WHEN TRUST MATTERS

Energy Transition Outlook 2023

MARITIME FORECAST TO 2050

A deep dive into shipping's decarbonization journey

FOREWORD

This is a critical decade for setting our industry decisively on course for net zero. The UN Secretary-General's warning that we are entering an era of 'global boiling' should ring an alarm bell also on the bridge.

Shipping's decarbonization is underway slowly like a supertanker coming about. That is clear from our latest Maritime Forecast to 2050 showing promising rising orders for new ships able to run on lower-carbon fuel options, but very few operating vessels doing so.

At MEPC 80, governments acknowledged this, leading to the IMO's revised greenhouse gas strategy driving accelerated net-zero ambitions. Moreover, ship emissions will be priced through the EU Emissions Trading System from 2024.

The clock is ticking louder on efforts to identify, define, and resolve barriers to successful and safe decarbonization. Complex and costly decisions form the backdrop for ship designs, propulsion systems, and fuel sourcing.

The best strategy will hinge on many parameters, such as vessel size and trading pattern. Yet pragmatism and a defined pathway for the vessel's life will be key to avoid unattractive or stranded assets. To support investment decisions, Maritime Forecast to 2050, produced from broad industry sources and DNV modelling, focuses both on challenges and possible actions.

The report predicts that meeting the IMO GHG goal for 2030 will require shipping to secure 30–40% of the estimated annual global supply of carbon-neutral fuels by then – a daunting, nearly impossible task considering that other sectors will compete for the same fuel supply. Thus, whatever can be achieved to reduce energy consumption is a no-brainer. Operational energy-efficiency measures like speed reduction, route optimization, and hull and propeller cleaning should be implemented wherever possible.

'Smart' and digital systems on individual vessels and fleets offer high rewards through operational efficiencies. Innovative air lubrication systems and wind-assisted propulsion can boost efficiency and reduce fuel consumption. Maritime Forecast to 2050 reviews their status and quantifies reported and potential benefits. There is also an urgent need for low-emission technologies for environmental benefits and as alternatives to carbon-neutral fuels that looks likely to become costly and hard-to-source.

Accordingly, Maritime Forecast to 2050 runs the numbers on carbon capture and nuclear propulsion technology versus existing and future marine fuels. Under some conditions, both onboard carbon capture and nuclear look feasible operationally and could compete with other decarbonization fuel strategies. There are caveats – there is a long road to travel before nuclear can be scaled, and a long logistics chain still needs to be developed for onboard carbon capture – but we should still evaluate these and other technologies to explore alternative pathways.

An expected shortfall in carbon-neutral fuels drives us to widen our scope and explore all available fuel options. So, Maritime Forecast to 2050 presents a detailed analysis of liquefied hydrogen, an energy source which could become a viable option.

Regulatory change, and stakeholder and public pressure to decarbonize, will impact commercial boundary conditions. It thus makes business sense to ensure sound long-term CAPEX decisions and prevent assets from becoming unprofitable. Flexibility is key. Everything should be considered – fuels, digital tools, fleet deployment and optimization – in seeking individually tailored strategies for collective industry gain.

Collaboration is needed to ensure that future fuel supply, infrastructure, and investment decisions are appropriate. Decarbonization of shipping will come with significant costs, costs that cannot be absorbed by single stakeholders, being shipowners or governments. New contractual arrangements will likely be needed in order to have the additional costs allocated through the value chain and eventually reaching the end consumer. Maritime Forecast to 2050 details how green shipping corridors can speed up change by piloting on a smaller, manageable scale. Successful green corridors may inspire global actions.

Together, we can make this decade decisive for maritime decarbonization.

Knut Ørbeck-Nilssen

CEO Maritime

DNV

CONTENTS

Click on the section you want to explore !

1

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 shipping's energy future. It also examines how the industry will be impacted by: new International Maritime Organization (IMO) ambitions for reducing greenhouse gas (GHG) emissions from shipping; the regulations that will be developed as a follow-up; and by recently adopted EU regulations.

