



WHEN TRUST MATTERS

MARITIME FORECAST TO 2050

Energy Transition Outlook 2021





A handwritten signature in black ink, reading "Knut Ørbeck-Nilssen". The signature is fluid and cursive, with a long horizontal stroke extending to the right.

Knut Ørbeck-Nilssen

CEO Maritime, DNV

FOREWORD

The demands on shipping to decarbonize are intensifying. It might be an oft-repeated refrain, but the imperative is more urgent now than it has ever been.

Decarbonization is no longer just a top priority for the IMO. Regional and national lawmakers are also demanding a quicker energy transition; and, driven by a changing climate of public opinion, so too are financiers and charterers.

The narrowing stringency of this patchwork of competing requirements is creating a complex operating environment for shipowners, who are left to grapple with a host of uncertainties - not least how to future-proof new vessels and their existing fleet.

That we are heading for carbon zero is clear, but the route there is far from it. There exists no 'silver bullet' solution. For shipowners, the grand challenge of our time remains: how to fuel the transition to a carbon neutral future?

With practical advice and cutting-edge solutions, the 5th edition of the Maritime Forecast to 2050 sets out to tackle this very question.

This year, our decarbonization experts have introduced a new carbon risk framework. The ambition is to enable shipowners to assess the technology, fuel, and energy landscape, thereby empowering them to make sound business decisions which keep their emissions below the carbon reduction trajectories.

The framework gives a detailed assessment of fuel ready and fuel flexible solutions. If you take just one thing away from the report, let it be this: Fuel flexibility is key to staying both compliant and competitive in a diverse and uncertain fuel future.

Data from our forecast shows that around 12% of current newbuilds ordered today have alternative fuel systems with LNG leading the way - double the 6% recorded in 2019.

While this is an encouraging trend, it is far from the momentum needed to meet regulatory and stakeholder demands. In August, the IPCC declared a "code red for humanity" with the publication of its climate change report showing that our earth may warm to an average of 1.5C by 2040 or earlier - far sooner than previously expected.

There is no time to waste. Inaction is not an option. The challenge in front of us is huge, but the incentive to transform couldn't be greater - the very future of our industry and society. The scene is set for a maritime renaissance.

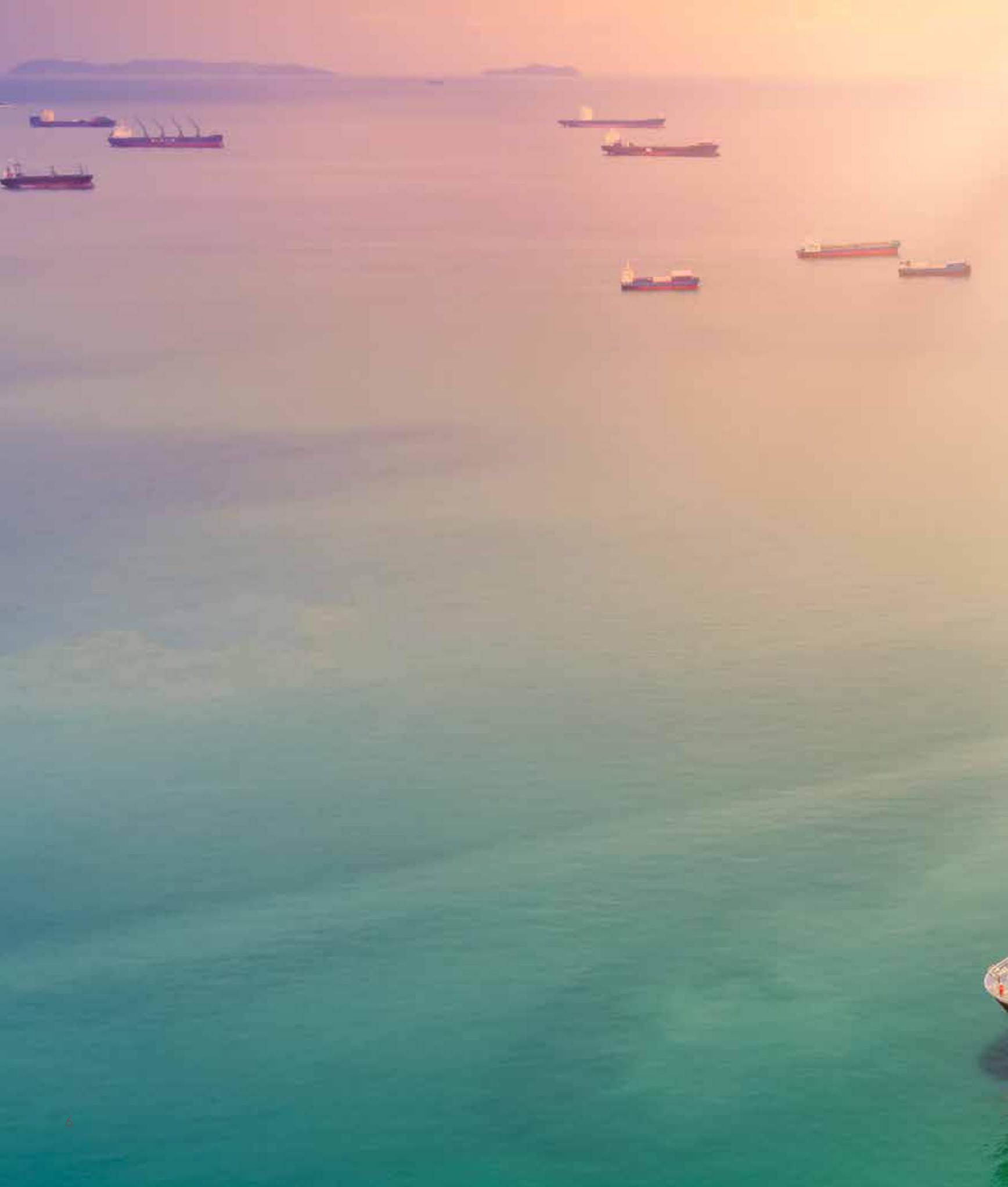
By working together as an industry (and beyond), by embracing fuel flexibility, and consulting with expert partners like Class, shipping can, and indeed must, reach its destination.

I therefore implore you to read on, and to learn more about how we can help you turn uncertainty into confidence.

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EXECUTIVE SUMMARY





EXECUTIVE SUMMARY

This publication is one out of DNV's suite of Energy Transition Outlook (ETO) reports. This latest publication examines how the increasing pressure to decarbonize shipping, and the resulting shifts in how they are powered, may affect shipowners contracting new tonnage - with focus on practical solutions and fuel strategies to tackle the shift from conventional to zero/carbon-neutral fuels.

The maritime industry will go through a period of rapid energy and technology transition that will have a more significant impact on costs, asset values, and earning capacity than many earlier transitions. Shipowners are already experiencing increasing pressure to reduce the greenhouse gas footprint of maritime transport. This report provides an updated outlook on the regulatory and commercial drivers for decarbonization of shipping:

- Three fundamental key drivers will push decarbonization in shipping in the coming decade: regulations and policies, access to investors and capital, and cargo-owner and consumer expectations.
- The Initial IMO GHG Strategy currently drives policy development within international shipping, and the first wave of regulations will take effect from 1 January 2023 (i.e. EEXI, CII). We expect them to have a significant impact on design and operations of all ships.
- While all ships need to fulfil the minimum compliance requirements from the IMO, commercial pressure may push shipowners to aim for a leading position in decarbonization, as we expect that poorly performing shipping companies will be less attractive on the charter market, and may also struggle to gain access to capital.

Further, this report provides an outlook on ship technologies and fuels that could help shipping respond to the decarbonization drive, introducing an updated timeline for the technical availability of selected alternative fuel technologies. We find that:

- The energy and technology transition in shipping has started, with nearly an eighth (12%) of current newbuilds ordered with alternative fuel systems. This is an increase from the 6% reported in the 2019 edition of DNV's Maritime Forecast to 2050. Except for the electrification underway in the ferry segment, the alternative fuels are currently still mainly fossil-based, and are dominated by LNG.
- There will be demonstration projects for onboard use of hydrogen and ammonia by 2025, paving the way for zero-carbon ships, and these technologies will according to our estimates be ready for commercial use in four to eight years. Methanol technologies are more mature and have already seen first commercial use. Fuel cells are far less mature than internal combustion engines, for all fuels.
- Safety is a prerequisite for the successful and timely introduction of the new fuels such as hydrogen and ammonia. Development of efficient safety regulations and guidelines is fundamental to evolve from large-scale demonstration to commercial use.
- A range of new technologies are emerging, including fuel cells, CCS, and wind power.

With the outlook on regulations, drivers, and technologies in mind, this report further presents an updated carbon risk-management framework. Our intention is to help shipowners navigate the technologies and fuels and respond to the drive for decarbonization by developing a 'decarbonization stairway' reflecting the shipowner's particular circumstances (Figure 1). Our framework consists of two main parts: an assessment of the economic potential of fuel and energy-efficiency strategies over the lifetime of a ship; and a structured review of the impact of the chosen fuel strategy on the ship design. Importantly, this updated framework is specifically designed to allow detailed assessments of fuel flexibility and Fuel Ready solutions. Considering the large uncertainties involved over the lifetime of ships, planning for fuel flexibility and Fuel Ready solutions could ease the transition and minimize the risk of investing in stranded assets.

We use a bulk carrier case study to illustrate the carbon risk-management framework. This study demonstrates how:

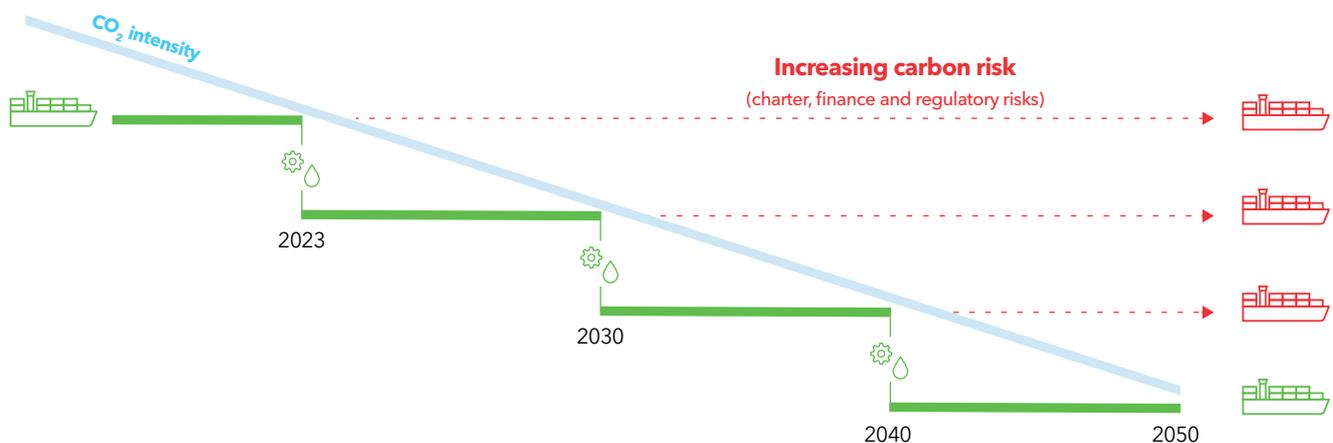
- Regulations and commercial drivers can be translated into practical target GHG trajectories reflecting a shipowner’s particular circumstances. In addition to a *minimum compliance trajectory*, we have developed a stricter trajectory *catering for cargo-owner ambitions*.
- The general overview of available fuels and technologies can be translated into practical design options for a shipowner’s newbuild. We explore seven possible fuel pathways, starting either with a mono-fuelled or dual-fuelled ship, with different possibilities of transitioning to carbon-neutral fuels - including options for alternative Fuel Ready designs. The solutions explored are targeted for deep-sea shipping and include use of MGO/VLSFO, LNG, LPG, biofuels, ammonia, and methanol as fuel.
- Our modelling capability allow us to calculate the cost of various fuel strategies over the lifetime of a ship. We explore ways to meet the target GHG trajectory by use of blend-in fuels and potential conversions.

- Vital design implications for the selected fuel strategy can be assessed; in the example case, an ammonia-ready design. We perform a structured engineering review addressing fuel storage, power plant, and integration of the fuel system in the ship design. We find that allocating sufficient space for fuel storage while maintaining a safe installation (e.g. protect against mechanical damage, fire, toxic exposure) and minimizing loss of cargo carrying capacity is the main design challenge. Implementation of design features (e.g. tank protection, structural preparations, location of openings) towards this goal at the newbuild stage may eliminate showstoppers and reduce cost and time spent at the conversion yard.
- Our findings from the engineering review illustrate a design principle generally applicable to newbuilds today. That is to incorporate basic measures to accommodate fuel flexibility in the newbuild specification, so that the ship is prepared for several possible fuel transitions when there is a business case for this.

While our proposed approach to managing carbon risk addresses key issues the shipowner must consider,

FIGURE 1

The decarbonization stairway and potential exposure to carbon risk



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there are additional barriers to the uptake of alternative fuels, as discussed in previous editions of DNV's Maritime Forecast. These barriers cannot be solved by the shipowner alone, but must be overcome by the efforts of multiple actors in an ecosystem of stakeholders. By analysing 12 decarbonization scenarios, we contribute brief insights into two such barriers; the access to capital needed for onboard technology investments, and the required scale of energy needed to produce the new fuels. We find that:

- Peak annual investments in onboard technology towards 2050 may reach USD 60 billion.
- To produce the necessary volumes of electrofuels for use in shipping, the required installed solar PV power capacity could be as high as 8000 GW in 2050.
- To produce the necessary volumes of 'blue fuels' for use in shipping, the required CCS capacity could be as high as 750 Mtpa in 2050.
- When compared with relevant reference numbers, these figures indicate that access to capital and infrastructure for fuel production may constrain the coming energy transition in shipping. Increased efforts are needed to develop and implement the mechanisms required to tackle these barriers to transition in a timely manner.





The background of the slide is a composite image. The top half shows a close-up of a white wind turbine's nacelle and blades against a clear blue sky with a few wispy clouds. The bottom half shows a large array of blue solar panels with silver grid lines, mounted on a metal frame. A white semi-transparent box with a dotted pattern on its right edge is overlaid on the top half of the image.

1

INTRODUCTION



1 INTRODUCTION

This publication is one out of DNV's suite of Energy Transition Outlook (ETO) reports. This latest Maritime Forecast to 2050 examines how the increasing pressure to decarbonize shipping, and the resulting shifts in how they are powered, may affect shipowners contracting new tonnage – with focus on practical solutions and fuel strategies to tackle the shift to zero/carbon-neutral fuels.

In previous fuel transitions, the shipping industry moved from wind, to coal and steam, and then to oil – every ship basically made the same transition driven by financial gains. The next transition is different; we know a move away from fossil-based fuels is coming – driven by the need to tackle climate change – but we do not know yet which fuel we are transitioning to. Last year's Maritime Forecast study showed that combinations of fuels will make up the maritime energy mix moving forward, but that the future fuel mix is uncertain. It suggested that promising alternative fuel candidates towards 2050 include ammonia from electrolysis (e-ammonia), or from reformation of natural gas coupled with carbon capture and storage (CCS) to make blue ammonia, and bio-methanol. In addition, bio-LNG, bio Marine Gas Oil (bio-MGO), and synthetic liquefied natural gas (LNG) and MGO produced from electrolysis (e-LNG and e-MGO), were found to be strong candidates as drop-in fuels for existing ships and some newbuilds. Considering the large uncertainties involved over the lifetime of ships, planning for fuel flexibility and alternative Fuel Ready solutions could ease the transition and minimize the risk of investing in stranded assets (DNV GL, 2019a, 2020a).

Choosing the right fuel strategy is one of the most important decisions an owner will have to make for a current newbuild. The key will be to optimize the fuel storage and propulsion system of the ship to accommodate current and future fuel requirements. Between 1,000 and 2,000 ships are expected to be ordered every year up to 2030, and the question is how their potential to reduce greenhouse gas (GHG) emissions can be maximized. A vessel built now faces a significant risk that the most competitive fuel type in the ship's early life will not be the same at a later stage.

Our aim with this year's study is to give guidance on how to develop robust fuel strategies and practical solutions complying with increasingly stricter decarbonization regulations and incentives. Our focus in this publication is to assist shipowners ordering new tonnage in deciding the best way to satisfy regulations and stakeholder demands related to GHG emissions – although our approach is applicable to existing ships as well. We are mainly addressing deep-sea shipping which accounts for the largest part of GHG emissions and has fewer available solutions compared with short-sea shipping, but the method can also be applied to the latter segment.

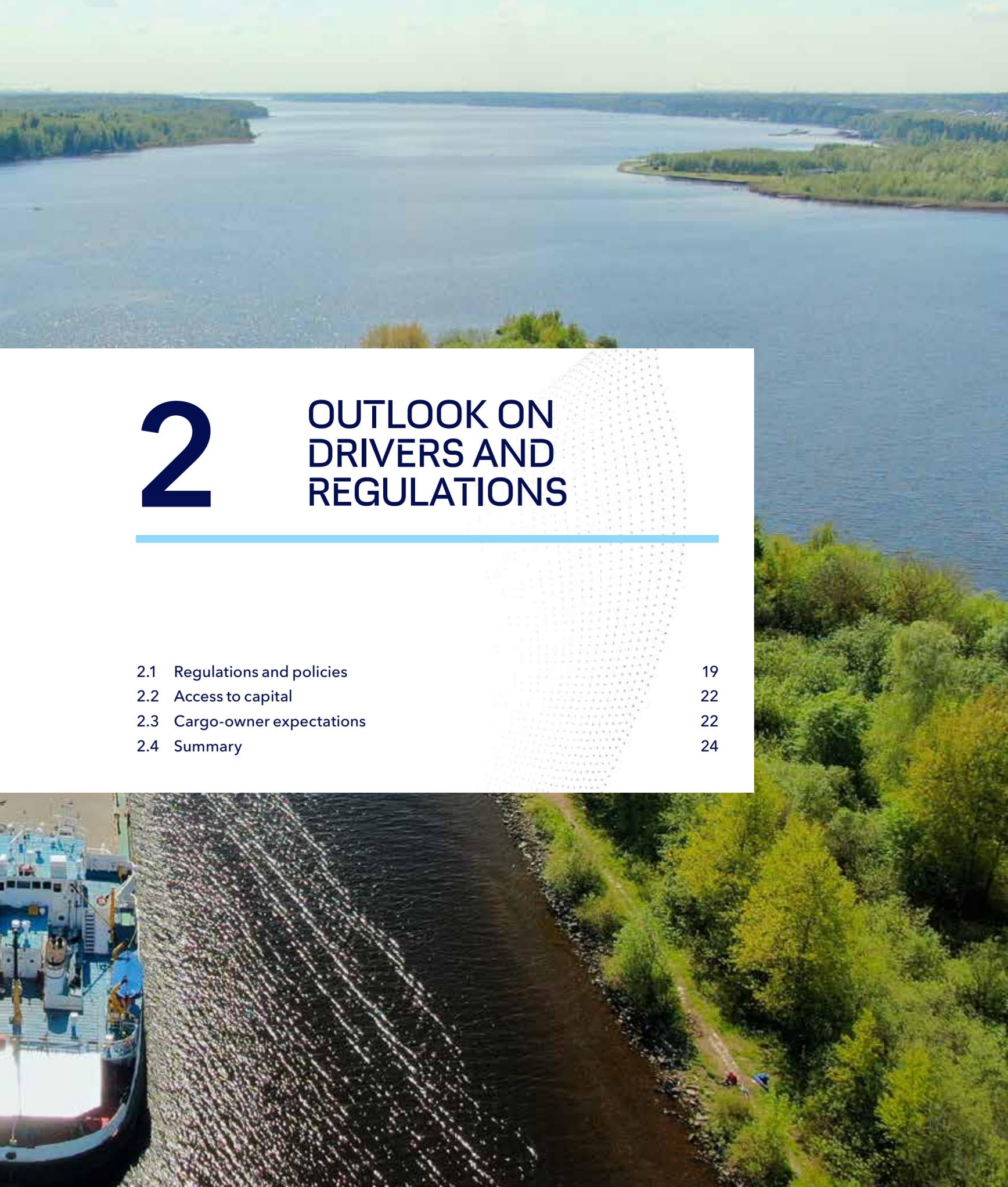
In this year's report, we first present an updated outlook on the rapidly developing regulations and drivers for decarbonization (Chapter 2). Second, we present the status and outlook for the ship technologies and fuels available to meet the demands imposed by upcoming regulatory and commercial needs for decarbonization (Chapter 3). Next, we present our updated framework for managing carbon risk in newbuild designs – taking a shipowner's perspective (Chapter 4). The first step in this framework is a techno-economic evaluation of fuel strategies (Chapter 5). The second step is to investigate the design implications of the chosen fuel strategy (Chapter 6). The use of the framework is exemplified through a case study in both chapters. In the final chapter, we place the issue of fuel transition in a wider perspective – investigating the need for financing of the green onboard investments associated with the energy transition, as well as the need for building supply-side capacity to supply the new, green fuels needed (Chapter 7).



Highlights

Three key fundamentals will continue to drive ship decarbonization throughout the 2020s:

- Regulations and other governmental policies remain key drivers for ship and fleet decarbonization, and the IMO is the most influential regulator.
- Access to finance will depend increasingly on being able to meet decarbonization targets over ship life cycles.
- We can expect ships and shipping companies that perform poorly on emissions to be less attractive on the charter market.



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2 OUTLOOK ON DRIVERS AND REGULATIONS

Pressure to reduce shipping's GHG footprint has risen sharply and keeps growing. Public and private actors are driving decarbonization efforts through various initiatives and mechanisms. Despite this shifting picture, we expect three key fundamentals – regulations and policies, access to investors and capital, and cargo-owner and consumer expectations – to keep driving ship decarbonization over the 2020s, as this chapter describes.

Regulations and policies will set direct requirements for ships and shipping companies to comply with. We also expect an increasing market pull from stakeholders, which will require more transparency on GHG emissions and subsequently promote decarbonization in the supply chain. The stakeholders include, among others, ports, shipyards, universities, governments, engine manufacturers, class societies, energy suppliers, banks, and cargo owners. Part of this market pull is due to reporting requirements and regulations placed on stakeholders, in particular on the cargo owners and the finance sector. We see many cargo owners and shipping companies having decarbonization as part of their

business strategy and publicly announcing decarbonization targets. Behind all three drivers shown in Figure 2.1 is the growing awareness of climate change among the general public, and how this increasingly translates into more climate-conscious behaviour affecting the way we act as consumers, voters, or investors.

This section first presents upcoming regulations on carbon dioxide (CO₂) and other GHGs from the International Maritime Organization (IMO) and the EU, before discussing other market drivers from cargo owners and finance institutions. The main regulatory milestones of possible policy measures are illustrated in Figure 2.2.



2.1 Regulations and policies

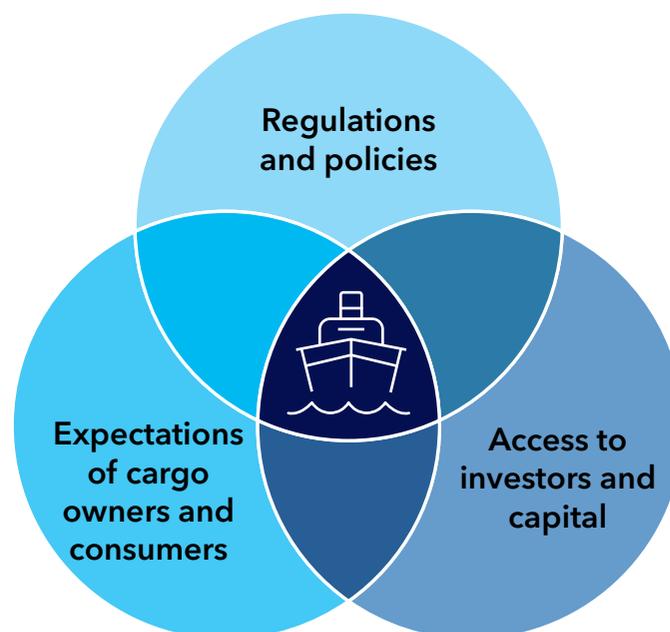
Regulations and other government policies remain a key driver for decarbonization, placing direct requirements on ships and shipping companies. In shipping, the IMO is the most influential regulator. The Initial IMO GHG Strategy currently drives policy development within international shipping, setting concrete ambitions for 2030 and 2050. The strategy is now being implemented through a package of short-term measures. Notably, in June 2021, the IMO adopted extensive new carbon dioxide (CO₂) regulations applicable to existing ships: the Energy Efficiency Existing Ship Index (EEXI) addressing the technical efficiency of ships; the Carbon Intensity Indicator (CII) rating scheme addressing the operational efficiency; and, the enhanced Ship Energy Efficiency Management Plan (SEEMP) addressing the management system. The new regulations will take effect from 1 January 2023, and we expect them to have a significant impact on ship design and operations.

