



WHEN TRUST MATTERS

MARITIME FORECAST TO 2050

Energy Transition Outlook 2022



FOREWORD

Let me start with the positive news: newbuild orders and recent industry projects prove that the maritime energy transition is accelerating. The necessary practical considerations are taking shape, and ship-owners have started to future-proof their assets. Applying our Carbon-Risk Framework, launched back in 2020, has also contributed to robust, cost-efficient ship designs.

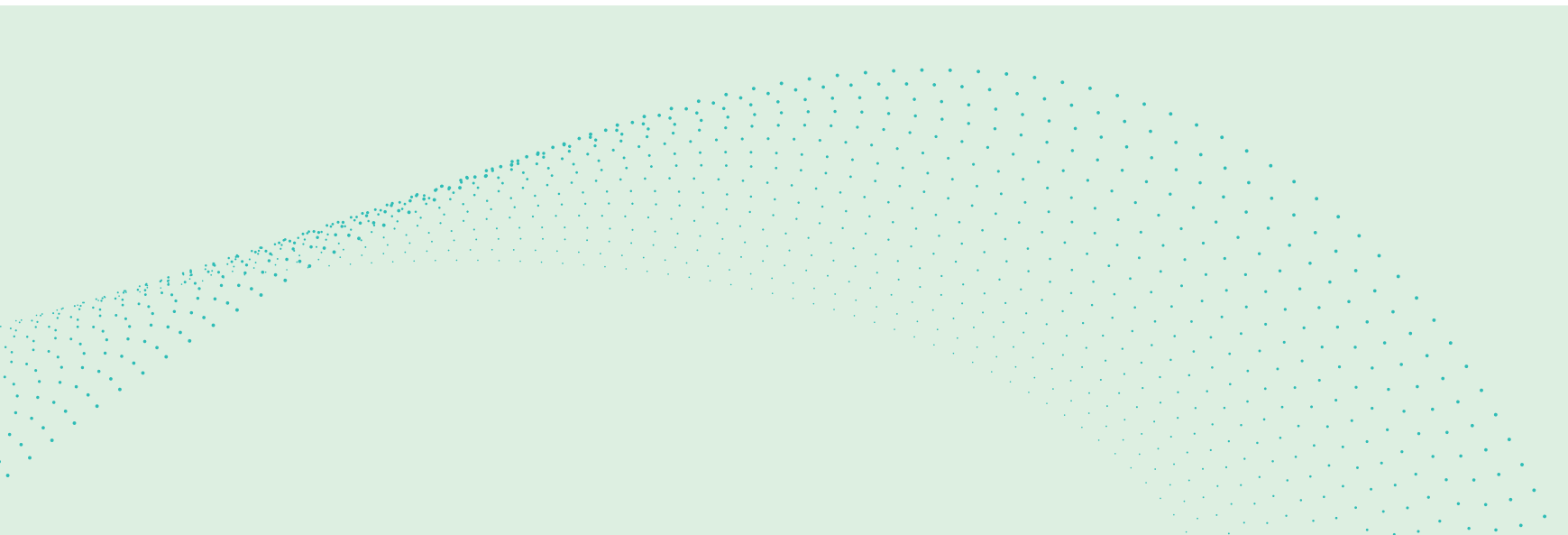
Encouragingly, newbuild vessels are increasingly being ordered ready to run on alternative fuels, with LNG dominant for now. Substantial investment is going into researching safe and economically feasible alternative carbon-neutral fuels and into developing fuel technologies. But this will count for little if the industry and its stakeholders do not collaborate to overcome the ultimate hurdle, fuel availability.

Our 6th Maritime Forecast to 2050 report zeroes in on this key issue and outlines under what conditions each new fuel type will proliferate. Which of them capture



sustainable shares in the 2050 fuel mix – be it biofuels, e-fuels, or fossil fuels with carbon capture and storage – relies on sound global industry decisions and collaboration. The maritime industry must continually seek consensus with other industries to ensure that sustainable energy resources are directed to where they can reduce greenhouse gas emissions most.

Already by 2030, 5% of the energy for shipping should come from carbon-neutral fuels, requiring huge investments in onboard technologies and onshore infrastructure. Navigating the options is complex, not least because there is no single ‘winner-takes-all’ alternative fuel and technology. Our updated model-



ling points to a diverse future energy mix of carbon-neutral and fossil fuels, with the latter gradually phased out by 2050.

We should use all available options to progress towards and reach net zero. Our findings reinforce the need for strong alliances to push the development of supply chains that can ensure fuel availability. The entire maritime value chain – charterers, energy majors, fuel suppliers, governments, financiers, ports, and shipowners – should collaborate to ensure adequate funding and apply it to the right projects. Green shipping corridors can serve as launch pads, also reducing the risk of port infrastructure becoming obsolete as the fuel mix shifts.

En route to decarbonization targets, employing the full power of digital tools for more energy-efficient vessels can deliver up to 15% of GHG emission savings required by 2050. Many such tools are available, and I am confident that even more promising ones will be launched in the coming decades.

If we push towards full decarbonization by 2050, the fuel infrastructure needs to deliver around 270 million tonnes of alternative fuels according to our modellings. A mammoth challenge. However, I am convinced that, together we can build a better, greener maritime future.

I hope that you enjoy reading the report and find value in its research findings for decision-making and strategizing.



Knut Ørbeck-Nilssen

CEO Maritime, DNV

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EXECUTIVE SUMMARY



EXECUTIVE SUMMARY

Maritime Forecast to 2050 is one out of DNV's suite of Energy Transition Outlook reports. This latest edition provides an independent outlook of the maritime energy future and examines how the energy transition will affect the industry. The focus is on fuel availability and infrastructure to tackle the shift to carbon-neutral¹ fuels. Our updated scenario analysis provides significant new insights compared with our 2020 analysis.

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 (GHG) footprint of maritime transport. This pressure is being exerted by three fundamental regulatory and commercial drivers: regulations and policies, access to investors and capital, and cargo owner and consumer expectations.

Our updated outlook for these drivers shows that:

- The Initial IMO Greenhouse Gas Strategy ('the IMO Strategy') currently drives policy development within international shipping, and the next wave of regulations will take effect from 1 January 2023. They are the CII, EEXI, and SEEMP Part III.² We expect them to have a significant impact on design and operations of all ships.
- The IMO Strategy will be revised in 2023, possibly strengthening its emission-reduction ambitions. This will be followed by developing the next wave of regulations including market-based measures setting a price on CO₂ and a requirement to account for well-to-wake GHG emission intensity of fuels.³
- The EU has proposed to include shipping in the EU Emissions Trading System (EU ETS) and the FuelEU

Maritime regulation which aims to increase the use of carbon-neutral fuels through an increasingly stringent well-to-wake GHG intensity requirement. These proposals may be finally adopted later in 2022 and take effect from 2024 and 2025, respectively.

- The regulatory and commercial drivers are enabled by supporting frameworks and standards specifying, for example, the setting of science-based, net-zero GHG emissions targets; taxonomies for sustainable activities; sustainability evaluation criteria and calculation methods for the well-to-wake GHG emissions of fuels; and supply-chain emission reporting requirements.

Figure 1 shows an overview of adopted and proposed regulations from the IMO and the EU.

Responding to the drivers for decarbonization, shipowners will need to apply new technologies and fuels to reduce emissions. This report provides an updated **outlook on ship technologies and fuels**, with an updated timeline for the technology readiness levels of selected alternative fuel technologies, including onboard carbon capture and storage (CCS).

We find that:

- The trend of larger ships being ordered with alternative fuel propulsion is continuing, with fossil LNG as the dominant fuel (see Figure 2). Around 5.5% of the total gross tonnage of ships operating today, and a third (33%) of the gross tonnage on order, can or will be able to operate on alternative fuels. This includes liquefied natural gas (LNG) carriers. The uptake of methanol and liquefied petroleum gas (LPG), and the first hydrogen-fuelled newbuilds, are starting to show in the statistics.

¹ Fuels that have no net GHG emissions; see Intergovernmental Panel on Climate Change (IPCC) definition of carbon-neutral at <https://www.ipcc.ch/sr15/chapter/glossary>

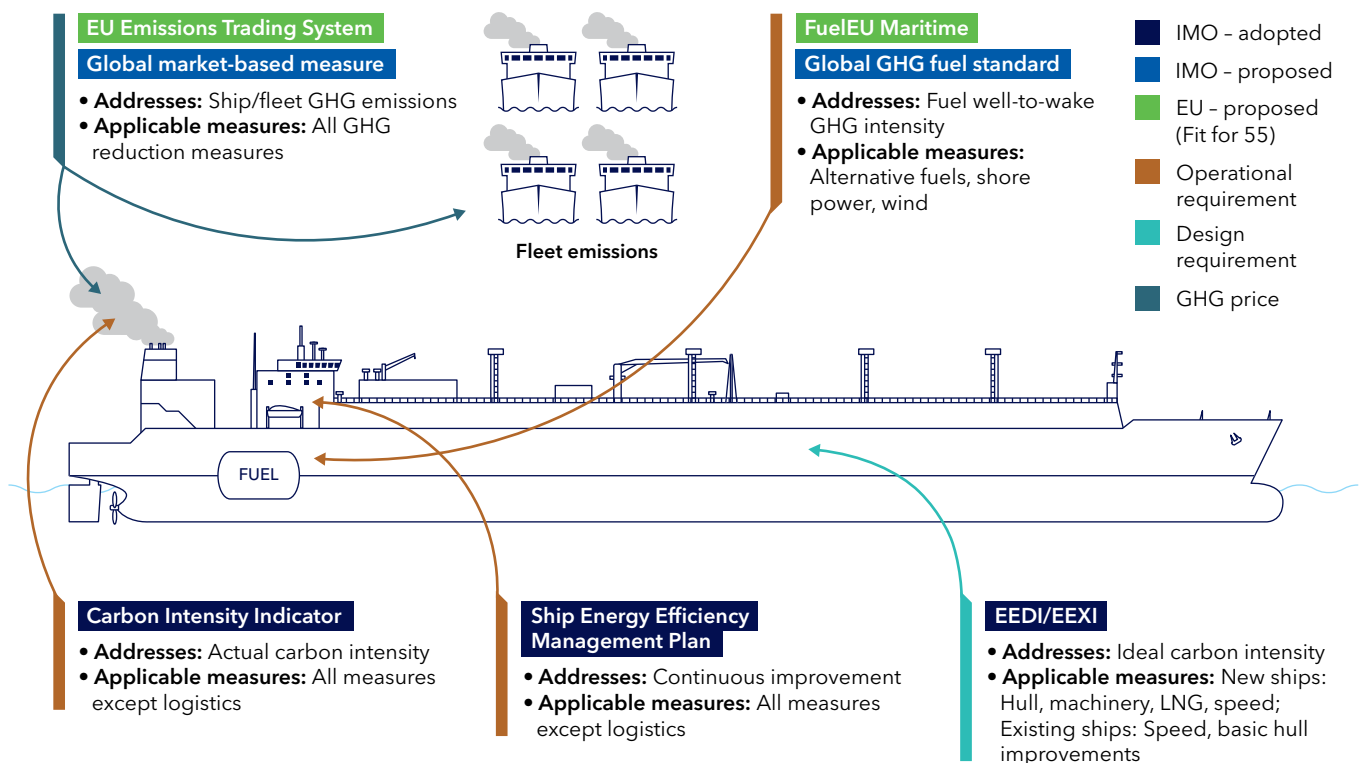
² Carbon Intensity Indicator (CII); Energy Efficiency eXisting ship Index (EEXI); Ship Energy Efficiency Management Plan (SEEMP)

³ Well-to-wake refers to the assessment of GHG emissions from primary production to carriage of the fuel in a ship's tank (well-to-tank, or 'upstream emissions') and from the ship's fuel tank to the exhaust (tank-to-propeller or tank-to-wake, or 'downstream emissions'). See <https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx>

- The strong interest in ammonia as fuel, as reflected in concepts and pilot studies, is currently restricted by immature converter technologies.
 - Ammonia and hydrogen onboard fuel technologies will be available in three to eight years, according to our estimates. For ammonia, we see development of 2-stroke and 4-stroke engine technologies on parallel paths, enabling uptake in deep-sea and regional short-sea shipping.
 - Short-sea shipping is expected to be instrumental for maturing hydrogen technology. Consequently, the development of fuel cells and 4-stroke engines is ahead of other hydrogen energy converters.
 - The current technology readiness levels of methanol fuel technologies are higher than for ammonia and hydrogen.
 - Using new fuels and fuel technologies will require all maritime industry stakeholders to focus increasingly on safety, including the development and implementation of safety regulations. The toxicity of methanol and ammonia, and extreme flammability of hydrogen, brings new safety challenges.
 - There is increased interest in using onboard CCS with conventional fossil fuels because of significant barriers to the uptake of carbon-neutral fuels. Onboard CCS may be applicable for some ship segments depending on regulatory and land-based infrastructure developments. More demonstration and pilot projects will be needed to enhance the technology readiness of onboard CCS. Several ongoing R&D projects address barriers to implementation.
- This report also provides an **outlook on alternative fuel production and infrastructure**. Decarbonizing shipping will result in a profound transition in the way future marine fuels are produced and made available to the shipping fleet.

Figure 1

IMO and EU regulatory framework for GHG emissions reduction from international shipping



We find that:

- Shipping's future fuel market will be more diverse, reliant on multiple energy sources, and more interconnected and integrated with regional energy markets, regional energy production, and regional industry.
- Future fuel supply for shipping will rely on availability and price of the energy sources: renewable electricity, sustainable biomass, or fossil energy with CCS (see Figure 3). Availability may constrain the coming energy transition in shipping.
- Because no industry can decarbonize in isolation, global industries need to make the right choices together, and sustainable energy should be directed to where it has the biggest impact on reducing

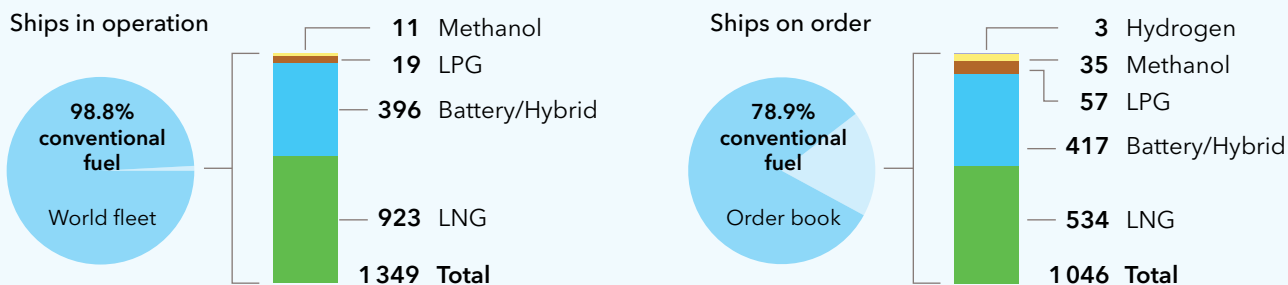
emissions. To maximize the GHG reduction potential of sustainable biomass - potentially an important source for carbon-neutral drop-in fuels for conventional machinery - this should be reserved for hard-to-abate sectors like shipping and aviation, rather than for electricity production.

- Provided that energy can be made available, production capacity will be a barrier and must be scaled up to meet shipping's coming demand for carbon-neutral fuels. This will require massive investment, though some existing production facilities can be reused. For the various fuel production and supply paths, the focus should be on reducing energy losses in production, distribution, and conversion on board. Developing the necessary infrastructure and production capacity will

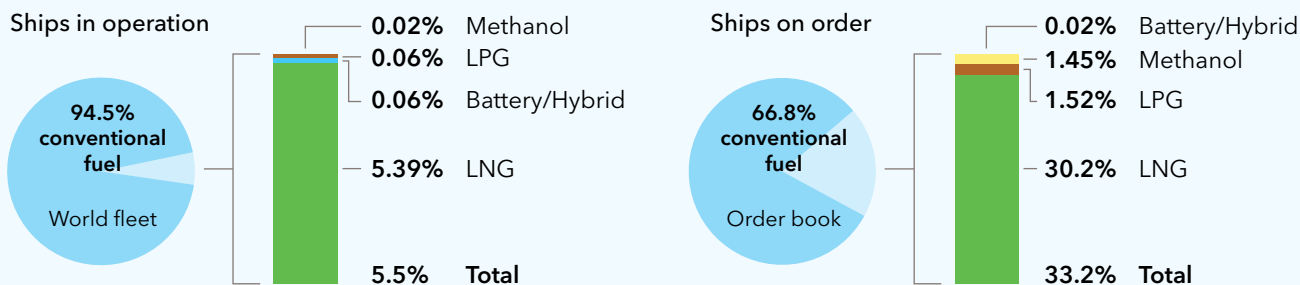
Figure 2

Alternative fuel uptake in the world fleet by number of ships and gross tonnage

NUMBER OF SHIPS



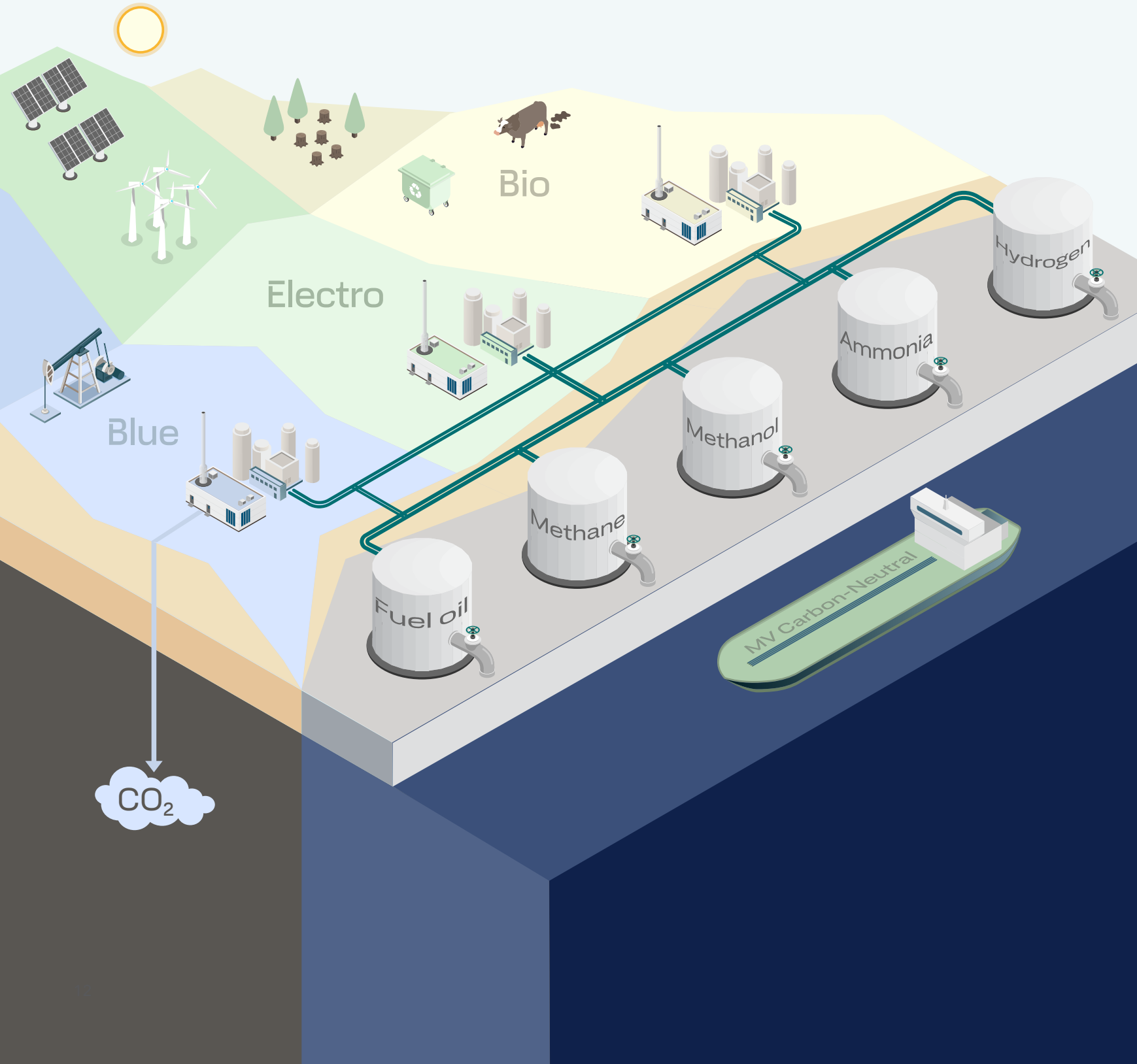
IN % OF GROSS TONNAGE



Key: Liquefied natural gas (LNG); liquefied petroleum gas (LPG)
 Sources: IHSMarkit (ihsmarkit.com) and DNV's Alternative Fuels Insights for the shipping industry - AFI platform (afi.dnv.com)

Figure 3

The future carbon-neutral energy supply chain



take time, be costly, and involve many stakeholders in the supply chain.

- Co-operation with major energy and fuel providers will be important to supply the future fuels. Ports will play key roles in the green maritime transition by serving as energy hubs providing both shore-side electricity and infrastructure for storing and fuelling ships with future fuels, as well as supporting the first movers and establishing green energy corridors.

This year we present an **updated portfolio of scenarios, built with an enhanced version of our GHG Pathway Model** to explore the fuel transition that shipping is facing. We investigate how the future fuel mix and uptake of carbon-neutral fuels are impacted by the availability of energy sources and other key inputs for fuel production, and by price assumptions on emerging fuels, technologies, and retrofits. We also assess fuel costs regionally, and how the build-up of regional fuel production and infrastructure impact the development of the fuel mix.

Significant uncertainties around several factors influence our projected energy transition from conventional to carbon-neutral fuels. Considering these uncertainties, which preclude developing a single ‘most likely’ projection, we have developed and provide a set of scenarios. Each describes a possible development of the future fleet composition, energy use and fuel mix, and emissions to 2050, under a particular set of framing conditions, and without prejudging the likelihood of these conditions.

We have developed 24 scenarios to explore:

- **two decarbonization pathways**, one in which shipping achieves the ambitions set in the current IMO GHG Strategy, including a 50% reduction of total GHG emissions in 2050; and a second, in which the ambition is to decarbonize the fleet by 2050.
- **variations on three fuel families**, in which we simulate the availability of sustainable biomass to produce biofuels, renewable electricity to produce e-fuels, and fossil fuels combined with CCS to produce blue fuels.

- **variations for specific fuel types**, in which key input factors impacting the relative cost differences between fuels within each family are examined.