The impact will be increased costs for individual shipowners from technology, carbon-neutral fuels, and/or carbon price. Commercial drivers will also be important, as GHG performance will affect commercial attractiveness and long-term profitability. This will have a large effect on shipowner decarbonization plans and fuel strategies. The most important steps towards zero-emission shipping should be taken now in what will be a decisive decade for shipping.

> A fuel technology transition is already underway in the maritime industry, with half the ordered tonnage capable of using LNG, LPG, or methanol in dual-fuel engines, compared to one third of the tonnage on order last year.

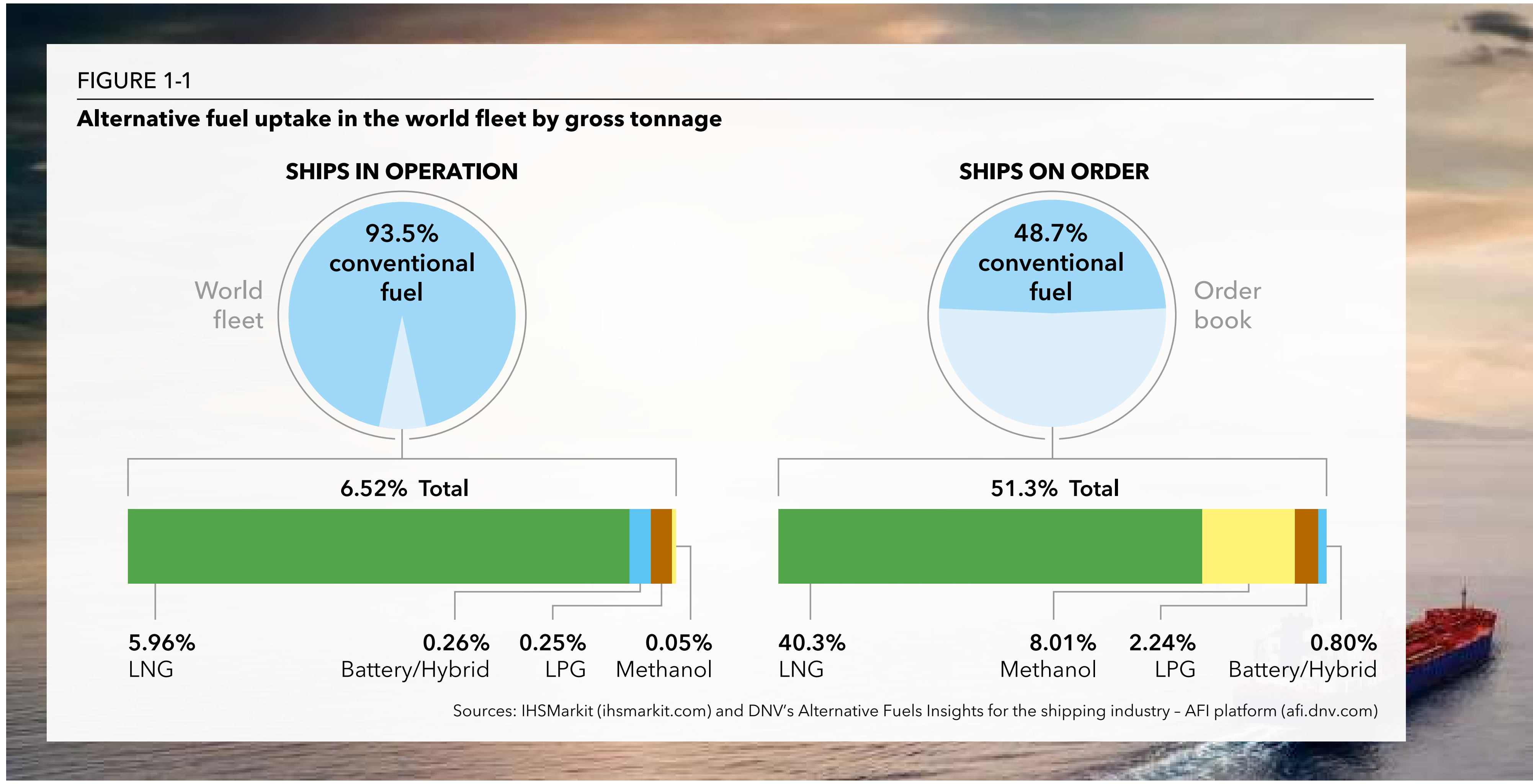
What we did

We present an updated outlook on a range of regulations and drivers for decarbonization of shipping; the most important being the new IMO ambitions, the EU's Emissions Trading Scheme (ETS) carbon price, and coming well-to-wake regulations. The revised IMO GHG strategy now aims for reaching net-zero GHG emissions by 2050. The EU ETS will for the first time in international shipping set a price on ship GHG emissions, a development that could be adopted in other regions or even globally by the IMO. Coming 'well-to-wake' regulations will impose requirements on fuel production. We calculate the total GHG emissions from shipping towards 2050 in a decarbonization scenario, which shows that without well-to-wake regulations and fuel production standards, the emissions will be transferred to other sectors.

A fuel technology transition is already underway in the maritime industry, with half the ordered tonnage capable of using LNG, LPG, or methanol in dual-fuel engines, compared to one third of the tonnage on order last year. For ships in operation, 6.52% of tonnage can now operate on alternative fuels, compared to 5.5% last year. The uptake of methanol and LPG is starting to show in the statistics together with the first hydrogen-fuelled newbuilds. Though several demonstration projects for ammonia-fuelled ships are ongoing, there are no ammonia-fuelled ships in the official order book.