Another ongoing task for the IMO is developing guidelines for establishing lifecycle GHG carbon factors for all fuel types, with the first version expected in 2022 or 2023 (see separate box page 23).

With the adoption of the short-term measures, the IMO has started to shift its focus towards the mid- and long-term measures that will take shipping towards meeting the 2050 ambitions. We are still in an early phase with proposals being made and the process being shaped. Part of this discussion will be the possible introduction of market-based measures such as a carbon tax or an emissions trading system. The timeline for this is highly uncertain, but a first assessment of possible measures could be finalized at the same time as the review, scheduled for 2023, of the Initial IMO GHG Strategy. The review could also lead to more ambitious strategic targets, which would need to be implemented through amending existing regulations (i.e. Energy Efficiency Design Index (EEDI), EEXI, or CII) or through new ones, to have an effect on individual ships.

FIGURE 2.1

Key drivers influencing ship decarbonization



Beyond the IMO, the EU is one of the most influential and ambitious regulators. Its ambition is to reduce emissions by 55% in 2030 relative to 1990, and to become climate-neutral by 2050. The EU is working on its 'Fit for 55' legislative package, which among other things is expected to include shipping in the EU Emissions Trading System (EU ETS) and the FuelEU Maritime initiative which aims to increase the use of sustainable fuels through an increasingly stringent lifecycle GHG intensity requirement. The scope is proposed to be 50% of emissions from inbound and outbound EU voyages and 100% of emissions from intra-EU voyages and when in EU ports. The draft proposals will be considered by the EU Council and Parliament before final adoption.

Recently, major countries have also announced concrete targets. China has set a target to be carbon-neutral by 2060; the US aims to reduce GHG emissions by 50% in 2030 relative to 2005; and, Japan and Canada have similar goals for a 40–45% reduction. We expect that these ambitions will also impact shipping through

national and international policies and actions plans, setting in motion incentives and activities to develop and implement new solutions.¹

In the following we describe the upcoming technical and operational requirements adopted by the IMO.

IMO technical and operational requirements from 2023

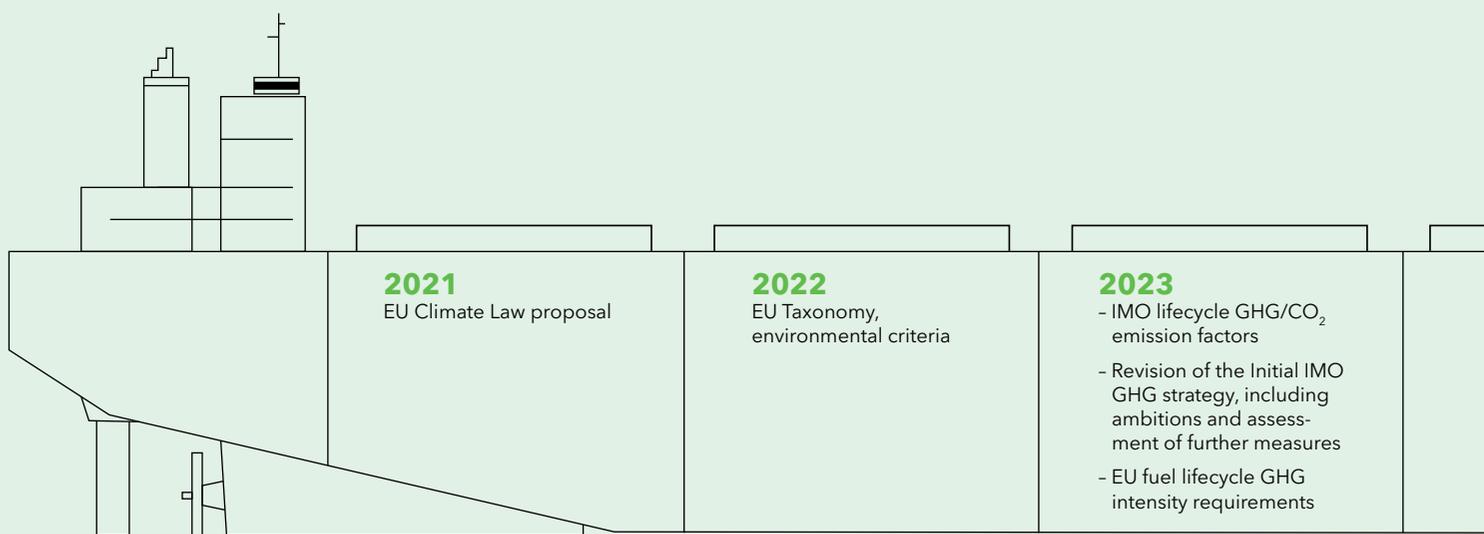
The EEXI will impose a requirement equivalent to EEDI Phase 2 or 3 (with some adjustments) to all existing ships. The scope is the same ship types and sizes for which the EEDI would apply, but includes all ships regardless of the year of build. It is intended as a one-off certification, and the attained EEXI is to be verified and a new Energy Efficiency Certificate issued no later than the first annual survey on or after 1 January 2023.

All cargo, RoPax, and cruise ships above 5,000 gross tonnage (GT) will from 2023 need to calculate a CII (e.g. Annual Efficiency Ratio, AER) given in terms of grams CO₂ per deadweight mile (DWT-mile) or gross tonnage mile

¹ See for example the Zero-Emission Shipping mission: www.mission-innovation.net/missions/shipping

FIGURE 2.2

Main regulatory milestones of possible policy measures



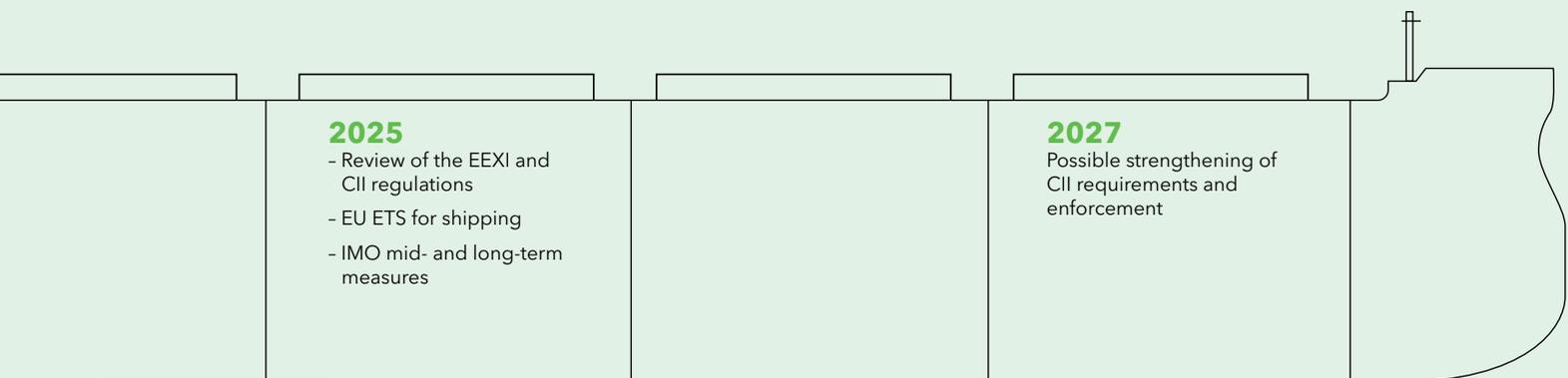
Key: Carbon Intensity Indicator (CII); Energy Efficiency Existing Ship Index (EEXI); EU Emissions Trading Scheme (EU ETS); Greenhouse gas (GHG); International Maritime Organization (IMO); Carbon dioxide (CO₂).

(GT-mile) depending on ship-type, and will be given an annual rating of A to E, with band A indicating the highest energy efficiencies. The rating thresholds will be set relative to a segment-specific 2019 reference line and annual reduction factor. The mid-point of the C-rating band will start at 5% below the reference line in 2023, and increase by 2% annually to 2026. Typically, an A-rating is 10-20% better than the mid-point of the C-rating band. For ships that achieve a D-rating for three consecutive years, or an E rating in a single year, a corrective action plan needs to be developed as part of the SEEMP, and approved.

By 1 January 2023, all ships subject to the CII requirements need to keep on board an approved SEEMP which must include mandatory content, such as an implementation plan on how to achieve the CII targets. The implementation of the SEEMP will also be subject to company audits, though the specific requirements of the audit are still under development and are expected to be approved by the IMO in 2022.

The new regulations will be reviewed by the end of 2025 to determine the reduction factors for 2027-2030 and to assess the effectiveness of the regulations in reducing the carbon intensity of shipping. The review may result in more stringent reduction requirements, and reinforced corrective actions, for ships with D or E ratings.

2020 also saw the adoption of amended regulations to advance the EEDI Phase 3 from 1 January 2025 to 1 April 2022 for new container ships, large gas carriers (>15,000 DWT), general cargo ships, LNG carriers, and cruise passenger ships having non-conventional propulsion. A stepwise reduction requirement will apply to container-ships, starting with a 30% reduction rate for small container vessels and increasing up to 50% for very large ones. There is an ongoing discussion on whether an EEDI Phase 4 should be introduced, but so far there is nothing concrete on reduction levels, introduction timeline, or other changes to the EEDI framework.



2.2 Access to capital

We see an increased focus on green and sustainable activities from finance institutions and institutional investors aiming to reduce exposure to non-sustainable activities and to contribute positively to mitigating climate change. This 'green drive' will make access to capital dependent on environmental credentials and meeting expected decarbonization trajectories throughout the lifetime of ships.

Financial institutions have for some time required Environmental, Social and Governance (ESG) reporting from their customers. This trend is driven by requirements related to the offering of financial instruments such as green and sustainability-linked bonds and low-carbon funds, and through direct disclosure regulations such as the EU Sustainable Finance Disclosure Regulation (SFDR). As the SFDR's name suggests, it is a directive on sustainability-related disclosures in the financial sector. The Poseidon Principles were established in 2019 by the major shipping banks to specifically assess and disclose the climate impact of their ship finance portfolios. This in turn requires shipowners to report emissions to the banks.

The Green Bond Principles² outline a process and set criteria for bonds that exclusively finance eligible green projects across industries. In 2020, the Climate Bond Initiative³ launched criteria for shipping activities in

certified green bonds, with segment-specific trajectories towards zero emissions in 2050 and excluding ships dedicated to transporting fossil fuels. Sustainability-linked bonds take it a step further, where the issuer commits to achieving credible sustainability-related key performance indicators (KPIs), and where the condition of the bond is linked to whether or not the KPIs are met. An example of a KPI can be one of the UN Sustainable Development Goals, or a concrete and science-based reduction target on direct and indirect GHG emissions. The bonds follow industry-independent criteria, but apply to the supply chain, which also includes shipping.

The EU Taxonomy Regulation directive in many ways codifies the Green Bond Principles and has the potential to substantially impact the shape and form of green and sustainable investments. Although investors can still invest in whatever projects they want, they will need to follow the EU Taxonomy to label it 'green' in Europe. The directive entered into force in July 2020 and establishes a framework and definitions of what can be considered sustainable economic activities. The intention is to direct investments towards sustainable projects and activities which can contribute to meeting the EU's climate change and environmental objectives. Specific environmental criteria for shipping are expected in 2022.

2.3 Cargo-owner expectations

Perhaps the most influential actor in the ecosystem surrounding a shipowner is the one paying for the shipping services – in most cases the cargo owner. The cargo owners are themselves subject to expectations from their customers throughout the supply chain which ultimately ends with the consumers, and from finance institutions and investors. This has led to major cargo owners announcing very ambitious decarbonization targets, with some aiming for carbon-neutral or carbon-positive impact by 2040, or even by 2030.

A group of major bulk cargo owners have committed to increased transparency and a carbon-intensity trajectory for their chartering activity through the Sea Cargo Charter scheme. This builds on the same method as the Poseidon Principles, but requires reporting per voyage and cargo carried.

With the establishment of a global carbon-intensity rating mechanism through the IMO, each ship will have an annual rating A to E. This rating can play an important

² www.icmagroup.org/sustainable-finance/the-principles-guidelines-and-handbooks/green-bond-principles-gbp

³ www.climatebonds.net

role for cargo owners when selecting ships for their transport operations. Similarly, the criteria set out in the EU Taxonomy Regulation may also be used when selecting ships for chartering.

Future expectations on reporting are likely to include reporting of all relevant GHG emissions from the supply chain. For shipping companies this would include not only the direct emissions from owned and controlled

sources (i.e. the ship's Scope 1 emissions) but also the emissions due to production of fuel (Scope 2), and finally all indirect emissions due to the operation of the company, upstream and downstream (Scope 3). This also means that cargo owners need to include shipping emissions in their Scope 2 (e.g. transport of fuel) and Scope 3 (transport of other goods) reporting, which again means they need this information from, among others, shipping companies.

Addressing other GHGs and well-to-tank emissions

When introducing alternative fuels, it will be vital to ensure that this will not lead to other unsustainable impacts in a lifecycle perspective. Current IMO regulations only address onboard tank-to-propeller CO₂ emissions from fossil fuels. Other GHGs with a significant emission from shipping include methane (CH₄) and nitrous oxide (N₂O). The IMO is working on guidelines to determine lifecycle CO₂ and GHG emission factors for all types of fuels, including biofuels and synthetic electrofuels. The first priority is to address tank-to-propeller emissions, while well-to-tank emissions and other sustainability aspects related to production will also be important to consider in order to ensure that fuels used by shipping do not create adverse impacts in the upstream phase. Due to COVID-19, the discussion and development of these guidelines have been delayed, but an early version could be ready by 2022.

Any emissions factors and calculation methods defined in the guidelines would need to be implemented in other regulations such as the IMO Fuel Oil Data Collection System (DCS), CII, and EEXI/EEDI before having an effect on actual emissions. Certification requirements for fuels

delivered to the ship are a likely consequence of applying well-to-tank emission factors and also of allowing for a reduced tank-to-propeller CO₂ emission factor for bio- and synthetic fuels. Certification schemes addressing sustainable feedstock already exist, e.g. ISCC (International Sustainability and Carbon Certification), REDcert (certification for sustainable bioenergy, biofuels, and bioliquids) and RSB (Roundtable for Sustainable Biomaterials).

Adding regulations on methane, both methane slip and volatile organic compounds are on the agenda, though no concrete proposals have yet been put forward. Such requirements could either be implemented as part of the CII regulations using the GHG emission factor calculation guidelines, or through specific technical requirements similar to the nitrogen oxides (NO_x) requirements, for example.

Black carbon is also identified as having a significant short-term climate forcing effect. Regulations are being discussed, but we expect to see recommendatory guidelines being issued first, before regulations are considered further.

2.4 Summary

In sum, these requirements and expectations will require: a large degree of control of own emissions to ensure compliance; exchange of information so that other companies may complete their reporting; and, meeting expectations towards finance institutions and cargo owners. With increased transparency on emissions, and the establishment of a carbon-intensity rating by the IMO,

All shipping companies need to fulfil the minimum compliance requirements from the IMO; but depending on the strategy, environmental ambitions, and market situation, they may also aim for a leading position in decarbonization.

we can expect that poorly performing ships and shipping companies will be less attractive on the charter market. They may also struggle to gain access to investors and capital. This in turn will drive companies to ensure that they achieve acceptable carbon-intensity ratings and deliver according to other performance indicators such as the Poseidon Principles, and Sea Cargo Charter climate alignment. Older ships that are not easily upgraded to meet carbon-intensity targets risk becoming stranded assets. This can have a significant impact on the equity and balance sheet of shipping companies, and we may see early scrapping of ships.

All shipping companies need to fulfil the minimum compliance requirements from the IMO; but depending on the strategy, environmental ambitions, and market situation, they may also aim for a leading position in decarbonization. Chapter 5 presents a case study illustrating the impact on a newbuilding project.



Highlights

We review selected ship technologies and fuels other than LNG and LPG and update our outlook on their technical availability:

- Methanol technologies are the most mature, and have already seen first commercial use.
- Demonstration projects for onboard use of hydrogen and ammonia by 2025 will pave the way for zero-carbon ships by 2030.
- Earlier availability of hydrogen and ammonia as fuel options would be important for achieving the IMO's GHG-reduction ambitions.

3

OUTLOOK ON SHIP TECHNOLOGIES AND FUELS

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3 OUTLOOK ON SHIP TECHNOLOGIES AND FUELS

Policy developments and stakeholders’ engagement over the next decades will drive shipowners to identify, evaluate, and use technologies, fuels, and solutions that help decarbonize ships, cut energy consumption, and meet other environmental requirements. This chapter provides a high-level overview of promising ship technologies and fuels, introducing an updated outlook for their technical availability.

The world fleet is mostly powered by diesel engines running on marine fuel oils. There is an increasing number of LNG-fuelled vessels and ships utilizing batteries, and vessels fuelled with liquefied petroleum gas (LPG) and methanol are emerging. The first hydrogen- and ammonia-fuelled vessels will soon be entering the world fleet. While the combustion engine as energy converter will continue to dominate the fleet, marine fuel cells are expected to be integrated in power systems over the next years, providing higher efficiency and thereby lower fuel consumption. The future fuel and technology shifts must go together with greater energy efficiency of ships, requiring intensified uptake of both technical and

operational energy-efficiency measures. The drive for decarbonization in global industrial value chains will also drive logistics optimization including measures such as increased fleet utilization and speed reductions – facilitated by digitalization. Figure 3.1 presents a high-level overview of the available solutions, covering logistics optimization, technical and operational energy-efficiency measures, and carbon-neutral fuels (see DNV GL, 2019a for further details). More radical and immature solutions such as onboard CCS (carbon capture and storage) and innovative wind powering concepts may also develop towards 2030.



3.1 High-level overview of ship technologies and fuels

The available GHG mitigation measures range from easily achievable operational measures to capital-intensive technical solutions. Newbuilds will have more available options than ships in operation. Abatement measures such as wind powering, air lubrication systems, and various hull and machinery measures, are now emerging.⁴ In this edition of the Maritime Forecast, we focus on the category with the highest reduction potential, but also significant uncertainty: that is fuels and energy (Figure 3.1). All alternative fuels for shipping face challenges and barriers to their uptake - although the severity of each barrier will vary between fuel types. Typical key barriers include the cost of required machinery and fuel storage on board vessels, additional storage space demand, low technical maturity, high fuel price, limited availability of fuel, and a lack of global bunkering infrastructure. Safety will also be a primary concern, with a lack of prescriptive rules and regulations complicating the use of such machinery and storage systems (see text box page 36).

Different solutions for different trades

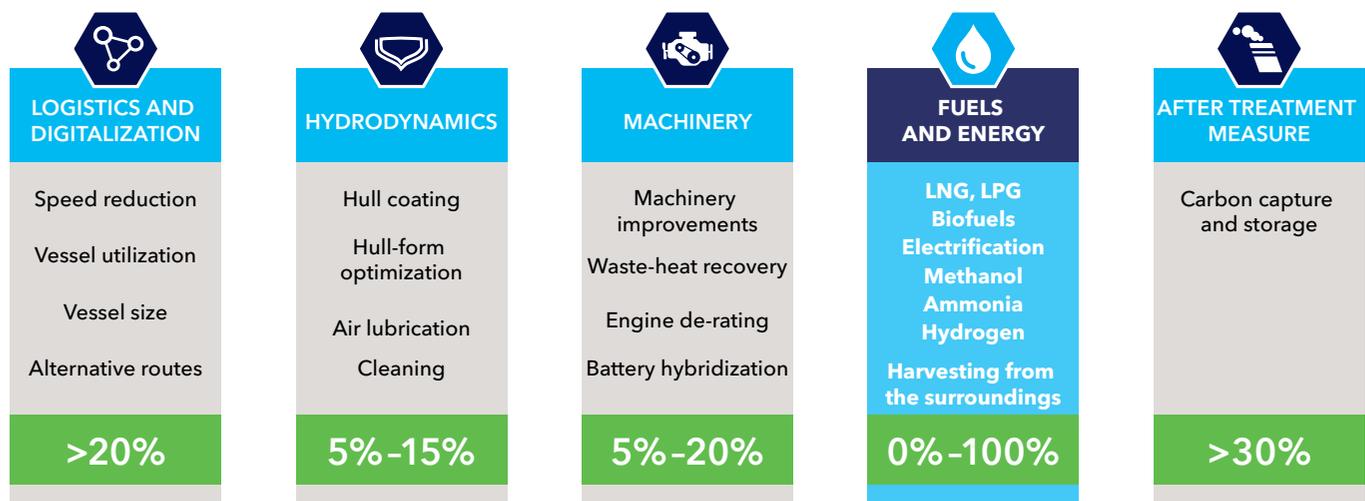
The technical applicability and commercial viability of alternative fuels will vary greatly for different ship types and trades. Deep-sea vessels have fewer options compared with the short-sea segment. Deep-sea shipping comprises large ocean-going ships that need to store very large amounts of energy, where the main proportion of energy consumption relates to propulsion of the ship at steady speed over long distances. Options for the deep-sea trade are currently limited to LNG and LPG, or to biofuels which are not yet widely available and are more expensive than LNG and LPG.

The decarbonization options for short-sea vessels are more diverse and include more alternative power sources and driveline configurations. For these ships, the shorter distances and highly variable power demands often make electric or hybrid-electric power and propulsion systems (including diesel/gas electric) more efficient than traditional mechanical drives. Short-sea shipping plays an important role in the maturing of some of the fuels and technologies for later use in deep-sea shipping.

⁴ See for instance 'Fuelling Transition: Tracking Technology Uptake': www.hellenicshippingnews.com/fuelling-transition-tracking-technology-uptake

FIGURE 3.1

Available technologies to decarbonize shipping and their GHG emission reduction potential. In the 2021 version of Maritime Forecast we focus on fuels and energy.



But it takes time to mature new fuels and developing infrastructure. Twenty years after the introduction of LNG as fuel, there are 509 (as of June 2021) LNG-fuelled ships in operation and on order, not including LNG carriers.

The recent uptake of batteries by ferries/passenger ships and service vessels has been quicker. In 2015 the first battery driven car ferry, Ampere, was put into service, and as of June 2021, there are 522 ships in operation and on order with batteries (including fully electric vessels, and chargeable and non-chargeable hybrids). Some of the ships can operate full-electric, but nearly all are still hybrid solutions where diesel or biofuels are used to extend the operating range or provide redundancy against power loss. For the Norwegian public ferry sector, the next step in the transition to zero-emission solutions is the introduction of hydrogen fuel cells. To make this technology scalable to larger vessels, the first ferry operating on hydrogen will store it in liquefied form. This development is supported by an increased number of zero-emission pilots and demonstration projects focusing on hydrogen, ammonia, and methanol/ethanol (Getting to Zero Coalition, 2021).