Regarding the future fuel mix in the modelled scenarios (Figure 4), we find the following:

- Regulatory policies and primary energy prices are key drivers for uptake of carbon-neutral fuel and the future fuel mix. The uptake of carbon-neutral fuel needs to pick up in the mid-2030s, reaching 40% of the fuel mix in 2050 under the current IMO ambitions and 100% to decarbonize shipping fully. Fossil very low sulphur fuel oil (VLSFO)/marine gas oil (MGO) and LNG are in rapid decline by mid-century or are phased out completely in the most ambitious decarbonization scenarios. LNG, however, sees significant uptake to around 20% to 30% of the fuel mix prior to the acceleration of the transition to carbon-neutral fuels. Figure 4 presents the energy mix in 2050 for the 24 modelled scenarios.
- It is hard to identify clear winners among the many different carbon-neutral fuel options given the uncertainties on price and availability, but we can outline under what conditions each will proliferate. Bio-LNG, bio-MGO and bio-methanol, which are relatively energy-dense hydrocarbons, would be the preferred fuels, given sufficient availability of sustainable biomass. The uptake of bio-methanol is very sensitive to the production cost compared with bio-MGO and bio-LNG. With low availability of sustainable biomass, the prices of biofuels will likely be uncompetitive with those of electrofuels and blue fuels.
- The availability of electrofuels depends firstly on the availability of renewable electricity to produce hydrogen by electrolysis. This requires the phasing out of fossil energy from power generation, which is still a long way off in most regions. Using electricity even partly generated from fossil fuels to produce electrofuels is not energy efficient and could lead to higher net emissions. The second prerequisite for electrofuels is the availability of sustainable carbon from either biogenic sources or direct air capture. This carbon

could be combined with the hydrogen produced by electrolysis to produce e-MGO⁴, e-LNG, or e-methanol, again taking advantage of using more energy-dense fuels. Without this carbon being available and affordable, e-ammonia would be the preferred

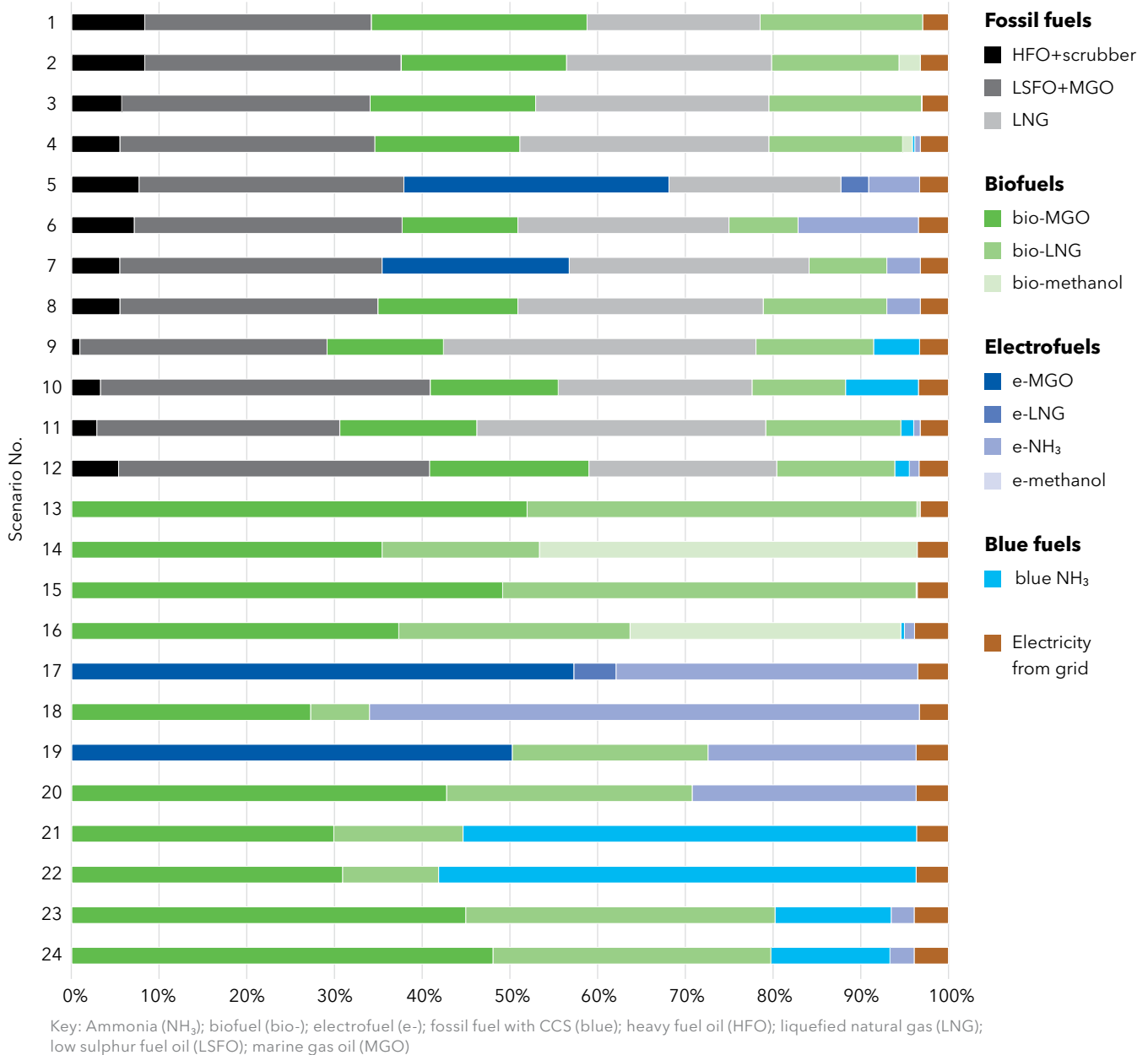
fuel, with bio-MGO or e-MGO being used as pilot fuels.

- The availability of blue fuels depends on the effectiveness of carbon capture, as well as infrastructure for permanent storage of the captured carbon. With high

4 The prefix 'e-' denotes an electrofuel, 'bio-' a biofuel, and 'blue' a fuel produced from fossil energy with CCS

Figure 4

Our 24 scenarios for the maritime energy mix in 2050



availability, blue ammonia is the preferred fuel, with bio-MGO or e-MGO as pilot fuels. Mature CCS technology and infrastructure could also make onboard CCS a viable alternative where fossil fuels continue to be used on the ship.

- The use of drop-in fuels – such as bio-LNG, e-LNG, bio-MGO and e-MGO – is significant in all scenarios and depends on the pace of decarbonization. With slower decarbonization with moderate operational requirements, fossil fuels combined with just the required amount of drop-in fuels are preferred to switching to ammonia or methanol fuel systems, even though these fuels are likely less expensive than the drop-in fuels.

Significant investment is needed in coming decades to enable the transition to carbon-neutral shipping. We find that:

- USD 8 billion (bn) to 28bn is needed annually in additional total investment on ships in a transition phase towards decarbonization in 2050. The largest investments come in scenarios with high uptake of ammonia or methanol.
- Fuel infrastructure investments will outpace onboard investments in almost all scenarios. Decarbonizing shipping completely by 2050 will require about 2.5 times more investment than if pursuing current IMO ambitions. About USD 28bn to 90bn per year is needed onshore to scale up production, fuel distribution, and bunkering infrastructure to supply 100% carbon-neutral fuels by 2050. The largest investments come in scenarios with high uptake of electrofuels.
- The more expensive energy sources and onshore investments could increase the annual fuel costs by more than USD 100bn to 150bn when fully decarbonized, a 70% to 100% increase from today.

Concluding remarks

The initial preparation for decarbonization is well underway with regulatory and commercial drivers and a supporting framework coming into place. Scrutiny is focused on full supply-chain emissions, including from ships and the production and supply of fuel. We see progress in onboard fuel technology development, and the fleet's uptake of alternative fuels is increasing. However, several fuel technologies that may be needed in 2050 are immature.

More effort is needed to bring down barriers and speed up the progress of next-generation carbon-neutral ships. This will require accelerated technology development, large-scale piloting for deep-sea vessels, and ensuring safe application of new fuels on board and onshore. Stronger emphasis is needed on system-level thinking and integration of all available technologies. This will require time, investment, and combining efforts from all stakeholders in the maritime supply chain. Green energy corridors, a concept taking shape now, could support this effort by pairing commitments on fuel supply and demand, and reducing first-mover risk. The idea is to help start shipping decarbonization by increasing the availability of alternative fuels in connected regions.

Shipowners and other stakeholders – such as governments, charterers, ports and fuel suppliers – can use our 24 scenarios to support decision-making to minimize carbon risk and explore effective policy interventions such as green corridors. Uncertainty over the price and availability of energy sources means that fuel flexibility and Fuel Ready solutions, combined with improved energy efficiency, remain key strategies that could ease the transition and minimize the risk of investing in stranded assets. Digitalization will enable the unlocking of further energy-efficiency potential and will support the necessary collaboration and information sharing needed to accelerate the transition.



1

INTRODUCTION



1 INTRODUCTION

This publication is part of DNV's 2022 suite of Energy Transition Outlook reports. This latest edition of Maritime Forecast to 2050 gives an independent outlook of the maritime energy future and examines how the transition will affect the industry. It provides valuable insights for decision makers ranging from shipowners, charterers, fuel suppliers, ports, finance and insurance, through to national and regional policymakers.



More specifically, the outlook focuses on fuel availability and infrastructure to tackle the shift to carbon-neutral⁵ fuels. We significantly update our 2020 scenario analysis of the maritime energy future (DNV, 2021c; DNV, 2020) as shipping experiences increasing pressure to decarbonize operations and reduce emissions to air. Regulatory requirements addressing greenhouse gas (GHG) emissions take shape in both the IMO and EU, and are enabled by supporting frameworks and standards. Examples of these enablers are: setting science-based net-zero GHG emissions targets; taxonomies for sustainable activities; sustainability evaluation criteria and well-to-wake GHG emission calculation methods for fuels; and supply chain reporting requirements. Most notably, in April 2018 the IMO adopted an ambitious GHG emissions-reduction strategy for international shipping. 2023 will see the implementation of further regulatory measures to address the decarbonization of shipping. In November 2021, the IMO Marine Environment Protection Committee's 77th session (MEPC 77) also recognized the need to strengthen the ambitions of its GHG strategy when it is revised in 2023. Increasingly, we also see key stakeholders such as banks and cargo owners focusing on decarbonization. All this points to a changing business environment for ships in the near future, shaping the future fleet in important ways, particularly in the choice of fuels and technologies.

In contrast to past environmental requirements, meeting GHG targets requires fundamentally more challenging technological and operational changes for shipping. In previous transitions, the industry moved from wind to coal and steam, and then to oil – and every ship made the same transition. For the transition now underway, there are many options for carbon-neutral fuels (bio, electro, or blue), such as ammonia, diesel, electricity, hydrogen, methane and methanol – all ships will probably not transition to the same fuel. The existence of many transition pathways is driving complexity. The challenges include a transition to new and alternative low or zero-carbon fuels and non-conventional technologies. This requires the simultaneous introduction of new technologies on ships and low or zero-carbon fuel production and infrastructure onshore, where significant

investments are needed during the next decades to enable the transition. While the industry has been discussing emissions reduction for many years, the most likely solutions still face challenges and barriers including – the focus of this year's study – fuel availability. DNV's alternative fuel uptake analysis indicates that the transition has started slowly, with 33% of gross tonnage in the order book able to operate on alternative fuel (heavily dominated by LNG).

In this year's report we have updated our scenario library of regulations, future technologies, and costs, to understand the coming transition so that stakeholders can make informed decisions. We have modelled two different decarbonization pathways: the current IMO ambitions to 2050, and a full decarbonization by 2050. We refer to these henceforth as *IMO ambitions* and *Decarbonization by 2050*. Our decarbonization modelling shows a diverse energy mix comprising both fossil and carbon-neutral fuels, where fossil fuels are gradually phased out by 2050.

This report starts by presenting updated outlooks on drivers and regulations (Chapter 2) then ship technologies and fuels (Chapter 3), with estimated maturation timelines for energy converters, onboard CCS technologies, and corresponding safety regulations for onboard use. We introduce an entirely new outlook on alternative fuel production and infrastructure, including availability and prices from the updated Marine Fuel Price Mapper (Chapter 4). These chapters provide input to our updated world fleet scenario modelling (Chapter 5), including modelling of the impact of measures to increase regional availability, such as green corridors.

⁵ Fuels that have no net GHG emissions; see Intergovernmental Panel on Climate Change (IPCC) definition of carbon-neutral at <https://www.ipcc.ch/sr15/chapter/glossary>

Highlights

Three key fundamentals are driving ship decarbonization: regulations, cargo owner expectations, and access to capital:

- We provide an updated outlook and timeline for regulatory developments impacting the maritime sector.
- We explore how evaluating well-to-wake GHG emissions and sustainability of fuels becomes important to avoid unintended emission increases from other sectors.
- We assess the need for investments on board and onshore to decarbonize shipping and explore why clear frameworks and standards are needed to accelerate and improve decision-making.



2

OUTLOOK ON DRIVERS AND REGULATIONS FOR DECARBONIZATION

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2 OUTLOOK ON DRIVERS AND REGULATIONS FOR DECARBONIZATION

2023 will see the implementation of further regulatory measures to address the decarbonization of shipping. The IMO GHG Strategy will be revised, strengthening the GHG emissions-reduction ambitions for international shipping. Standards for calculating and verifying lifecycle emissions of marine fuels are maturing. Expectations from cargo owners and financial institutions continue to be strong drivers for ship decarbonization with increased requirements on transparency and reporting of emissions throughout the supply chain.

In this chapter, we first summarize the latest developments on drivers and regulations for decarbonization since our last report in September 2021. This is followed by more details on the latest regulatory developments from the IMO and EU before we take a closer look at two themes related to drivers. One is taking a closer look at lifecycle perspective on GHG emissions. The other is the need for standards to support decision-making and the funnelling of capital for decarbonization projects.

2021 saw significant developments on the regulatory arena with the IMO's adoption of carbon intensity requirements –the **CII**, **EEXI**, and **SEEMP**⁶ – and the EU announcing its **Fit for 55** package⁷ including several proposals impacting ships directly. On the margins of COP26⁸, several high-level declarations underscored the continued push from a wide range of stakeholders to work towards shipping's decarbonization in 2050, including the establishment of green corridors to focus on actions and resources. As mentioned earlier, MEPC 77 also recognized the need to strengthen the ambitions of the IMO's GHG strategy when it is revised in 2023.

Following up on these decisions, 2022 is a working year in the IMO and EU with multiple ongoing regulatory processes developing frameworks and standards that will shape shipping in the next decades. Late in 2022 or early 2023 we expect the final agreed proposals from the EU to be adopted. In June 2023, the IMO will hold a key meeting – MEPC 80 – that will adopt a revised GHG strategy and shortlist regulatory measures that will set requirements on individual ships to ensure that the ambitions are met. These could include both technical requirements and market-based measures. 2022 may also see the first version of IMO guidelines for calculating lifecycle GHG emissions for marine fuels. The green corridors concept will be transformed into actual actions through concrete projects such as the Nordic Roadmap for the introduction of sustainable zero-carbon fuels in shipping⁹, and the C40 Green Ports Forum¹⁰.

Pressure and expectations from cargo owners, financial institutions, and other stakeholders continues to increase, and is enabled by the establishment of a wide range of frameworks, standards, and requirements. The Poseidon

⁶ Carbon Intensity Indicator (CII); Energy Efficiency Existing Ship Index (EEXI); Ship Energy Efficiency Management Plan (SEEMP)

⁷ Fit for 55 refers to the EU's target of reducing net GHG emissions by at least 55% by 2030

⁸ COP 26: the 26th UN Climate Change Conference of the Parties in Glasgow, Scotland, 31 October – 13 November 2021

⁹ <https://www.dnv.com/news/dnv-to-lead-nordic-roadmap-partnership-for-zero-carbon-ship-fuels-223169>

¹⁰ <https://www.c40.org/news/la-shanghai-green-shipping-corridor>

Principles for Marine insurance¹¹ were established in December 2021. The Science Based Targets initiative (SBTi) launched its Net-Zero Standard¹² in October 2021. SBTi enables companies to set net-zero targets in line with climate science and covers the complete value chain. The US has proposed rules that mandate companies listed there to disclose direct and indirect GHG emissions and related climate risks, including material. These requirements - combined with expectations on environmental, social and corporate governance (ESG) reporting and disclosure of emissions in practice - mean shipping companies will need to provide more detailed reporting on emissions and ensure that future decarbonization requirements are met.

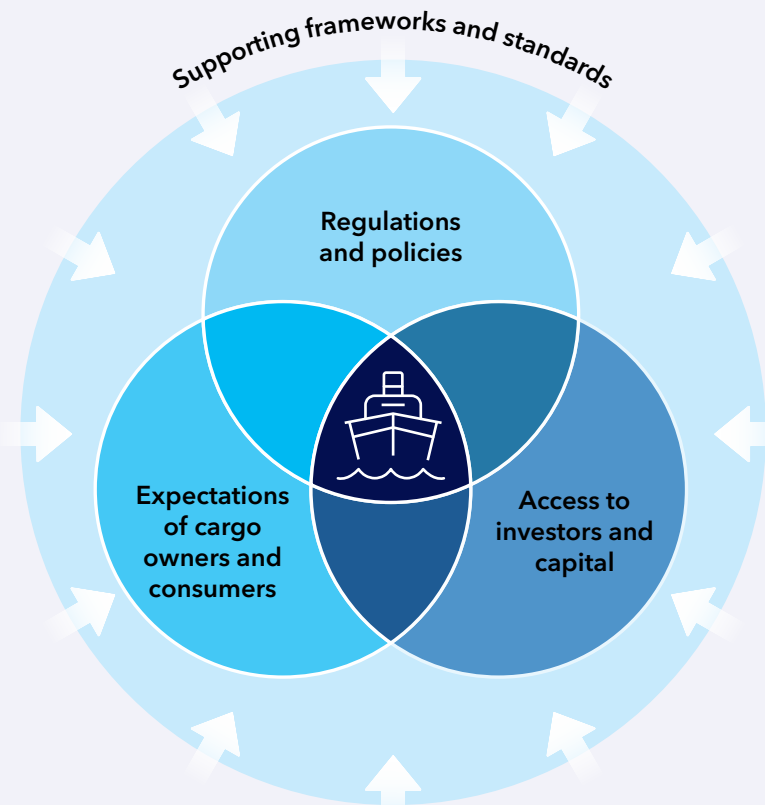
Investors looking to build robust portfolios of green assets are closely scrutinizing any investment opportunity to avoid future stranded assets, which may fail to reach decarbonization requirements because of making the wrong fuel and technology choice. The mounting pressure means shipowners need to see GHG emissions both from their own activities and from fuel production as a business-critical issue that needs their attention today, not in 2040 or 2050. Fuel flexibility remains a key strategic element in ship newbuilding to ensure that those built today can apply carbon-neutral technologies and fuels when they become available in the future.

¹¹ <https://www.poseidonprinciples.org/insurance>

¹² <https://sciencebasedtargets.org/net-zero>

Figure 2.1

Three key fundamentals are driving ship decarbonization, supported by frameworks and standards specifying sustainability evaluation criteria and targets, GHG emission calculation methods, and reporting requirements



2.1 Regulatory developments

As noted earlier in this chapter, the regulatory framework addressing GHG emissions from international shipping is taking shape (see Figure 2.2). To recap, the IMO's extensive new carbon dioxide (CO₂) regulations applicable to existing ships include the EEXI addressing the technical efficiency of ships; the CII rating scheme addressing ships' operational efficiency, and the enhanced SEEMP Part III 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. At MEPC 78 in June 2022 the final guidelines supporting these regulations were adopted, including correction factors for the CII calculations and guidelines for development of the SEEMP Part III.

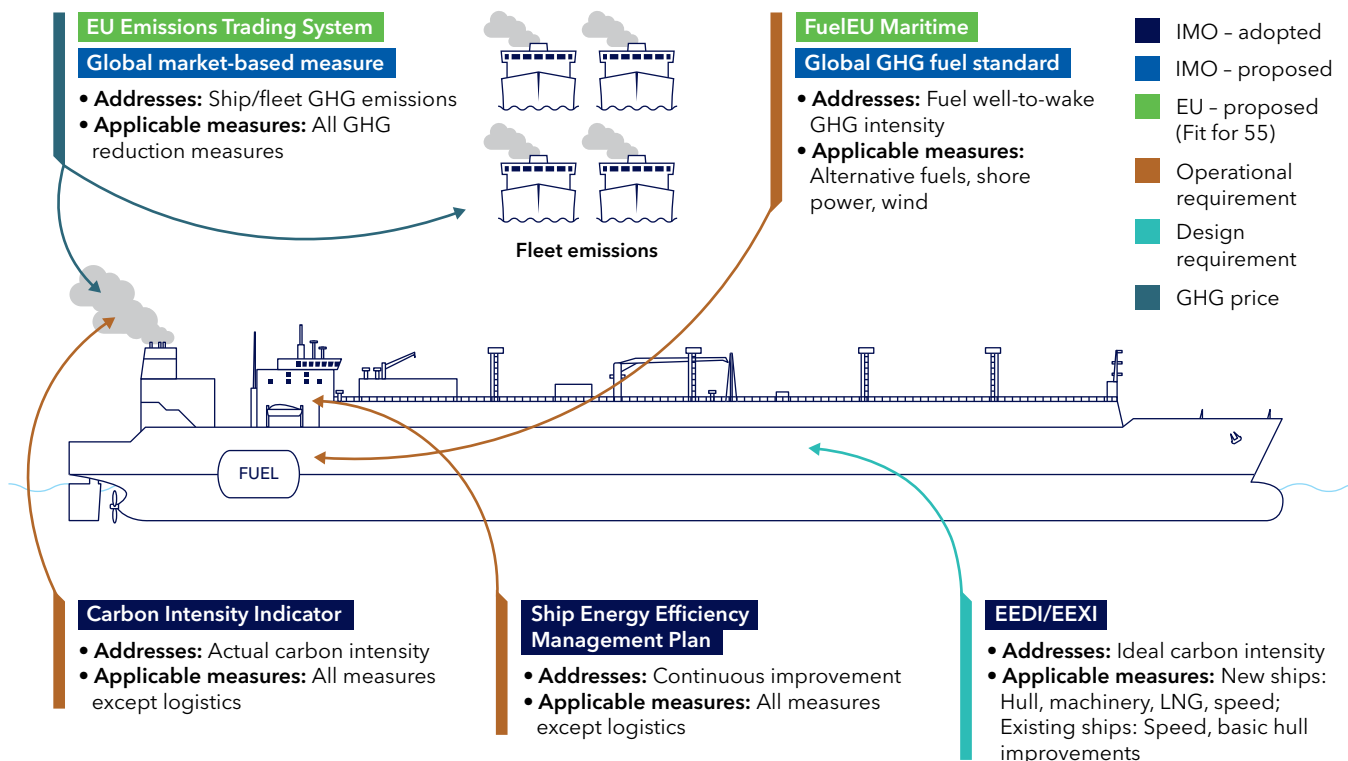
In parallel with developing guidelines, two other significant processes are ongoing in the IMO. One is the

scheduled revision of its GHG Strategy in 2023, which includes revising the current ambitions for both carbon intensity and reducing total GHG emission, and developing further regulatory measures to ensure that international shipping can achieve these ambitions. In November 2021, MEPC 77 agreed that the ambitions need strengthening, but without stating by how much. Concrete proposals have been submitted arguing for full decarbonization by 2050, and negotiations have begun, with a decision expected at MEPC 80 in July 2023.

Proposals have also started to come forward on what type of regulations should be implemented to ensure that shipping achieves the strategy ambitions. One set of proposals consists of market-based measures (MBMs) which aim to set a price on CO₂ or GHG emissions, either well-to-wake or tank-to-wake, creating a financial

Figure 2.2

IMO and EU regulatory framework for GHG emissions reduction from international shipping





incentive driving uptake of GHG emission reduction measures indirectly rather than through a technical requirement. The four variants of MBMs currently proposed are:

- A levy system based on absolute well-to-wake GHG emissions. The IMO would determine the GHG price.
- A levy system based on CII performance, where ships with CII performance below a benchmark would pay a contribution per tonne CO₂, and those performing above the benchmark would receive a reward. The IMO would determine the contribution. The reward would depend on the fleet's level of achievement.
- A levy system based on absolute tank-to-wake CO₂ emissions, with the revenues being used partly to provide direct rebate to zero-emission vessels. The IMO would determine the CO₂ price and rebate.
- An emissions cap-and-trade system, similar to the EU ETS, where the IMO would set the well-to-wake GHG emission level and allowances would be auctioned. The market would then determine the carbon price.

The revenues from market-based schemes could, besides specific rebates and rewards as described above, be used for climate mitigation and adaptation both in shipping and outside shipping. The proposals will be further discussed towards MEPC 80 in July 2023, and a future MBM measure could integrate elements from several of the above proposals.

The initial impacts assessments¹³ of the MBM proposals indicate a CO₂ or GHG price between USD 50/tCO₂ and USD 300/tCO₂ towards 2050, and a transport cost increase of 50% to 90%, when following a *Decarbonization by 2050* pathway. However, these prices depend on the abatement costs and especially the future price gap between fossil and carbon-neutral fuels.

In addition to the MBMs, the IMO has also received a proposal for a technical requirement, the GHG Fuel Standard¹⁴, which will set a requirement on the well-to-wake GHG emission per unit of energy provided to the ship, either as a fuel or as electricity.

¹³ ISWG-GHG 12/3/14, ISWG-GHG 12/3/17

¹⁴ ISWG-GHG 12/3/3

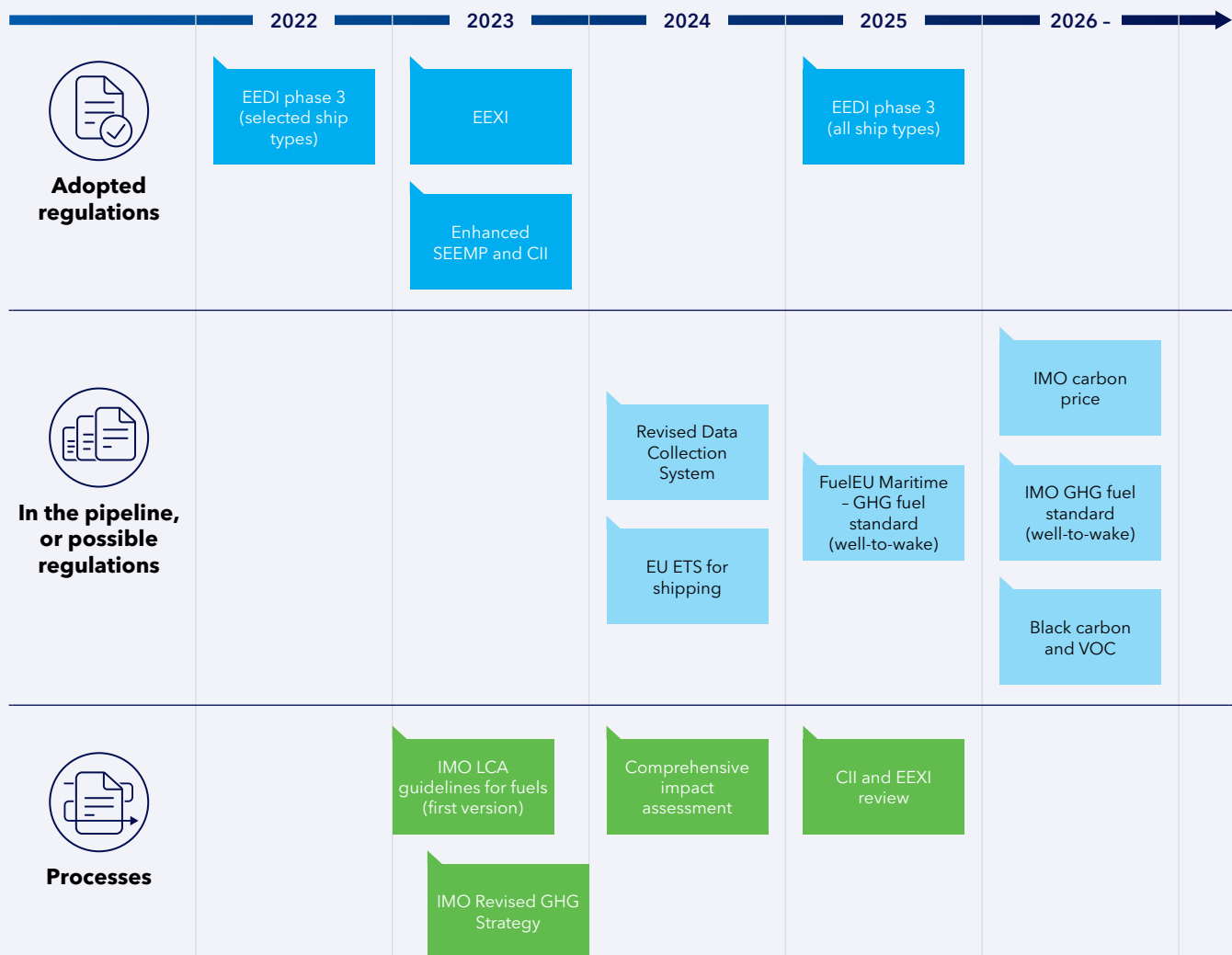
Beyond the IMO, the EU is one of the most influential and ambitious regulators of ships. Its ambition is to reduce emissions by 55% in 2030 relative to 1990, and to become climate neutral by 2050. In July 2021, the EU proposed its Fit for 55 legislative package and FuelEU Maritime regulation. Fit for 55 is expected to include shipping in the EU Emissions Trading System (EU ETS). FuelEU Maritime aims to increase the use of sustainable fuels

through an increasingly stringent lifecycle GHG intensity requirement.¹⁵ These two proposals related specifically to ships are very likely to be adopted. The EU Council and Parliament are considering them in draft form before final adoption timetabled for late 2022 or 2023. The timetables for finalization vary due to Fit for 55 having many items to discuss, and because of the varying complexities between the proposals.

