 2020

MARITIME

This year's Maritime Forecast aims to enhance the decision-making of shipowners as they navigate the technological, regulatory and market uncertainties surrounding decarbonization:

- A library of 30 scenarios has been developed that project future fleet composition, energy use, fuel mix, and CO_2 emissions to 2050. Each of our scenarios belongs to one of three distinct decarbonization pathways.
- We model 16 different fuel types and 10 fuel technology systems, analysing how particular fuel technology alternatives perform commercially in a new Panamax bulk carrier as a case study.

Managing decarbonization risks is critical to protect the future value, profitability, and competitiveness of a vessel. Picking the wrong fuel solution today can lead to a significant competitive disadvantage.

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DNV GL is the world's leading classification society and a recognized advisor for the maritime industry. We enhance safety, quality, energy efficiency and environmental performance of the global shipping industry – across all vessel types and offshore structures. We invest heavily in research and development to find solutions, together with the industry, that address strategic, operational or regulatory challenges.

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