Status of fuel transition

Figure 3.2 shows that alternative fuel uptake in the world fleet⁵ is increasing, with methanol, hydrogen, and

ammonia emerging (see Section 3.2). Less than 1% of the ships in operation are running on alternative fuels, dominated by the short-sea segment and non-cargo ships, and this has little impact on total maritime emissions. However, around 12% of current newbuilds are ordered with alternative fuel systems. This is around double the 6% reported in the 2019 edition of DNV’s Maritime Forecast. The numbers are taken from DNV’s Alternative Fuels Insight platform, launched in 2018 as the industry go-to source for information on uptake of alternative fuels and technologies in shipping, and on bunkering infrastructure for alternative fuels. Looking at orders for newbuild ships over the next few years, we see an increase in deep-sea LNG-fuelled ships globally, and in batteries for full-electric or part-electric operations in the short-sea segment. Except for the electrification underway in the short-sea segment, the alternative fuels are currently still mainly fossil-based.

For deep-sea applications, the storage capacity is a key barrier to many alternative fuels, and the current options for the deep-sea trade are limited to LNG and LPG, which is not carbon-neutral, or to biofuels, which are far more expensive and not yet widely available. As of June 2021, 79 ships using LPG as fuel, and 25 on methanol, are either in operation or on order. These ships are primarily LPG carriers and chemical tankers, utilizing

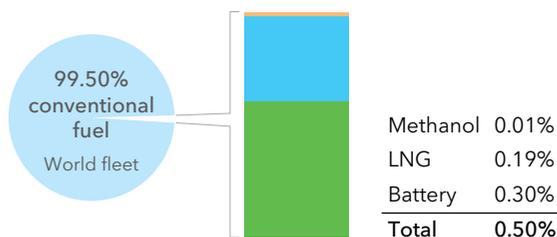
⁵ The fleet consists of about 110,700 vessels above 100 GT, and does not include inland waterways, non-merchant and non-propelled vessels.

FIGURE 3.2

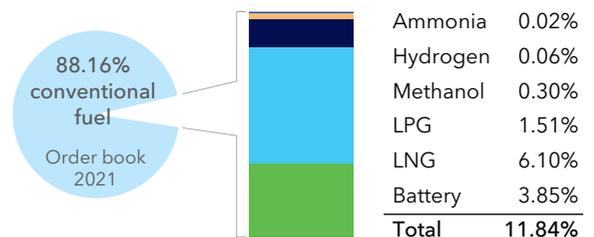
Uptake of alternative fuels for the world fleet as of June 2021 including ships in operation and on order ^a

Alternative fuel uptake (percentage of ships)

Ships in operation



Ships on order



Key: Liquefied natural gas (LNG); liquefied petroleum gas (LPG)

a) Sources: IHSMarkit (ihsmarkit.com) and DNV’s Alternative Fuels Insights for the shipping industry – AFI platform (afi.dnv.com)

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their cargo as fuel. It is thus important now to find technically feasible and cost-effective solutions for large-scale uptake in the deep-sea segment, which accounts for more than 80% of world fleet CO₂ emissions (DNV GL, 2019a). LNG and LPG are currently the only alternative fuels that are scalable commercially and globally for long-distance transport at sea.

In previous transitions in shipping, the industry moved from wind to coal and steam, and then to oil – and every ship made the same transition. As projected in the 2020 edition of DNV’s Maritime Forecast, this will be different in the future transitions – all ships will probably not make a transition to the same fuel. Our decarbonization pathway modelling in that forecast showed a diverse energy mix comprising both fossil and zero/carbon-neutral fuels, where fossil fuels were gradually phased out by 2050. The zero/carbon-neutral fuels are introduced both as drop-in alternatives, and for use with dedicated technologies. Fossil LNG is projected to gain a significant share until regulations tighten in 2030 or 2040 depending on the decarbonization pathway. Our modelling shows uptake of carbon-neutral fuel picking up in the late 2030s or mid-2040s, reaching between 60% and 100% of the fuel mix in 2050, depending on decarbonization scenario. It is hard to identify clear winners among the many different fuel options across all scenarios, but ammonia (electro-based and ‘blue’) and bio-based methanol are the most promising carbon-neutral fuels in the long run.

Carbon-neutral energy

The zero/carbon-neutral fuels can be produced from primary energy sources categorized, for example, as follows (DNV GL, 2020a):

- **Biofuels** from sustainable bioenergy sources
- **Electrofuels** from renewable electricity, with non-fossil carbon, or nitrogen
- **‘Blue’ fuels** from reformed natural gas with CCS.

The fuels’ potential for reducing GHG emissions vary widely in a well-to-tank perspective, depending on the primary energy source, the fuel processing, and the supply chain. Alternative fuels that require a lot of energy

and produce extensive emissions in their production and processing phases are likely to be expensive and to have high lifecycle-GHG emissions. Their cost and future demand could also be impacted substantially by future GHG and environmental regulations. Such energy-intensive fuels will require access to low-price renewable energy to be competitive.

Our focus in this study is on the ship (the tank-to-propeller perspective). What we refer to as carbon-neutral fuels⁶ and apply in our modelling are assumed to be produced by renewable electricity, from sustainably provided bioenergy, or from fossil sources with CCS. In reality, shipping must also carefully consider the total lifecycle impact and climate effect of the future fuels it uses – which will need to be carbon-neutral and sustainable. Current IMO regulations only address onboard tank-to-propeller CO₂ emissions from fossil fuels. The IMO is, however, working on guidelines to determine lifecycle CO₂ and GHG emission factors for all types of fuels, including biofuels and synthetic electrofuels (see separate text box page 23).

New energy converters

New onboard energy converters could also reduce the CO₂ emissions compared with combustion engines. In particular, there is growing interest in maturing fuel-cell technology in shipping. Fuel cells combined with alternative fuels such as hydrogen and ammonia can efficiently reduce and even eliminate emissions and noise, while energy efficiency can be higher than for conventional combustion engines. Fuel cells have other potential benefits such as reduced maintenance, modular and flexible design, and improved part load operation efficiency. However, fuel cells come with significant disadvantages related to cost and durability. These challenges will need tackling before fuel cells can make a meaningful contribution to compliance with stricter emission requirements.

Fuel cells with low operational temperatures are more tolerant of dynamic load variations than high-temperature fuel cells. Smaller and medium ships in the short-sea segment may favour low and medium temperature

⁶ The term carbon-neutral refers to a variety of energy sources or energy systems that have no net GHG emissions or carbon footprint.

Proton-Exchange Membrane fuel-cell technology. Ships in the short-sea segment are typically smaller than in deep-sea trade, with more varied operational profiles and a greater share of their time and energy spent on purposes other than steady propulsion. For these ships, the shorter distances and highly variable power demands can make a combination of hydrogen fuel cells and batteries a viable alternative. This is reflected by the first hydrogen ferry, the MF-Hydra, planned to be put into operation this year (2021) in Norway.

It is hard to identify clear winners among the many different fuel options across all scenarios, but ammonia (electro-based and 'blue') and bio-based methanol are the most promising carbon-neutral fuels in the long run.

For application on larger deep-sea ships, which can more easily accommodate waste-heat recovery solutions, high-temperature fuel-cell systems such as molten-carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) could be explored. For large ocean-going ships, a very large proportion of their energy consumption relates to propulsion of the ship at steady speed over long distances. Combining fuel-flexible high-temperature fuel cells with batteries (or other hybrid configurations) and waste-heat recovery solutions will reduce thermal strain on the fuel cell and increase energy efficiency of the system. For ships with high energy demand and long bunkering intervals, non-hydrogen fuels with higher volumetric energy density – such as ammonia, methane, and methanol – could be considered.

The future uptake of fuel-cell technologies is hard to project due to high market and regulatory uncertainties, as well as uncertainty in the anticipated reduction in investment costs for installing fuel-cell systems on board vessels. The most promising marine application in the short term is for short-sea shipping such as ferries – e.g. low-temperature proton-exchange membrane fuel cell (LT-PEMFC), as well as for auxiliary/harbour-mode solutions, where ships will benefit from reduced local and GHG emissions, and from the reduction of noise and vibrations. From the auxiliary/harbour-mode solutions, it will eventually be possible to scale up to hybrid fuel-cell configurations for deep-sea shipping.

After treatment - onboard carbon capture and storage

Carbon dioxide emission can also be reduced applying onboard carbon capture and storage (CCS). While CCS is primarily being developed for large, stationary emission points such as factories, refineries, or power generation plants, use of the technology for onboard carbon capture and temporary storage on large, ocean-going vessels is also being considered. Onboard CCS is a potential option for decarbonizing the deep-sea portion of the world fleet. However, there has not yet been any large-scale demonstration or implementation of onboard CCS systems on merchant ships for substantial recovery rate. Currently, interest in maritime CCS is reviving, and the liquid absorption technology, with or without membranes, is becoming a popular option for system concepts. Past DNV studies, including hazard assessments, have showed that marinification of such systems is technically feasible. However, uptake of these systems is being hindered by their complexity, space and resource requirements, costs, and lack of applicable rules and regulations. The industry needs financial incentives to subsidize part of the CCS technology costs. An additional key barrier to this technology is that infrastructure for the total CO₂ value chain must be in place for the trade in question. In other words, there must be solutions ready to handle the captured CO₂ in relevant locations.

3.2 Outlook for the availability of selected alternative fuel technologies

Decarbonizing shipping will require both the substitution of fossil fuels and changes to onboard technology for using alternative fuels. This chapter focuses on the *onboard technology*, introducing a timeline for the development of selected solutions and fuels. It illustrates the expected availability for using alternative fuel technologies on board, covering the energy converter (internal combustion engine (ICE) and marine fuel cells), the fuel-storage systems, and all associated shipboard systems and functions. Key factors assessed in the development of the timeline include the maturity, planned developments, and rules for safe design and use. The timeline is our best estimate for when the onboard engine and fuel systems can be expected to be available for use on board (actual availability of fuel is not included as a limitation in the shown timeline). We have applied a colour scale in Figure 3.2 to indicate two important phases for onboard use:

- **First demonstration projects (red colour):** The technology is ready for demonstration on the ship, and the primary intention will be further development and maturation. Typically, a risk-based approach will address regulatory and safety challenges for the installations. This could require an extensive and costly process of design, approval, and bringing the technology on board. The technology readiness level (TRL) is typically 6–7 (see overview on the right).
- **Commercial application (green colour):** The technology is qualified for maritime application through tests and demonstrations, and can be applied to commercial use on board. Statutory approval will be based on accepted international standards. The TRL level is typically 8–9.

The two phases reflect that technology availability and maturity is not a binary issue – but something that must be seen as a gradual or stepwise process (reflected through the use of a colour scale). Included in the timeline are technologies for use of **hydrogen, ammonia, and methanol**.

For technology readiness level (TRL), the following definitions apply (EU)

- TRL 1 - basic principles observed
- TRL 2 - technology concept formulated
- TRL 3 - experimental proof of concept
- TRL 4 - technology validated in lab
- TRL 5 - technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 - technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 - system prototype demonstration in operational environment
- TRL 8 - system complete and qualified
- TRL 9 - actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

We have not included alternative fuels such as LNG and LPG. Although these technologies can contribute to decarbonization directly and/or through use of electrofuels/biofuels the technology is considered relatively mature and thus not relevant for this timeline. However, we recognize that fuel cells which can use these fuels are under development and that this technology could be added.

It should be recognized that the timeline does not reflect an expected uptake of a certain fuel type. It only reflects our view of when the onboard energy converters and fuel systems can be expected to be available for onboard use. The timelines do not reflect many other important aspects that will finally determine the actual uptake of these technologies in the fleet – e.g. fuel availability (production volumes), distribution and bunkering infrastructure, policy and incentives for uptake, fuel prices, technology cost, and so on. These key barriers are described and illustrated in our Alternative

Fuel Barrier Dashboard, providing indicative status of key barriers for selected alternative fuels (DNV GL, 2019a; 2020). The dashboard also identifies the stakeholders in the ecosystem who have traditionally driven its development and can further reduce barriers to uptake of fuel. Initiatives fostering cooperation throughout the value chain and between public and private entities are also needed to overcome barriers. One example is the Green Shipping Programme (GSP) in Norway.⁷

Our resulting timeline is shown in Figure 3.3. Methanol technologies are the most mature, and have already seen first commercial use. There will be demonstration projects for onboard use of hydrogen and ammonia by 2025, paving the way for zero-carbon ships, and these technologies will be ready for commercial use in 4-8 years. Making them available earlier than this will be of great importance for the shipping industry to achieve the IMO's GHG-reduction ambitions. The timeline also reflects that fuel cells are far less mature than ICEs. Fuel cells have not been applied commercially in shipping, but testing for marine applications has been performed

during the last decade. For hydrogen fuel cells, the PEMFC technology is quite mature; the fuel itself is the main challenge. For ammonia and methanol, it is likely that the types of fuel cells will be different from those for hydrogen. Instead, high-temperature PEMFCs or SOFCs will possibly be used due to potentially higher efficiencies using the waste heat to convert the fuel to hydrogen. However, these are less mature than the PEMFCs used for hydrogen. There is growing interest in maturing the fuel-cell technology in shipping.

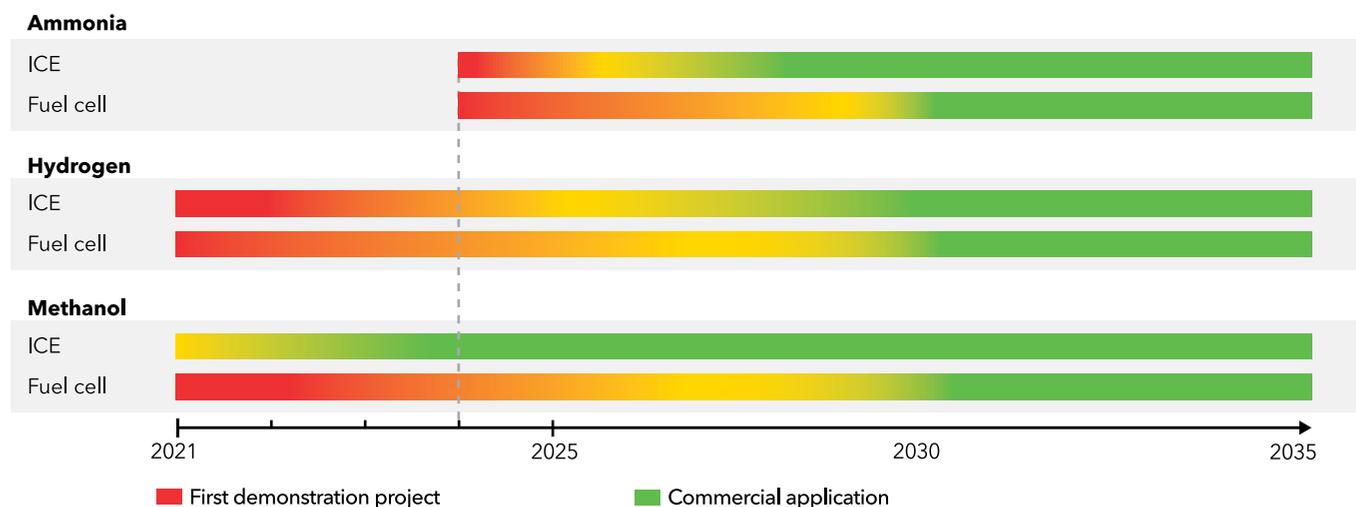
Applying information about the key factors – maturity, planned developments, and safety rules – our assessment of the respective fuels and fuel technologies can be summarized as follows:

- **Hydrogen:** Current barriers to using hydrogen as marine fuel include lack of safety requirements; low maturity of technology; onboard storage space required; and, the high investment cost. Demonstration projects have been initiated for both ICEs and fuel-cell installations. Since 2017, the smaller inland

⁷ www.greenshippingprogramme.com

FIGURE 3.3

Timeline for expected availability of alternative fuel technologies - our best estimate for when these may be available for onboard use



Key: Internal combustion engine (ICE)

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water vessel Hydroville has used ICEs running on hydrogen, and there are also ongoing developments and plans to introduce hydrogen as a fuel on short-sea ships with ICEs. Examples include a hydrogen dual-fuelled tug planned to enter operation in 2021⁸; a hydrogen-fuelled bulk ship planned to enter operation in 2024⁹; a small hydrogen dual-fuelled engine already launched¹⁰; and, hydrogen-fuelled 2-stroke and 4-stroke engines¹¹ to be developed. Using compressed or liquefied hydrogen in fuel cells is a realistic option for the short-sea shipping segment in the medium term. We expect the first limited demonstration applications in the ferry sector this year.

The Getting to Zero Coalition has mapped projects focusing on hydrogen ship technologies (Getting to Zero Coalition, 2021). They find that while only two hydrogen projects for ships above 5,000 DWT were initiated before 2020, six new projects have since begun. For smaller vessels, 12 projects were initiated before 2020, and five since. This demonstrates a shift towards hydrogen projects focusing on larger ships. Scaled commercialization is hampered by significant barriers as mentioned above, and is not expected before 2030 at the earliest. The hydrogen timeline reflects ongoing technology development in the short-sea segment, where a TRL level of 6-7 is estimated for ICEs and fuel cells. The timeline also reflects the lack of rules for use of hydrogen on board, and ongoing efforts on developing input to rules and standards. Flag state approval of hydrogen fuel installations is currently based on the alternative design approach in the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), which is a risk-based approach intended to demonstrate equivalent safety.

- **Ammonia:** Safety and regulatory challenges, and space/weight and cost considerations related to storing large quantities of hydrogen on ships, have generated interest in exploring alternative hydrogen-

based energy carriers such as ammonia. Key challenges include ammonia's toxicity, combustion properties, nitrous oxide (N₂O) emissions, and potential ammonia slip. Prototyping of technology, and demonstration projects, are in progress. Development work on engines that can burn ammonia is underway as indicated in the timeline, and they are expected to be ready within the next few years. In an ongoing EU project, demonstration of a 2 MW ammonia-driven SOFC system is planned during 2024, retrofitting an existing supply vessel, Viking Energy.¹² Such demonstration and pilot projects are expected to significantly improve the speed of maturing the technology. Some commercial applications are also expected as several shipowners have announced plans for use for ship types such as RoPax, tankers, and bulk ships. The Getting to Zero Coalition has also mapped projects focusing on ammonia ship technologies (Getting to Zero Coalition, 2021). It finds that while only four ammonia projects for ships above 5,000 DWT were initiated before 2020 – 10 new projects have since started. For smaller vessels, one project was initiated before 2020, and once since. This demonstrates an increased number of ammonia projects, focusing on larger ships. The current TRL level is estimated to 5-6 for ICE and fuel cell. The ammonia timeline reflects this status and developments on the technical side, and the fact that the first-ever class rules have recently been released. Currently flag state approval of ammonia fuel installations is based on the alternative design approach in the IGF Code. Class rules may be used to ease this approach if accepted by the Flag Administration.

- **Methanol:** Methanol can be stored in integral fuel tanks for liquid fuels if modifications are made to accommodate its low flashpoint properties. Two-stroke methanol engines are commercially available and already have more than 100,000 hours of operations. Four-stroke engines are under development. Fuel-cell technology utilizing methanol has been

8 www.cmb.tech/hydrotug-project

9 www.shipinsight.com/articles/norway-plans-worlds-first-zero-emission-vessel

10 www.abc-engines.com/en/news/behydro-hydrogen-dual-fuel-engine-launched-in-ghent
www.innio.com/en/news-media/news/press-release/new-hydrogen-engine-from-innio-ready-for-operation-after-passing-all-tests
www.man-es.com/marine/strategic-expertise/future-fuels/hydrogen

11 www.motorship.com/news101/alternative-fuels/japanese-engine-builders-to-develop-hydrogen-fuelled-2-stroke-and-4-stroke-engines

12 www.eidesvik.no/viking-energy-with-ammonia-driven-fuel-cell

demonstrated in test installations (e.g. the Viking Line ferry, MS Mariella). Methanol has attracted interest as an alternative, low-carbon fuel because it is also possible to produce with renewable feedstocks such as municipal and industrial waste, bioenergy, and from CO₂ and hydrogen (DNV GL, 2016). The Getting to Zero Coalition has also mapped projects focusing on methanol/ethanol ship technologies (Getting to Zero Coalition, 2021). They find that while only one methanol/ethanol project for ships above 5,000 DWT was

initiated before 2020, three new projects have since started. For smaller vessels, three projects began before 2020, and once since. These data sets also include ships in operation. Compared with hydrogen and ammonia projects, the number of such methanol/ethanol ship technology projects is less. The methanol timeline reflects the TRL level of 9 for ICEs and 5-6 for fuel cell. It also reflects the facts that class rules are in place and that the IMO has developed interim guidelines and has thus provided an international standard

Safety - a prerequisite for the successful and timely introduction of alternative fuels

Decarbonization involves alternative fuels and operations with new safety-related risks (DNV GL, 2020a). Through our white paper on safety published earlier this year (DNV, 2021a), we argued that with all eyes focused on transformations in digitalization and decarbonization, we as an industry need to commit ourselves as much to safety as to transformation. After all, the safe and timely transition towards a digitally smart and carbon-neutral future may be compromised if the safety-related risks that these transitions bring about are not accounted for.

A successful uptake of alternative fuels depends on the development of efficient safety regulations and the ability to implement a safety culture where all stakeholders take the responsibility to handle the new challenges introduced with the new fuels.

The gradual introduction of LNG as a fuel, examples set by first movers, and the experience of decades of carriage and consumption of boil-off on gas carriers have been important for the wider uptake for deep-sea shipping we see indications of today. The entry into force of the IGF Code 17 years after the launch of a Norwegian LNG-fuelled ferry, Glutra, provided an international regulatory framework to handle gases and other low-flashpoint fuels, and is a result of 20 years of learnings and

experiences of designers, shipowners, manufacturers, yards, flag states and classification societies in how to safely integrate onboard LNG fuel systems. Based on these experiences and the carriage on board gas carriers, DNV has also developed rules for the other relevant hydrocarbon gas, LPG, applying the same safety principles.

To a lesser degree, similar experiences have been gained for methanol through carriage and use as fuel on chemical carriers and as a common cargo on offshore supply vessels. An IMO interim guideline for methyl/ethyl alcohols as fuel is in place, providing guidance and support for the integration of the onboard fuel system.

For ammonia the picture is different. The maritime industry has experience with carriage of ammonia in gas carriers and as a refrigerant in refrigeration plants, but not as a fuel. Due to its toxicity, the introduction of ammonia as fuel creates new challenges related to safe bunkering, storage, supply and consumption. Available energy converters could be 3-4 years away, and regulatory developments in IMO are not yet initiated. Considering the urgency to decarbonize shipping, major deployment of ammonia as fuel may happen faster than for LNG, LPG, and methanol, which means additional

for the use of methanol as fuel. Regulations for fuel-cell installations are currently under discussion in the IMO, but this process has not yet been completed. Consequently, Flag Administrations will have to resort to the alternative design approach laid out in the IGF Code for approval of fuel-cell installations. Class rules for fuel cells are in place and may be used to ease this approach if accepted by the Flag Administration.

In summary - this chapter has shown that although technologies enabling the use of ammonia and hydrogen are being developed, these are still relatively immature, and that time and effort is needed to make these technologies available for widespread onboard use. For methanol, the technologies are more mature.

focus should be on the installation and safe operational practices. DNV published the first class rules for ammonia as fuel in July 2021 to accommodate owners, shipyards, and designers considering ammonia as fuel.

Hydrogen is not transported as a marine cargo, and the experiences as a marine fuel are currently limited to small-scale R&D projects. The safety implications of storing and distributing hydrogen on board ships are not clear. The general understanding of hazards and risk associated with hydrogen, and particularly liquefied hydrogen (LH₂), is limited. Consequently, no class rules or prescriptive international regulations have yet been developed. Several R&D initiatives are currently ongoing to improve the understanding of LH₂ and associated hazards. For hydrogen the potential explosion risk related to the low ignition energy and the wide flammability range requires special attention. The very low boiling temperature for hydrogen makes it more challenging to store in its liquefied form.