¹⁵ https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en

Figure 2.3

Timeline with key regulatory processes and decisions in the EU and the IMO



Key: Carbon Intensity Indicator (CII); Energy Efficiency Design Index (EEDI); Energy Efficiency Existing Ship Index (EEXI); Emission Trading System (ETS); Lifecycle Assessment (LCA); Ship Energy Efficiency Management Plan (SEEMP); Volatile Organic Compounds (VOC)

Within a few years, the ETS will impose costs on ships trading in, or in and out of, the EU. As of May 2022, the allowance price was around EUR 80/tCO₂ to 90/tCO₂.¹⁶ This will add EUR 250 to 290 to the cost per tonne of fuel combusted, representing a 30% to 50% increase in fuel costs if operating in the EU. The EU ETS price will be determined by the abatement cost across all industrial sectors in the scheme and not only by the cost in the shipping sector. The number of allowances put on the market will be reduced by 4.2% per year, which means that the price may increase further.

The impact of FuelEU Maritime is more long term. The reduction requirement is set relative to the average well-to-wake fuel GHG intensity of the fleet in 2020. The initial requirement is a 2% reduction compared with the fossil fuel comparator by 2025, 6% by 2030, and accelerating from 2035 to reach a 75% reduction by 2050.

The compliance requirement can also be pooled for a group of ships where the average GHG intensity needs to be below the requirement, though individual ships may have a higher intensity. In the short term, a key impact from 2025 will be a focus on calculating lifecycle GHG emissions and establishing fuel certification schemes.

This section has focused on EU and global regulations, but other countries such as the US and China have implemented local and national requirements that could impact international shipping, and which should be monitored depending on trading area. Figure 2.3 shows a timeline with key regulatory processes and decisions expected in the coming years from the IMO and EU. The EU is expected to agree on regional regulations that will have an effect from 2023, while new IMO measures are anticipated after 2025.

2.2 Well-to-wake GHG emissions and sustainability of fuels

Decarbonizing shipping should not lead to shifting emissions to other sectors. Examples could include producing ammonia or hydrogen from non-renewable electricity (from fossil sources without CCS), or using non-sustainable biofuels, which leads to emissions from land-use change. A clear framework and standards for calculating well-to-wake emissions and sustainability evaluation are needed to ensure that using a fuel does not have unintended consequences in other sectors.

Work is ongoing to define ship-specific calculation methods for well-to-wake GHG emissions when using marine fuels. The EU has proposed a lifecycle GHG emissions standard through its proposed FuelEU Maritime regulation, which includes a method for calculating lifecycle emissions as well as a requirement. The IMO is also working on guidelines for calculating lifecycle GHG emissions for marine fuels, including sustainability

criteria. The guidelines include a placeholder for adding provisions for onboard CCS, but there are no details yet related particularly to requirements on the permanent storage of CO₂ after capture. A first version of the guidelines, which includes the most relevant fuels today, is expected by the end of 2022. These guidelines do not include any provision for application or requirements, but the IMO is considering a submission proposing a GHG Fuel Standard setting limits on well-to-wake emissions.

The regulatory focus on lifecycle emissions and sustainable production implies that marine fuels will be subject to certification to verify their origin. Certification schemes already exist for biofuels, such as those from the International Sustainability & Carbon Certification (ISCC)¹⁷ and the Roundtable of Sustainable Biomaterials (RSB)¹⁸. In addition to their own standards, ISCC and RSB provide certification according to the International Civil Aviation

¹⁶ <https://www.eex.com/en/market-data/environmental-markets/auction-market>

¹⁷ <https://www.iscc-system.org>

¹⁸ <https://rsb.org>

Organization (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), for aviation fuels; the EU's renewable energy directive (RED II); and Japan's mandate for using biofuels. Several initiatives are underway in different parts of the world for developing schemes for other types of fuels such as hydrogen and hydrogen-derived fuels to certify their origin, such as Australia's guarantee of origin scheme¹⁹, the China Hydrogen Alliance²⁰ and the EU's CertifHy²¹. A similar model where certification schemes are recognized according to IMO requirements can also be used for marine fuels.

At the company level there will also be a need to calculate and report on emissions from fuel production. The GHG Protocol²² includes reporting standards dividing emissions into three scopes. For a shipping company, the direct emissions from combustion of non-biogenic fuels on owned or operated ships are part of Scope 1, while emissions from fuel production, including biofuels, should be reported as Scope 3 emissions. Direct CO₂ emissions from combustion of biofuels are not part of any

of the scopes but should be reported in a separate memo. Scope 3 emissions would also include emissions from manufacturing of ships, but there are not yet any specific methods for calculating this. For a wide range of businesses like cargo owners, banks, insurance and so on, ship emissions, including the lifecycle emissions from fuels, are part of their Scope 3 emissions.

As mentioned above, the SBTi launched its Net-Zero Standard²³ in October 2021 enabling companies to set net-zero targets in line with climate science, which covers the complete value chain. Many cargo owners – such as Unilever, IKEA, and Amazon – have already set more ambitious targets for decarbonization and expect low- and zero-emission shipping services in this decade. The US has proposed rules that mandate US-listed companies to disclose direct and indirect GHG emissions and related climate risks, including material Scope 3 emissions. These requirements mean many shipping companies will need to report on lifecycle emission from marine fuels and meet specific targets, even if this does not yet apply to specific ships.

2.3 The need for standards to support decision-making and funding

Significant investments are needed during the next decades to enable the transition to carbon-neutral shipping. DNV estimates that an additional USD 8bn to 28bn per year is needed for investing in ships in a transition phase towards decarbonization in 2050 (see Section 5.6). For comparison, the average annual investment in newbuild contracts over the last 10 years is around USD 85bn (Clarkson Research, 2022). In addition to the investments on ships, DNV projects that about USD 30bn to 90bn per year is needed onshore to produce the amount of carbon-neutral fuels required for ships to 2050, and for fuel distribution and bunkering infrastructure. The

more expensive energy sources and onshore investments could increase the annual fuel costs by more than USD 100bn to 150bn when shipping is fully decarbonized, which would be a 70% to 100% increase from today.

It is critical to ensure that sufficient funds are available and invested in the right projects on ships and land. There is a need for standardized criteria for what is considered sustainable. The EU and China are setting up taxonomy schemes to ensure that capital is channelled to economic activities that contribute significantly to environmental objectives.

¹⁹ www.cleanenergyregulator.gov.au/Infohub/Markets/guarantee-of-origin

²⁰ www.h2cn.org.cn/en/about.htm

²¹ <https://www.certifyhy.eu>

²² <https://ghgprotocol.org>

²³ <https://sciencebasedtargets.org/net-zero>



The focus on green and sustainable activities from financial institutions and institutional investors aims to reduce exposure to non-sustainable activities and to contribute positively to mitigating climate change. Access to capital depends increasingly on environmental credentials and meeting expected decarbonization trajectories throughout the lifetime of ships. Financial institutions are required to report on their portfolios' compliance with sustainable investment taxonomies. It is expected that this will gradually be linked to the capital requirements for the financial institution, thus directly impacting the cost of capital.

The need for standardized criteria and ensuring that capital is channelled to green and sustainable projects are closely linked to reporting standards and requirements, at both company and ship level, and to the development of ship-specific indicators and benchmarks in regulations.

Requirements for sustainability reporting, including disclosure of performance and evaluation of sustainabil-

ity risks, are being further expanded. The EU is progressing towards adopting a Corporate Sustainability Reporting Directive (CSRD) which would mandate detailed sustainability reporting for all large companies and all listed companies - almost 50,000 of them in total. As mentioned above, the US has proposed rules mandating US-listed companies to disclose direct and indirect GHG emissions and related climate risks.

We also see significant regulatory standard developments for ships and fuels. Stakeholders can easily apply criteria based on the implementation of the CII with an annual rating. The next standard to be applied could be the fuel lifecycle emission intensity, which is expected to be mandated first through FuelEU Maritime, and possibly later by the IMO through the GHG Fuel Standard. These standards will also allow cargo owners to set specific requirements for their transportation needs.

The Poseidon Principles as of spring 2022 represent 29 banks and 50% of global ship financing and require them to specifically assess and disclose the climate alignment of their ship finance portfolios. It has been in operation for two reporting years. The Sea Cargo Charter is a similar scheme for cargo owners, but with only one year of operations. As previously mentioned, marine insurers recently set up their own Poseidon Principles for Marine Insurance scheme requiring disclosure of their portfolios' climate alignment.

The learning from the annual reports of these schemes is that operational patterns have a significant effect between years and that longer-term trends need to be seen before impacts relating to the assets can be reliably assessed. The questions are: How will the banks, investors, insurers and cargo owners use the metrics reported to them, and how will they act on projects that impact the climate alignments of their portfolios? More information and increased transparency should enable stakeholder to take better decisions, but the information needs to be organized and standardized to be useful. To make the correct decisions, it is also critical to understand what the information does and does not tell you.



Highlights

Decarbonization requires new fuels, greater energy efficiency, and better logistics:

- We provide a new snapshot of alternative fuel uptake in the world fleet.
- We assess the current and future technical readiness of onboard fuel technologies.
- We emphasize safety challenges in the transition to new fuels.
- We explore how digitalization can enable maritime decarbonization.

3

OUTLOOK ON SHIP TECHNOLOGIES AND FUELS

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3 OUTLOOK ON SHIP TECHNOLOGIES AND FUELS

Policy developments and stakeholder 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 is our high-level overview of promising ship technologies and fuels, introducing an updated outlook for their technology readiness levels.

We also discuss how digitalization can enable the decarbonization of shipping in several important ways such as improved design, energy-efficient operation, and greater fleet utilization.

Decarbonizing shipping will predominantly require new fuels, but also greater energy efficiency and improved logistics (Figure 3.1). Irrespective of efficiency improvements, meeting ambitious decarbonization goals will require a change to carbon-neutral fuels.

Unfortunately, the new fuels are not available today in the sufficient quantities, usually require more space, and are much more expensive. All these factors improve the business case for energy efficiency (and harvesting) solutions. The focus on fuel savings will probably be emphasized even more by the present situation with high prices for fuel oil and LNG. Ship concepts being developed show significant fuel-saving potential when implementing energy-efficiency measures and wind-assisted propulsion.

3.1 Available ship technologies and fuels for decarbonization of shipping

While we expect the internal combustion engine (ICE) will remain the dominant energy converter in the fleet, future integration of marine fuel cells in power systems has potential to provide greater efficiency and thereby reduce fuel consumption. Fuel cells combined with alternative fuels such as hydrogen can efficiently reduce and even eliminate emissions and noise, while energy efficiency can be increased compared with conventional combustion engines (DNV, 2021e). The modularity and electric efficiency of fuel cells will be used in hybrid systems alongside electric motors for propulsion, batteries for energy storage, and gensets. More complex systems offer more degrees of freedom to obtain greater efficiency throughout the operational profile by using more advanced power and energy management systems.

We see increased interest in the use of nuclear power; for example, Small Modular Reactors (SMRs) using molten salt reactor technology can be used on board ships. Novel reactor technologies first need to be developed and operated onshore before sufficient experience is available to guide the public perception, risk, and costs associated with taking the technology on board ships (DNV, 2021e). For nuclear propulsion to achieve significant uptake in commercial shipping, public opposition to nuclear power, and the concerns related to misuse, must be addressed.

The significant barriers against the uptake of carbon-neutral fuels may also make a business case for continued use of fossil fuels with onboard CCS. This may be applicable

for some ship segments depending on regulatory and land-based infrastructure developments. Recent years have also seen the development of numerous digital tools that can be used in the shipping industry. These tools can provide digital-enabled optimization and reduced emissions in shipping, either independently or in conjunction with other digital technologies. However, it should be recognized that to a large extent, the onboard technologies needed to support the maritime energy transition are still immature.

While technical and operational efficiency measures can significantly reduce GHG emissions, uptake of more advanced technical energy-saving methods is currently limited. However, we expect this to increase in the coming years due to IMO requirements and stakeholder expectations (see Chapter 2).

Exhaust gas economizers, propeller efficiency equipment, bow enhancement, hull fins and air lubrication systems are gaining in popularity, according to data from Clarkson (Clarkson Research, 2022). There are also ways to harvest energy from surroundings, as well as onboard CCS:

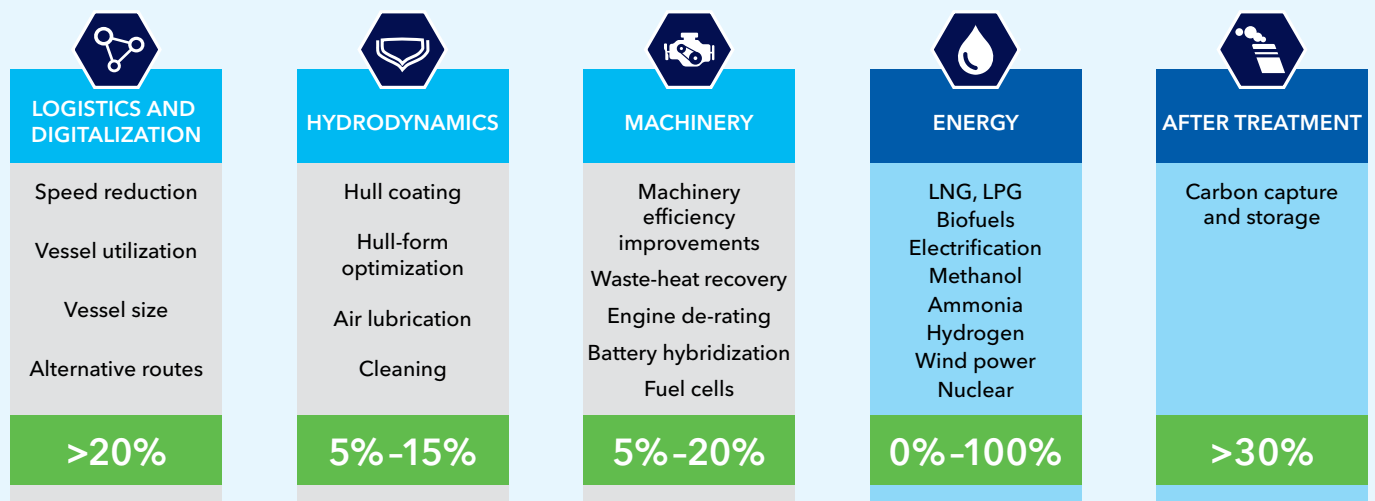
- Sail arrangements such as sails, kites, fixed wings and Flettner rotors have been tested on merchant vessels

over the years. Typically, sails can save 3% to 15% of propulsion power under relevant conditions, but greater percentages are also reported. Very few ships currently operate with variants of sail arrangements.

- Waves, normally associated with resistance and increased demand for propulsion power, can also be an energy source. This can be achieved by using foils or ‘wings’ in the bow. Typical fuel savings are reportedly 1% to 3% under relevant conditions, but greater in some reports. A few applications have recently been reported in the passenger segment. As the motion of a ship is important in determining the fuel saving potential, smaller vessels generally have greater potential.
- Installing solar panels will allow for electricity production at sea and in port. However, solar power production requires daylight. This results in solar panels having the potential to save only around 1% of auxiliary power, though this could be greater depending on the area available on board for panels. A few vehicle carriers have installed solar panels on the top deck.
- Onboard CCS technology can play an important role in reducing CO₂ emissions in the deep-sea shipping segment in the coming decades. Liquid absorption technology, with or without membranes, is becoming

Figure 3.1

GHG emission-reduction potential of technologies that can contribute to shipping decarbonization



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a popular option for CCS system concepts. However, no full-scale CCS system has yet been implemented on board, nor any large-scale demonstration projects.

Our focus in the following sections shifts to fuel technologies because reducing vessel GHG emissions by up to 100% can only be achieved with carbon-neutral fuels.

3.2 Status of fuel transition

Key barriers to the uptake of low or zero-carbon fuels include increased capital investment, limited fuel availability, lack of global bunkering infrastructure, high fuel prices, and the additional demand for onboard storage space. The severity of such barriers will vary between fuels. Safety is also a primary concern, with the absence of prescriptive rules and regulations complicating the implementation of required technology on board.

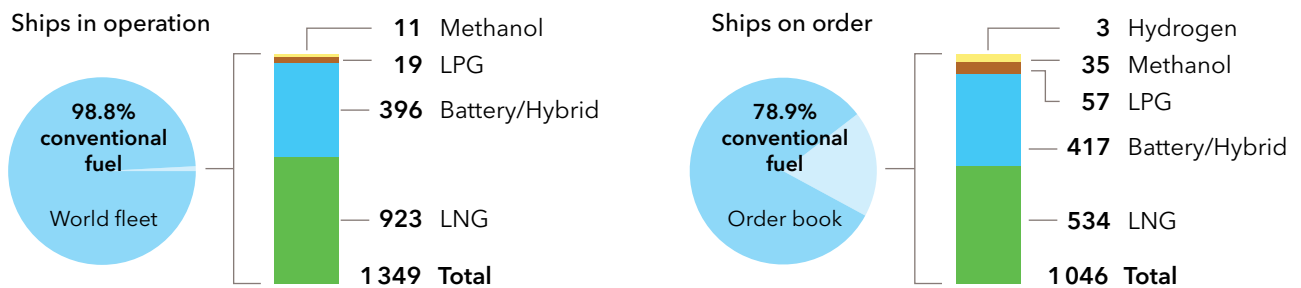
The technical applicability and commercial viability of alternative fuels will vary greatly for different ship types and trades.

Figure 3.2 shows the current status of the uptake of alternative fuels in the fleet – as well as in the order book as of June 2022. In gross tonnage (GT) terms, 5.5% of ships in operation and 33% of those on order can operate

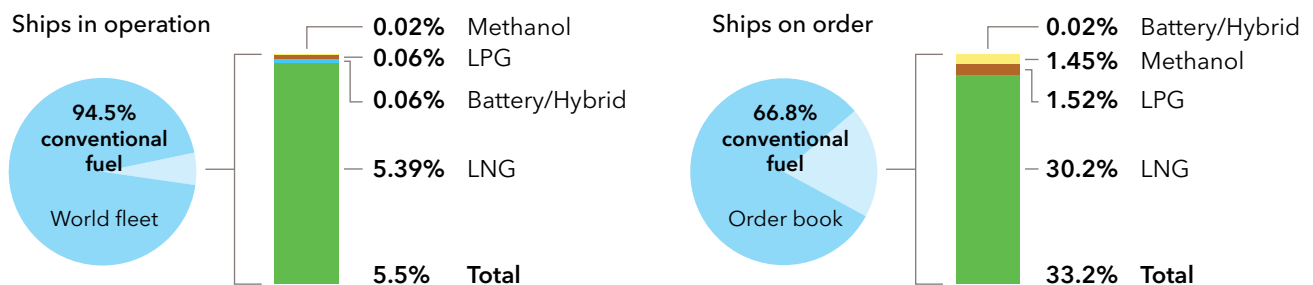
Figure 3.2

Alternative fuel uptake in the world fleet by number of ships and gross tonnage

NUMBER OF SHIPS



IN % OF GROSS TONNAGE



Key: Liquefied natural gas (LNG); liquefied petroleum gas (LPG)
Sources: IHSMarkit (ihsmarkit.com) and DNV's Alternative Fuels Insights for the shipping industry – AFI platform (afi.dnv.com)

on alternative fuels (including LNG carriers). The equivalent percentages when considering numbers of ships are 1.2% and 21%, respectively. In other words, 1,046 out of 4,967 ships are ordered with alternative fuel capability.

By number of ships, uptake is dominated by battery/hybrid ships together with LNG fuel. However, in gross tonnage terms LNG fuel dominates, which reflects the fact that battery/hybrid solutions are applied mostly on smaller vessels. Of the 923 ships in operation with LNG fuel, there are 630 LNG carriers and 293 LNG-fuelled ships of other types. Uptake of methanol and LPG is starting to show in the statistics together with the first hydrogen-fuelled newbuilds. In addition, numerous potential newbuilds with various alternative fuels are being projected.

The trend of larger ships being ordered with alternative fuel propulsion is continuing, with LNG as the dominant fuel. LNG is a popular fuel choice in the car carrier and containership segments, and significant uptake is also being seen for tankers and bulk carriers. Of the 1,046 ships on order with alternative fuels, 167 are LNG-fuelled LNG carriers; 367 are LNG-fuelled ships of other types; and 417 are using battery/hybrid propulsion. In the short-sea segment - which was the first mover on LNG fuel years ago - the clear trend towards electrification for ferries is continuing, with some looking towards hydrogen and fuel-cell technology to increase range.

Methanol had previously been a choice exclusively for tankers in the methanol trade, with 11 ships in operation and 14 new tankers on order. This year we also see uptake in the container segment, with 21 ships on order with methanol as fuel. 76 LPG carriers using LPG as fuel are either in operation or on order.

It should be noted that the majority of ships using alternative fuels can also burn conventional fuel oils.

The strong interest in ammonia as fuel, reflected in concepts and pilot studies, is currently restricted by immature converter technologies. This is expected to change when the technology becomes available.

In the previous editions, we reported these numbers without LNG carriers (which have been running on boil-off gas from cargo for decades) to better illustrate the 'new' uptake of LNG fuel technology in other segments. For a full picture, we present the current statistics with the LNG carriers included. Excluding LNG carriers would suggest that currently 18% of newbuilds can use alternative fuels, compared with 12% in 2021 and 6% in 2019.

The statistics are 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.

3.3 Outlook for the readiness of onboard fuel technologies

The transition from fossil fuels to carbon-neutral fuels, will have to coincide with a corresponding development in onboard fuel technology, while onboard CCS technology enabling continued use of fossil fuels may become an alternative for some ships. In this chapter we introduce an updated timeline presenting the current maturity level of selected onboard fuel technologies required for the energy transition, and the future expected improvement in technological readiness. This is an enhanced version of our Timeline for Expected Availability of Alternative Fuel

Technologies (DNV, 2021c) with separate assessment of different energy converters, onboard CCS, and safety regulations for onboard use of alternative fuels.

Key factors in the timeline development have been the technology readiness level (TRL) assessment of individual technologies; known planned development and testing programmes; and mapping of regulatory development on safe design and use of alternative fuels. For TRL definitions, see the separate text box.

The resulting timeline is our best estimate of the maturation for energy converters able to use methanol, ammonia, or hydrogen as energy carriers, and for onboard CCS technology. We have categorized the energy converters into 2-stroke engines, 4-stroke engines, auxiliary boilers, and fuel cells. 2-stroke engines are typically used for propulsion by larger cargo ships, having the largest share of total installed power in the world fleet and accounting for most of the maritime fuel consumption and emissions. However, 4-stroke engines used for propulsion and auxiliary power generation dominate by sheer numbers (about 82% of ship engines). Boilers are mainly used to generate steam for heating purposes on board and represent a small part of the overall fuel consumption and emissions. Fuel cells are expected to be integrated in hybrid power systems in the coming decades.

Figure 3.3 applies a colour scale to indicate the maturation of energy converters, CCS technologies, and corresponding safety regulations for onboard use of relevant fuels. The technology maturation scale ranges from validated technologies (TRL 4) to technologies that are available from one or more manufacturers (TRL 9). It may be expected that technologies and power ranges serving the core markets will be available first, followed by an expansion in product range depending on demand.

The maturity of safety regulations for onboard use of respective fuels is indicated separately. This is to emphasize that they must be developed in parallel with the technological development to ensure efficient uptake of new fuels and technologies in the world fleet. The low end of the scale represents a state where prescriptive international standards are not in place to support designers and yards in the building process. We consider that regulations have reached a high maturity level when statutory approval can be based on accepted international standards.