FIGURE 1-1

Alternative fuel uptake in the world fleet by gross tonnage



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

While the fuel technology transition gathers pace, the search for solutions continues. We know that technology to reduce both energy consumption and the need for expensive fuel will be important. Given the need to understand and have a clear view of all the options, we present an outlook on six selected technologies that are receiving increased attention in the industry: solid oxide fuel cells, liquefied hydrogen, wind-assisted propulsion, air lubrication systems, onboard carbon capture, and nuclear propulsion. With the industry seeing energy-saving technologies as increasingly important, wind-assisted propulsion systems have now been installed on 28 large vessels. Air lubrication systems are installed on or ordered for more than 250 vessels in total.

Considering onboard carbon capture and nuclear propulsion, we have performed a feasibility study using the FuelPath model of a 15,000 TEU container vessel as a case, benchmarking against fuel oil, LNG, methanol and ammonia. We find that onboard carbon capture can be operationally feasible for a large container vessel using 4,000 cubic metres (m³) of carbon dioxide (CO_2) storage on board, offloading CO_2 twice per trip Asia-Europe, and annually capturing 70% of the carbon dioxide. If the increase in energy use to capture the CO_2 can be kept below 15%, and if the cost for offloading, transporting, and sequestering the CO_2 is below 40 USD/tonne, onboard carbon capture can be a competitive option for decarbonization.