It is sometimes argued that experience from land-based installations proves that a technology can be safely used on board ships. There are however principal differences to be considered. It is a well-established principle in the

IMO and class rules that the level of safety requirements is increased when land-based technology is applied to ships. This relates to a variety of conditions:

- A ship operating out in the open seas is self-reliant and can in most instances not rely on help from outside.
- Crew and passengers cannot escape to safety in the same way as from a car or within a building on shore.
- Due to space constraint, the safety distances are much smaller on ship than a comparable installation on shore.
- The environmental conditions are challenging on board ships with humidity, sea spray, vibrations and inclinations.
- The power demand for a ship is in a different order of magnitude compared to other applications (for instance automotive) considering similar fuel technology.
- Low temperature materials are a necessity for many fuels. As opposed to supporting structures for onshore facilities, ship steel is not resistant to low temperatures.

For the above reasons, land-based solutions are not directly transferable to ships. The qualification of land-based technologies for maritime use adds time and cost.

Highlights

We introduce our updated framework for managing carbon risk, with input from our Class Notation, Fuel Ready:

- The framework can guide development of robust fuel strategies and practical solutions to comply with decarbonization regulations and access incentives.
- It models financial performance of different fuel and energy-efficiency strategies to identify robust design choices.
- These choices undergo a structured review to map out vital implications for design at newbuilding stage and a (possible) conversion stage.



4

OUR APPROACH TO MANAGING CARBON RISK

4 OUR APPROACH TO MANAGING CARBON RISK

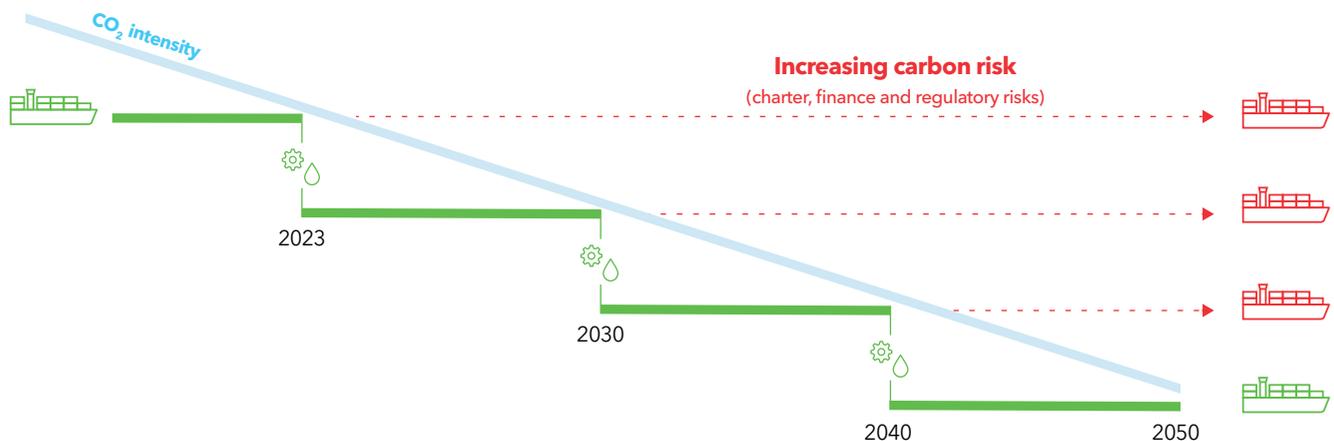
Uncertainty over future change in regulation and other drivers – combined with the uncertain development of fuel and technology options – means that a shipowner considering newbuilding orders today is faced with a complex carbon-risk picture. This chapter focuses on key concepts and our updated framework for managing this risk with input from our new Class Notation, Fuel Ready.

Figure 4.1 illustrates how pressure from regulators and key commercial stakeholders like financiers and charterers will push shipowners to ensure that their ships stick to an acceptable GHG emission trajectory (such as the IMO Carbon Intensity Indicator (CII) requirements). Above this trajectory, the shipowner is exposed to regulatory and commercial risk; so, for a new ship to retain its asset value throughout the next decades, taking GHG target trajectories into account in design will be critical. Figure 4.1 also illustrates how a shipowner will need to identify a 'decarbonization stairway' to remain below the required GHG emission trajectory. This stairway illustrates the chosen risk-mitigation strategy and how the introduction of new fuels and technologies at various points in time enables

the emission intensity for the ship to stay below the required level. Naturally, understanding the costs associated with the stairway is vital – as is the understanding of the technical design implications of the chosen strategy. In the shorter term, energy-efficiency measures and energy harvesting combined with operational measures may be sufficient; but in the longer term, the use of alternative fuels will be necessary to meet the GHG trajectory. This also means that the ship should be designed to allow for the needed upgrades or fuel changes later in its lifetime. Thus, it is an important intervention point when a vessel is being commissioned, to influence its emissions through its lifetime in a cost-effective manner.

FIGURE 4.1

The decarbonization stairway and potential exposure to carbon risk



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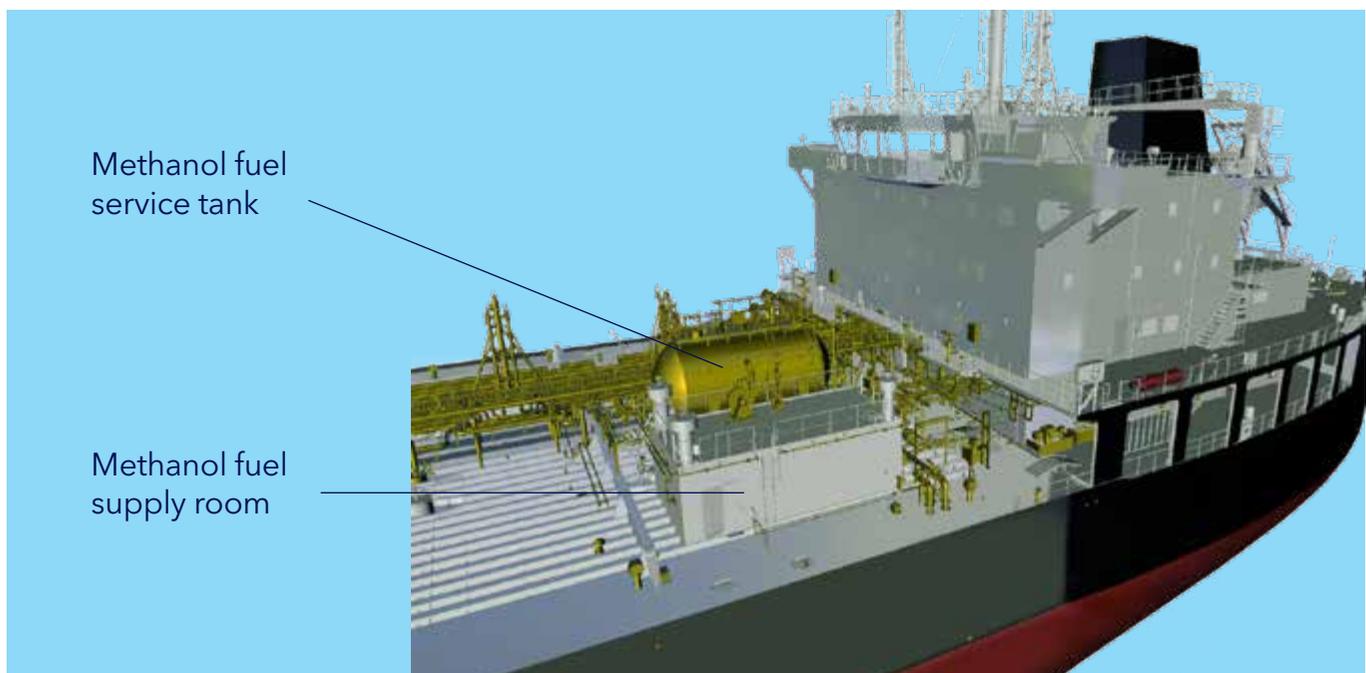
In previous editions of this report, we have asserted that uncertainty can be managed by applying a structured and knowledge-based approach to newbuilding projects and conversion of existing tonnage. Supported by modelling tools, this can go a long way towards helping shipowners meet their GHG targets and protect the future value, profitability, and competitiveness of their ships. Expanding on this framework for future-proofing ship designs (DNV GL, 2018; 2019a), this section outlines our updated framework for risk management, with the aim to provide guidance on how to develop robust fuel strategies and practical solutions complying with increasingly stricter decarbonization regulations and incentives.

A ship should be designed to allow for the needed upgrades or fuel changes later in its lifetime.

Our framework has two main parts:

- First, we apply a techno-economic model to explore the financial performance of different fuel and energy-efficiency strategies available to a specific ship. The aim of this step is to identify robust design choices – i.e. designs that are resilient to future changes and perform well under a range of scenarios. This is achieved by re-running the model under a range of varying assumptions and frame conditions (scenarios).
- Second, the design choices identified in the first step are subjected to a structured review of the design, intended to map out vital implications for the ship's design at both a newbuilding stage and a (possible) conversion stage.

Importantly, this updated framework is specifically designed to allow detailed assessments of fuel flexibility and Fuel Ready solutions. Considering the large uncertainties involved over the lifetime of ships, planning for fuel flexibility and Fuel Ready solutions could ease the transition and minimize the risk of investing in stranded assets (DNV GL, 2019a, 2020a).



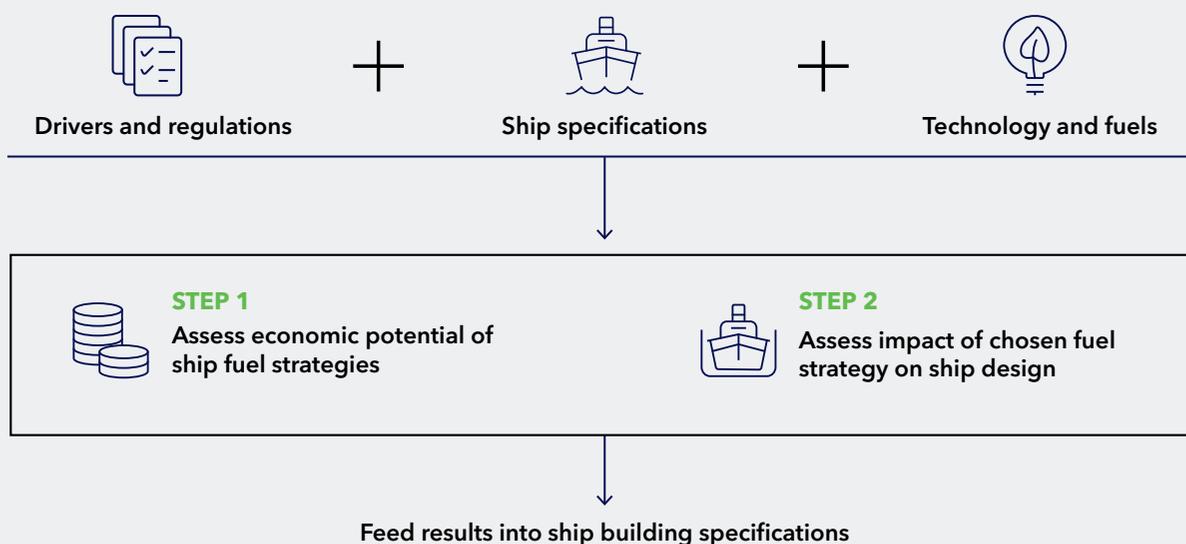
Fuel Ready refers to a new DNV Class Notation and indicates that a conversion to an alternative fuel has been accommodated and verified in the newbuild design (see text box page 43). There are many ways to reach a Fuel Ready design complying with rules and regulations. The cheapest or most convenient solution at the newbuilding stage is not necessarily the most cost-efficient and favourable option when the ship shall be converted, nor the best overall solution.

In the following chapters, we will describe in more detail the content of both the techno-economic evaluation of fuel strategies (Chapter 5) and the assessment of design implications of the chosen fuel strategy (Chapter 6). In both chapters, we will exemplify the use of the framework using a 210K DWT Newcastlemax bulk carrier as a case study.

Figure 4.2 illustrates the two steps in our updated approach. It shows that the outlook on drivers, regulations, ship technologies and fuels explored earlier in this report is vital input to the first step. The case study is used to illustrate fuel strategies for a Newcastlemax bulk carrier, but only analyses one specific fuel-price scenario. When used for actual newbuild decision support, multiple fuel-price scenarios and design options should be tested to identify the most robust choices for the shipowner’s specific ship type and trade. The number of variables could be narrowed down depending on ship type, trade, and the shipowner’s perspective of fuel availability and price.

FIGURE 4.2

Illustration of our updated framework for carbon risk management



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DNV Class Notation Fuel Ready

The class notation applies to ships that are planned for, and/or partly prepared for, later conversion to one or more alternative fuels. It indicates that DNV has verified compliance with the rules for the applicable fuel for a future ship design or fuel tank installed at newbuilding.

The alternative fuel(s) the ship is prepared for is represented by a qualifier in the class notation: **Fuel Ready (LPG, LNG, ammonia and/or methanol/ethanol).**

The level of preparation is represented by attributes to the qualifier (s). A minimum level of preparation is required to qualify for the class notation. Examples are given for the two possible mandatory pathways to a Fuel Ready notation:

- **Fuel Ready (Ammonia, D, MEc, S)** means that the future ammonia-fuelled design is examined and found to be in compliance with rules for ammonia in force at time of the newbuilding (D), and the main engine is of a type that can be converted to ammonia (MEc). Structural preparations required to support the future ammonia containment system are carried out (S).
- **Fuel Ready (Ammonia, Ti, S)** means that fuel tank(s) are installed that can be used for ammonia (Ti). Structural preparations for storage of ammonia are carried out (S). Design verification outside scope of fuel tank(s) has not been performed.





Highlights

We use a bulk carrier case study to illustrate the carbon risk-management framework. This study demonstrates how:

- Regulations and commercial drivers can be translated into practical target GHG trajectories reflecting a shipowner's particular circumstances. In addition to a *minimum compliance trajectory*, we have developed a stricter trajectory *catering for cargo-owner ambitions*.
- The general overview of available fuels and technologies can be translated into practical design options for a

shipowner's newbuild. We explore seven possible fuel pathways, starting either with a mono-fuelled or dual-fuelled ship, with different possibilities of transitioning to carbon-neutral fuels - including options for alternative Fuel Ready designs. The solutions explored are targeted for deep-sea shipping and include use of MGO/VLSFO, LNG, LPG, biofuels, ammonia, and methanol as fuel.

- Our modelling capability allow us to calculate the cost of various fuel strategies over the lifetime of a ship. We explore ways to meet the target GHG trajectory by use of blend-in fuels and potential conversions.

5

TECHNO-ECONOMIC EVALUATION OF FUEL STRATEGIES

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5 TECHNO-ECONOMIC EVALUATION OF FUEL STRATEGIES

In this chapter we apply an updated techno-economic model to explore the financial performance of different fuel strategies available to a specific ship, as the first step in our carbon risk-management framework outlined in Chapter 4. We illustrate the use of the framework using a 210K DWT Newcastlemax bulk carrier as a case study, limited to one chosen fuel-price scenario and one target GHG trajectory.

To explore the financial performance of different fuel technology options, we have developed the FuelPath Model (Figure 5.1). This model builds on those presented in previous editions of our Maritime Forecast to 2050 reports, such as the GHG Pathway Model and Carbon-

Robust Model. However, the latest model provides increased flexibility in the choice of design options related to fuels, and increases the user's ability to investigate in detail a shipowner's real-world strategies over the lifetime of individual ships.



5.1 Model description

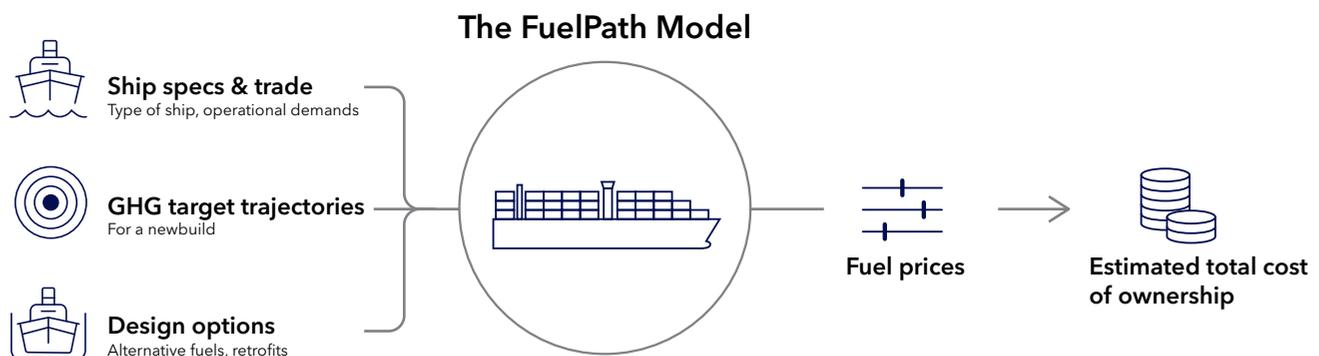
The FuelPath Model takes as input four main parameters:

- **Ship specifications and trade information:** The model takes as input the ship's annual energy demand.
- **GHG target trajectories:** All shipping companies need to fulfil the expected minimum compliance requirements from the IMO over a vessel's lifetime; but depending on the strategy, environmental ambitions, and market situation, they may also aim for a leading position in decarbonization. Requirements at international (IMO), regional (e.g. EU), and local levels should be considered. Upcoming operational requirements from the IMO will already impact on business in 2023 and should form the minimum acceptable targets (minimum compliance). In the longer term, the recommended trajectory should at least follow the ambitions in the IMO GHG strategy. Further, we expect that charterers, financial institutions, and other stakeholders will impose their own requirements on shipping – and shipowners should carefully consider if their GHG target trajectory should be aligned with such commercial requirements. To reflect uncertainty, several trajectories should be evaluated.
- **Design options related to fuels:** The model draws on a set of design options relating to alternative fuels. The fuel flexibility of each analysed fuel-system design option is defined. Cost and impact on emissions are defined.
- **Fuel prices:** The financial performance of a vessel design is heavily dependent on the cost of the fuels it can use. Also, CO₂ pricing mechanisms are under development, and the model allows for investigating the impact of such potential costs. To reflect uncertainty, several fuel-price and CO₂ price assumptions should be evaluated.

Provided with the above input, the model evaluates the economic performance of all the available design options related to fuel over the lifetime of the vessel, expressed in terms of *total cost of ownership*, and other relevant economic parameters. To make this evaluation, the vessel's GHG performance is assessed year-by-year, and compared against the chosen GHG target trajectory. If the GHG intensity exceeds the target, all measures available to reduce emissions are assessed, and the least costly is selected. Thus, the model minimizes the fuel cost (including CO₂ cost) of the ship for each year of operation, under the constraint that the ship cannot exceed the carbon intensity of its GHG target trajectory.

FIGURE 5.1

Illustration of the FuelPath Model used for techno-economic evaluation of design options



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5.2 The bulk carrier case

This Newcastlemax bulk carrier newbuilding case study is an evaluation of seven different design options related to immediate and future use of alternative fuels. The case results presented in Chapter 5.3 are the output from one of many analysed fuel-price scenarios where renewable energy prices are low compared with bioenergy prices – this does not constitute a complete review. In the case study, we have used constant fuel prices and no CO₂ price for simplicity.

5.2.1 Ship specification and trade

The case ship is intended for the iron ore and coal trade between Australia and China. It is assumed that the base design will implement state-of-the-art energy-efficiency measures compliant with EEDI Phase 2, and that further carbon-intensity reductions must be accommodated by fuel changes.

Case study: 210K DWT Newcastlemax bulk carrier State-of-the-art concept design, EEDI Phase 2 compliant

Main dimensions [m]	Loa:300, B:50, D:25
Loading capacity	210 000 DWT
Design speed	14 knots @15% sea margin
Minimum cruising range	~ 16 000 nautical miles
Trade route	Australia - China
Energy-efficiency measures implemented	<p>Hydrodynamics (~ 5%)</p> <ul style="list-style-type: none"> - Hull optimization - High-efficiency propeller - Efficient coating system - Energy-saving devices <p>Machinery: (~ 10%)</p> <ul style="list-style-type: none"> - Variable Frequency Drive (VFD)-controlled pumps, fans, etc. - Shaft generator Power Take Off / Power Take In (PTO/PTI) - Waste-heat recovery - Battery hybridization - Light emitting diode (LED) lighting

The 16,000 nautical miles cruising range was selected for dimensioning the fuel-storage requirement, assuming one bunkering per round trip, also allowing for the flexibility on some of the major coal trading routes.¹³ A lifetime of 25 years is assumed for the ship.

5.2.2 Greenhouse gas target trajectories

For our Newcastlemax bulk carrier study, we have considered two different GHG trajectory ambition levels (Figure 5.2).

The **minimum compliance trajectory** is based on the IMO's GHG ambitions:

- From 2023 to 2026 – short-term IMO CII regulations with line representing a C-rating threshold for bulk carriers. The reduction requirement starts at 5% in 2023 relative to the 2019 CII reference line, and increases by two percentage points annually up to 2026. In addition, there is an extra margin for the C-rating threshold.
- Beyond 2026 – further reduction in carbon intensity by two percentage points annually. Although no reduction requirements have been decided by the IMO beyond 2026, this is the same rate of reduction as applied between 2023 and 2026.

A stricter trajectory *catering for cargo owner ambitions*, has also been developed. It considers that, for the iron ore trade, some mining companies have carbon-neutrality targets that may drive decarbonization of the Newcastlemax bulk carrier segment. Rio Tinto¹⁴, BHP¹⁵, Glencore¹⁶, Vale¹⁷ and South32¹⁸ aim to become carbon-neutral by 2050, while Anglo American¹⁹ and Fortescue Metals Group (FMG)²⁰ have a goal of reaching the same target in 2040 and 2030, respectively. We therefore consider the following *catering for cargo-owner ambitions - trajectory*:

- From 2023 to 2026 – short-term IMO CII regulations with line representing an A-rating threshold for bulk carriers.

¹³ The Green corridor JIP: www.dnv.com/expert-story/maritime-impact/LNG-fuelled-Newcastlemax-for-the-Green-Corridor.html

- Beyond 2026 - further linear reduction in carbon intensity to achieve full decarbonization by 2040.

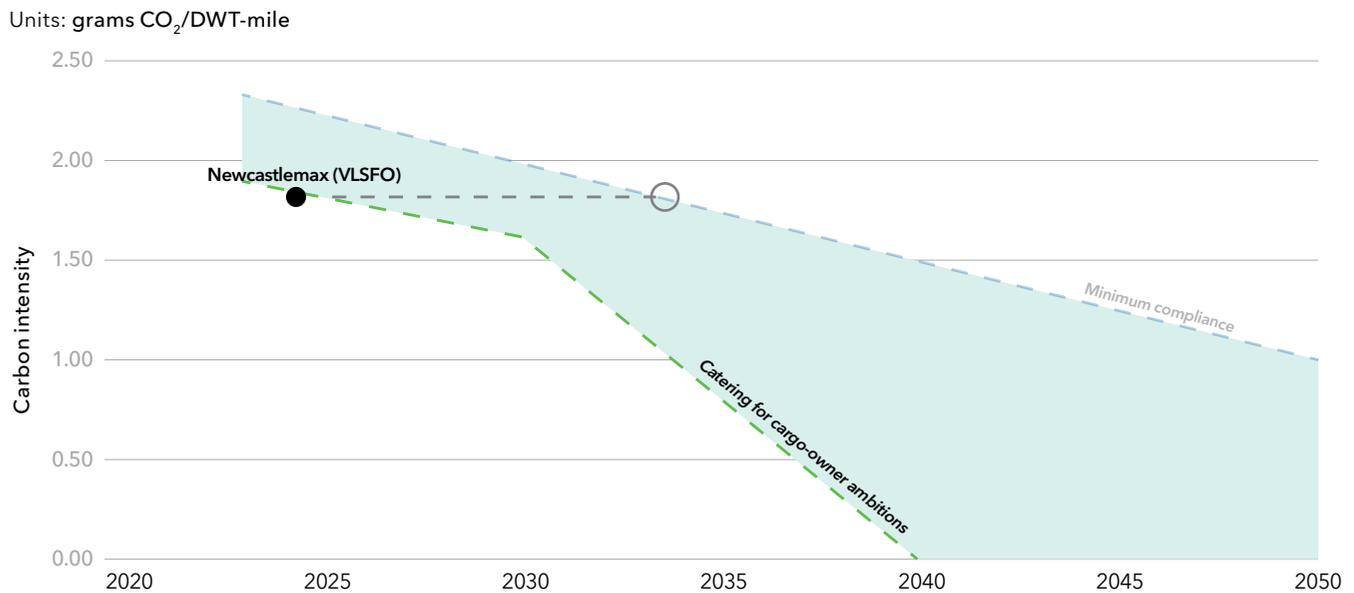
This more ambitious decarbonization scenario has been selected as the target trajectory for our case study. We emphasize that this is selected only for the purposes of this case study, and that each shipowner must assess and identify the GHG target trajectory most relevant for their market strategy. Furthermore, the robustness of the final design choices should also be stress-tested using several possible GHG target trajectories.