We have considered a time frame 10 to 12 years ahead and do not expect all technologies to reach maturity within this period.

It is important to be aware that the maturity timelines do not reflect expected availability of a given fuel type. The

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)

timeline simply assumes that the fuels are available, with market demand for the respective fuel technologies. Other aspects – for example, distribution and bunkering infrastructure, policies and incentive schemes, fuel prices and technology cost – will of course affect actual uptake of these technologies. We describe and illustrate these key barriers in our Alternative Fuel Barrier Dashboard providing their indicative status for selected alternative fuels. The Alternative Fuel Barrier Dashboard also identifies the stakeholders in the ecosystem who can contribute to further reduce barriers to uptake of fuel. Successful uptake of CCS technology will depend on a fully developed infrastructure for the total CO₂ value chain.

We have not included alternative fuels such as LNG and LPG. These technologies can contribute to decarbonization directly and by using electrofuels and biofuels. This onboard fuel technology is, however, considered relatively mature and thus irrelevant for this timeline. It is worth mentioning that there are also fuel cells under development which can use these fuels and could

potentially increase efficiency compared with combustion engines.

Figure 3.3 shows that the current maturity level of methanol fuel technologies is higher than those of ammonia and hydrogen. For ammonia, we see a development of 2-stroke and 4-stroke engine technologies on parallel paths enabling uptake in deep-sea and regional short-sea shipping. For hydrogen, the timeline reflects that short-sea shipping is expected to be instrumental in maturing the technology. Consequently, the development of fuel cells and 4-stroke engines are ahead of other

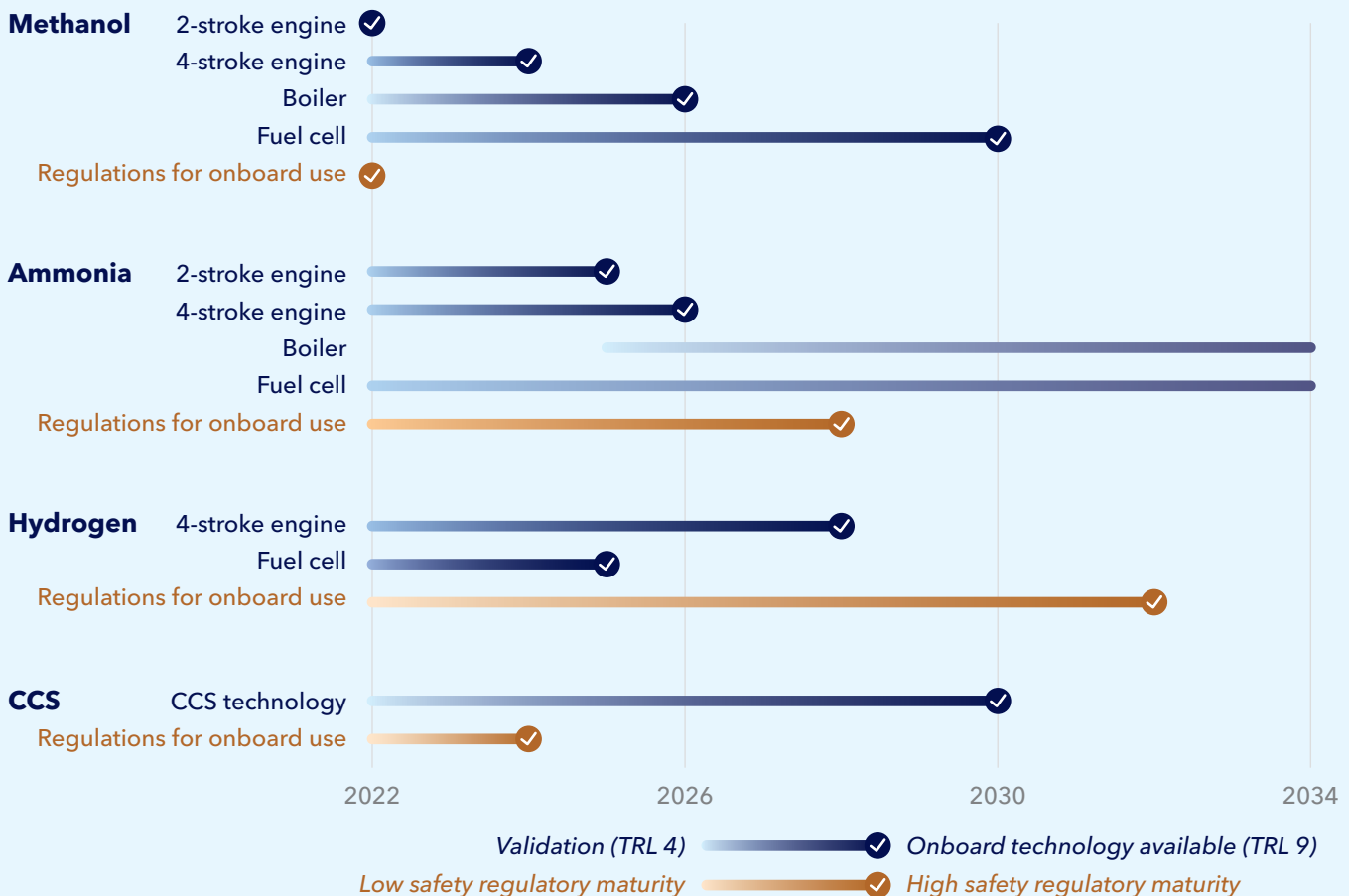
hydrogen energy converters. The new fuels have reached different level of regulatory maturity - with methanol regulations for onboard use being the most mature, and hydrogen the least mature, of the three fuels assessed (see safety text box on page 40).

Compared with most alternative fuels, which are gases and low-flashpoint liquids falling under the IGF Code²⁴, introducing CCS installations does not pose the same safety risks. It is expected that if CCS technologies are identified as a viable option, class rules could quickly be developed to cover the installation risks.

24 International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels

Figure 3.3

Estimated maturation timelines for energy converters, onboard CCS technologies, and corresponding safety regulations for onboard use



Our outlook for the readiness of the different onboard fuel technologies is further discussed below:

Methanol

Tankers carrying methanol as cargo have successfully been using dual-fuel 2-stroke methanol engines for propulsion since 2017. With increased interest in methanol as fuel for other deep-sea ship applications as well, the commercially available product range is expected to increase²⁵, and we also foresee other makers entering this market^{26,27}. Retrofit options for a range of 2-stroke engines are also available²⁸, resulting in a current assessed TRL level 9 for 2-stroke dual-fuel engines.

We also see an increased interest in methanol as fuel from shipowners operating in segments where 4-stroke engines are the preferred choice. This has triggered a technology development from manufacturers aiming to serve both the newbuilding market and potential retrofits.^{29,30} Stena converted one existing 4-stroke engine to methanol fuel on one of their RoPax vessels in 2015. The current TRL level is estimated to be 6 but the first contract for delivery of dual-fuel 4-stroke methanol engines for a newbuild, an Offshore Wind Installation Vessel being built for Dutch contracting company Van Oord, is in 2023.³¹ Consequently, we also expect to see a rapid increase in technological maturity level for 4-stroke engines. Conversion kits for selected engine types are anticipated in the next couple of years.

It may also be desirable to use low-carbon fuels for ship segments requiring auxiliary steam in operation. To meet this demand, steam boiler technology fuelled by methanol is being developed and tested by at least one manu-

facturer.³² The current TRL level is estimated to be 4 with an expected rapid increase in maturity within the next couple of years when the technology enters into use.

In the cruise segment there is interest in methanol as fuel and alternative energy converters. This drive can be expected to accelerate the development in fuel cell technologies using methanol as an energy carrier³³, also benefiting other segments. The current TRL level is estimated to be 5 with an expected longer maturation time than for internal combustion engines.

Ammonia

Compared with methanol, engine technologies for ammonia are less mature. Neither 2-stroke nor 4-stroke engines using ammonia as fuel are currently commercially available. Given the large interest in ammonia as fuel, engine manufacturers have for some time developed their technologies to meet this demand and the current TRL level is estimated to be 5–6. Key challenges include ammonia's combustion properties, nitrous oxide (N₂O) emissions, and potential ammonia slip. Significant development efforts are being made to get these engines to market within the next couple of years.^{34,35,36} It may be expected that engine technologies and sizes serving the core markets will be available first, followed by retrofit options and expansion in product range.

Steam boilers running on ammonia are an immature technology. However, at least one boilermaker has begun concept development and testing is planned within the next couple of years, resulting in an estimated TRL level of 2. In addition to the environmental benefits, having boilers able to burn ammonia could also contribute to

25 <https://www.man-es.com/company/press-releases/press-details/2021/08/25/milestone-order-for-world-s-largest-methanol-dual-fuel-engine>

26 <https://www.wingd.com/en/news-media/press-releases/wingd-sets-development-timeframe-for-methanol-and-ammonia-engines>

27 <https://vpoglobal.com/2021/08/26/eight-new-maersk-ships-to-be-fuelled-by-methanol>

28 <https://www.man-es.com/company/press-releases/press-details/2022/01/28/dual-fuel-retrofits-of-low-speed-engines-key-in-push-towards-decarbonisation>

29 <https://www.wartsila.com/media/news/17-03-2022-wartsila-to-deliver-first-dedicated-methanol-fuel-supply-system-3068213>

30 <https://www.man-es.com/company/press-releases/press-details/2021/11/29/man-energy-solutions-upgrading-four-stroke-engines-for-green-future-fuels>

31 <https://www.wartsila.com/media/news/24-01-2022-wartsila-hits-methanol-milestone-with-first-newbuild-engine-order-3039731>

32 <https://www.alfalaval.com/media/news/2021/abs-grants-alfa-laval-the-marine-industry-s-first-approval-in-principle-aip-for-firing-boilers-with-methanol>

33 <https://www.alfalaval.com/industries/marine-transportation/marine/marine-news/a-carbon-neutral-methanol-fuel-cell-system-is-taking-shape-at-the-alfa-laval-test-training-centre>

34 <https://www.man-es.com/company/press-releases/press-details/2021/11/29/man-energy-solutions-upgrading-four-stroke-engines-for-green-future-fuels>

35 <https://www.wingd.com/en/news-media/press-releases/wingd-sets-development-timeframe-for-methanol-and-ammonia-engines>

36 <https://www.wartsila.com/media/news/17-03-2022-wartsila-to-deliver-first-dedicated-methanol-fuel-supply-system-3068213>



Fuel cells with a total capacity of 400kW will power the world's first liquid hydrogen-powered car ferry, the MF Hydra.

solving issues related to operational discharges of toxic gases from the ammonia fuel installation.

Solid oxide fuel cells (SOFCs) are interesting for shipping due to their ability to use different fuels, among them ammonia, and for their potentially higher energy efficiency compared with diesel engines. In an ongoing EU project, demonstration of a 2 MW ammonia-driven SOFC system is planned during 2024, retrofitting an existing supply vessel, the Viking Energy. Such demonstration and pilot projects are expected to significantly improve the speed of maturing the technology.^{37,38,39} The current TRL level is estimated to be 5-6 with a projected maturation longer than for internal combustion engines.

Hydrogen

Given its low energy density and corresponding space demands, limited hydrogen uptake is expected in deep-sea ship segments where 2-stroke engines are a natural choice for propulsion. For the short-sea segment, however, major engine manufacturers are experimenting

with blend-in technologies mixing hydrogen with other fuels to improve the performance of 4-stroke engines.⁴⁰ Hydrogen 4-stroke engines are also being projected with an estimated current TRL level of 6-7. The world's first hydrogen-powered cargo ship (With Orca) and the first hydrogen-powered tug (Hydrotug), using 4-stroke engines are scheduled to be put into operation within the next couple of years.^{41,42,43,44}

Blending in of hydrogen is being tested and investigated in households using natural gas-fired heaters.⁴⁵ However, hydrogen-fired boilers for marine use do not seem to be high on the agenda.

The proton-exchange membrane fuel cell (PEMFC) technology used to convert hydrogen to electricity is relatively mature with an estimated current TRL level of 8.⁴⁶ Ballard Power Systems has recently delivered two fuel cell modules (total capacity 400 kW) to Norwegian ferry operator Norled. The DNV-approved fuel cell modules will power the world's first liquid hydrogen-powered ferry, the MF Hydra, later this year.⁴⁷

37 <https://www.offshore-energy.biz/worlds-1st-ammonia-powered-fuel-cell-to-be-installed-on-a-vessel>

38 <https://shipandbunker.com/news/world/977374-eidesvik-aker-bp-seek-to-retrofit-offshore-support-vessels-with-ammonia-fuel-cells>

39 <https://www.alfalaval.com/industries/marine-transportation/marine/marine-news/maritime-industry-players-join-forces-to-realize-the-decarbonisation-potential-of-solid-oxide-fuel-cells>

40 <https://www.man-es.com/marine/strategic-expertise/future-fuels/hydrogen>

41 <https://www.behydro.be/en/home.html>

42 <https://presse.enova.no/pressreleases/the-worlds-first-hydrogen-powered-cargo-ship-receives-nok-104-million-in-support-from-enova-3173745>

43 <https://www.argusmedia.com/en/news/2207781-japans-tsuneishi-cmb-to-build-hydrogenpowered-tug>

44 <https://www.marineinsight.com/videos/watch-worlds-first-hydrogen-powered-tug-hydrotug-in-port-of-antwerp/>

45 <https://www.britisg.co.uk/the-source/greener-living/hydrogen-boilers.html>

46 <https://www.offshore-energy.biz/germany-welcomes-1st-emission-free-hydrogen-fueled-tugboat>

47 <https://hydrogen-central.com/fuel-cells-first-liquid-hydrogen-ferry-ballard-fcwave-norled>

CCS

Interest in maritime CCS is reviving, with chemical absorption technology seeming to be the popular option for system concepts. While this technology is well matured for land-based industries, this is not the situation for marine onboard installations. To enhance the technology readiness of maritime CCS, demonstration and pilot projects will be needed, and several R&D projects have been planned to address barriers for implementation on board.^{48,49,50,51}

Many capture technologies are sensitive to the purity of the exhaust, favouring ships burning cleaner fuels. A substantial amount of energy is required to capture and condition the CO₂ for storage. Further, CCS installation and storage is demanding onboard space. Hence, this technology is better suited for some ship segments than others. Gas carriers may have suitable characteristics to efficiently implement CCS technology on board and would be likely candidates for early full-scale demonstration projects. The current TRL level is estimated to be 5.

48 <https://www.kline.co.jp/en/news/csr/csr818532238088767329/main/0/link/211020EN.pdf>

49 <https://solvangship.no/2022/02/18/a-game-changer-is-within-reach>

50 <https://www.marinelink.com/news/solvang-ethylene-carrier-retrofitted-ccs-491461>

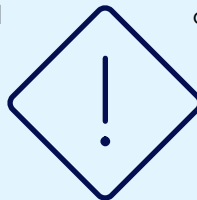
51 <https://everlongccus.eu>

Immature safety regulations – a safety challenge

With the introduction of new marine fuels, the toxicity of methanol and ammonia, and the extreme flammability of hydrogen, bring new sets of safety challenges originating from the physical properties of each fuel. Their successful implementation requires development of international regulations to ensure a safe integration of onboard fuel installations. This must be done in parallel with maturation of fuel technologies related to storage, distribution and energy conversion through pilot projects and adoption by first movers.

The IMO has provided an international mandatory regulatory framework for alternative fuels through the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). However, neither methanol, ammonia nor hydrogen are currently covered by detailed technical requirements in the Code. The lack of design guidance is complicating the building process for everyone involved. A shipbuilder will have to demonstrate through extensive risk evaluations that the chosen fuel

system design solution meets the intent of the goal and functional requirements of the IGF Code, and that it is as safe as a conventional oil-fuelled ship. This is not a process that most shipbuilders and designers are used to working with. It requires more time and resources, and is creating uncertainty and an additional business risk for the project since acceptance of design premises are not necessarily a given outcome.



From a regulatory point of view methanol gained an advantage over ammonia and hydrogen in December 2020 when the IMO approved the interim guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel. If agreed with the Flag Administration, these guidelines can be used in lieu of the risk-based alternative design process for methanol-fuelled ships. No such international standard is currently in place for ammonia or hydrogen, but the development of guidelines for these fuels is included on the IMO's already extensive work plan related to alternative fuels. This work can draw on experience from

3.4 Digitalization – enabling the transition

Digitalization and decarbonization are currently the most transformative forces in shipping, and the two topics are entwined – with digitalization enabling the decarbonization of shipping in several important ways.

Numerous digital tools have been developed in recent years and used by the shipping industry to optimize and decarbonize operations, either independently or in conjunction with other digital technologies (Agarwala, 2021). Digital technologies such as blockchain, Machine Learning (ML) and Artificial Intelligence (AI), Internet of Things (IoT), connectivity, and computer-based simulation and optimization platforms have progressed rapidly.

Application of these technologies will have a significant and multifaceted impact on decarbonization of shipping. We can summarize some of the most direct impacts as follows:

- **Evolving more energy efficient ship designs** through model-based simulation and optimization. Better computerized design tools have already improved optimization of hull design to accommodate lower hydraulic resistance. Marine energy systems have similarly been improved through use of advanced simulation techniques. In the next decade, virtual ship models will become a standard tool for designing and

marine transport of ammonia and the use of ammonia as refrigerant on board. Also, some classification societies have issued initial class rules for the use of ammonia as fuel. Hydrogen does not have the same history in maritime applications, and there are currently no class rules for hydrogen as fuel. The process of developing statutory regulations is a long process.

The prescriptive rules and regulations the maritime industry is used to working with have been proven through experience gained over decades of designing, building and operating oil-fuelled ships. Major revisions of IMO conventions like SOLAS and MARPOL have to a large extent been triggered by incidents or accidents. The safety regulations for the new fuels being introduced do not benefit from the same level of experience being fed back from the operational phase.

For ships planning to use ammonia or hydrogen as fuel, the experience gap is even bigger than for methanol-fu-

elled ships. Given the typical timeline for development of safety regulations in the IMO, it is likely that the first ships applying ammonia or hydrogen as fuels will be built without the support of existing detailed statutory regulations. The safety barriers implemented in the first projects will be very important as they will influence the coming industry standards on safety-critical design solutions.

An accident involving a new alternative ship fuel would, in addition to the risk to persons directly involved, be a serious set-back for the use of this fuel for the whole industry. Further, it is critical that the new industry standards maintain the same safety level as for conventional oil-fuelled ships. This cannot be achieved through development of regulations alone but depends on how ships are designed, built, and operated on this basis. An increased focus on safety will be required for all stakeholders in the maritime industry going forward with the implementation of new fuels.



commissioning ships and will also be used to operate and maintain ships and fleets of ships (see Figure 3.4). The virtual vessel, a 'digital twin', is a simulator modelling all onboard equipment, machinery, networks and control systems; all of it connected and integrated in cyberspace (DNV, 2017a).

The digital twin can be tested in simulated conditions close to those encountered on board. From an environmental perspective, this can enable evaluation of promising abatement measures and assist in finding cost-effective GHG reduction strategies in operation. In addition, a virtual environment will allow for simulation and demonstration of remote-controlled autonomous ships (DNV, 2018b). Such vessels can reduce energy demand and emissions. For example, reducing manning will reduce energy demands for sustaining the people on board the ship. Reducing or eliminating the manning will reduce weight and volume through optimized designs, such as removal of the ship bridge and accommodation.

- **Optimizing GHG performance for ships in operation** through monitoring, better routing and planning, diagnostic and corrective actions, and simulator-based crew training. In addition, improved

synchronization of ship arrival in ports ('just-in-time') will allow for fuel saving from slow steaming. In operation, the digital twin will continuously learn and update itself via sensor data providing various operational parameters; input from experts with relevant industry knowledge using data from similar assets; and from interaction with the environment. Having access to sensor data will allow decision makers to react in real-time, or within a decision interval enabling actions to still have value, to optimize fuel performance and the vessel's CII rating in operation.

Generating representative models of ship systems and their energy flows allows for continuous monitoring of fuel consumption distributed across sources such as generators, boilers, fuel cells and batteries.

FellowSHIP was the first large-scale installation and demonstration project of a fuel cell on a merchant ship, reaching a total of 18,500 hours of operation. It involved installation of a 320 kW molten carbonate fuel cell system fuelled by LNG and providing auxiliary power. In this project, DNV applied the Complex Ship Systems Modelling & Simulation (COSSMOS) tool to successfully implement a digital twin which

was used to model, simulate, and optimize the fuel cell system integration with the ship machinery systems (Ovrum & Dimopoulos, 2012).

- **Optimizing fleet utilization and GHG performance** through simulating and optimizing fleet size, composition, and speed. In a digital ecosystem of many vessels, one can integrate applications and data models and leverage the cloud, Big Data, and the Internet of Things to create exciting opportunities that will harness the power of advanced predictive analysis. This can be used to optimize fleet performance, improve information integrity, and deliver energy and cost savings. Better integration and communication between ships, shore offices and ports will enable improved planning, scheduling and logistics, further increasing fleet utilization. The digital ecosystem has enabled fleet operators establishing onshore control and operation centers. There are different justifica-

tions for this but cost reduction and improved GHG management are the most evident (DNV, 2020).

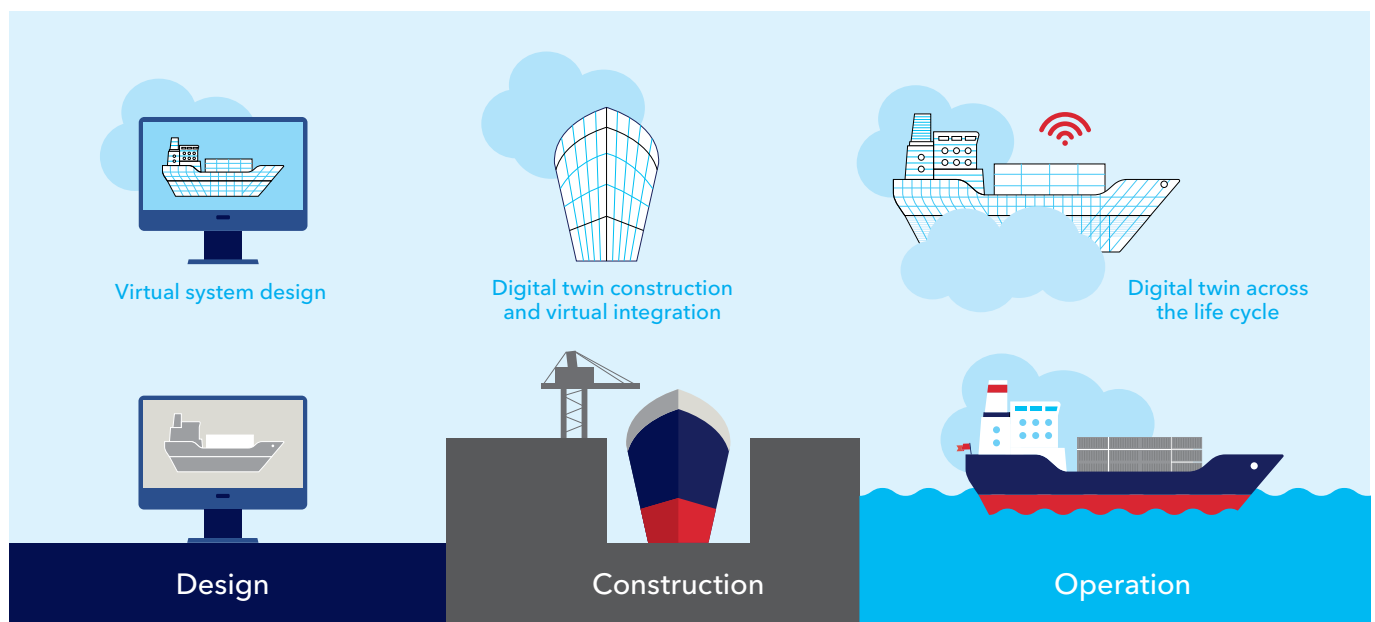
The current wave of digitalization will transform the shipping industry and have a profound impact on the way we design and operate ships through digital twin opportunities. In the energy transition for shipping, use of digital twins can demonstrate cost-efficient fuel and technology paths, assisting in keeping GHG emissions below the desired decarbonization targets.

Beyond the direct impacts described above, digitalization is also enabling decarbonization in more indirect ways - in particular through performance data management platforms linked to the DSC and MRV regimes.⁵² Digital tools are a necessary component of these systems, which in turn allows regulatory bodies, cargo owners, banks, and other stakeholders to successfully monitor, control and make plans.

⁵² The EU Monitoring, reporting and verification (MRV) requirement and IMO Data Collection System (DCS) have been mandatory since 2017 (MRV) and 2018 (DCS). See www.dnv.com/maritime/insights/topics/MRV-and-DCS/index.html

Figure 3.4

Illustration of the next-generation ‘digital twin’ ship built prior to and in parallel with the physical construction, enabling better system designs, more efficient system integration and commissioning, and improved safety and performance in operation



©DNV 2022, Source: <https://www.dnv.com/to2030/technology/bringing-it-all-together-digital-twins.html>

Highlights

The maritime industry must reduce barriers for a shore-side transition in fuel production and bunkering infrastructure:

- We identify supply chain and infrastructure constraints on carbon-neutral fuel use in ships.
- We conclude that supply chains will need to change dramatically to supply several such fuel options for ships.
- We analyse what will determine which carbon-neutral fuels will be available for large-scale maritime use.