Only tank-to-propeller GHG emissions, more specifically CO₂ and methane emissions, are accounted for. Nitrous oxide (N₂O) is an additional GHG, not considered here, which could become increasingly important in the future with adoption of ammonia-fuelled vessels.

14 www.riotinto.com/sustainability/climate-change
 15 www.bhp.com/sustainability/climate-change
 16 www.glencore.com/media-and-insights/news/Climate-Report-2020--Pathway-to-Net-Zero
 17 www.vale.com/en/sustainability/pages/carbonneutral.aspx
 18 www.south32.net/who-we-are/sustainability-approach/climate-change
 19 www.angloamerican.com/sustainability/environment/climate-change
 20 www.fmg.com.au/workingresponsibly/climate-change-and-energy

FIGURE 5.2

GHG target trajectories considered for the Newcastlemax bulk carrier newbuilding case study. The 'Catering for cargo-owner ambitions' trajectory has been selected as target. A Newcastlemax state-of-the-art concept design is shown as a point of reference.



Key: Very low sulphur fuel oil (VLSFO)

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5.2.3 Design options

As pointed out in Chapter 3, and in earlier editions of the Maritime Forecast study, several possible combinations of fuels and energy converters can enable a ship to stay aligned with a defined target GHG trajectory. Based on a review of the maturity and suitability of relevant fuel technologies for a Newcastlemax bulk carrier, we conclude that there are currently four available fuel system and energy converter design options:

- Conventional oil-fuelled (mono-fuel) internal combustion engines (ICEs).
- Dual-fuel ICEs using LNG, LPG, or methanol as fuel.

Additionally, we included design options related to fuels making it possible to convert to an alternative fuel in the future to increase fuel flexibility. In total, seven design options are selected for this case study, as shown in Table 5.1 below. The table shows the various fuels that can be applied with each of the seven design options – for a newbuild and after a possible conversion.

For each design option shown in Table 5.1, we input the newbuild cost including additional cost relating to preparing the ship for later conversion (for the Fuel Ready designs), as well as cost of conversion. Main cost differences are related to fuel-storage and energy-conversion technology.

Figure 5.3 shows the estimated operational carbon intensity of the different design options assessed in the case study. MF, DF LPG, and DF LNG indicates the designs running on VLSFO, LPG and LNG respectively, with no blend-in of carbon-neutral fuels. DF Ammonia and DF Methanol indicate vessels running on ammonia and methanol as main fuel with carbon-neutral pilot fuel²¹ oil, thus achieving zero-carbon intensity. For this case study, the model has applied a pilot fuel consumption of 23% for ammonia and 8.5% for methanol, in terms of the share of annual energy consumption.

²¹ Pilot fuel is injected into the combustion chamber to ensure proper combustion of the main fuel.

TABLE 5.1

Design options related to fuel, investigated for a Newcastlemax bulk carrier. Fuel flexibility at newbuild and after conversion (if applicable) are shown for each design option.

Design option at newbuild*	Fuel flexibility at newbuild		Fuel flexibility after conversion	
	Fossil fuels	Carbon-neutral fuels	Fossil fuels	Carbon-neutral fuels
MF	VLSFO MGO	(bio-/e-)MGO	–	
MF Fuel Ready (methanol)			VLSFO MGO	(bio-/e-)methanol (bio-/e-)MGO
MF Fuel Ready (ammonia)			VLSFO MGO	e-ammonia (bio-/e-)MGO
DF LNG	LNG MGO	(bio-/e-)LNG (bio-/e-)MGO	–	
DF LNG Fuel Ready (methanol)			MGO	(bio-/e-)methanol (bio-/e-)MGO
DF LNG Fuel Ready (ammonia)			MGO	e-ammonia (bio-/e-)MGO
DF LPG Fuel Ready (ammonia)	LPG MGO	(bio-/e-)MGO	MGO	e-ammonia (bio-/e-)MGO

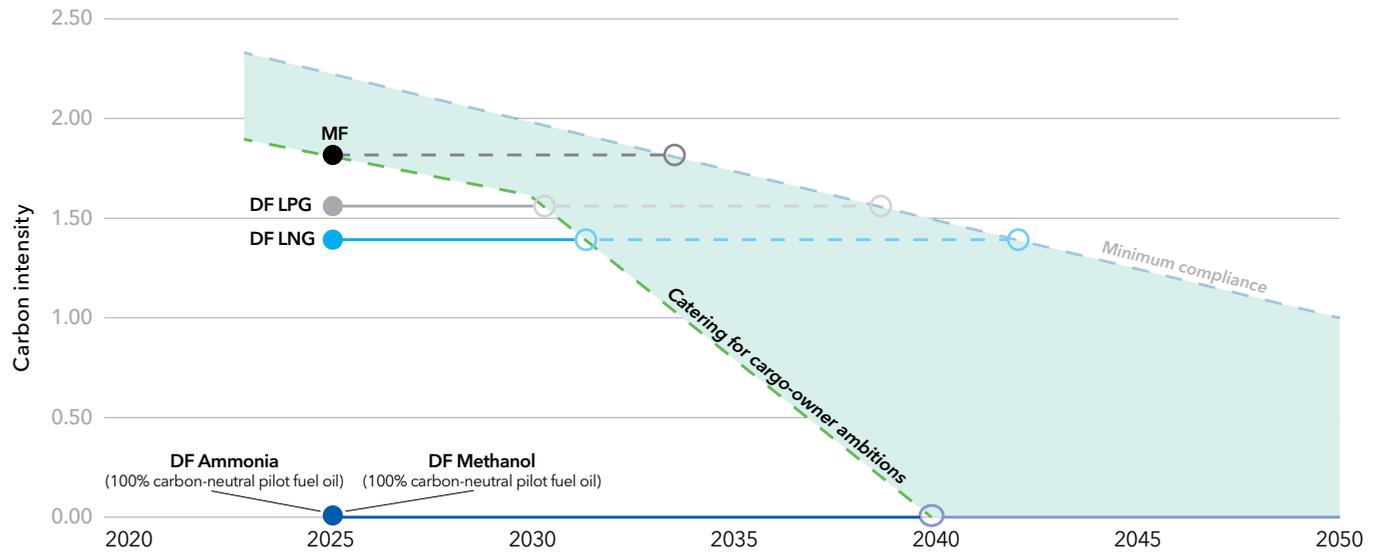
* All design options use internal combustion engines as the choice of energy-converter

Key: Mono-fuel (MF); dual-fuel (DF); very low sulphur fuel oil (VLSFO); marine gas oil (MGO); liquefied natural gas (LNG); liquefied petroleum gas (LPG)

FIGURE 5.3

Carbon intensity of design options at newbuild (MF, DF LPG and DF LNG), and when converted to DF Ammonia or DF Methanol. Note that MF represents a conventional (but state-of-the art energy-efficient) VLSFO-fuelled vessel.

Units: grams CO₂/dwt-mile



Key: Dual-fuel (DF); liquefied natural gas (LNG); liquefied petroleum gas (LPG); mono-fuel (MF); very low sulphur fuel oil (VLSFO)

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Aurora class from HÖEGH AUTOLINERS has DNV's new 'Fuel Ready (ammonia)' notation, which makes it the first in the segment to be ready for operation on carbon-neutral ammonia.

5.2.4 Fuel and carbon price assumptions

The financial performance of various design options related to fuel is heavily dependent on the cost of the fuels that can be used. In addition, CO₂ pricing mechanisms are under development, and the model allows for investigating the impact of such potential operational expenses. When our FuelPath Model is used for newbuild decision support, multiple fuel-price scenarios should be tested to identify the most robust choices.

In principle, the price of a fuel is a function of the cost of raw material / primary energy source, production and distribution, as well as the relationship between supply and demand in the market. Fuel prices have historically seen large variations²² in response to changes in demand and supply, as well as to changes in the price of underlying raw material used for production (e.g. crude oil and natural gas). As a result, future fuel prices are hard to predict. This is especially true for the case of carbon-neutral fuels, where there is often no historical price data available.

In order to simplify prediction of future fuel prices, DNV's Marine Fuel Price Mapper uses levelized cost of production and distribution as a proxy for fuel price (DNV GL, 2020a). The relationship between the price of primary energy from various sources (i.e. renewable electricity, bioenergy, natural gas, crude oil) and the cost of production for different fuels has been modelled from literature sources (e.g. ICCT, 2020; IRENA, 2021; Concawe, 2020; Agora, 2018). Distribution costs have been added on top of production cost estimates.

The assumed fuel prices used to illustrate fuel choice strategies in this case study reflect one future scenario where low-cost renewable electricity is available for production of electrofuels at a lower cost than biofuels. This scenario resembles the 'low electricity price' fuel scenario from last year's study. No carbon price is considered, and all fuel prices are kept constant throughout the time-period modelled in this case study, as shown in Table 5.2.

²² See, for example, historic price development of natural gas, crude oil, MGO, and HFO: www.dnv.com/maritime/insights/topics/lng-as-marine-fuel/current-price-development-oil-and-gas.html

TABLE 5.2

Fuel prices applied in the Newcastlemax case study. The prices are given as future averages and reflect a scenario in which low-cost renewable electricity is available for production of carbon-neutral electrofuels.

	Fuel	Price (USD/GJ)	Price (USD/toe)
Fossil	MGO	13.8	578
	VLSFO	12.0	502
	LNG	7.8	327
	LPG	10.2	427
Carbon-neutral	Ammonia	22.9	959
	Methanol	29.8	1 248
	MGO	40.0	1 675
	LNG	30.7	1 285

5.3 Case study results

We use the FuelPath Model to investigate how the seven fuel-system design options given in Table 5.1 compare with one another in one specific scenario. The scenario we have chosen depicts a future with a given set of fuel prices in which ammonia is the lowest-cost carbon-neutral fuel (see Table 5.2), the shipowner caters to the most forward-leaning customers (see Figure 5.2), and there is no CO₂ price. The total discounted costs of the seven possible designs in this scenario are shown in Figure 5.4.

The figure shows that **in our chosen scenario**, a conventional ship (MF) has the highest total discounted cost.²³ Even though this design option has the lowest capital expenditure (CAPEX) of all investigated designs, it has the highest fuel expenditure (FuelEX) throughout its lifetime due to the assumed high price of carbon-neutral MGO, the

only fuel option for this design to be aligned with the GHG target trajectory. The ammonia-ready solutions, have a higher CAPEX, but comparatively lower FuelEX, in their lifetimes. The two design options with lowest discounted costs are MF Fuel Ready (ammonia) and DF LNG Fuel Ready (ammonia). DF LPG Fuel Ready (ammonia) is also identified as a low-cost option, but we do not investigate this design option further in this case study.

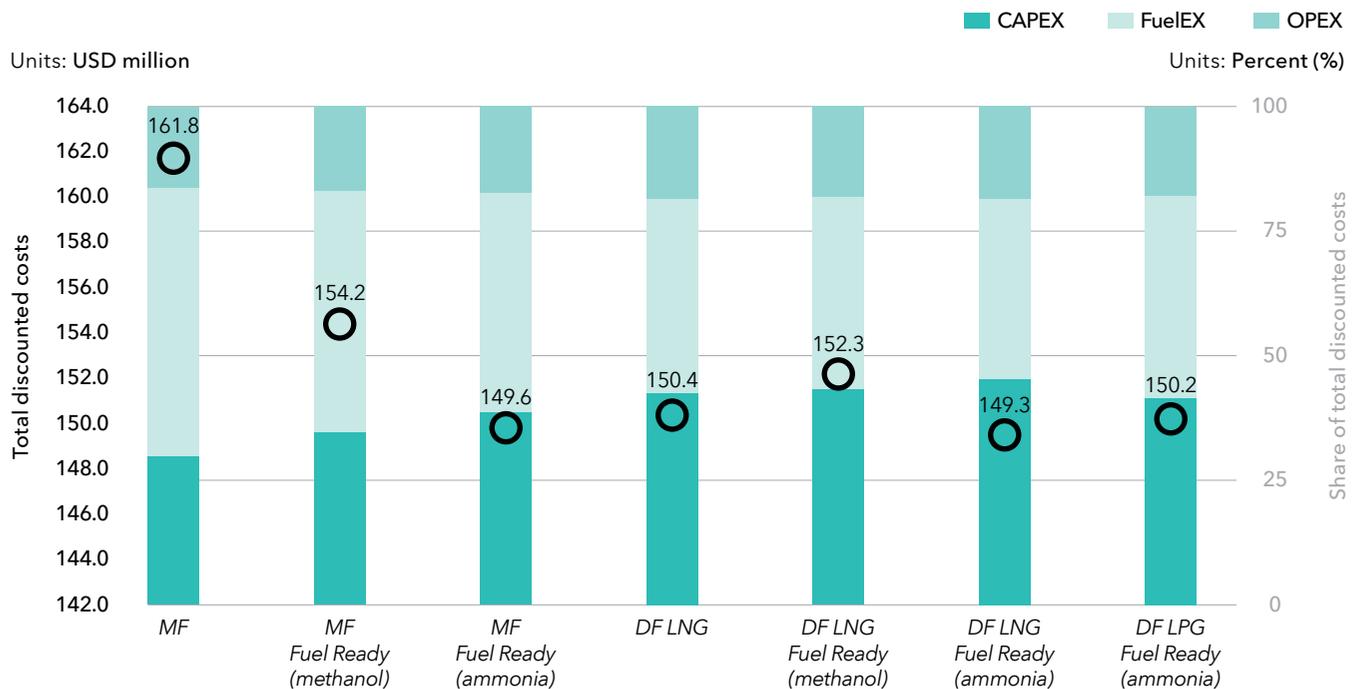
In Figures 5.5, 5.6 and 5.7 we illustrate the economic consequences of the MF Fuel Ready (ammonia) and DF LNG Fuel Ready (ammonia) design options and their respective design counterparts without possibility of retrofit to ammonia (MF and DF LNG). Figures 5.5 and 5.6 show a breakdown of annual costs, and Figure 5.7 shows break-even daily rate²⁴ and total discounted cost.

²³ A discount rate of 8% and a ship lifetime of 25 years have been applied for financial calculations.

²⁴ Break-even daily rate expresses the annualized operating costs (CAPEX, FuelEX, and operational expenditure (OPEX)) for the design in terms of a daily rate.

FIGURE 5.4

The total discounted cost (black circles) and the relative distribution between CAPEX, FuelEX and OPEX (columns)

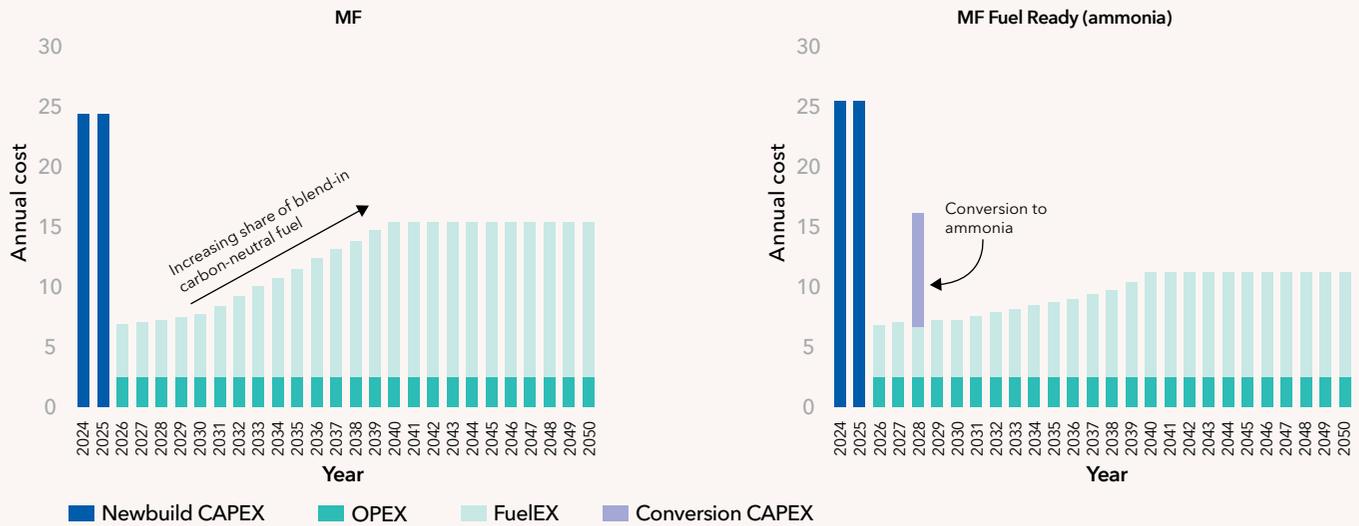


Key: Dual-fuel (DF); liquefied natural gas (LNG); liquefied petroleum gas (LPG); mono-fuel (MF)

FIGURE 5.5

Break-down of annual costs for the conventional vessel, MF, and the ammonia-ready vessel, MF Fuel Ready (ammonia)

Units: USD million



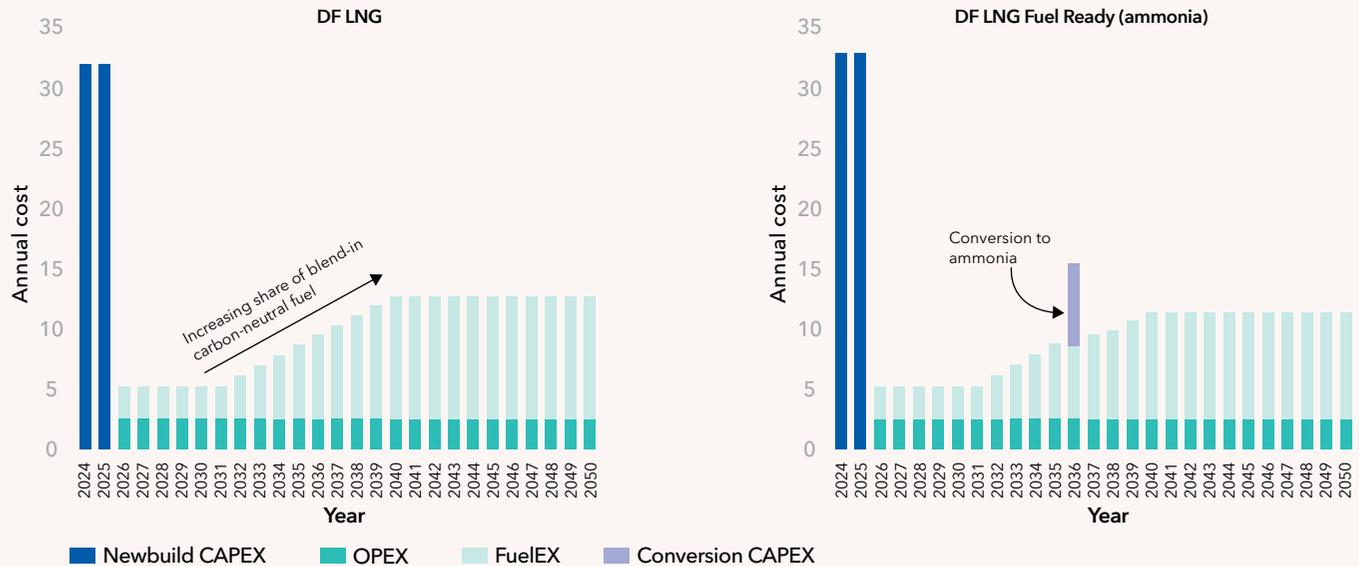
Key: Capital expenditure (CAPEX); FuelEX (fuel expenditure); mono-fuel (MF); operational expenditure (OPEX)

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FIGURE 5.6

Break-down of annual costs for the dual-fuel vessel running on LNG, DF LNG, and the ammonia-ready vessel, DF LNG Fuel Ready (ammonia)

Units: USD million

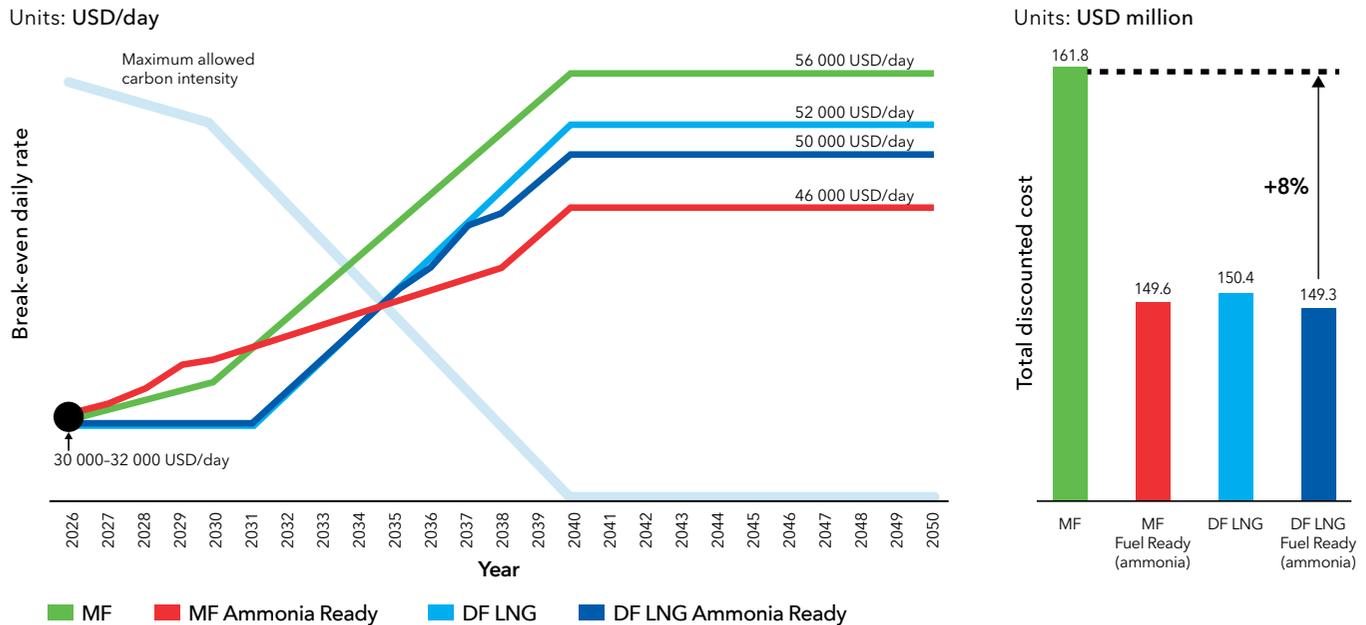


Key: Capital expenditure (CAPEX); FuelEX (fuel expenditure); liquefied natural gas (LNG); mono-fuel (MF); operational expenditure (OPEX)

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FIGURE 5.7

Break-even daily rate and total discounted costs for selected vessels with different fuel system designs



Key: Capital expenditure (CAPEX); Dual-fuel (DF); liquefied natural gas (LNG); mono-fuel (MF)

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As the figures show, all designs must have a steadily increasing blend-in of carbon-neutral fuels as the ship follows the diminishing carbon-intensity trajectory (seen in Figure 5.7 as a light blue trajectory). The *MF* and *MF Fuel Ready (ammonia)* designs start blend-in of carbon-neutral MGO at once, while *DF LNG* and *DF LNG Fuel Ready (ammonia)* can delay the blend-in of carbon-neutral fuels due to the lower GHG emissions of LNG (tank-to-propeller, including methane slip).

The *MF Fuel Ready (ammonia)* design converts to ammonia as fuel in 2028, when the fuel cost of VLSFO and the increased share of carbon-neutral MGO exceeds the alternative costs of MGO and the increased share of ammonia. The *DF LNG Fuel Ready (ammonia)* design converts to using ammonia as fuel in 2036. At conversion, the designs do not immediately use the maximum amount of ammonia, but use enough of it to fulfil the GHG target trajectory, with MGO meeting the remaining energy demand. The year of conversion is thus a factor of the

prices of not only ammonia, but also the other fuels available to the fuel-flexible designs.

In Figure 5.7, the left diagram shows the break-even daily rate year-by-year, with the carbon intensity decreasing to zero in 2040 as per the chosen GHG target trajectory (see Figure 5.2). This figure shows that the *MF Fuel Ready (ammonia)* design has the highest daily rates for a few years beginning in 2025. This is due to the fact that the ship initially uses VLSFO, which has a higher unit price than LNG, and that it converts quite early to ammonia, increasing the capital costs of its operation. From that point on, it uses the lowest-cost carbon-neutral fuel, and has a less steep slope than the other designs towards 2040, as it gradually increases its use of ammonia and finally must use carbon-neutral MGO as pilot fuel.

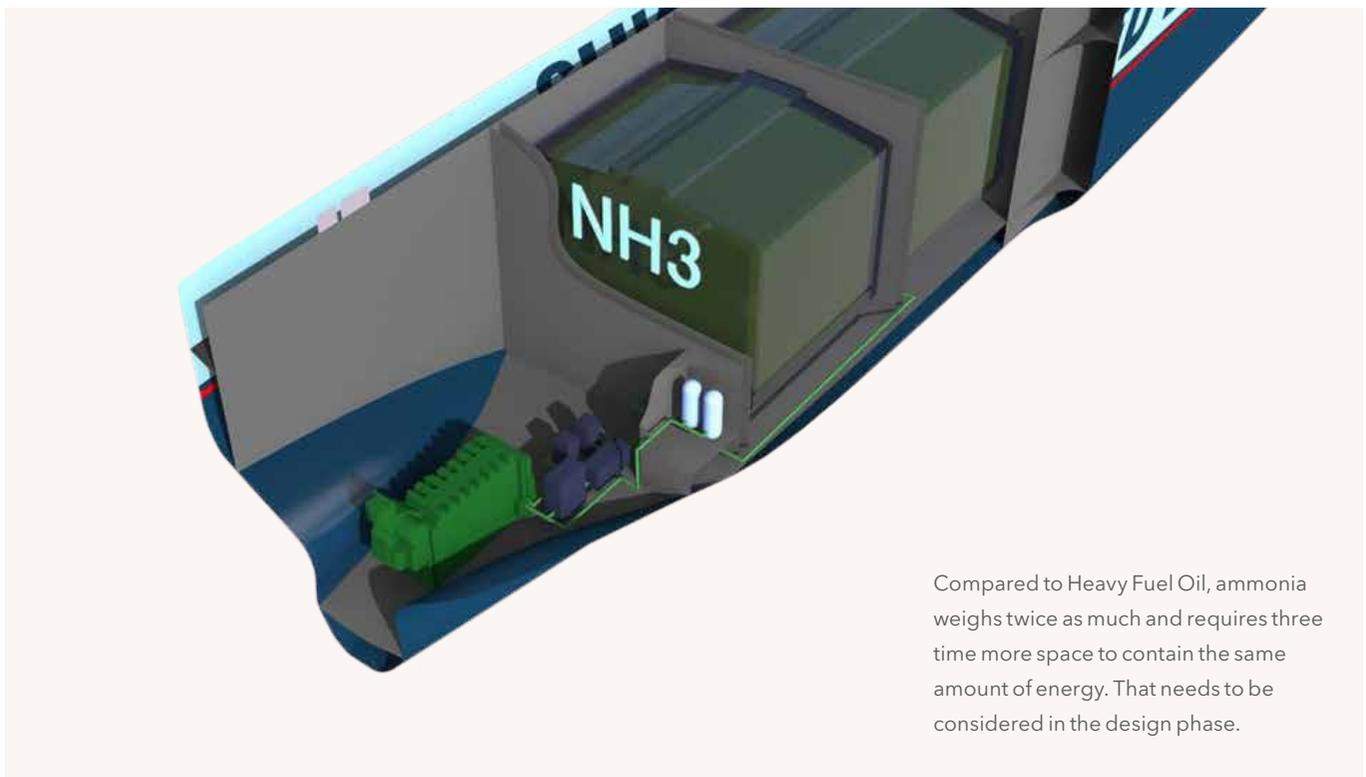
The *DF LNG Fuel Ready (ammonia)* design follows a similar, but delayed, trajectory. The blend-in of carbon-neutral LNG starts at a later stage, and the ship

finally converts to ammonia in 2036. The main reason that the daily break-even rate of this design is higher than for the conventional ammonia-ready design in 2050 is that the conventional ship had a longer time to pay down the cost of conversion because it occurred at an earlier stage.

The total discounted lifetime costs of the two ammonia-ready designs are comparable, which can be seen in Figure 5.7 (right diagram). This also shows that the total discounted costs are approximately 8% higher for the conventional benchmark *MF* design than for the *MF Fuel Ready (ammonia)*, *DF LNG*, and *DF LNG Fuel Ready (ammonia)* designs.

Furthermore, the year of conversion is a significant difference between the *MF Fuel Ready (ammonia)* and *DF LNG Fuel Ready (ammonia)* designs in the modelled scenario. Delayed conversion could be an advantage in

view of the time needed for establishment of bunkering infrastructure. When considering a future conversion to an alternative fuel, a shipowner should map the ship's trade and likely bunkering locations, and assess the likelihood of a chosen alternative fuel being available at bunkering ports in the amounts required to follow the GHG target trajectory. A ship in regular trade between a few large ports that already have plans for providing ammonia can then perhaps acquire the required volume of ammonia after conversion of the *MF Fuel Ready (ammonia)* design in 2028. Other shipowners may choose the *DF LNG Fuel Ready (ammonia)* design and delay conversion for an additional eight years until 2036.



Compared to Heavy Fuel Oil, ammonia weighs twice as much and requires three time more space to contain the same amount of energy. That needs to be considered in the design phase.

5.4 Summary and discussion of validity of case results

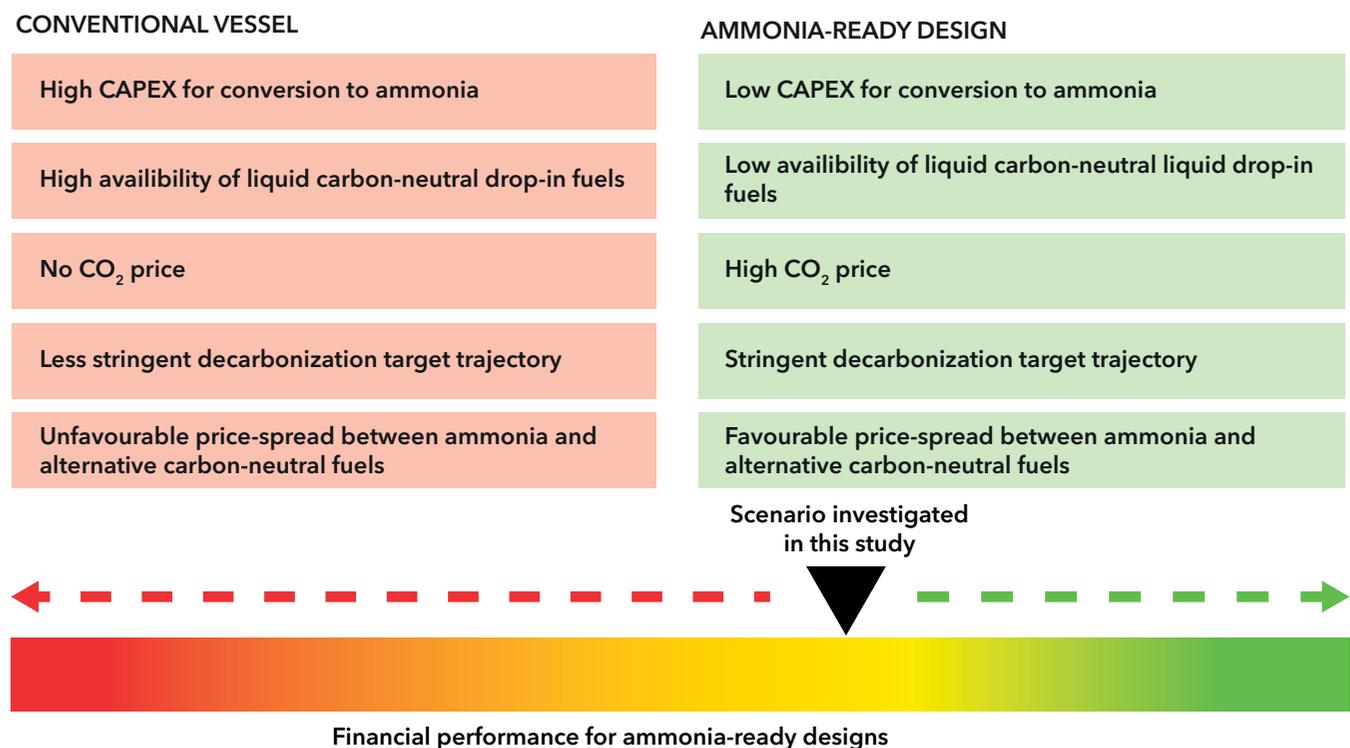
The FuelPath Model described in this chapter is designed to help explore the financial performance of different fuel strategies. By applying the model to a vessel design, under a range of varying fuel and CO₂ prices, and multiple GHG trajectories, the results provide decision support by giving a clearer picture of the robustness of each fuel strategy. In other words, they indicate to what degree designs are resilient to future changes and perform well under a range of scenarios reflecting the unique set of circumstances that each shipowner has to contend with. To make the results more robust, their sensitivities to uncertainties in investment cost, future retrofit cost, and so on should be investigated.

The Newcastlemax newbuild case study used to illustrate our approach is limited to one set of fuel-price assumptions, and one target GHG trajectory. It exemplifies parts of the proposed approach to select a robust fuel strategy, but is not valid as a recommendation to an owner. The modelled financial performance is heavily dependent on the fuel prices applied. As Figure 5.8 illustrates, several factors influence the financial performance of the ammonia-ready design highlighted in our case study. In scenarios where these factors are changed, other designs may outperform the ammonia-ready designs.

Thus, the results of this case study should be interpreted in light of the narrowly defined assumptions applied, and we stress that the results do not show that the ammonia-ready designs are necessarily the most robust choice.

FIGURE 5.8

Important factors influencing the business case for an ammonia-ready design, compared to a conventional vessel



Key: Capital expenditure (CAPEX); carbon dioxide (CO₂)

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Highlights

Our structured review of design for a Newcastlemax case study answers key questions about implications of a fuel-flexible strategy:

- What are the most important actions required for a Fuel Ready design at newbuild and conversion?
- What are the most important preparations at newbuilding and conversion stages for ships to be ready for switching from conventional oil-fuel or LNG to ammonia fuel?
- How do different LNG tank types compare with respect to ammonia conversion compatibility?



6

DESIGN IMPLICATIONS OF CHOSEN FUEL STRATEGIES

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| 6.1 | Preparing an oil-fuelled (mono-fuel) ship for conversion to ammonia | 61 |
| 6.2 | Preparing an LNG-fuelled (dual-fuel) ship for conversion to ammonia | 64 |
| 6.3 | Summary and discussion | 69 |

6 DESIGN IMPLICATIONS OF CHOSEN FUEL STRATEGIES

While main design features and associated costs must be captured in the techno-economic assessment from Chapter 5, layers of practical design implications also need consideration in newbuild decisions. This chapter describes step two in our carbon risk-management framework from Chapter 4. We now present a structured review of the design choices to map out vital implications for ship design at a newbuilding stage and a (possible) conversion stage.

To develop the mono-fuelled and dual-fuelled ammonia-ready designs for the 210K DWT Newcastlemax bulk carrier implies adapting and preparing the newbuild for possible future fuel transitions using a systems engineering approach:

- **Fuel storage**
 - Evaluating optimal storage capacity, tank type, tank materials and tank design pressures for the intended operation
 - Evaluating the capacity required for pilot fuel
 - Establishing a General Arrangement that can accommodate the fuel-storage system with minimal impact on operations
 - Identifying structural modifications required to accommodate the fuel-storage system
- **Power plant**
 - Evaluating the consequences of a fuel change for installed energy converters
 - Evaluating the consequences for any existing fuel preparation and supply system
- **Integration of fuel system in the ship design**
 - Verifying that trim and stability considerations are within acceptable boundaries
 - Ensuring that the ship design does not conflict with safety measures laid down in statutory regulations and class rules

The conclusions from this engineering review should be fed into the building specification forming the basis for the newbuild design.

We will illustrate this approach using the Newcastlemax bulk carrier as a basis for reflections. We will discuss some of the most important technical design implications of Fuel Ready solutions. The design implications of fuel flexibility are addressed reflecting the two ship designs; a newbuild with a conventional mono-fuelled power plant, and a newbuild designed for dual-fuel LNG engines. For both designs, we are evaluating the required changes to prepare them for a transition to ammonia as fuel at a later stage.

A successful Fuel Ready design depends on the extent to which details of the desired future alternative fuel solution are incorporated into the newbuild specification.

6.1 Preparing an oil-fuelled (mono-fuel) ship for conversion to ammonia

A conventional mono-fuelled Newcastlemax bulk carrier deciding to reduce its carbon footprint by changing fuel must use biofuels and/or synthetic fuel oils as 'drop-in' fuels. A future use of ammonia or other carbon-neutral or zero-carbon fuels will require major changes to the fuel-storage systems and power plant.

Finding sufficient space to store the new fuel on a ship in operation may be limited by the existing arrangement, potentially excluding the possibility for a meaningful conversion. For instance, the aft deck behind accommodation is a natural place to arrange an ammonia tank storage system for this ship type (Figure 6.1). If a complete re-arrangement of engine room casing and superstructure is required to fit the fuel tanks on board, the conversion cost would likely be too high to justify a change of fuel.

A proper evaluation at the newbuild stage of the implications of a future fuel change to ammonia make it possible to design the ship accordingly in the first place. A successful Fuel Ready design depends on the extent to which details of the desired future alternative fuel solution are incorporated into the newbuild specification. It is important to develop a clear understanding of the

optimal storage capacity in relation to ship type, trading pattern, and selected fuel strategy, as well as what type of storage system is the best fit with respect to integration on board and to operational needs.

In the following sections, we address three important issues for a shipowner's consideration in the process of detailing a Fuel Ready newbuild specification.

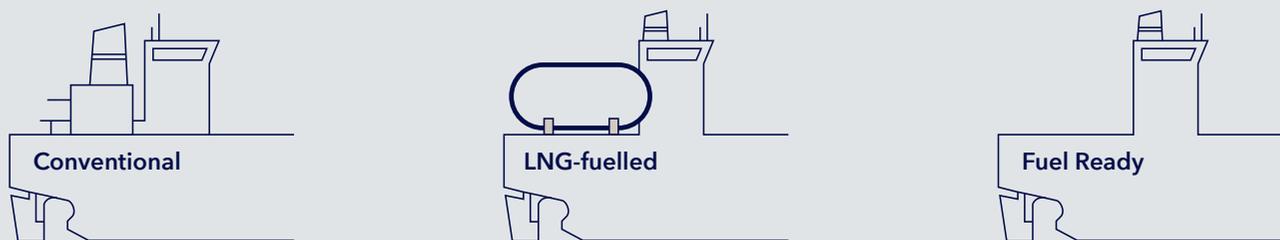
6.1.1 Fuel storage

Being able to determine the tank location and incorporate certain design features required for safe implementation of the fuel system at the planning stage may eliminate showstoppers and streamline a future conversion, hence reducing cost and time spent at a conversion yard.

From a design point of view, the main challenge with ammonia and other less carbon-intensive fuels is in most cases to find space to store a suitable amount of fuel without affecting the cargo capacity of the ship to an unacceptable degree. Keeping the fuel away from the cargo area while simultaneously balancing the limitations of safety requirements and the low volumetric energy density of the fuel will often result in compromises to an

FIGURE 6.1

Aft deck arrangement (in principle) for Conventional (left), LNG-fuelled (middle) and Fuel Ready (right) Newcastlemax bulk carrier



ideal layout. Safely managing fuel properties like high flammability and toxicity is also a challenge, both for design and in operation.

The result of this exercise will probably require the shipyard to deviate from its current standard design portfolio, with consequences for the newbuild cost. To maximize the storage space on aft deck, a redesign of the conventional superstructure and engine-room casing arrangement should be explored.

Irrespective of what type of fuel(s) the ship will prepare for, it is essential to establish how much fuel it is possible to fit on board, and to evaluate this against the operational needs and bunkering logistics.

Ammonia will contain less energy per volume unit than fuel oil (see Figure 6.2). From a volumetric energy density perspective, ammonia will require 2.9 times more space than MGO to store the same amount of energy. Corresponding ratios for other fuels are 2.3 for methanol, 4.3

for liquefied hydrogen (LH₂), 1.6 for LNG, and 1.4 for LPG. Additionally, the fuel-containment systems are less space-efficient than integral tanks for oil, and the usable tank volume for gases is smaller than for liquids due to filling-limit constraints and tank heel.

It is generally fair to assume that many ships will face a reduced operating range on ammonia compared with what is obtainable with the existing oil-tank capacity.

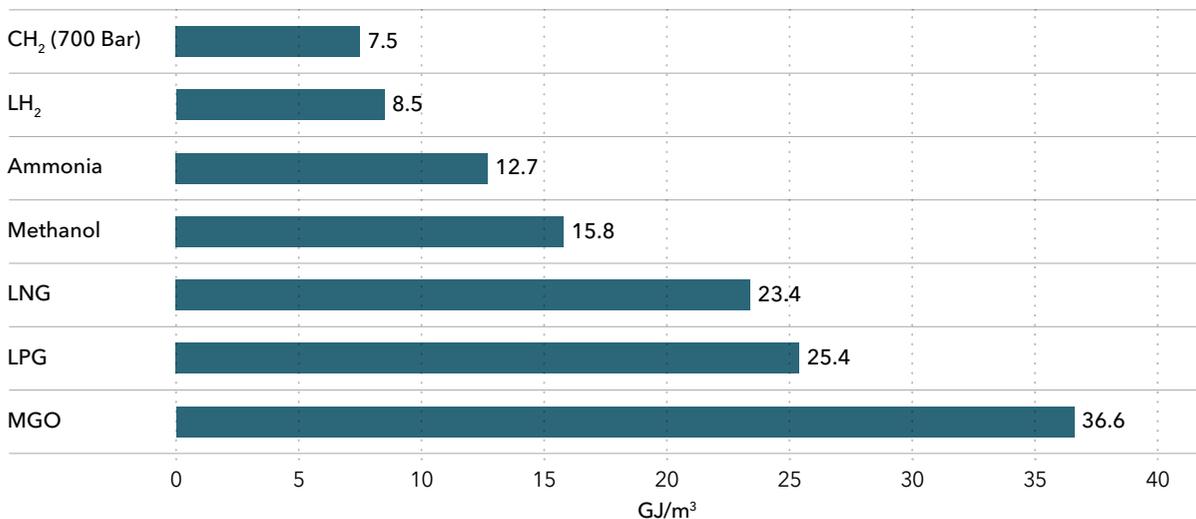
One way to approach this challenge is to evaluate the possibility for shorter bunkering intervals. In the current situation, with no ammonia fuel bunkering infrastructure, this is not an easy task. However, it is obvious that ships operating in a regular trade will have more future possibilities to optimize storage volumes / bunkering intervals to their operating pattern than ships that have a more irregular trade.

Modification of the engines to enable dual-fuel operation will typically be part of a future ammonia solution. It is

FIGURE 6.2

Volumetric energy density of alternative fuels

Units: Gigajoules per cubic metre (GJ/m³)



Key: Compressed hydrogen (CH₂); liquefied hydrogen (LH₂); liquefied natural gas (LNG); liquefied petroleum gas (LPG); marine gas oil (MGO)

therefore possible to increase the amount of pilot oil fuel to compensate for limited ammonia storage volumes, and thus extend the bunkering intervals to acceptable levels. If this approach does not lead to required carbon-intensity reductions, a blend-in of carbon-neutral pilot fuel could be an option.

Fuel storage requirements for gases like ammonia are different than for liquid fuels. Biodiesels, synthetic oils, and methanol are liquids with a low vapour pressure that can be stored in tanks forming part of the ship structure. Fuels like ammonia, LNG, LPG and hydrogen are classified as gases, and must be carried in tank containment systems that can either handle a certain pressure or keep the fuel at a temperature where the vapour pressure is close to atmospheric. These tank systems are in general more difficult to integrate without affecting the cargo capacity of the ship, and must comply with specific design criteria laid out in the IGF Code.

For gaseous fuels, the choice of tank type will also influence the boil-off gas management systems required. Tanks where pressure accumulation can be used to maintain an acceptable fuel-storage condition tend to be simpler to manage in operation than pressureless tanks. The latter depend on continuous consumption or re-liquefaction of tank vapours to prevent opening of safety valves and thereby release of tank vapours to the atmosphere.

6.1.2 Power plant

Changing to ammonia as fuel will require modification of the power plant. It should be considered to what extent the installed energy converters can be retrofitted or converted to operate on a different fuel, and whether it is beneficial to convert auxiliary engines in addition to the main engine. A potential de-rating of engine power on new fuels should also be investigated. Major engine manufacturers are working on internal combustion engine designs burning ammonia, and are claiming that conversion kits for some of their engines will be made available for relevant fuels.^{25,26} Engines operated on LNG, LPG, and methanol are commercially available.

²⁵ www.wartsila.com/insights/article/what-does-an-ammonia-ready-vessel-look-like

²⁶ www.man-es.com/discover/two-stroke-ammonia-engine

6.1.3 Integration of fuel system in the ship design

Specific design features affecting the General Arrangement will be required to account for the additional safety challenges posed by storage and consumption of ammonia. Consequently, it may be worthwhile to consider some of these at the design stage. It will also be useful to evaluate features like location of hazardous/toxic zones, fire insulation related to tank containment, and strengthening of deck and hull beam to support a future tank installation.

Further, it will be necessary to ensure that the ship is built to carry additional loads of a future tank installation. This normally implies strengthening the support structure below the tank(s) and, in some cases, reinforcement of the hull girder. Depending on tank location, segregation requirements linked to fire safety may introduce the need for cofferdams. It should also be ensured that trim and stability will be acceptable with future additional tank loads installed.

Fitting a fuel storage and supply system for alternative fuels on board will give rise to hazardous and/or toxic zones depending on which fuel the ship is prepared for. Location of these zones can significantly impact the General Arrangement and should be considered at the design stage. Vent masts and ventilation openings from hazardous spaces are important in this respect. Their location will affect the acceptance of other openings in the ship; exhaust outlets; escape ways and mustering stations; lifesaving equipment; ignition sources; and other items which may be difficult to re-locate during a conversion.

It might be worth considering at the newbuild stage that regulations require fire insulation for parts of the superstructure facing the fuel tank, and that escape routes and mustering stations shall also have fire insulation towards the tank area.

A summary of the most important actions required for a Fuel Ready design at newbuild and conversion is shown in Table 6.1.