4

OUTLOOK ON ALTERNATIVE FUEL PRODUCTION AND INFRASTRUCTURE

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4.2 Future energy supply chains - and main barriers	48



4 OUTLOOK ON ALTERNATIVE FUEL PRODUCTION AND INFRASTRUCTURE

Shipping's future fuel market will be more diverse, reliant on multiple energy sources, as well as more interconnected and integrated with regional energy markets, regional energy production, and with regional industry. This chapter provides a high-level overview and an outlook on key barriers to, as well as opportunities to accelerate, the upcoming shore-side transition in fuel production and bunkering infrastructure to supply the future decarbonized world fleet.

Shipowners need to apply new technologies and fuels in response to GHG requirements imposed by policy-makers and other stakeholders. This will result in a profound transition in the way future marine fuels are produced and made available to the shipping fleet. Cooperation with major energy and fuel providers will

be important to supply the future fuels. Ports will play a key role in the green maritime transition by serving as energy hubs providing both shore-side electricity and infrastructure for storing and fuelling ships with future fuels, as well as supporting the first movers and green corridors.



4.1 Existing fuel supply chain

The bunkering situation today is that of a global market of oil, a mature market with a fully developed infrastructure, where the crude oil price mostly determines the cost of energy delivered to a ship. The current bunker market is dominated by different types of fossil fuels such as fuel oil (e.g., heavy fuel oil (HFO), marine diesel oil (MDO), marine gas oil (MGO), very low sulphur fuel oil (VLSFO) and liquefied natural gas (LNG)). Almost all (99.95%) of bunker fuel consumed in 2019 fell into this category, according to the IMO (IMO, 2021). The total bunkers volume sold to ships in international trade was about 217 million tonnes (Mt) in 2019, including LNG, according to sales figures from IEA (International Energy Agency, 2021). These sales volumes are supported by the IMO (International Maritime Organization Marine Environment Protection Committee, 2020), which reports 213 Mt for 2019 (for

vessels bigger than 5,000 GT, and for international trade), based on shipowners' reporting.

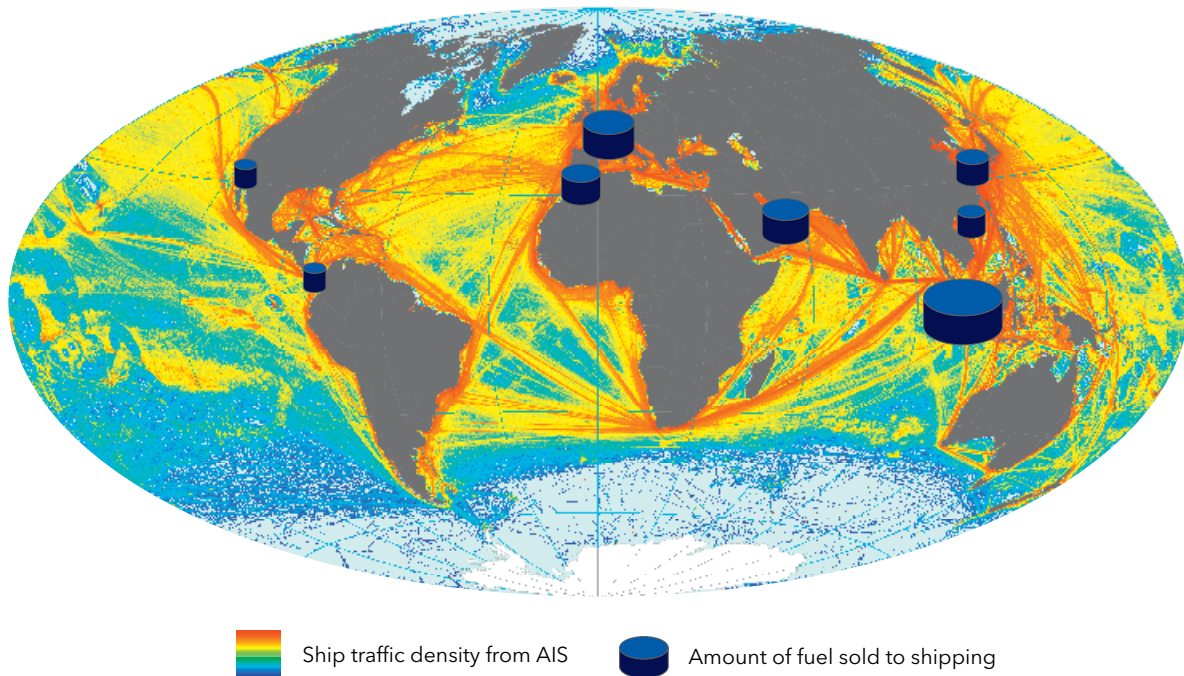
In addition, sales of fossil fuels to domestic shipping and fishing amount to another 57 Mt (IEA, 2021).

LNG has been an increasingly popular low-emission fuel with consumed volumes rising from about 10.5 Mt in 2019 to about 12 Mt in 2020 (IMO, 2021). About 75% of the total reported fuel usage of all types reported to the IMO was consumed by three ship types: tankers, bulk carriers, and containerships.

An estimated 55% of total bunker volumes for international navigation are sold in the 10 major bunkering hubs shown in Figure 4.1, but conventional fuel oils (including

Figure 4.1

Graphic shows 10 major bunkering hubs, with geographically close hubs combined, that provide an estimated 55% of fuel for international trade, and a heatmap of AIS data for ship traffic in 2021⁵⁴



⁵⁴ The bunkering volumes in the different hubs shown in the figure are estimates based on IEA and other sources, combining ports and areas that are geographically close - e.g., Algeiras and Gibraltar, Antwerp and Rotterdam

MDO) are available in most ports. Most bunker operations for deep-sea shipping take place at the major bunkering hubs, which are located strategically along the major international trade lanes. There are usually price differences between the different bunker locations, often allowing shipowners to take an opportunistic approach to bunkering. Tank capacities on board the vessels usually allow for bunker quantities that are sufficient for several voyages. In a location with comparatively low bunker prices, an owner will tend to bunker the vessel to the maximum. In cases where the vessel runs low on fuel, but the closest bunkering port has high prices, the owner will tend to bunker just enough to reach the next bunker port with lower prices. In his day-to-day considerations around bunkering, the owner will also take into account the vessel's cargo carrying capacity, safety margins, price differences over time, and available bunker qualities.

There are different bunkering methods which we briefly describe here using LNG as an example. Truck-to-ship transfer is today used for significant amounts of LNG bunkering but is less common for fuel oil. Truck-to ship

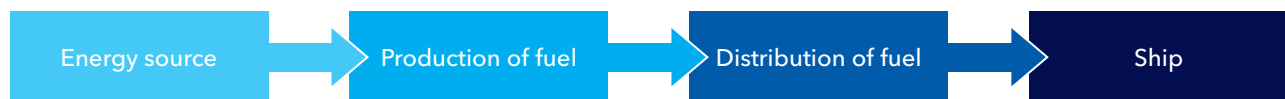
transfer is a flexible solution with comparatively low investment costs and risk. However, this type of bunkering is suitable for smaller quantities only.

Some ports with stable and long-term bunker demand also use shore-to-ship transfer, where a tank facility is connected to a bunker quay via a pipeline. This is the practice, for example, for LNG at some offshore bases along the Norwegian coast. High bunkering rates and consequently short bunkering time can be achieved with this system. However, shore-to-ship bunkering has the disadvantage of being inflexible.

For seagoing vessels in international trade, ship-to-ship transfer by bunker barges or seagoing bunker vessels is often used in bunkering operations. This type of bunkering allows for transfer of large fuel quantities. Seagoing bunker vessels provide good flexibility regarding the location for bunkering, as their operational range is not limited to harbour areas. We see for example that there are several seagoing LNG bunker vessels operating out of Rotterdam that serve vessels at anchorage as well as vessels in other ports in the vicinity.

Figure 4.2

A traditional fuel supply chain from energy source to the ship



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4.2 Future energy supply chains – and main barriers

A relatively simple supply chain – energy source, fuel production, distribution – supplies the shipping fleet with fuels currently used (Figure 4.2). For example, one chain consists of oil extraction, refineries, and distribution of fuels such as HDO, MDO, and VLSFO to the ship. This becomes natural gas extraction, liquefaction, and distribution in the case of LNG. The future carbon-neutral fuel mix is as yet undecided, but supply chains will need to change dramatically to supply several carbon-neutral fuel options.

There are several candidates for carbon-neutral⁵⁴ fuels, and three main energy source ‘families’ used to make them:

- Sustainable biomass – for example, forestry residue or agricultural waste with no emissions from land-use – can be used to make fuels that can be considered carbon-neutral compared with the alternative of natural CO₂ release from these sources: **Biofuels**

⁵⁴ Energy sources or energy systems that have no net GHG emissions or carbon footprint

- Renewable electricity can be used to create carbon-neutral fuels based on hydrogen made by electrolysis of water, and other reactions: **Electrofuels**
- Fossil energy can also be used to create carbon-neutral fuels by capturing the CO₂ in the production process and storing this permanently (CCS): **Blue fuels**

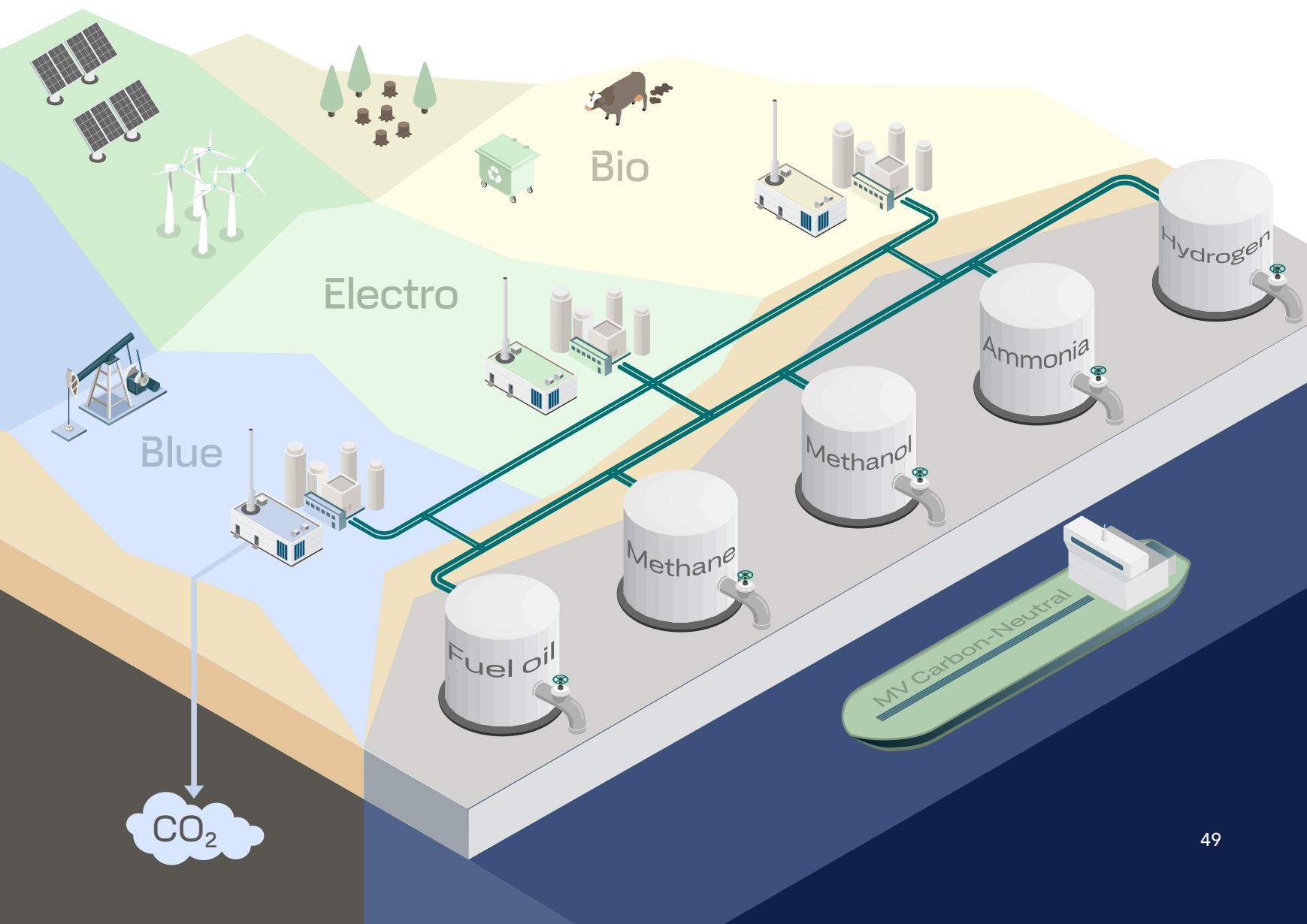
Irrespective of the energy source, production methods vary for different fuels, and for each fuel, even when made from the same energy source. Bio-LNG can be

made in different processes from biowaste or from forestry residue, for example. The ship may therefore receive the same fuel type produced in different ways from different origins. The supply chain impacts both cost and the sustainability of a fuel. Once produced, the carbon-neutral fuels will have to be distributed - with various requirements for containment, pressure, temperature, and so on. Figure 4.3 illustrates the complexity of such future fuel supply chains.



Figure 4.3

The future carbon-neutral energy supply chain





4.2.1 Energy source

Future fuel supply for shipping will rely on availability and price of energy sources: electricity from renewable sources, biomass, or fossil energy with CCS.

Helpfully, the cost of renewable electricity is falling as it develops rapidly, as analysed in DNV's Energy Transition Outlook over several years (DNV, 2021b). Production of electrofuels for shipping will nevertheless require the installation of massive amounts of additional renewable energy production capacity. The need for substantial investment is compounded by that fact that renewable electricity is also required to decarbonize several other sectors; for example, grid electricity, land transport, and industrial production including demand for carbon-neutral methanol and ammonia for industrial purposes.

A key consideration in this regard is the overall energy efficiency of the various energy pathways. When using electricity directly to power ships – via shore power ('cold ironing') or for charging onboard batteries – most of the electric energy generated is used, and there is a high energy efficiency. When using electricity to create electrofuels, however, there are large energy losses during production, distribution, and conversion on board. This can imply that only about 20% of the input electric energy consumed on land reaches the propeller on the ship. This low efficiency means that about 26 megawatt hours (MWh) of electric energy on land is needed to replace one tonne of fossil fuel oil, with a heating value (the energy going into the engine) of about 12 MWh.⁵⁵ The low well-to-wake energy efficiency of electrofuels adds to the required capacity of renewable electricity production, with corresponding investment. This is an important aspect when considering combined global emissions from both shipping and electricity generation for onshore use.

Feedstock availability is a potential barrier to widespread use of sustainable biofuels. However, studies reveal large amounts of biomass that can be used to create oil, methane, or methanol for ship fuel – for example, forestry residue, agricultural waste, and used cooking oil (IRENA,

Future fuel supply for shipping will rely on availability and price of energy sources: electricity from renewable sources, biomass, or fossil energy with CCS.

2014, 2017a; Lauri, 2014; WBA, 2016; IEA, 2017a, 2017b, 2019). The estimated potential varies between studies depending, for example, on what sustainability constraints are imposed on the biomass supply, and what types of biomass are considered. Many of the sources also consider the technical supply potential of biomass, not considering feasibility and logistics of transporting biomass from extraction site to biofuel plant. Nevertheless, there seems to be a consensus that there is significant potential to scale up biofuel production to make a meaningful contribution to decarbonizing sectors such as shipping and aviation.

Fossil energy is available in abundance, but for creating potential carbon-neutral fuels from fossil energy (blue fuels) large investments must be made in expensive CCS infrastructure. The CCS value chain consists of three main elements: CO₂ capture, transportation, and permanent storage (or utilization). Sources of CO₂ include direct air capture, flue gas from power stations, and CO₂ from industrial plants. Methods of transporting large volumes of CO₂ include pipelines and ships.

The limited deployment of CCS infrastructure so far is a major barrier for the prospects of blue fuels. Admittedly, CO₂ capture is not new. It is a proven technology with commercial units for carbon capture and utilization existing in a range of capacities depending on scope, with the largest plants aiming at natural gas cleaning. Furthermore, CO₂ as a commodity is widely used in the oil and gas industry, and other applications including in chemical manufacturing (as a feedstock, dry ice, inert

⁵⁵ A 14,000 twenty-foot equivalent (TEU) containership with about 27,500 tonnes of oil equivalent (toe) annual consumption, would require about 1% of Singapore's electricity production to run on electrofuels

gas, and for solvent extraction). However, the CCS value chain is immature and needs significant scaling. Furthermore, it appears likely that even a mature CCS value chain will be unable to capture the CO₂ from all relevant sources. The process itself will not capture all the CO₂ and requires more energy to achieve a higher capture rate. Only five of the current 21 CO₂ capture projects include dedicated storage, while most installed capacity is for utilizing CO₂ for Enhanced Oil Recovery. The integration of emission-abatement carbon capture plants into the existing CO₂ value chain has not yet built momentum; if it did, it would change carbon capture technology economics.

4.2.2 Fuel production

At the same time, some existing facilities can be reused, such as bio-MGO blending in oil refineries, or partially using existing ammonia or methanol production plants. Currently, total yearly production (for various purposes) of 176 Mt of ammonia and 98 Mt of methanol has a total energy content corresponding to 45% of shipping's

annual energy needs. Current production of ammonia and methanol is mostly fossil based.

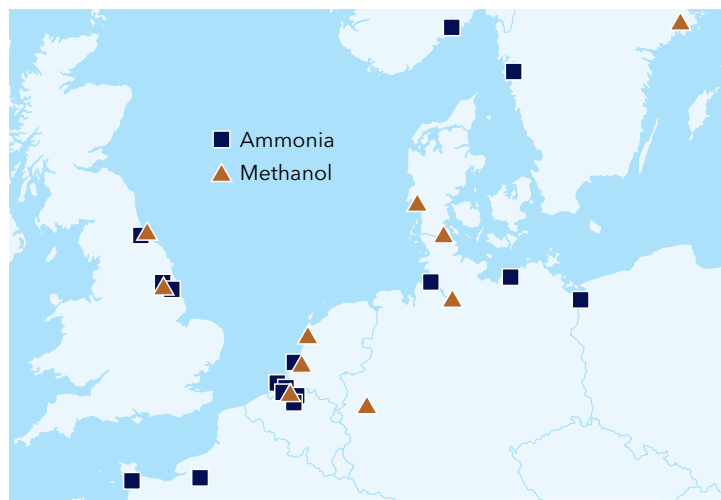
For this edition of DNV's Maritime Forecast to 2050, we have performed a market study identifying 128 projects planning to produce green or blue hydrogen, methanol, or ammonia, that could potentially be used as carbon-neutral fuels by ships. The planned energy output is 109 million tonnes of oil equivalent (Mtoe) by 2027. However, only a few of these projects are dedicated to shipping, as other industrial sectors also require zero or low-carbon variants of these commodities to decarbonize. Of the planned projects, 69 are in Europe with a planned output of 79 Mtoe by 2027, indicating the region's potential to be the first to have substantial amounts of green fuels available.

A complicating issue for the production of some carbon-neutral electrofuels - for example, methanol⁵⁶ - is that they contain carbon, and the production processes need the input of sustainably sourced and GHG-neutral

⁵⁶ Planned e-methanol production: <https://www.mip.no/en/2020/fast-track-to-carbon-capture-in-norwegian-industry> and <https://www.maersk.com/news/articles/2022/03/10/maersk-engages-in-strategic-partnerships-to-scale-green-methanol-production>

Figure 4.4

Existing infrastructure for supply and storage of ammonia and methanol in Northern Europe - see afi.dnv.com for updated world map of infrastructure for all alternative fuels



©DNV 2022



CO₂ such as biogenic carbon dioxide. The cost of sustainably sourced CO₂ is expected to be low in the beginning – for example, from biogas or paper production – but will increase once the lowest-cost sources are used. Potentially, direct air capture of CO₂ has to be used to produce electrofuels containing carbon, but the current cost of such CO₂ is prohibitively high. However, sustainable CO₂ capture capacity is not an issue when it comes to producing ammonia from hydrogen and nitrogen.

Additionally, large amounts of water are needed for electrolysis, which in some regions can either put pressure on fresh water supply or increase the energy input to the fuel production process by requiring desalination of the input water.

4.2.3 Distribution and bunkering of fuel

Provided there is sufficient energy availability and production capacity, the final barrier in the supply chain is the availability of infrastructure for distribution and bunkering of the relevant alternative fuels. Bunkering infrastructure for ships consists of storage and bunkering through trucks, pipes, or ships, to the receiving ship.

Existing infrastructure can be reused for some carbon-neutral fuels, even if blending them in with fossil fuels during the transition. Carbon-neutral fuel oil (bio-MGO, e-MGO) can use fuel oil infrastructure, and carbon-neutral liquefied methane (bio-LNG, e-LNG) can use LNG infrastructure. The degree to which ammonia can use the existing LNG infrastructure is being investigated.

For fuels which will require new dedicated bunkering infrastructure, the cost can be limited for non-cryogenic liquids such as methanol and liquid organic hydrogen carriers. For others, such as compressed or liquid hydrogen, a substantial cost will be incurred for bunkering infrastructure.

Distribution cost will vary with fuel properties; for example, there will be high distribution costs for cryogenic fuels. However, these costs can be reduced by using existing distribution infrastructure if it is available. There is already a significant shipping network for ammonia and methanol annually; it transports in the order of 50 Mt in total. To put this in perspective, a total of 50 Mt of methanol and ammonia used as ship fuel could



substitute 25 Mt of oil, about 10% of the world fleet’s energy demand. Figure 4.4 summarizes existing supply and storage infrastructure close to one of the world’s largest bunkering hubs. This infrastructure can possibly serve as a starting point for a distribution network for the use of ammonia and methanol as fuels for shipping, bringing down the ‘last-mile’ distribution costs.

Several projects for alternative fuel bunkering vessels are underway, and also for ammonia⁵⁷. Yara recently announced plans to build 15 bunker facilities for ammonia across Scandinavia by 2024. About 120 ports globally are today involved in seaborne transport of ammonia. In port, the commodity is usually stored in surface tanks. The fuel can be transported from production facilities to a central hub for storage, and from there via trucks, pipes, or bunkering vessels to ships. Green corridors can catalyse greater availability of alternative fuels in connected regions.

Ports will play a key role in the maritime fuel transition by serving as energy hubs providing both shore-side

electricity and infrastructure for storing and fuelling ships with alternative fuels. Ports are hubs connecting many different sectors through transportation and logistics. They are now emerging as energy hubs bringing together the many trends driving energy system integration. Ports might also become CCS hubs if this technology emerges as a viable option for ships. The Port of Rotterdam in the Netherlands, and the Northern Lights consortium⁵⁸ involving the ports of Oslo and Bergen in Norway are already actively involved in CCS.

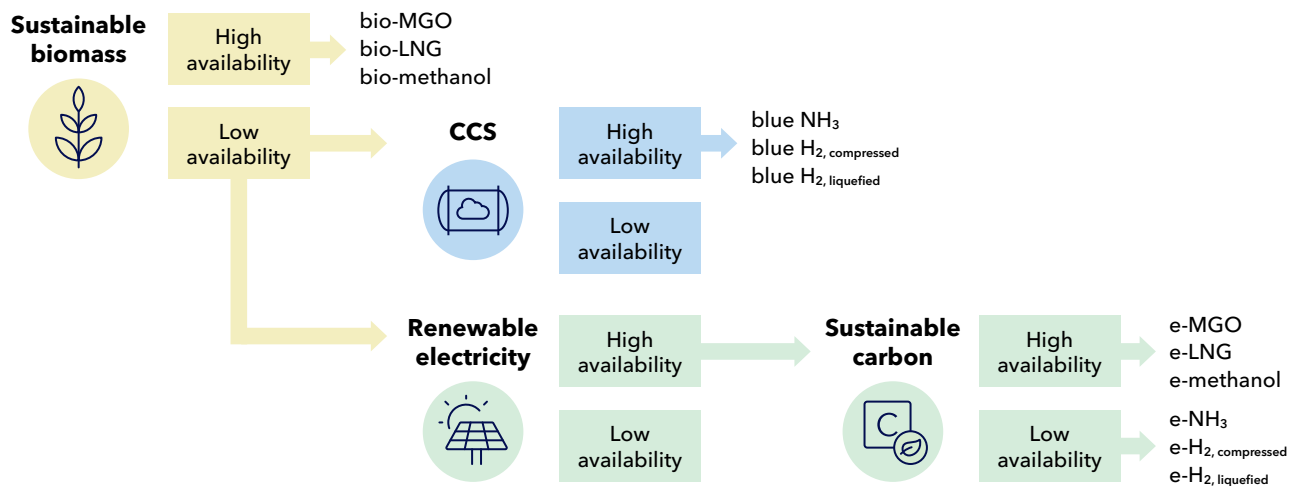
It will be critical for ports to address the regulatory and safety issues posed by some of the fuels. Another bunkering aspect to consider is that the lower energy density of the alternative fuels may require ships to bunker more frequently between major bunkering hubs. A more diverse fuel mix also challenges ports to decide which fuel infrastructures to invest in. Investment in electric charging infrastructure, with corresponding infrastructure for distribution of electric energy to the ports, for shore power and hybrid ships, will often be a good option.