TABLE 6.1

Fuel Ready - preparations at newbuilding stage and conversion for a mono-fuelled (conventional) ship

Conventional Newcastlemax bulk carrier - Fuel Ready (ammonia)	
Newbuild	Conversion
<p>Ensure feasibility in design by planning for</p> <ul style="list-style-type: none"> – Capacity, type, and future space for fuel-storage system – Potential location and arrangement of future tank connection spaces and fuel preparation room – Potential routing of fuel supply system including position of bunkering system – Potential location of tank vents and vent openings to evaluate toxic zones <p>Structural preparations - strengthening hull to support tank structure and account for increased loading of hull beam</p> <p>Choose energy converters suitable for conversion to ammonia</p> <p>Ensure trim and stability calculations are also acceptable with ammonia in tanks</p> <p>Consider structural fire protection - cofferdam segregation between tanks and high fire risk spaces, and fire insulation of superstructure facing tank area</p>	<p>Fit tank containment system</p> <p>Modify energy converters to ammonia</p> <p>Install new fuel-supply system, tank connection spaces, and fuel preparation room</p> <p>Install bunkering systems</p> <p>Arrange auxiliaries to the fuel installation (power, heating, cooling, purging, water spray systems for deck tanks, fire extinguishing systems)</p> <p>Install control and safety systems for fuel installation</p> <p>Provide water curtains at exits, emergency showers and eye washes, water spray bunkering stations, personal protective equipment (PPE)</p>

6.2 Preparing an LNG-fuelled (dual-fuel) ship for conversion to ammonia

The inherent fuel flexibility for our LNG-fuelled (dual-fuel) Newcastlemax is in principle greater than that of the oil-fuelled ship. In addition to biodiesel and synthetic oils, it will also have the possibility to use (bio-/e-) LNG as drop-in fuels. To extend this fuel flexibility to include ammonia, we must ensure compatibility with the LNG tank system. The tanks must (at the newbuilding stage) be prepared for fuel conversion, while preparatory arrangements for fuel systems and engines are limited by their use as dual-fuel LNG systems. An ammonia fuel system will require a different set-up than for LNG engines, and we expect that extensive revisions will be required at conversion.

A ship arrangement that has accounted for the safety implications of fitting an LNG fuel system will be well prepared for an ammonia conversion. However, additional concerns include increased extent of toxic zones, and increased weight of the storage system.

6.2.1 Fuel storage

Ammonia contains approximately half the energy by volume compared with LNG. When a Fuel Ready (ammonia) ship converts from LNG to ammonia using the existing tanks, the operating range will be reduced. Compensatory measures can include acceptance of shorter bunkering intervals, installing more fuel storage, or increased oil blend-in.

Prismatic tanks are the preferred choice for storing large LNG volumes, while pressure vessel designs are typically used for tank sizes up to 3,000–4,000 cubic metres (m³). Vacuum-insulated pressure vessels of relatively small size have superior insulation properties resulting in low boil-off rates and have been used for tank volumes up to 1,000 m³.

The Newcastlemax example ship has two pressure vessel type (single-walled Type C) LNG tanks installed on aft deck.

Ammonia is more than a third (~ 36%) heavier than LNG, so the increase in fuel density will require reinforcements of the fuel-storage tank and corresponding support structure. Potentially more challenging is the fact that the preferred LNG tank materials are incompatible with ammonia. Consequently, LNG tanks designed to also carry ammonia may need to apply alternative materials to accommodate both fuels. Ammonia can cause Stress Corrosion Cracking in materials commonly used for LNG fuel tanks. To minimize this risk, regulations have limitations on the use of carbon-manganese steels with enhanced mechanical properties and nickel (Ni) steel

alloys with more than 5% nickel. Considering the other cryogenic materials applicable for use in LNG containment systems, stainless steel is currently the only alternative for combined LNG and ammonia application.

Single-walled Type C tanks for LNG are normally made from 9% Ni alloy. The need for increasingly larger fuel-storage capacity makes the choice of materials with enhanced material properties more attractive as a means to save on steel weight and production cost. For large Type C tanks, the internal pressure is the dominant factor in determining the amount of steel needed, but the effect of the fuel density becomes more apparent with increasing tank size. For a Fuel Ready (ammonia) tank, the combined effect of changing to a material with lower material properties and a fuel of greater liquid density is expected to increase the weight of the tank significantly.

Using a 3,000 m³ LNG fuel tank made from 9% Ni-steel alloy as an example, our evaluation shown in Table 6.2 indicates that the potential additional steel weight resulting from preparing an LNG tank for ammonia would be significant.

TABLE 6.2

Steel weight estimate for a 3,000 m³ LNG tank to be converted to combined LNG/ammonia tank

Tank liquids	Material	Steel weight [tonnes]	Weight increase ratio
LNG (original tank)	9% Ni	156	1.00
LNG	304L	227	1.46
LNG	316LN	180	1.15
Fuel Ready (ammonia)	304L	237	1.52
Fuel Ready (ammonia)	316LN	185	1.19

Note: The weight estimate includes the steel weight of cylinder, end caps, seven vacuum rings, and two support rings. The additional weight of the support rings due to material change and weight increase are approximated. Weight associated with other internal structure including piping, insulation, and saddle support is not included. 9% Ni refers to 9% nickel-steel alloy; 304L and 316LN are grades of stainless steel.

In this example, the 6 bar design pressure is governing the dimensioning of the tank and the contribution from the fuel density is less apparent. Hence, the main portion of the additional steel weight is related to the change of steel material.

By reducing the design pressure to 3.6 bar for ammonia and using stainless steel with enhanced mechanical properties (e.g. 316LN or similar) for the tank material, scantlings similar to the original LNG tank can be used. This approach could also be applicable if the tank were to be used for methanol, which does not have material compatibility issues and is stored at close to atmospheric pressure.

The form factor of prismatic **Type B LNG fuel tanks** is typically considered preferable for larger ships with storage-space constraints and tanks arranged below deck. The first tanks of this type have recently been built using 9% Ni-steel, and prismatic Type B tanks specified with high-manganese austenitic steel are also planned.

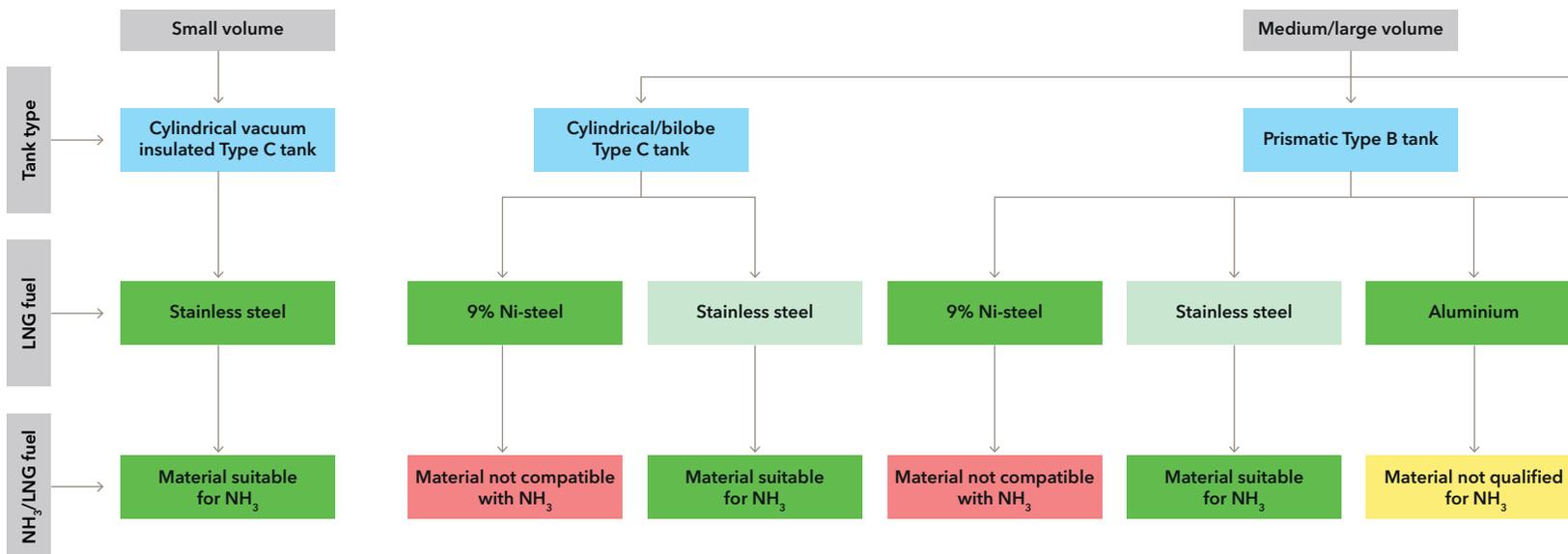
The liquid is stored at atmospheric pressure (no internal vapour pressure), implying that the tank scantlings will fully depend on the fuel density. Hence, a change to stainless steel and increased fuel density will significantly increase the tank weight for a Fuel Ready (ammonia) prismatic LNG tank.

A few **membrane tank systems for LNG fuel** application are available on the market. Depending on the materials used in membranes and insulation, such tanks could in principle be qualified for use with ammonia and methanol. Main issues to be solved would be related to the increased density of the fuel, the compatibility of the containment system with ammonia, and how to deal with the toxicity of ammonia vapours in a leakage scenario. Currently, no membrane systems are approved for ammonia use, but we assume that manufacturers of these systems are reviewing the possibility of such conversions.

Vacuum-insulated LNG fuel tanks are typically used for smaller storage capacities. Consequently, the tank shell

FIGURE 6.3

Compatibility of liquefied natural gas (LNG) fuel tanks if converted to ammonia (NH₃) fuel



Key: Ammonia (NH₃); liquefied natural gas (LNG); manganese (Mn); nickel (Ni)

has moderate shell thicknesses, and the use of steel with enhanced mechanical properties is not normally required. Most of these tanks are built in stainless steel which is compatible with ammonia. As the tank scantlings are mainly governed by the internal vapour pressure, an increase of the density of the fuel will only have marginal effect. The internal supporting ring frames, the connection between the inner tank and the outer jacket, and the saddle structure, are governed by the fuel weight and will have to be reinforced accordingly.

The above indicates that a vacuum-insulated LNG tank can be ammonia-ready with minor reinforcements, potentially only by reinforcement of the ring stiffeners and/or the inner tank supports.

An LNG-fuelled ship and its fuel-storage system are designed using the density of LNG as an input parameter. Preparation for a fuel change to ammonia will require factoring in the increased density of the new fuel in addition to the possible increased tank weight. This

weight increase will affect dimensioning of the tank and the support structure below the tank, and possibly the required longitudinal strength of the hull girder. Trim and stability calculations should also be verified for the greater weights.

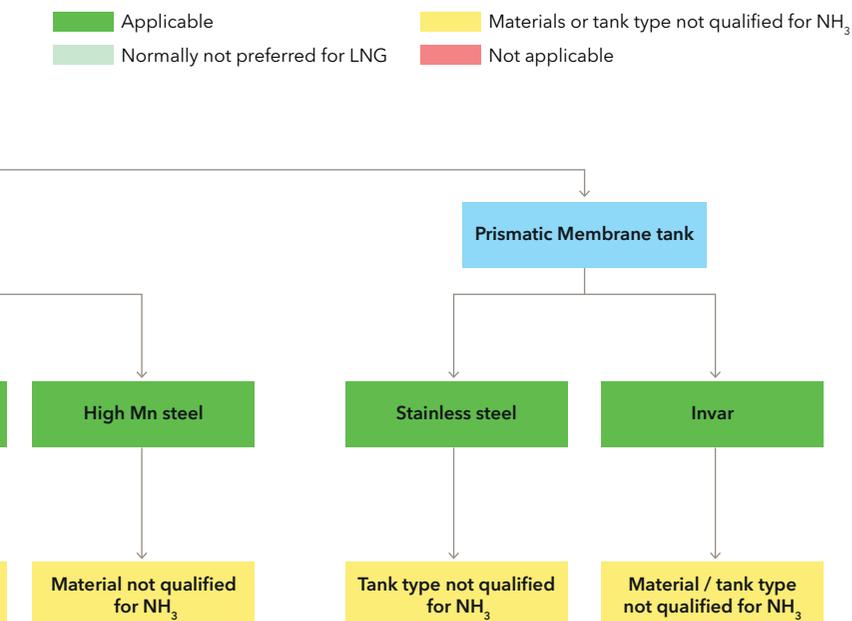
A summary of how the different LNG tank types compare with respect to ammonia conversion compatibility is shown in Figure 6.3.

6.2.2 Power plant

Changing to ammonia as fuel will require modification of the power plant. As mentioned in Section 6.1.2, major engine manufacturers are planning to develop ammonia conversion kits for some of their engines. It should be considered to what extent the installed energy converters can be retrofitted or converted to operate on a different fuel, and whether it is beneficial to convert auxiliary engines in addition to the main engine. A potential de-rating of engine power on new fuels should also be investigated.

Gas-fuelled ships are subject to redundancy requirements for propulsion which are not applicable to conventionally fuelled SOLAS ships. As a safety precaution, gas-fuelled ships are arranged with automatic shutdown systems that will cut off gas supply to the consumers to reduce the consequences of a leakage. For dual-fuel engines, redundancy is built in by having two separate fuel-supply systems on the engine where the oil system will take over seamlessly with no stop in propulsion power or power generation. However, the regulations do not specify a required storage capacity for the oil fuels. From an operational point of view, the available storage capacity of oil fuel (and how much oil fuel is carried at any time) should be carefully evaluated as this will affect the ship's ability to reach its intended destination. Having fuel-oil storage capacities for regular trade will also provide operational flexibility and future fuel flexibility in applying carbon-neutral oil fuels.

It should also be noted that the consumption of pilot fuel may increase with a conversion from LNG to ammonia.



6.2.3 Integration of fuel system in the ship design

Because LNG (methane) is more flammable than ammonia, the same arrangement layout as for the hazardous areas for an LNG fuel installation will also cover the explosion risk areas generated by an ammonia fuel plant. However, due to the toxicity of ammonia, safety distances from leakage points and discharges will be significantly greater than what is required for methane. Consequently, it should be ensured that vent masts, ventilation openings from fuel preparation rooms, open tank connection spaces, and other leak sources are arranged to comply with requirements for both fuel types.

It should also be noted that ammonia tanks with design pressure less than 18 bar will require a boil-off gas management system to prevent discharges of ammonia to the atmosphere.

A summary of the most important actions required for a Fuel Ready design at newbuild and conversion is shown in Table 6.3.

TABLE 6.3

Fuel Ready - preparations at newbuilding stage and conversion for a dual-fuelled (LNG) ship

LNG-fuelled Newcastlemax bulk carrier - Fuel Ready (ammonia)	
Newbuild	Conversion
Install LNG tanks suitable for ammonia:	Modify energy converters - LNG to ammonia
<ul style="list-style-type: none"> – Material selection – Strength and fatigue calculations based on greater weight of tank and fuel 	Modify fuel-supply system
Install energy converters suitable for conversion to ammonia	Modify bunkering station and associated safety systems
Consider designing bunkering system for partial reuse with ammonia	Fit boil-off gas system for ammonia
Investigate possibility for partial re-use of fuel- supply system with ammonia	Modify auxiliaries to the fuel system (heating, cooling, purging)
Base structural preparations on greater ammonia density - hull strength and tank support	Modify control and safety systems for fuel installation
Ensure that trim and stability calculations are acceptable with ammonia in tanks	Provide water curtains at exits, emergency showers and eye washes, water spray bunkering stations, PPE equipment
Ensure that toxic zones for ammonia are accounted for:	
<ul style="list-style-type: none"> – Distance between vent mast, tank connections, ventilation openings in relation to other openings in ship – For example, mustering stations, escape ways, lifeboat, not in conflict with toxic zones 	

6.3 Summary and discussion

The structured review of the design described in this chapter maps out vital implications for the ship's design from choosing a fuel-flexible strategy. The review completes the two-step approach to managing carbon risk for a shipowner, providing input to the newbuild specification.

The presented output from the Newcastlemax case study in Chapter 5 is used to illustrate parts of our proposed approach. The output is not valid as a recommendation to an owner, but it shows how such a robust recommendation could be reached by extending the analysis to cover multiple fuel-price scenarios and design options. It also provides guidance on how to develop practical solutions complying with increasingly stricter decarbonization regulations and incentives (Chapter 6).

The case study also illustrates a design principle generally applicable to newbuilds today, which is to incorporate basic measures to accommodate fuel flexibility in the newbuild specification, so that the ship is prepared for several possible fuel transitions when there is a business case for this (Figure 6.4).

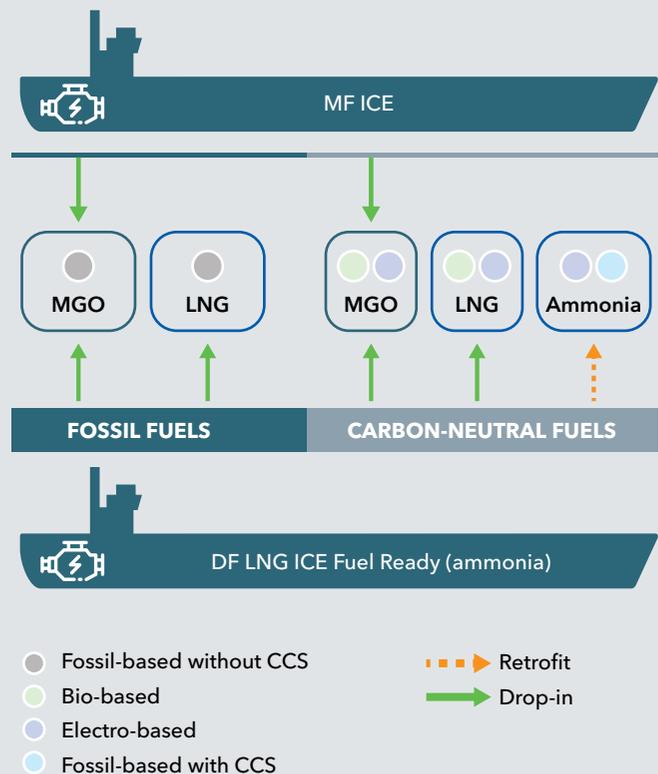
Importantly, the business case will be influenced not only by the fuel price, but also the fuel availability and bunkering infrastructure, an aspect not directly covered in our case study. However, the future availability of any of the new carbon-neutral fuels is uncertain, and a critical assessment of this availability should be integrated into the fuel strategy decision. In this regard, the ability to utilize more than one fuel increases a vessel's resilience and reduces the risk of it becoming a stranded asset.

Assume, for illustrative purposes only, a 30% probability that one of the carbon-neutral fuel options being contemplated (e.g. ammonia, biodiesel, methanol) is not available when needed. If the ship can use two of these fuels, the risk of not obtaining the fuel needed to be compliant drops from 30% to 9%. If the vessel can use three fuels, this risk drops to 3%. Hence, Fuel Ready solutions may be regarded as an insurance premium against the risk of investing in stranded assets.

While our proposed approach to managing carbon risk addresses key issues the shipowner must consider, there are additional barriers to the uptake of alternative fuels, as discussed in previous editions of this report (DNV GL, 2019a, 2020). These barriers cannot be solved by the shipowner alone, but must be overcome by the efforts of multiple actors in an ecosystem of stakeholders. In the following chapter, we contribute insights into two such barriers; the access to capital needed for onboard technology investments, and the required scale of energy needed to produce the fuels.

FIGURE 6.4

Main retrofit and drop-in fuel options available for a Newcastlemax bulk carrier today and in the future if fitted with different engine and fuel systems



Key: Carbon capture and storage (CCS); dual-fuel (DF); internal combustion engine (ICE); liquefied natural gas (LNG); marine gas oil (MG); mono-fuel (MF)

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Highlights

We estimate shipping's future fuel technology investment and energy supply needs, and conclude that:

- The sector may need to tap into the wider green finance sector to avoid capital constraints on decarbonization.
- Transition to greener ship fuels may be slowed by insufficient renewable power capacity to produce them.
- Availability of greener fuels could hit the barrier of inadequate carbon capture and storage capacity.
- Greater effort is needed to tackle these barriers to a timely transition.

7

OUTLOOK ON FLEET TECHNOLOGY INVESTMENTS AND ENERGY SUPPLY

- 7.1 Onboard technology investments
- 7.2 Scale of energy supply

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7 OUTLOOK ON FLEET TECHNOLOGY INVESTMENTS AND ENERGY SUPPLY

In this chapter we shift focus to present an outlook on selected aspects of what the fuel transition means in a global fleet perspective for various scenarios. We shed light on two barriers to the uptake of new fuels and technologies: the capital needed for onboard technology investments, and the scale of energy infrastructure required to produce some key alternative fuels.

To gauge the technology investment and energy supply that will be required in the future, we select 12 decarbonization scenarios, chosen from among the 30 scenarios developed in last year's Maritime Forecast to 2050 (DNV GL, 2020a). In these scenarios, we used DNV's GHG Pathway Model to estimate the uptake of 17 different fuel types and 10 fuel-technology systems, in addition to energy-efficiency technologies and speed reduction. Each scenario was constructed by varying the assumptions in three different main dimensions, with high uncertainty and high impact on the results. These dimensions were: regulatory ambition, fuel prices, and seaborne trade growth. In the following we briefly recap on the applied assumptions for each of the three dimensions, for the 12 selected scenarios.

First, each scenario belongs to one of two distinct **decarbonization pathways**, reflecting the regulatory ambition level:

- *IMO ambitions (IMO)*: A pathway where shipping achieves ambitions set in the Initial IMO GHG strategy – aiming for 50% reduction by 2050.
- *Decarbonization by 2040 (DC40)*: This is a highly ambitious pathway where shipping decarbonizes by 2040.

Second, each scenario applies one of three different **fuel-price levels** constructed by changing the underlying primary-energy price assumptions for fossil fuels,

renewable electricity, and bioenergy as illustrated in Table 7.1. This addresses the sensitivity between different 'fuel families', e.g. biofuels and electrofuels. It should be noted that in all scenarios, the prices for electrofuels and biofuels are higher than the fossil-fuel prices.²⁷ Note further that the price of 'blue' fuels made from reforming natural gas and using CCS depends on the fossil-fuel price.

Third, for each of the six combinations of decarbonization pathway and fuel-price levels, we explore two different trajectories for seaborne trade demand: 25% and 180% total growth between 2020 and 2050, representing our 'Low growth' and 'High growth' trajectories.

In summary, the two regulatory ambition pathways, the three fuel-price levels, and the two trajectories for seaborne trade growth result in a total of 12 scenarios. Modelling results from each of these scenarios are presented in the following.

We note that in all the 12 selected scenarios, a simulated introduction of technical and operational requirements to the fleet was used to drive uptake of measures at a rate compatible with the regulatory ambition level. Among the 18 scenarios excluded from last year's forecast, 12 scenarios used a simulated CO₂ price to drive the uptake of measures. The remaining 6 excluded scenarios reflected a regulatory ambition level where no further regulations are imposed on shipping.

²⁷ For instance, the Low e-ammonia price in 2050 is more than the double the High LNG price.

TABLE 7.1
Fuel-price levels

Price levels	Renewable electricity price	Fossil-fuel price	Bioenergy price
Low renewable	Low	High	High
Low fossil	High	Low	High
Low bioenergy	High	High	Low

7.1 Onboard technology investments

Figures 7.1 and 7.2 show the modelled investment costs (CAPEX) for onboard technology - including engine/ converter and tank systems, and energy-efficiency technologies - for the 12 selected scenarios from 2020 to 2050. Annual and accumulated CAPEX figures are both presented. Figure 7.1 shows results for the six scenarios where *IMO ambitions* are applied. Figure 7.2 shows the results for the remaining six scenarios in which the regulatory pathway is *DC40*. In each figure, separate panels are presented for the sub-group of three scenarios in which a *High growth* trajectory for seaborne trade has been applied (right panel), and for the sub-group of three scenarios in which a *Low growth* trajectory has been applied (left panel).

The accumulated CAPEX for the period up to 2050 for the 12 selected scenarios varies by a factor of almost four. However, the CAPEX range does not differ much between the two regulatory pathways: from Figure 7.1 we see a range of USD 250–800 billion (bn)²⁸ in scenarios based on the *IMO ambitions* pathway. A quite similar range is seen in scenarios using the *DC40* pathway in Figure 7.2. Despite a much faster deployment of zero-carbon fuels in the whole fleet, the scenarios for *DC40* do not have higher accumulated onboard investment costs, though the investment level is higher in the first decade than in scenarios for the *IMO ambitions*. This is because the rapid decarbonization in the *DC40* pathway is realized by more carbon-neutral drop-in fuels rather than onboard investments in alternative fuel technology.