57 MOL Acquires AIP for Ammonia Bunkering Vessel - Toward Realizing Ammonia Bunkering Business in Singapore - | Mitsui O.S.K. Lines

58 <https://www.equinor.com/energy/northern-lights>

Figure 4.5

These factors will determine the future fuel mix of shipping



Key: ammonia (NH₃); biofuel (bio-); carbon capture and storage (CCS); electrofuel (e-); fossil fuel with CCS (blue); hydrogen (H₂); liquefied natural gas (LNG); marine gas oil (MGO)

For shipowners to choose carbon-neutral fuels, the fuels must be available in relevant ports, and coordinated plans must be made for increasing availability.

For shipowners to choose carbon-neutral fuels, the fuels must be available in relevant ports, and coordinated plans must be made for increasing availability: from extracting energy from an energy source, to fuel production and distribution. There are plans for development and investments, including for international collaborations such as green corridors; these initiatives, and more, will need to be realized. The many plans and projects all aim to increase availability of carbon-neutral fuels. In the next chapter, we use DNV's model of the development of the global fleet to simulate the effects of having increased availability of carbon-neutral fuels in one or more regions.

4.2.4 Determining factors for the future fuel mix

The availability of sustainable energy sources and feedstock for production impose constraints on the use of different types of carbon-neutral fuels. Figure 4.5 shows the main factors whose – as yet uncertain – level of availability will determine which carbon-neutral fuels will be available for large-scale maritime use.

If sufficient **sustainable biomass** becomes available, it would be the preferred fuel as it is easily converted to relatively energy-dense hydrocarbon fuels such as bio-MGO, bio-LNG, or bio-methanol. The availability of such biomass needs to be seen in light of demand from other hard-to-abate sectors where energy-dense hydrocarbons are likely to be needed; for example, in aviation, where it is difficult to electrify long-haul flights. If there is low availability of sustainable biomass the prices of biofuels are unlikely to be competitive with those of electrofuels and blue fuels.

The availability of electrofuels depends on the availability of **renewable electricity** to produce hydrogen. This requires phasing out the use of fossil energy for electricity generation, a transition that is still a long way off in most regions. Using electricity even partly made from fossil fuels to produce electrofuels is not energy efficient and could lead to higher net emissions.

The availability of **sustainable carbon** from biogenic sources or direct air capture is also important. This carbon could be combined with hydrogen from electrolysis to produce e-diesel, e-methane, or e-methanol, again taking advantage of using more energy-dense fuels.

The availability of **blue fuels** depends on the effectiveness of carbon capture and the provision of infrastructure for permanent storage of the captured carbon. Mature CCS technology and infrastructure could also make onboard CCS a viable alternative where fossil fuels continue to be used.

In the next chapter, we use DNV's model of the development of the global fleet to evaluate the effect on the future fuel mix of high and low availability for each of the determining factors in Figure 4.5.



Highlights

Our scenario modelling explores the fuel transition facing shipping:

- We update our portfolio of decarbonization scenarios built with an enhanced version of our GHG Pathway Model.
- We investigate what will determine the future fuel mix and uptake of carbon-neutral fuels.
- We assess fuel costs by region, and how regional fuel production and infrastructure impact the future fuel mix.

5

PATHWAYS FOR DECARBONIZATION OF SHIPPING

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5 PATHWAYS FOR DECARBONIZATION OF SHIPPING

This chapter presents an updated portfolio of scenarios, built with an enhanced version of our GHG Pathway Model to explore the fuel transition that shipping is facing. We investigate how the future fuel mix and uptake of carbon-neutral fuels are impacted by the availability of energy sources and other key inputs for fuel production, and by price assumptions on emerging fuels, technologies, and retrofits. We also assess fuel costs regionally, and how the build-up of regional fuel production and infrastructure impact the development of the fuel mix.

This year's work builds on and extends our findings in previous editions of our Maritime Forecast to 2050, where we presented the GHG Pathway Model and our Carbon-Robust framework for future-proofing ship designs (DNV, 2018a, 2019, 2020, 2021c). Central to the use of the model is to generate a library of scenarios, each describing a possible development of the future fleet composition, energy use and fuel mix, and emissions to 2050.

Significant uncertainties around several factors influence the transition from conventional to carbon-neutral

fuels. Considering these uncertainties, scenario analysis is a well-established method that can provide valuable input to strategic decisions on newbuilding plans. The method can also enhance fleet flexibility and resilience to a range of possible futures related to regulatory and technology landscapes. A scenario describes a path of development under a particular set of framing conditions, without prejudging the likelihood of these conditions. It is not intended to represent a conclusive view on what the future will look like, but instead to highlight key factors that need to be in place to realize the pathway

5.1 Updated GHG Pathway Model

DNV's GHG Pathway Model is a flexible modelling tool for assessing alternatives for maritime decarbonization (Eide et al., 2011; Eide, Longva, Hoffman, & Endresen, 2011; Acciaro, Chryssakis, Eide & Endresen, 2012; Eide, Chryssakis, & Endresen, 2013; DNV, 2017b, 2018a, 2019, 2020; International Maritime Organization, 2021). The model has been further developed and enhanced since our previous Maritime Forecasts to 2050, though its basic structure and capabilities remain as described in the 2020 version of our report (DNV, 2020).

Figure 5.1 illustrates the model comprising of two core evaluation modules:

- **The Fleet Development Module**, in which the future fleet is simulated by adding and removing ships year-by-year. The world fleet of 2019 is used as a starting point, with associated ship data and estimated energy consumption based on Automatic Identification System (AIS) tracking data. The fleet develops according to the seaborne trade demand, with breakdown on main ship types. Seaborne trade growth is given as input from the 2021 version of DNV's Energy Transition Outlook model of the global energy system (DNV, 2021b).
- **The Abatement Uptake Module**, in which the model evaluates available solutions for CO₂ emission reduc-

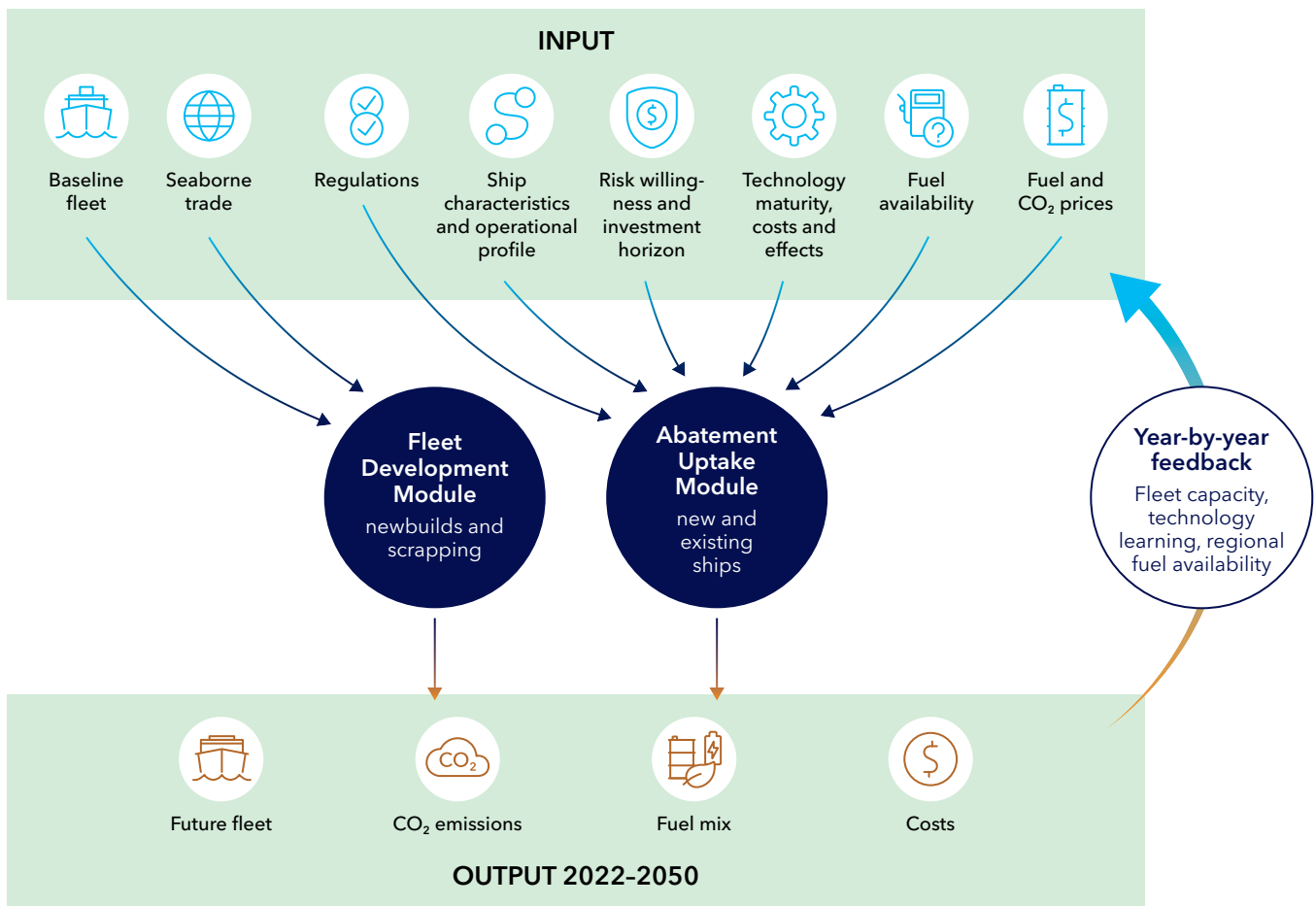
tion on all existing vessels and newbuilds for each year, including alternative fuels, energy-efficiency measures and speed reduction. Both newbuild technology options and possible fuel transition options for existing vessels, such as drop-in fuels or retrofit of engine and fuel system, are given as input to the model. The fuel price input is differentiated for 10 regions, and regional availability of fuels is used as an uptake criterion. With these inputs, the model simulates the economic and risk evaluations made by shipowners facing the shifting landscape of emission regulations, technology development, and fuel availability and prices. The ships are fitted with the

most cost-effective of the feasible combinations of abatement measures that fulfil regulatory requirements imposed as input. The model has a regulation look-ahead function allowing the investment decision to be made based on knowledge of upcoming regulations.

The model includes three feedback loops, where the choices made by shipowners one year affect the situation the next year. First, if speed reductions are adopted by a ship, thereby reducing the trading capacity of the fleet, the fleet development module ensures that additional ships are built to replace the lost capacity. In a second

Figure 5.1

GHG Pathway Model



feedback loop, uptake of technical measures and fuel technologies results in year-by-year technology learning, which reduces the investment costs for future installations. In the third feedback loop, the regional availability levels of emerging fuels are updated year-by-year based on uptake, simulating the development of fuel production and bunkering infrastructure.

Details regarding input to the model, including fuel prices and technology investment costs for newbuilds, and retrofit costs of existing ships, are given in the Appendix (page 81). These inputs are significantly updated from previous versions of this report. Note that while most technologies and fuels are included in the modelling, onboard CCS and nuclear powering are currently not.

The output of the model is vessel specific and provides an overview of energy use, uptake of measures, associ-

ated costs and other activity data. At the fleet and segment levels, the output provides projections of the future fleet, fuel mix, CO₂ emissions and abatement cost up to mid-century. The model also provides output on financial parameters such as capital and operational expenditure (Capex and Opex). Our modelling covers tank-to-wake CO₂ emissions, but our fuel price projections for carbon-neutral fuels assume sustainable feedstock with low or very limited well-to-tank emissions. We expect there will be variations across regions and development over time on well-to-wake emissions, having an impact on the uptake of various fuels. See also Section 2.2 on emerging well-to-wake emission standards and requirements. We have excluded non-CO₂ GHG emissions such as methane slip and nitrous oxides from the analysis. We anticipate that they will be addressed by regulations and reduced through technology development.

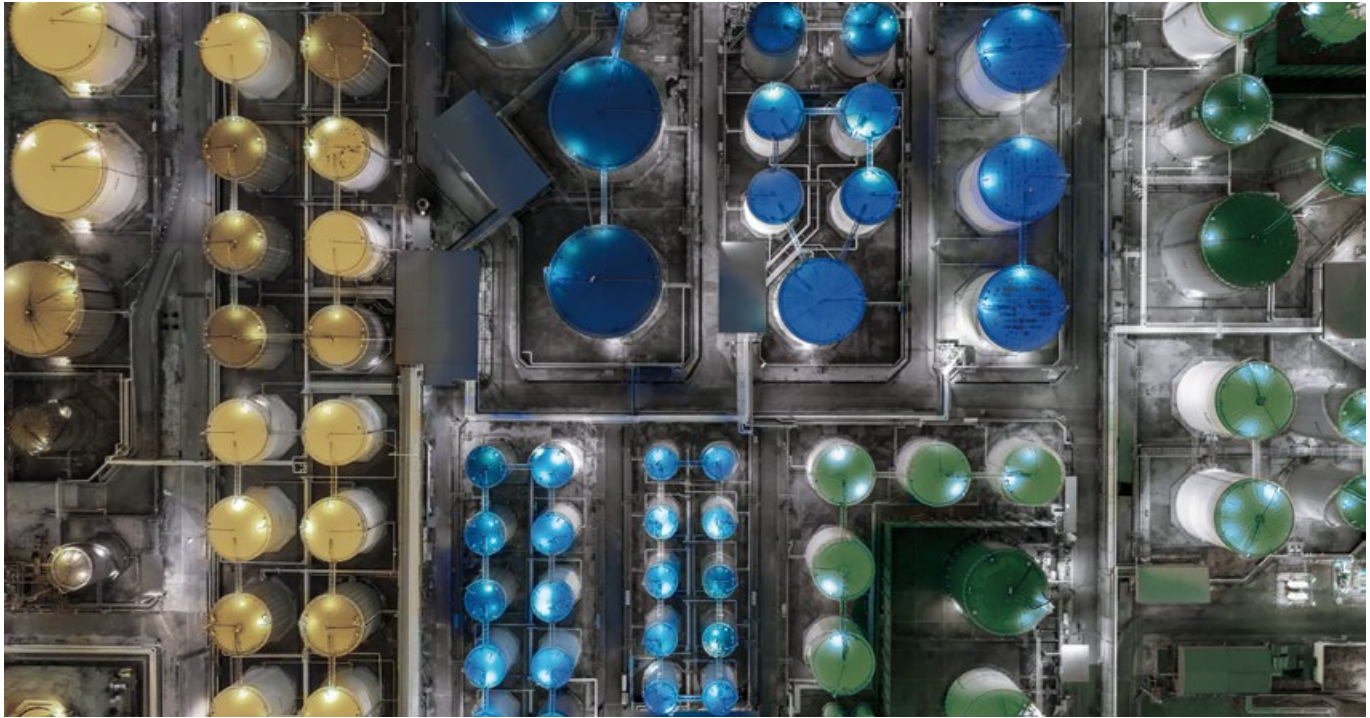
5.2 Exploring decarbonization scenarios

In this year's scenarios, we focus on the uncertainty in decarbonization ambitions (as outlined in Chapter 2) as well as on the variability in cost and availability of carbon-neutral fuels (as outlined in Chapter 4).

- We explore **two decarbonization pathways**: In the first, *IMO ambitions*, shipping achieves the ambitions set in the current IMO GHG Strategy, including a 50% reduction of total GHG emissions by 2050 compared with in 2008. In the second, *Decarbonization by 2050*, the fleet is fully decarbonized by 2050.
- We explore **six fuel family variations**, in which we simulate the availability of sustainable biomass to produce biofuels; renewable electricity to produce e-fuels; and fossil fuels with CCS to produce blue fuels. In each variation we provide a high or very high fuel-price advantage to one fuel family over the others, based on the bounds of uncertainty found in literature (see Appendix, page 75).

- We explore **three cost variations for specific fuel types**, in which changes in the relative cost differences between fuels within each family are explored:
 - For producing carbon-based electrofuels, a higher sustainable carbon feedstock price (for example, CO₂ from direct air capture) is used rather than lower-cost CO₂ feedstock from biogenic sources.
 - A higher price for bio-MGO and bio-LNG relative to bio-methanol, reflecting potentially higher production costs of such fuels.
 - Higher LNG price, reflecting natural gas prices that are potentially higher relative to other fossil fuels.

Further details on input are found in the Appendix (page 73). Table 5.1 summarizes the resulting 24 scenarios. The results from modelling with these scenarios are then presented in succeeding sections.



5.3 Scenario results

In most of our scenarios, around 5% of the energy use in 2030 is from carbon-neutral fuels. Under the *IMO ambitions* pathway, this share grows to around 20% in 2040, depending on the scenario. In the *Decarbonization by 2050* pathway, the share of carbon-neutral fuels grows significantly quicker, reaching 40% to 50% in 2040. In the following, we look closer at the energy mix in 2050.

Figure 5.2 shows the energy mix in mid-century for each of the 24 scenarios in Table 5.1. The total energy consumption is in the range 10.6 to 11.3 exajoules (EJ)⁵⁹ or about 253 to 270 Mtoe, varying between scenarios due to different uptake of energy-efficiency measures and speed reduction.

Among the *IMO ambitions* scenarios (1-12), the ratio of fossil fuels in the mix is quite consistent and varies from 53% to 63% of total energy consumption. Fuel oil (HFO

and LSFO/MGO) constitutes 55% to 65% of fossil fuel use in 10 of the scenarios, while LNG use is slightly higher than fuel oil use in the remaining two scenarios (9 and 11) where the LNG price advantage is the greatest. The share of carbon-neutral fuels (not including electricity from grid) is in the range of 30% to 40% in the *IMO ambitions* scenarios. In *Decarbonization by 2050* scenarios, all fossil fuels are eliminated. In all scenarios, around 3.5% of total energy is from grid electricity, mainly from shore power, but also from battery-driven ships.

Overall, the carbon-neutral fuels dominating the 2050 energy mix in at least one scenario are bio-MGO, bio-LNG, e-MGO, e-ammonia and blue ammonia, and bio-methanol. Among the carbon-neutral fuels, the share of drop-in fuels (bio-MGO, e-MGO, bio-LNG, e-LNG) is higher in the *IMO ambitions* scenarios than in the *Decarbonization by 2050* scenarios. Looking for example at

⁵⁹ Fuel lower heating value.

Table 5.1

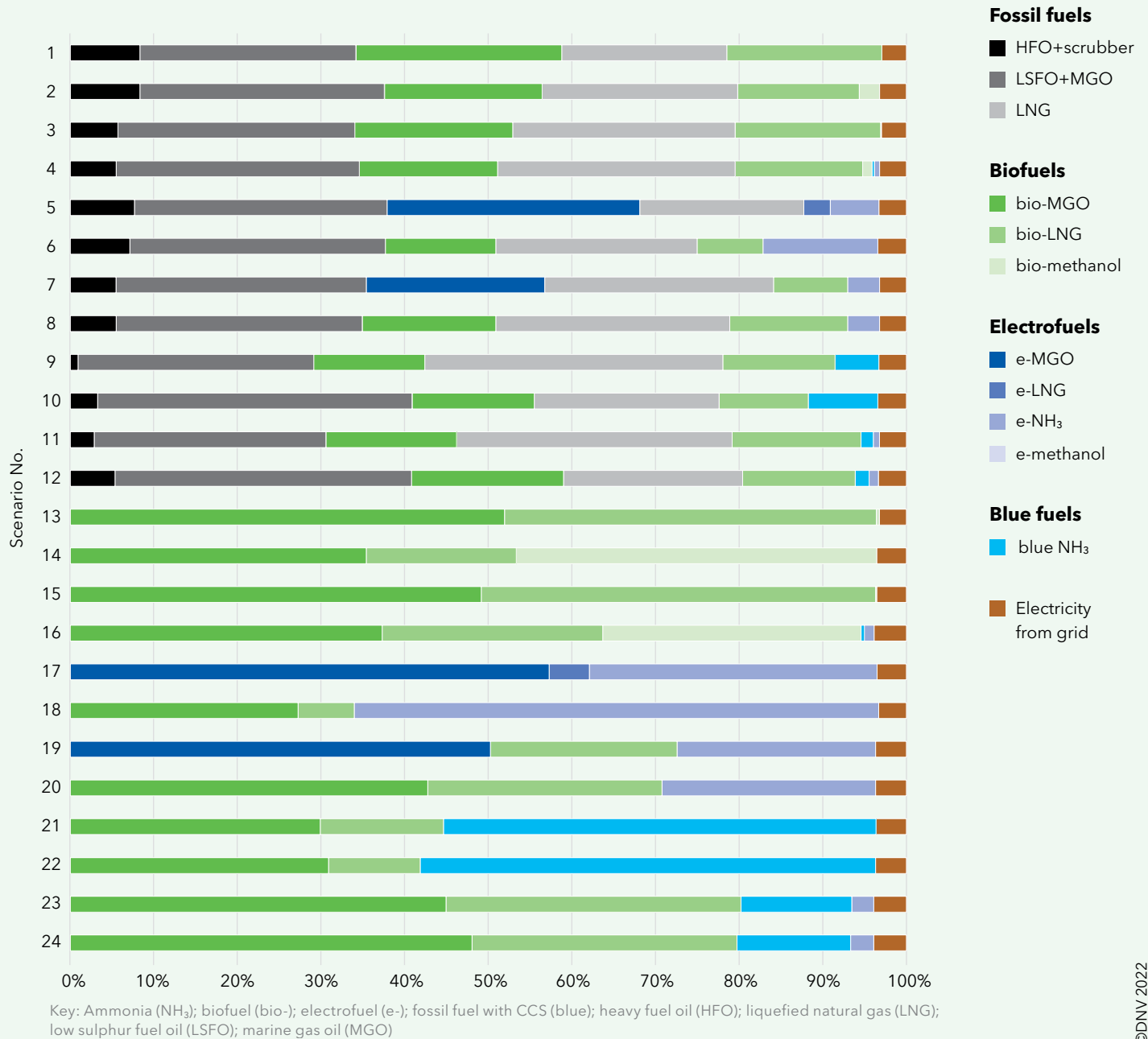
List of scenarios explored in this study

Decarbonization Pathway	Fuel family variation	Specific fuel cost variation	Scenario No.
IMO ambitions	Very Low bio		1
	Very Low bio	+ 20% bio-MGO and bio-LNG	2
	Low bio		3
	Low bio	+20% bio-MGO and bio-LNG	4
	Very Low electro		5
	Very Low electro	+150% to 200% e-MGO, e-LNG, e-methanol	6
	Low electro		7
	Low electro	+150% to 200% e-MGO, e-LNG, e-methanol	8
	Very Low fossil and blue		9
	Very Low fossil and blue	+20% LNG	10
	Low fossil and blue		11
	Low fossil and blue	+20% LNG	12
Decarbonization by 2050	Very Low bio		13
	Very Low bio	+20 % bio-MGO and bio-LNG	14
	Low bio		15
	Low bio	+ 20 % bio-MGO and bio-LNG	16
	Very Low electro		17
	Very Low electro	+150% to 200% e-MGO, e-LNG, e-methanol	18
	Low electro		19
	Low electro	+150% to 200% e-MGO, e-LNG, e-methanol	20
	Very Low fossil and blue		21
	Very Low fossil and blue	+20% LNG	22
	Low fossil and blue		23
	Low fossil and blue	+20% LNG	24

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Figure 5.2

Energy mix in 2050, share of energy use per fuel type, all 24 scenarios



Overall, the carbon-neutral fuels dominating the 2050 energy mix are bio-MGO, bio-LNG, e-MGO, e-ammonia and blue ammonia, and bio-methanol.

scenario 5 (Very Low electro, *IMO ambitions*), drop-in fuels constitute 85% of carbon-neutral fuels, while in case 17 (Very Low electro, *Decarbonization by 2050*), drop-in fuels make up 64%. This is due to a larger share of ships with ammonia or methanol dual-fuel engines in the *Decarbonization by 2050* scenarios because of faster strengthening of emission regulations. With moderate emission-reduction requirements as in the *IMO ambitions* scenarios, the use of drop-in fuels in combination with fossil fuels is more cost-effective than converting to ammonia or methanol engines and fuels. It should also be noted that a pilot fuel share of 23% for an ammonia dual-fuel combustion engine is assumed; in the Very Low electro scenarios, this is typically covered by e-MGO.⁶⁰

In the Low and Very Low electro scenarios (5-8, 17-20), the dominant electrofuels are e-MGO and e-ammonia, with less contribution from e-LNG. In scenarios 5, 7, 17 and 19 (with low sustainable CO₂ feedstock cost), there is more e-MGO than e-ammonia, even though the cost for e-MGO is higher. This indicates that with a high availability and sufficiently low cost of sustainable CO₂ to produce e-MGO or e-LNG from hydrogen, there is less incentive to invest in a significantly more expensive ammonia engine and fuel system, including the build-up of infrastructure. On the contrary, scenarios 6, 8, 18 and 20 have a high cost of CO₂ feedstock from direct air capture, leading to a shift from e-MGO and e-LNG to e-ammonia. Under these conditions, bio-MGO becomes the preferred drop-in and pilot fuel.