²⁸ USD billion, equal to USD 1,000 million.

An evident difference is seen between the scenarios based on *High growth* and *Low growth* trajectories, with ranges around USD 250–800bn and USD 200–450bn, respectively. *High growth* involves a greater number of ships in the fleet, and consequently larger investments to be made. The annual CAPEX remains fairly high through to 2050, as opposed to *Low growth*, where investments drop more in the 2040s.

Importantly, the figures show that the CAPEX varies significantly depending on the fuel-price levels; i.e. the fuel-price assumptions significantly impact on the choices the shipowners make regarding onboard investments. Everything else being equal, the CAPEX in scenarios with *Low fossil* price levels is two to three times higher than with *Low bioenergy* prices. The reason is that biofuels are applied on conventional fuel technologies with relatively low CAPEX in the *Low bioenergy* cases, as opposed to the use of blue ammonia in the *Low fossil* cases, which require additional investment in onboard technology. The scenarios assuming a *Low renewable* price fall somewhere between, with e-MGO and e-LNG (conventional technologies with relatively low CAPEX) in addition to e-ammonia.

Peak investment in any single year ranges between USD 20bn and USD 35bn for scenarios with *Low bioenergy* and *Low renewable* price levels - but for *Low fossil*, the annual investment peak reaches as high as USD 60bn.

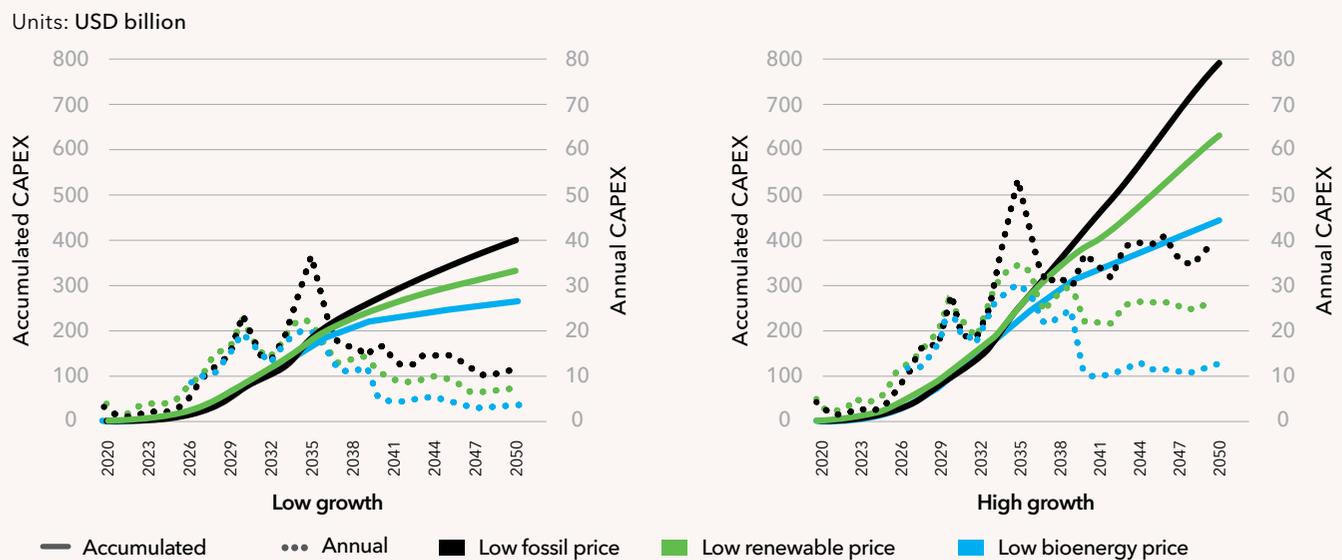
To place the CAPEX figures in context, green bond issuance in 2019 included USD 52bn in the US and USD 32bn in China. Green bonds are fixed-income instruments specifically designed to raise money for climate and environmental projects. Another benchmark is the global investment in solar energy technologies, which rose from about USD 11bn in 2004 to almost USD 150bn a decade later. So, although the annual onboard CAPEX volumes we see in our results are lower than the current volume of green bond issuance globally (or the volume of investments in solar energy), they are still of the same order of magnitude.

In a narrower, shipping-specific context, the sums are relatively larger. For instance, the leading 40 banks that finance the industry had a combined portfolio of USD 294bn at the end of 2019. The 27 leading banks who have come together to commit to the Poseidon Principles jointly represent approximately USD 185bn in shipping finance. Adding an additional USD 30bn in CAPEX would increase the total portfolio of the 40 largest banks by 10% in only one year. In a 10-year perspective, it would double the current portfolio of these banks.

FIGURE 7.1

Modelled capital expenditure (CAPEX) results for the six scenarios where the IMO ambitions are applied

The CAPEX is the sum of investment costs for onboard fuel and energy technology, including engine/converter and tank systems, as well as energy-efficiency technologies. Annual and accumulated figures are presented as dotted and full lines, respectively. The left panel shows three scenarios assuming Low growth in seaborne trade; the right panel shows three scenarios in which High growth is assumed. The fuel-price assumption for each scenario is also indicated.



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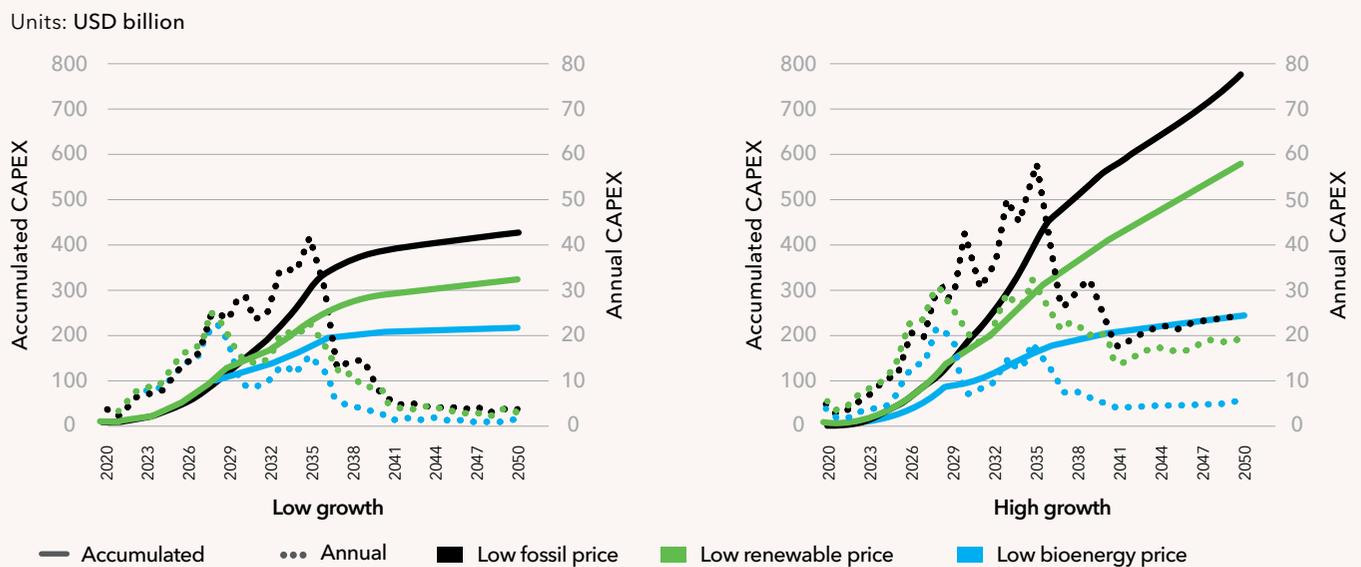
This indicates that access to capital may constrain the green transition in shipping, and the industry may need to look beyond the traditional means of ship financing and tap into the wider green finance sector to overcome this barrier. To do so effectively, effort is needed to streamline, standardize, and commoditize green finance instruments for shipping.

Clearly, onboard CAPEX is only part of the total cost picture. The major part of the accumulated cost of running a fleet using zero-carbon and/or low-carbon fuels is the fuel expenditure, which in our scenarios makes up 85–95% of the total additional cost compared with a business-as-usual scenario. However, access to sufficient capital for shipowners is a barrier in itself, and is the focus of this section.

FIGURE 7.2

Modelled capital expenditure (CAPEX) results for the six scenarios where the regulatory ambition level is Decarbonization by 2040

The CAPEX is the sum of investment costs for onboard fuel and energy technology, including engine/converter and tank systems, as well as energy-efficiency technologies. Annual and accumulated figures are presented as dotted and full lines, respectively. The left panel shows three scenarios assuming Low growth in seaborne trade; the right panel shows three scenarios in which High growth is assumed. The fuel-price assumption for each scenario is also indicated.



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7.2 Scale of energy supply

In addition to additional onboard investment needs, the energy transition in shipping will require major investments in infrastructure for the production and supply of carbon-neutral fuels. Compared with the extraction and supply of fossil energy currently fuelling global shipping, this transition incorporates new industrial sectors. However, the three price levels imply quite different consequences in terms of energy infrastructure:

- *Low renewable* electricity price: Drives investments in renewable power capacity and carbon capture and utilization (CCU) to produce electrofuels.
- *Low fossil* energy price: Drives investments in carbon capture and storage (CCS) capacity to produce blue fuels.
- *Low bioenergy* price: Drives investments in biofuel production facilities.

Most of the carbon-neutral fuel used in the *Low renewable* electricity price scenarios is e-ammonia, and some e-LNG and e-MGO is also used. Purely for illustrative

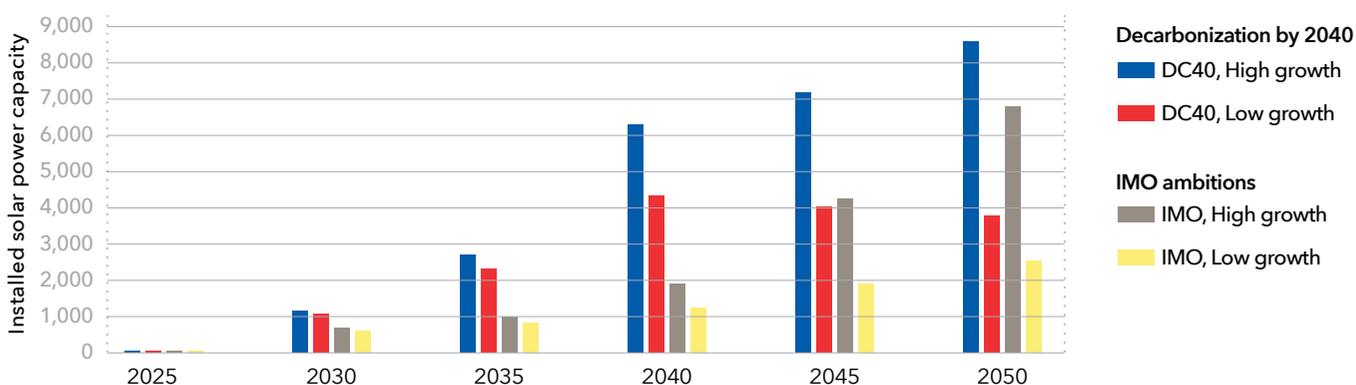
purposes, Figure 7.3 indicates the installed solar photovoltaic power generation capacity that would be required if the renewable electricity were to be produced exclusively from this source.²⁹ In reality, electrofuel production at this scale globally would also incorporate other renewable energy sources. It should also be noted that carbon-based electrofuels like e-MGO and e-LNG need input of carbon captured from a non-fossil source to be considered carbon-neutral. The *DC40/High growth* scenario leads to more than 8,000 GW of renewable energy production capacity being required in 2050, while the *IMO/Low growth* scenario would require about 2,000 GW. For comparison, installed solar power capacity globally was around 600 GW in 2019, and DNV’s latest Energy Transition Outlook (DNV, 2020b) forecasts 1,000 GW in 2022 and around 10,000 GW in 2050. This suggests that indirect renewable power demand generated by shipping is potentially very high, and that the transition to new fuels may be constrained by capacity issues.

²⁹ Here average efficiencies of 55%, 49%, 43% and 34% have been assumed for production of liquid hydrogen, liquid ammonia, e-LNG and e-MGO, respectively (Transport & Environment, 2018), and an average capacity factor for solar PV increasing from 14% to 23% in 2050 (DNV GL, 2020b).

FIGURE 7.3

Installed solar power capacity for electrofuel production in scenarios with low renewable electricity price

Units: Gigawatts (GW)



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In the scenarios with *Low fossil* price assumptions, the most prevalent carbon-neutral fuel is blue ammonia. In these scenarios, cost-competitive CCS needs to be in place. Figure 7.4 shows the estimated CCS capacity required for production of blue fuels through to mid-century. The volume varies greatly with assumptions for growth in seaborne trade demand (*High/Low*) and decarbonization pathways (*IMO/DC40*), but could be as much as 750 million tonnes per annum (Mtpa) in 2050. For comparison, DNV’s Energy Transition Outlook estimates global CCS capacity from SMR (steam methane reforming) will reach 885 Mtpa in 2050. The IEA (2021) Sustainable Development Scenario estimates that a global carbon capture capacity of around 6,000 Mtpa is required in 2050 to achieve sustainability goals including meeting the Paris Agreement climate change mitigation targets. Again, these figures indicate potentially very high demand for CCS capacity induced by shipping, and that the transition to new fuels may be constrained by capacity issues.

In the scenarios assuming a *Low bioenergy* price, biofuels constitute 7-18 exajoules (EJ) of the maritime fuel mix, depending on seaborne trade demand growth and the decarbonization pathway.³⁰ Despite their relatively low additional cost for investments on board and fuel expenditure, use of biofuels may be constrained due to limited availability. The long-term (2030–2060) global potential production of sustainable biofuels is estimated to be 80–150 EJ (DNV GL, 2019b). This is mirrored by IPCC (2018), indicating general agreement that the sustainable bioenergy potential by 2050 is around 100 EJ per year. Projections for actual production of biofuels range from 10–20 EJ in 2050, an increase from the current 4 EJ (DNV GL, 2019b).

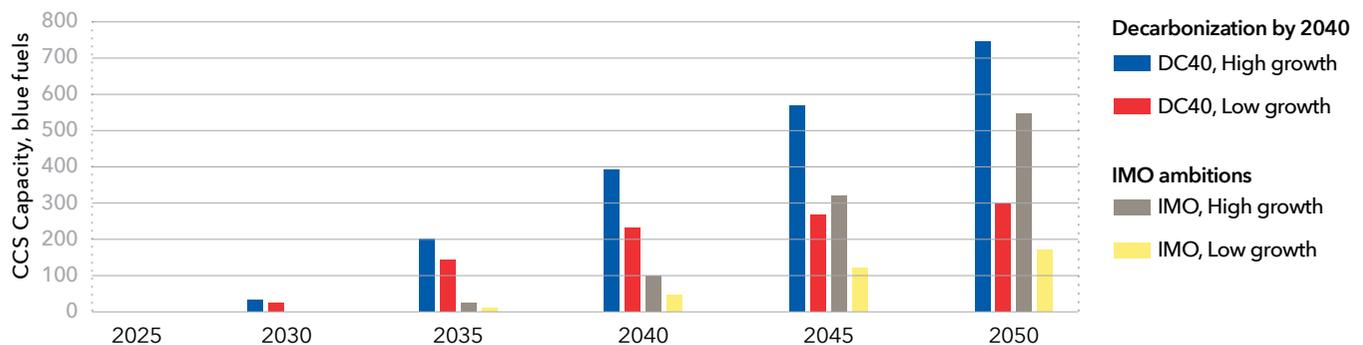
To summarize, this chapter illustrates how access to both capital and infrastructure for fuel production may constrain the coming energy transition in shipping. Increased efforts are needed to develop and implement the mechanisms required to tackle these barriers if the industry is to transition in a timely manner.

³⁰ 1 EJ is equivalent to just more than 23.88 Mtoe.

FIGURE 7.4

Required carbon capture and storage (CCS) capacity for production of blue fuels in scenarios with low fossil fuel price

Units: Million tonnes per annum (Mtpa)



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Historical data

This work is partly based on the World Energy Balances database developed by the International Energy Agency © OECD/IEA 2020, but the resulting work has been prepared by DNV and does not necessarily reflect the views of the International Energy Agency.

For energy-related charts, historical (up to and including 2019) numerical data is mainly based on IEA data from World Energy Balances © OECD/IEA 2021, www.iea.org/statistics, License: www.iea.org/t&c; as modified by DNV.

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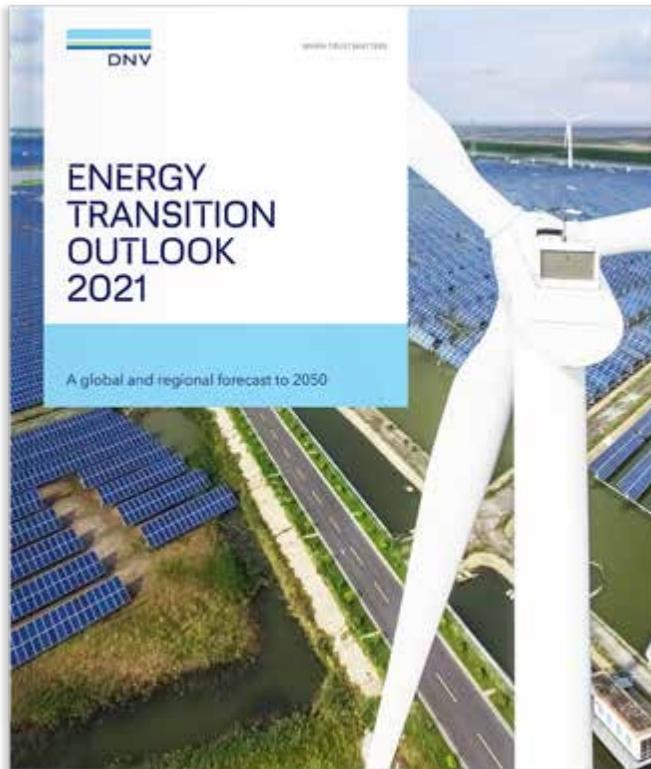
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ENERGY TRANSITION OUTLOOK 2021 REPORTS OVERVIEW

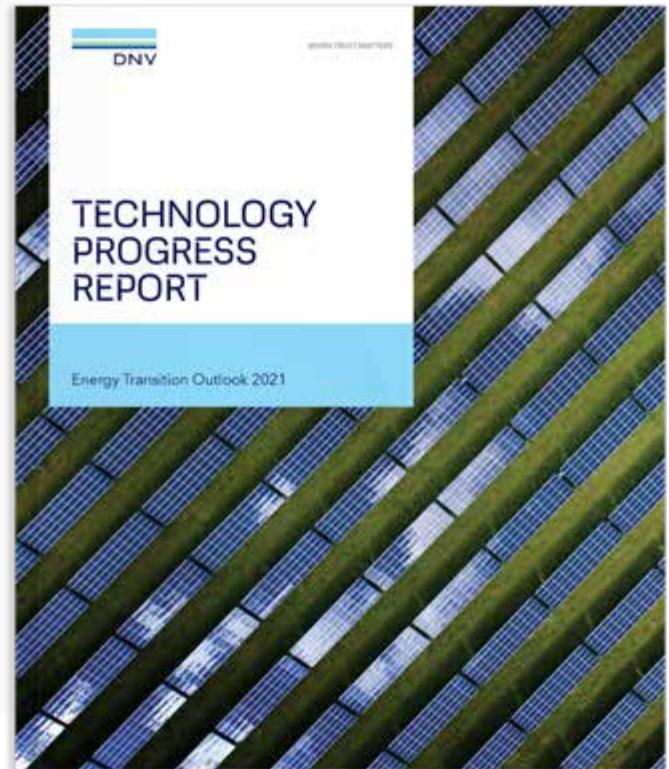


Energy transition outlook

Our main publication details our model-based forecast of the world's energy system through to 2050. It gives our independent view of on the most likely trajectory of the coming energy transition, and covers:

- **The global energy demand** for transport, buildings, and manufacturing
- **The changing energy supply mix**, energy efficiency, and expenditures
- **Detailed energy outlooks** for 10 world regions
- **The climate implications** of our forecast.

We also provide details on our model and main assumptions (i.e., population, GDP, technology costs and government policy). Our 2021 Outlook explores, inter alia, the impact of COVID-19 and the growing importance of hydrogen as an energy carrier.



Technology progress report

We explore how key energy transition technologies will develop, compete, and interact in the coming 5 years. The ten technologies are:

- **Energy production:** floating wind, solar PV, and waste to fuel and feedstock
- **Energy transport, storage, and distribution:** pipelines for low-carbon gas; meshed HVDC grids, new battery technology
- **Energy conversion and use:** novel shipping technologies, EVs and grid integration, green hydrogen production, CCS.

We attempt to strike a balance between technical details and issues of safety, efficiency, cost, and competitiveness. The interdependencies and linkages between the technologies are a particular area of focus.

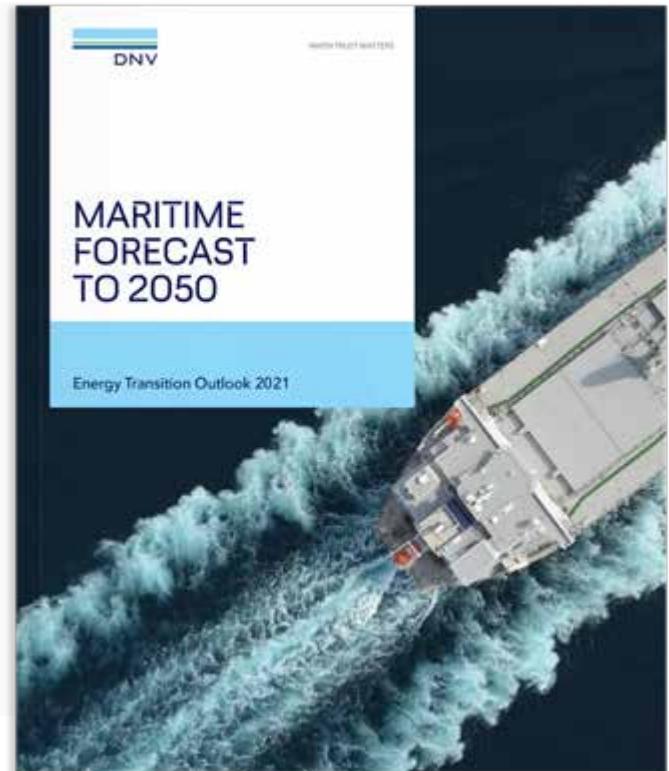


Financing the energy transition

Focuses on the financial opportunities and challenges for financiers, policymakers, developers, and energy companies:

- **An affordable transition** - considering whether a Paris-compliant transition is affordable, and what may be needed to mobilize and redirect capital
- **Accelerating the transition** - examining the role of financial markets, policy, and regulation, and how to get capital to flow to where it can have the most impact on emissions
- **Ensuring a just transition** - exploring the importance of balancing sustainable priorities, ensuring co-benefits, and building climate resilience.

The report combines DNV's independent energy forecast to 2050 with views from a diverse set of leaders in the energy and finance sectors.



Maritime forecast

The 2021 Maritime Forecast to 2050 offers shipowners practical advice and solutions as shipping's carbon reduction trajectories rapidly head towards zero.

- **DNV's new carbon risk framework** allows detailed assessments of fuel flexibility and Fuel Ready solutions, the economic robustness of fuel and energy efficiency strategies, and their impact on vessel design.
- **Decarbonization** is leading to increased regulatory requirements, new cargo-owner and consumer expectations, and more rigorous demands from investors and institutions.
- **Investments in energy and fuel production** will be essential to shipping's efforts to decarbonize.

This is the grand challenge for the maritime industry. But by working together as an industry, embracing fuel flexibility, and consulting with expert partners, shipping can reach its destination.

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