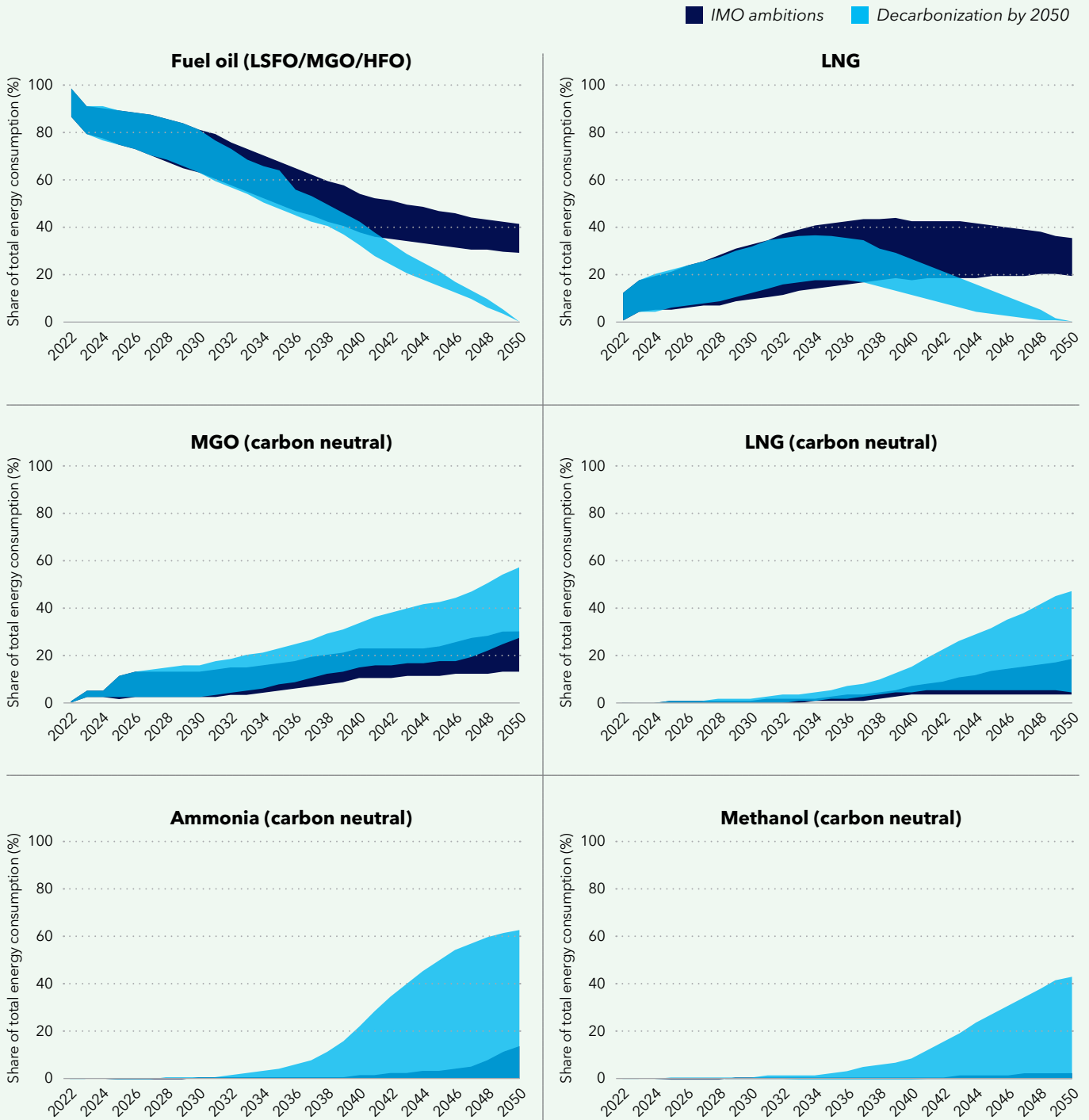
In the scenarios with higher cost for bio-MGO and bio-LNG (2,4,14,16), the bio-methanol share of the 2050

⁶⁰ This may be a conservative assumption, as engine manufacturers have a stated goal to achieve engine designs requiring a lower share of pilot fuel than this



Figure 5.3

The uptake over time for each fuel type - expressed by the range from minimum to maximum across all scenarios within the pathways *IMO ambitions* and *Decarbonization by 2050*



energy mix gradually increases as we go from Low biofuel prices to Very Low biofuel prices. This same trend is then further emphasized in the *Decarbonization by 2050* scenarios compared with *IMO ambitions* scenarios, yielding a substantial amount of bio-methanol in the energy mix of 2050 for scenario 14. This indicates that the uptake of methanol is very sensitive to the production cost of bio-methanol compared with bio-MGO and bio-LNG. If the fuel price advantage is not large enough there is limited incentive to invest in a methanol fuel system.

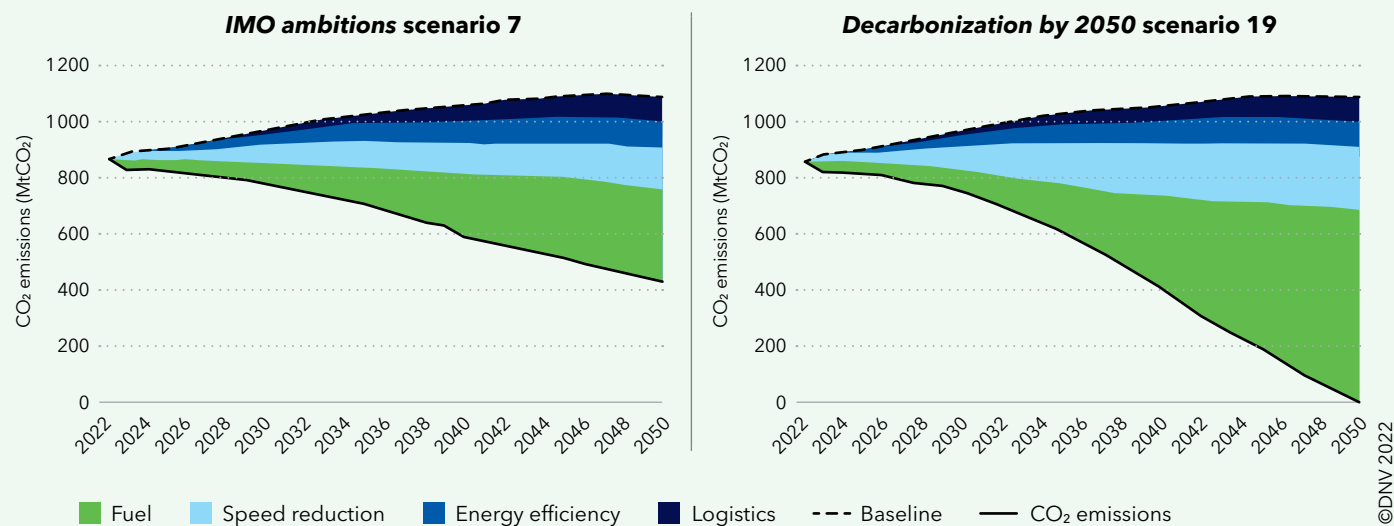
In the *IMO ambitions* Low and Very Low blue scenarios (9-12), there is a shift from LNG to MGO and ammonia when the LNG price is increased (10,12). In the *Decarbonization by 2050* variants (21-24), the higher LNG price leads to a shift from LNG to ammonia.

There are some differences between this year's scenario results and those presented in the 2020 edition of our forecast (DNV, 2020). The list of scenarios was different in

the 2020 version: *No ambitions*, *IMO ambitions*, or *Decarbonization by 2040*; regulations for emission reduction or carbon pricing; and low or high trade growth. This year we have a fleet growth scenario similar to the low trade growth scenario in 2020; we use technical requirements, not carbon price as the driver; and we use *IMO ambitions* and *Decarbonization by 2050*. The differences can be explained by changes in the GHG Pathway Model or in the input to the model. The modelling now includes pilot fuel for dual-fuel technologies, leading to an increase of MGO, e-MGO, and bio-MGO uptake, compared with the 2020 edition. The Capex of alternative technologies has been revised and increased (see Appendix, page 80) leading to a trend of more MGO, e-MGO, and bio-MGO. This trend is despite, for example, bio-methanol modelled as costing less than bio-MGO. Drop-in of fuels has been added to the model, leading to a preference for using lower Capex technologies and using drop-in as long as possible, even though e-MGO and bio-MGO are assigned higher costs than ammonia and methanol variants.

Figure 5.4

Shipping emissions reduction contribution by measure type compared with a baseline with current carbon intensity for *IMO ambitions* scenario 7 (left) and *Decarbonization by 2050* scenario 19 (right)



5.4 Emissions reduction contribution by measure

Figure 5.4 shows CO₂ emission trajectories towards 2050 for scenarios 7 (*IMO ambitions*, Low electro) and 19 (*Decarbonization by 2050*, Low electro), and the contribution to emission reductions from various measure types. These trajectories are compared with a baseline where the 2022 emission intensity is kept constant throughout the period. In line with previous analysis (DNV, 2021a), carbon-neutral fuels make only a limited contribution to emission reduction before 2030. Requirements are met primarily by the increased share of LNG, energy-efficiency measures, logistics improvements and speed reduction. After 2030, the use of

carbon-neutral fuels picks up. Beyond 2040, the use of carbon-neutral fuels become the dominant measure to reduce CO₂ emissions from baseline. Comparing scenarios 7 (*IMO ambitions*) and 19 (*Decarbonization by 2050*), there is a somewhat higher uptake of speed reduction in the latter, as well as more carbon-neutral fuel being required. For other scenarios, the picture looks the same as in these two plots; the higher cost of carbon-neutral fuels causes most ships to benefit from energy-efficiency measures, logistics improvement and speed reduction before the use of carbon-neutral fuels is scaled up.

5.5 Fuel families' contribution to the 2050 energy mix

We now look closer at how the different fuel families contribute to the 2050 energy mix in our scenarios. Figure 5.5 shows the mid-century energy mix of the fuel family variation scenarios for the *IMO ambitions* scenarios with no fuel-specific variation (i.e., 1,3,5,7,9,11).

Across these scenarios, 55% to 65% of the consumed energy is fossil. This stable share reflects uptake of carbon-neutral fuels being governed primarily by policy, and that only in the Very Low bio and electro scenarios is the fossil ratio slightly lower due to biofuels and electro-fuels being cost-competitive with fossil fuels in some regions.

The biofuels dominate the carbon-neutral share in scenarios where the bio-price is advantageous (Low or Very Low bio). In scenarios where electrofuels have the price advantage (Low or Very Low electro) they can outcompete the bio-alternatives.

Both the bio- and electrofuel families have drop-in fuels that are compatible with conventional fossil fuel technology. These drop-in fuels are bio-LNG or e-LNG for LNG, and bio-MGO or e-MGO for MGO/LSFO. This is not the case for the blue fuel family, and bio-alternatives therefore also dominate in the *IMO ambitions* scenarios where

the blue fuels are given preference (Low or Very Low blue). In these scenarios, the price of fossil fuels is also low. Hence, drop-in solutions – combining cheap fossil fuels with expensive biofuels – compare well with solutions requiring more expensive onboard fuel technology.

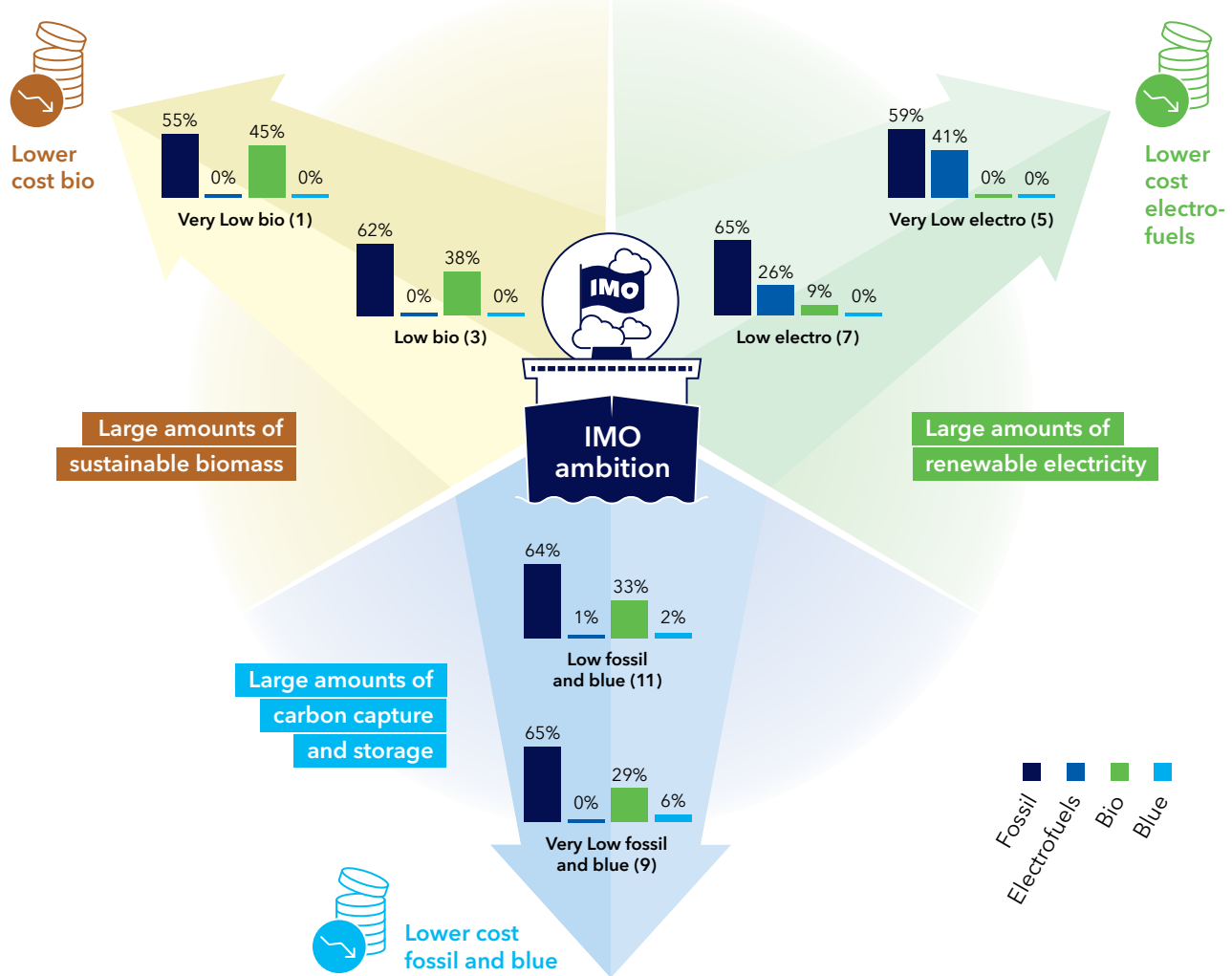
Looking at the energy mix in the *Decarbonization by 2050* scenarios (Figure 5.6), all fossil fuels are removed by policy requirements. As expected, the biofuels dominate the fuel mix in scenarios where the bio-price is advantageous (Low and Very Low bio). However, the bio-alternatives are also strongly present in scenarios where blue fuels are given preference (Low and Very Low blue), with blue fuels reaching only a 58% share under the most advantageous conditions.

In scenarios where electrofuels have the price advantage (Low and Very Low electro) they are able to outcompete the bio-alternatives.

In general, the share of drop-in fuels among the carbon-neutral fuels is lower in *Decarbonization by 2050* scenarios than in *IMO ambitions*. This is because the decarbonization regulations require all ships to be fully carbon-neutral when 2050 is approaching (and newbuilds from 2040), more ships tend to invest in

Figure 5.5

The 2050 energy mix of IMO ambitions family variation scenarios



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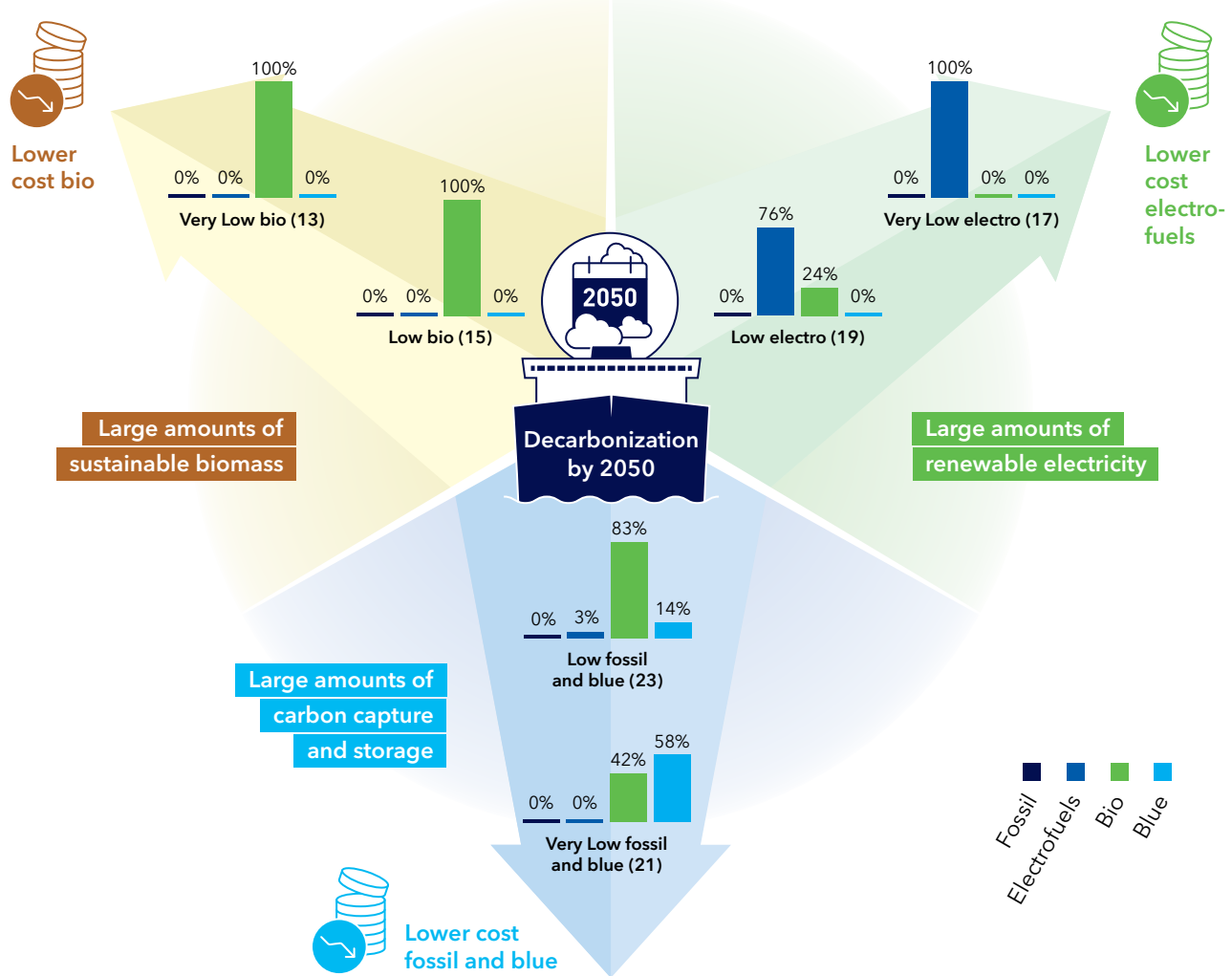
ammonia or methanol technology instead of fulfilling the requirements with carbon-neutral drop-in fuel.

As Figure 4.4 depicts, these results show that the question of availability of sustainable biomass for biofuel production is the most crucial question for the future energy mix. However, the electro and blue fuels also come with constraints on availability, mainly related to ramp-up of production rather than availability of energy sources. The

modelling does not apply specific limits on the availability of fuels but simulates availability constraints through variation in fuel prices between the fuel families. The results show what will be taken up of the various fuels given the prices in each scenario. If for example the level of sustainable biomass is lower than needed, the price will be too high and other fuels will take their place, leading to either the Low electro or Low blue scenarios, in which biofuels will be replaced with electro or blue fuels.

Figure 5.6

The 2050 energy mix of Decarbonization by 2050 family variation scenarios



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5.6 Investment needs

All scenarios described in the preceding section will require substantial investments if they are to be realized. This investment is needed in onboard technologies allowing ships to use new fuels (see Chapter 3) and in onshore infrastructure for producing and distributing

carbon-neutral fuels (see Chapter 4). The Capex for carbon-neutral fuel infrastructure includes investment needs for production of primary energy⁶¹ (e.g., generation of renewable electricity for electrofuels); fuel production plans (e.g. electrolysis plant or methanol

⁶¹ Due to lack of reliable data, the capital cost associated with cultivation and harvesting of biomass has not been included in the estimate of investment need

synthesis plan); and, distribution and bunkering of fuels to ships. Data is taken from DNV’s main Energy Transition Outlook report (DNV, 2022), as well as from literature sources (e.g., Brynolf, 2018; Navigante, 2019; IEA, 2020). The data is used to estimate the total investment needs.

The investment needs in the 24 scenarios are shown in Figure 5.7, accumulated for the period 2022-2050 and separated between fuel infrastructure and onboard investments. Averaging the accumulated onboard investments over the period gives annual investment costs in the range USD 8bn to 28bn for the *Decarbonization by 2050* scenarios. The largest investments come in scenarios with high uptake of ammonia or methanol, which require more expensive fuel systems. Figure 5.7 also shows that fuel infrastructure investments will outpace onboard investments in almost all scenarios.

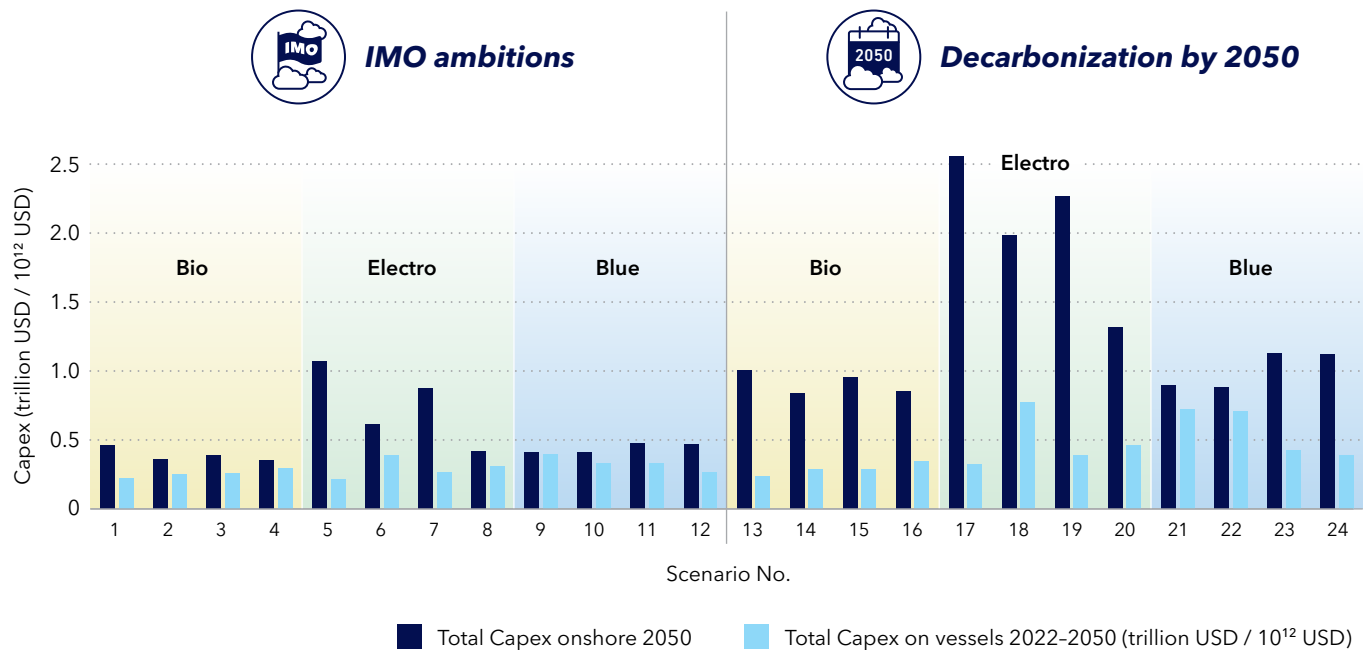
Our modelling also indicates that decarbonizing shipping completely by 2050 will require significantly higher investments than following the present IMO ambitions.

As can be seen from the fuel mixes in Figure 5.5 and Figure 5.6, *Decarbonization by 2050* scenarios require about 2.5 times more carbon-neutral fuel and corresponding capital for investment onshore compared with *IMO ambitions* scenarios. The average annual fuel infrastructure costs are in the range USD 28bn to 90bn to decarbonize by 2050. Including the added energy costs, the annual fuel costs for the ship could increase by more than USD 100bn to 150bn when fully decarbonized, 70% to 100% more than today.

The results show that the largest onshore investment needs are associated with renewable electricity production and electrolysis plants, seen in scenarios with Low and Very Low electrofuel prices.

Figure 5.7

Accumulated investment need in fuel infrastructure and onboard technologies allowing ships to use new fuels, for all 24 scenarios



5.7 Exploring the effect of first movers and increased availability of fuels

It is not only cost considerations that drive the evaluations made by the shipowner. How shipowners perceive the availability of fuels, and the knock-on effects of decisions made by other players, are both likely to play a role. We use our GHG Pathway Model to explore the impact of increased availability of ammonia in selected regions. Specifically, we run scenario 19 (*Decarbonization by 2050* scenario) with increased initial availability of ammonia in Europe (EUR) and South East Asia (SEA). This may represent a situation where first movers such as shipowners, energy suppliers or cargo owners initiate projects making large volumes of the fuel available in these regions (e.g., related to green shipping corridors).

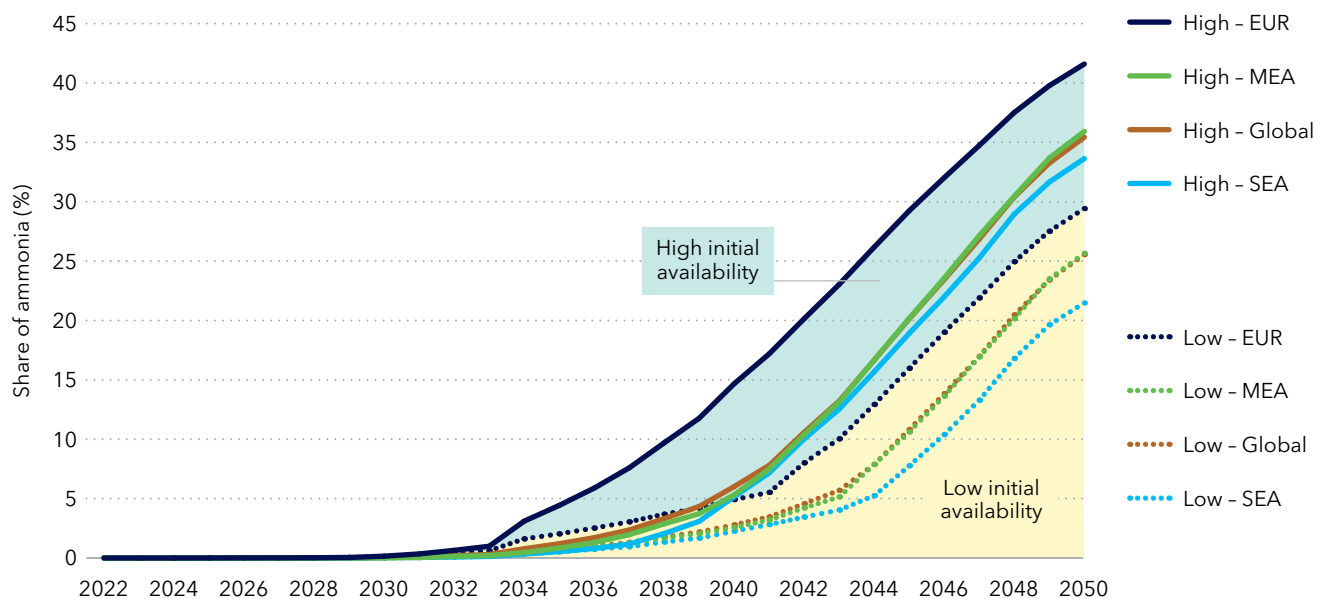
Figure 5.8 shows the uptake of ammonia in EUR and SEA, with both low and high initial availability. We see that the

uptake increases significantly with higher initial availability, both in the short and long terms. But Figure 5.8 also shows that uptake of ammonia increases in other regions – exemplified by Middle East and North Africa (MEA) – as well as globally, meaning that the initial availability in selected regions has ripple effects beyond their borders.

We have modelled the effects of increased initial availability in a scenario favourable to ammonia. We expect similar effects for other carbon-neutral fuels, given that they have been assigned favourable conditions in the scenario design. With higher initial availability, uptake of new fuels increases significantly within and beyond the region.

Figure 5.8

Ammonia’s share in total fuel consumption globally and in regions Europe (EUR), South East Asia (SEA), Middle East and North Africa (MEA), in scenario 19 (a *Decarbonization by 2050* scenario). Dotted lines show scenario with low initial availability of ammonia in all regions, solid lines show case with high initial availability of ammonia in EUR and SEA





APPENDIX

A.1 Regulatory input

The main uncertainty on the regulatory input is the level of ambition in 2050. The current IMO ambitions are for a 70% reduction in carbon intensity and a 50% reduction in total GHG emission relative to 2008. These will be reviewed in 2023, and a proposal is on the table to fully decarbonize shipping by 2050. This uncertainty is reflected in our scenarios with two ambition pathways, current *IMO ambitions* and *Decarbonization by 2050*.

The IMO has finalized developing the first regulations to support its ambitions in the short term - the EEXI and CII. Both ambition levels in our modelling, *IMO ambitions* and *Decarbonization by 2050*, include these measures. The IMO has started working on the next set of regulations to ensure that the 2050 ambitions will be met. There are proposals for both market-based measures setting a price on CO₂ and technical requirements setting emission intensity limits. The CO₂ price would be negotiated by the IMO in the case of a levy, and by the market in the case of a

cap-and-trade scheme. In both cases, assuming that the ambition will be met, the price will be the cost gap between current and carbon-neutral solutions. We assume that the technical requirement is likely to be implemented as this is a well-known approach by the IMO, while market-based measures is a novel concept in the IMO. As a simplification, we model the trajectories in the two ambition pathways through design and operational requirements, and do not include a global CO₂ price. Assuming that a technical requirement is implemented, the trajectory would be the same and the technology decision would not be different. We have included a regional carbon price for ships trading in Europe based on projections on the EU ETS price under the two scenarios modelled by DNV's Energy Transition Outlook global energy system model in (DNV, 2021d) and (DNV, 2022).

Table A.1 gives the specific assumptions for the two ambition levels.

Table A.1

Assumptions on regulatory measures and GHG emissions reduction (%)

Ambition	Technical requirements		Market-based measure
	Newbuild requirements	Operational requirements (gradually increasing)	Carbon price
IMO ambitions	Currently adopted EEDI requirements: up to 30% reduction depending on ship type <ul style="list-style-type: none"> ■ From 2035: 50% to 80% reduction depending on ship type ■ From 2040: 90% reduction 	Currently adopted CII and EEXI requirements <ul style="list-style-type: none"> ■ 2030: 40% reduction ■ 2050: 75% reduction 	ETS allowance prices for ships when operating in Europe <ul style="list-style-type: none"> ■ 2023-2030: USD 22/tCO₂ to 95/tCO₂ ■ From 2030: up to USD 135/tCO₂
Decarbonization by 2050	Currently adopted EEDI requirements: up to 30% reduction depending on ship type <ul style="list-style-type: none"> ■ From 2035: 50% to 80% reduction depending on ship type ■ From 2040: 90% reduction 	Currently adopted CII and EEXI requirements <ul style="list-style-type: none"> ■ 2030: 40% reduction ■ 2050: 100% reduction 	ETS allowance prices for ships when operating in Europe <ul style="list-style-type: none"> ■ 2023-2030: USD 14/tCO₂ to 150/tCO₂ ■ From 2030: up to USD 250/tCO₂

A.2 Projection on fuel prices

Future fuel prices are challenging to predict, but a systematic analysis of different fuel supply chains (Figure 4.3) allows us to estimate realistic spans in production and distribution costs per fuel. This in turn gives us insights into the most important cost drivers for carbon-neutral fuels. We have updated DNV's Marine Fuel Price Mapper tool (DNV, 2020) that models the cost of various marine fuels (Figure A.1). It specifically models the production steps for different processes, and includes the regional costs for different kinds of biomass, electricity, fossil energy and CCS, aligned with DNV's Energy Transition Outlook model of the global energy system until 2050 (DNV, 2021b, 2022).

Two different approaches are applied for carbon-neutral and fossil fuels:

Carbon-neutral fuels: Levelized cost of production and distribution are used as proxy for price. Bottom-up costs are estimated per carbon-neutral fuel supply chain, including:

- Production and processing steps
- Distribution
- Cost of CO₂ feedstock (as applicable)

Fossil fuels: Historical relationship between fossil fuel price and the price of crude oil or natural gas are used to estimate future fuel prices

Figure A.2 shows estimated high and low prices for fuels in mid-century, calculated as a global mean average of all 10 global regions as defined in DNV's Energy Transition Outlook model of the global energy system to 2050.

Figure A.1

DNV Marine Fuel Price Mapper

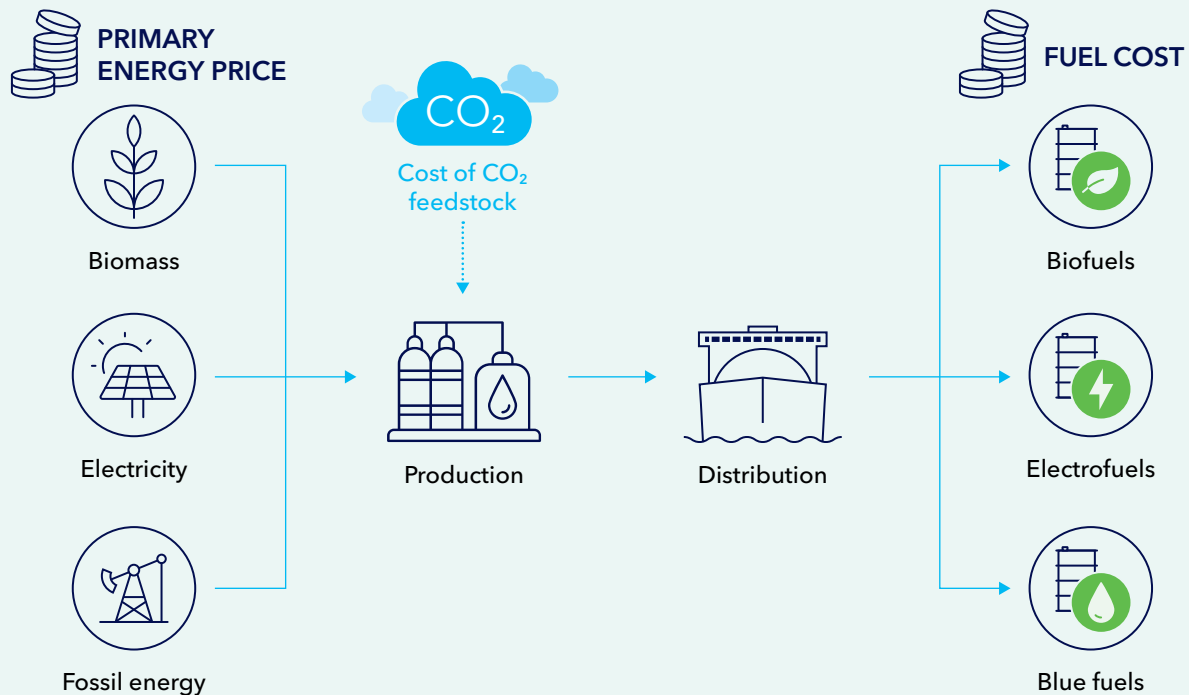
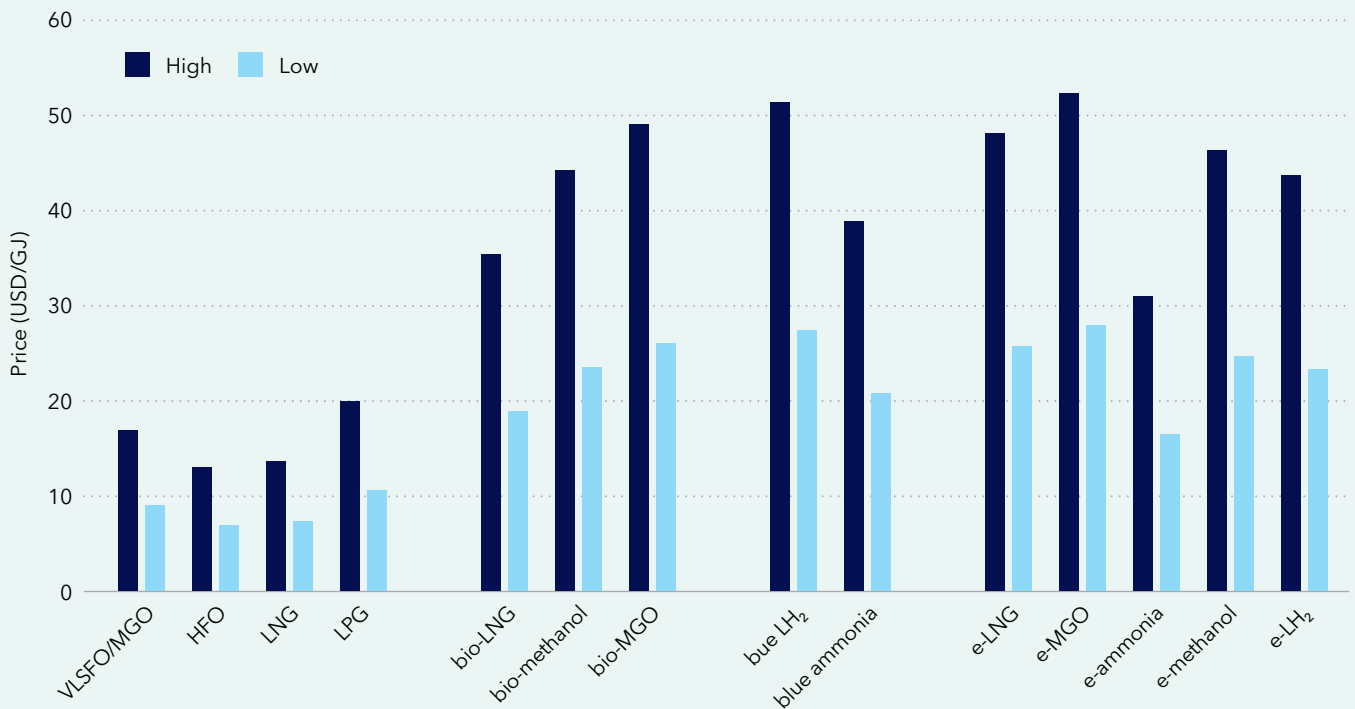




Figure A.2

Estimated high and low prices for fuels in 2050. The prices shown include both production and distribution costs and have been taken as a global mean average of all regions. Fossil-fuel prices do not include carbon price



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A.3 Energy-efficiency measures

DNV’s own Abatement database for different ship types is used as input to DNV’s GHG Pathway Model. The Abatement database covers costs and emission-reduction potential for many technical and operational measures allocated into predefined ship categories. Data on costs and reduction effects for operational and technical measures are based mainly on data from available literature; more than 30 three-phased energy management projects; fuel-consumption data from ship reports; DNV’s Technology Outlook activities; and COSSMOS⁶² modelling and simulation projects.

Our model does not evaluate the uptake of each single measure (e.g., waste-heat recovery, air-cavity lubrication). Interactions between the measures are complex to model. We instead compile the energy efficiency (EE) measures into internally consistent packages as presented in Table A.2.

The measures included in the different EE packages will depend on the applicability for the ship type in question. This study allocates the EE measures in packages for six main ship segments.

A.4 Speed reduction

The model applies five different levels of speed reduction: 0% (sailing at 75% to 80% of maximum continuous rating, MCR⁶³), 10%, 20%, 30% and 50%. The resulting reductions in main-engine power for an individual vessel

are estimated based on reported fuel-consumption data from more than 2,000 vessels. Percentage main power reduction is larger at 10% and 20% speed reduction than at 30% and 50% where the resistance from wind and

⁶² DNV COSSMOS: Computer platform for modelling, simulation, and optimization of complex ship energy systems

⁶³ The MCR is the maximum power output from an engine operating continuously within safety limits

Table A.2

Defining the energy-efficiency (EE) packages

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

waves becomes more prominent. As much as 30% to 35% less fuel is used when speed is reduced by 20%, and 60% to 67% less when the speed reduction is 50%. Speed reduction comes at a cost. As the transport capacity of the vessel is reduced, its earning capacity also declines. More vessels would have to be built to cover for the lost capacity. In addition, the cargo owner has increased costs due to capital being tied up through longer sailing times. This is reflected in the modelling, where the cost of speed reduction is based on the charter rate of the vessel type and included when considering the most cost-effective measure to apply. The model factors in the applied speed reduction and adds more vessels to make up for the reduced transport capacity.

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

A.5 Logistics

Toward 2050 we expect gradual improvements in the supply chain to increase vessel utilization by about 25% for deep-sea trades except bulk; approximately 5% for deep-sea bulk; and, by some 20% for short-sea trades.

We expect average ship sizes to increase by 40% for LNG tankers, 30% for containerships and 10% for bulkers. The sizes of other types of ship will remain as today.



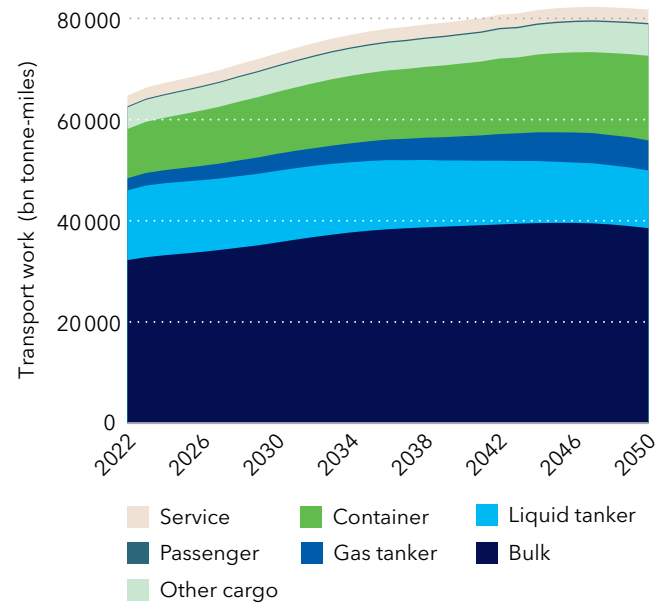
A.6 Trade growth

Studies have reported that international world maritime trade could grow between 25% and 250% by 2050 (Smith et al., 2014; ITF/OECD, 2019; DNV, 2019a, 2020a). The Fourth IMO GHG study projects between 40% and 115% growth (Faber et al., 2020). The large span in the projections indicates substantial uncertainty, which has been explored in the 2020 edition of our Maritime Forecast to 2050 (DNV, 2020).

This year we use only DNV’s own updated projection with overall 29.55% growth between 2022 and 2050 in seaborne trade in tonne-miles, used in Maritime Forecast 2021 edition (DNV, 2021c), see Table A.3 and Figure A.3. Most of the growth will come before 2030, after which global seaborne trade will stabilize. Growth in certain segments, especially gas and the container trade, will outpace the average rate. However, as the global demand for coal and oil peak, so will their trade, reducing their seaborne trade by more than two-thirds and one-third, respectively.

Figure A.3

Projected transport work (billion tonne-miles) up to 2050 by main ship categories



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Table A.3

Seaborne-trade demand growth assumptions

Assumptions	Average annual change			Total change 2022-2050
	2022-2030	2031-2040	2041-2050	
Bulk	1.4 %	0.9 %	-0.1 %	22.3 %
Liquid tank	0.5 %	-0.9 %	-1.3 %	-15.9 %
Gas tanker	4.4 %	3.6 %	2.2 %	160.2 %
Container	2.9 %	1.7 %	1.5 %	77.2 %
Other cargo	2.2 %	1.2 %	1.0 %	50.5 %
Passenger and Service	1.7 %	0.8 %	0.3 %	31.2 %
Total growth	1.6 %	0.9 %	0.3 %	29.5 %

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A.7 Converter options, maturity, and compatibility

The allowed engine/fuel cell and fuel-system options, compatible fuels and retrofit options are indicated in Figure A.4. Drop-in fuels are those that can be used in an engine or fuel cell without any additional retrofit Capex. For each converter option, the model calculates the cheapest fuel combination that will meet the regulatory requirements. Thus, for a dual-fuel methanol engine, the cheapest combinations of bio-methanol, e-methanol, bio-MGO, e-MGO and VLSFO/MGO will be calculated. Drop-in fuel may be utilized 100%, or in different fuel blends; for example, a mono-fuel engine can run on a 30% VLSFO/MGO and 70% bio-MGO blend.

We also allow for retrofits from certain engine options to another, as indicated in Figure A.4. In such cases, this will

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

Figure A.4

The energy converters, fuel options and transitions allowed in the GHG Pathway Model

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

Key: Dual fuel (DF); electric motor (EM); fuel cell (FC); internal combustion engine (ICE); liquefied natural gas (LNG); liquefied petroleum gas (LPG); mono fuel (MF)

✅ Drop-in ⚙️ Retrofit



A.8 Newbuild and retrofit fuel technology Capex

Our GHG Pathway Model estimates the investment cost of implementing alternative fuels and energy-efficiency measures on board the analysed fleet. Investment costs are different for each engine/fuel cell and fuel system shown in Figure A.4. They are divided into the cost of engine and fuel-supply system and the cost of the fuel-storage system. The investment cost of implementing alternative fuels depends on whether the vessel in question is a newbuild or an existing vessel needing a retrofit.

As an example, the engine and fuel-supply system of vessels running on LNG are assumed to be more expensive than those running on methanol. Likewise, storing methanol as a fuel on board a vessel is assumed to be cheaper than storing LNG. Estimated cost-data are based on an extensive review of literature (Taljegard, Brynolf, Grahn, Andersson, & Johnson, 2014; FCBI, 2015; de Vries, 2019) reported newbuild prices for vessels running on

alternative fuels, and communication with industry actors.

There have been a number of developments within the uptake of alternative fuels in shipping since the 2020 edition of DNV's Maritime Forecast to 2050 was published (DNV, 2020). For example, 2021 saw the world's first order of a methanol-fuelled container vessel⁶⁴ and delivery of the first ferry to be fuelled by liquefied hydrogen⁶⁵. These developments have provided us with new information regarding the cost associated with implementation of alternative fuels on board vessels. In turn, this has caused us to make some changes to our input data for Capex in the GHG Pathway Model. In general terms, the costs have been revised upwards compared with in the previous Maritime Forecast to 2050 study. In particular, this is the case for vessels running on methanol.

⁶⁴ <https://www.maritime-executive.com/article/maersk-orders-first-methanol-fueled-containership>

⁶⁵ <https://www.offshore-energy.biz/worlds-1st-hydrogen-powered-ferry-delivered>

A.9 New features of our model

This year's enhanced model includes three major upgrades: regionalization of fuel prices and fuel availability, improved fuel blend-in and pilot fuel functionality, and a simple lookahead for technology investments.

Regionalization of fuel prices and fuel availability

Fuel prices are differentiated based on 10 regions as per DNV's Energy Transition Outlook global energy system model (DNV, 2021b). The fuel price considered in the NPV calculations for each ship will then depend on the area of operation.

In each of the 10 regions, each fuel is assigned with an availability level of 1 (low), 2 (medium), or 3 (high). The initial availability level of bio-MGO and e-MGO is set to 3, since they can use the existing distribution and bunkering infrastructure of liquid fossil fuels. LNG, bio-LNG and e-LNG are set at initial level 2, while hydrogen, ammonia and methanol are at availability level 1. Shipowners with high-risk willingness will see fuels at any availability level (level 1 through 3) to be available and feasible for their operation. More risk-averse owners will only consider fuels with higher availability (2 or 3). The availability level per fuel in each region is updated year-by-year, following how the uptake of fuel develops in that region. With increasing availability, an increasing share of shipowners will consider the fuel a feasible option for their operation. Eventually, it will be the cost evaluation of all feasible options that will determine which fuel will be chosen for the ship.

Fuel blend-in functionality and pilot fuels

For each vessel, the most cost-effective share of drop-in fuels for each converter is calculated, allowing the shipowner to use the exact required amount of the expensive drop-in fuels to reduce the CO₂ emissions. This allows shipowners to run longer on existing technologies and delay expensive investments.

DNV's GHG Pathway Model

estimates the investment cost of implementing alternative fuels and energy efficiency measures on board the analysed fleet.

The dual-fuel ICE engines are configured with some share of pilot fuel, resulting in a need for MGO (fossil or carbon-neutral) to have a share in the fuel mix for these converters.

Simple lookahead for technology investments

Depending on the shipowner's investment horizon, the model looks some years ahead when evaluating technology newbuild and retrofit options. When a technology has been selected, the cheapest compliant drop-in and speed reduction combination (and for newbuilds, the energy-efficiency package too) is calculated each year. A ship, newbuild or retrofit, may then, for example, install dual-fuel ICE ammonia to be prepared to meet the compliance requirements 10 years ahead, but will use only MGO in the initial years before it becomes necessary to use an increasing share of carbon-neutral fuel to comply with regulations.

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THE PROJECT TEAM

This report has been prepared by DNV. In addition, we have been greatly assisted by an external network of maritime experts.

Steering committee:

Remi Eriksen, Ditlev Engel, Ulrike Haugen, Trond Hodne, Liv Hovem

Lead authors:

Eirik Ovrum, Tore Longva, Linda S. Hammer, Nikolai Hydle Rivedal, Øyvind Endresen, Magnus S. Eide

Contributing authors:

Henrik Helgesen, Øyvind Sekkesæter, Marius Leisner, Kristian Hammer, Helge Drösemeyer, Kjersti Aalbu, Jakub Walenkiewicz, Jeannette Schäfer

Reviewers:

Håkon Hustad, Christos Chryssakis, Jan Kvålsvold, Martin Wold, Eirik Nyhus, Terje Sverud

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www.dnv.com/maritime-forecast

Headquarters:

DNV AS
NO-1322 Høvik, Norway
Tel: +47 67 57 99 00
www.dnv.com

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