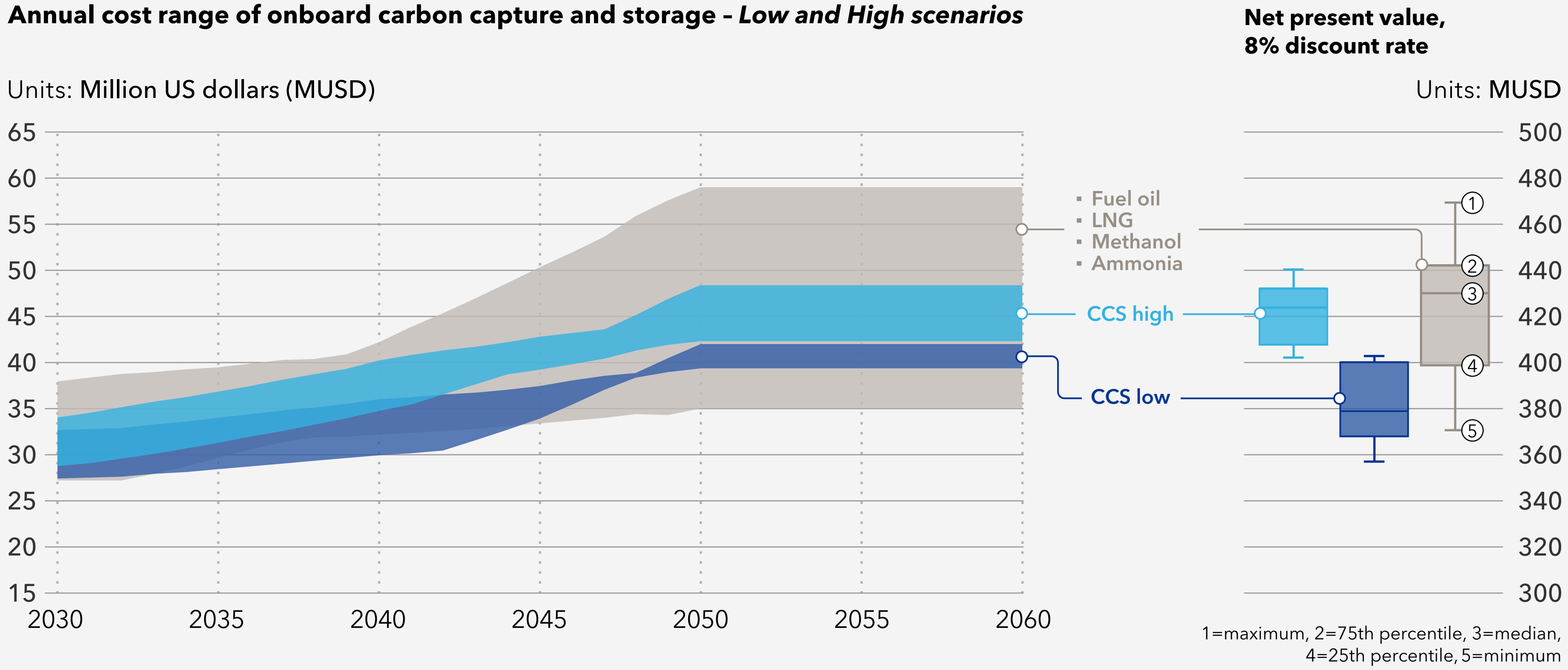
There are 160, mostly naval, nuclear-powered vessels today, and we find that it is a technically feasible solution for the case-study ship, with a reactor and gensets for redundancy and take-me-home functionality. We find that nuclear propulsion can be a competitive option if reactor costs are in the lower range of historical costs for land-based nuclear power plants.

While energy saving will reduce the need for alternative fuels, and both nuclear and onboard carbon capture may alleviate the need for such fuels, we still see that large volumes of carbon-neutral fuels will be needed to decarbonize shipping, and that the production of these fuels will be a key challenge. Currently, only 0.1% of fuels used by merchant shipping are biofuels, while 99.9% are fossil fuels. We present a new and comprehensive global database of more than 2,200 existing and planned production plants for relevant fuels: all biofuels, methanol, ammonia, hydrogen, including bio-, electro-, and blue versions of all fuels. We find that the probability-adjusted global cross-sector production volume in 2030 is between 44 and 62 million tonnes of oil equivalent (Mtoe). The estimated demand for carbon-neutral fuel in shipping is 17 Mtoe in 2030, meaning that 30% to 40% of our estimated global cross-sector production volume will be required to supply the shipping sector.

As the shipping industry will compete for carbon-neutral fuels with aviation and road transportation, as well as other industries, the production of carbon-neutral fuel alternatives needs to significantly accelerate if the emission-reduction goals are to be met. The period of ramping up production of different carbon-neutral fuels may come with uncertainty in supply, and price fluctuations are therefore expected. Thus, fuel flexibility will be key for shipowners to navigate these uncharted waters.

FIGURE 1-2

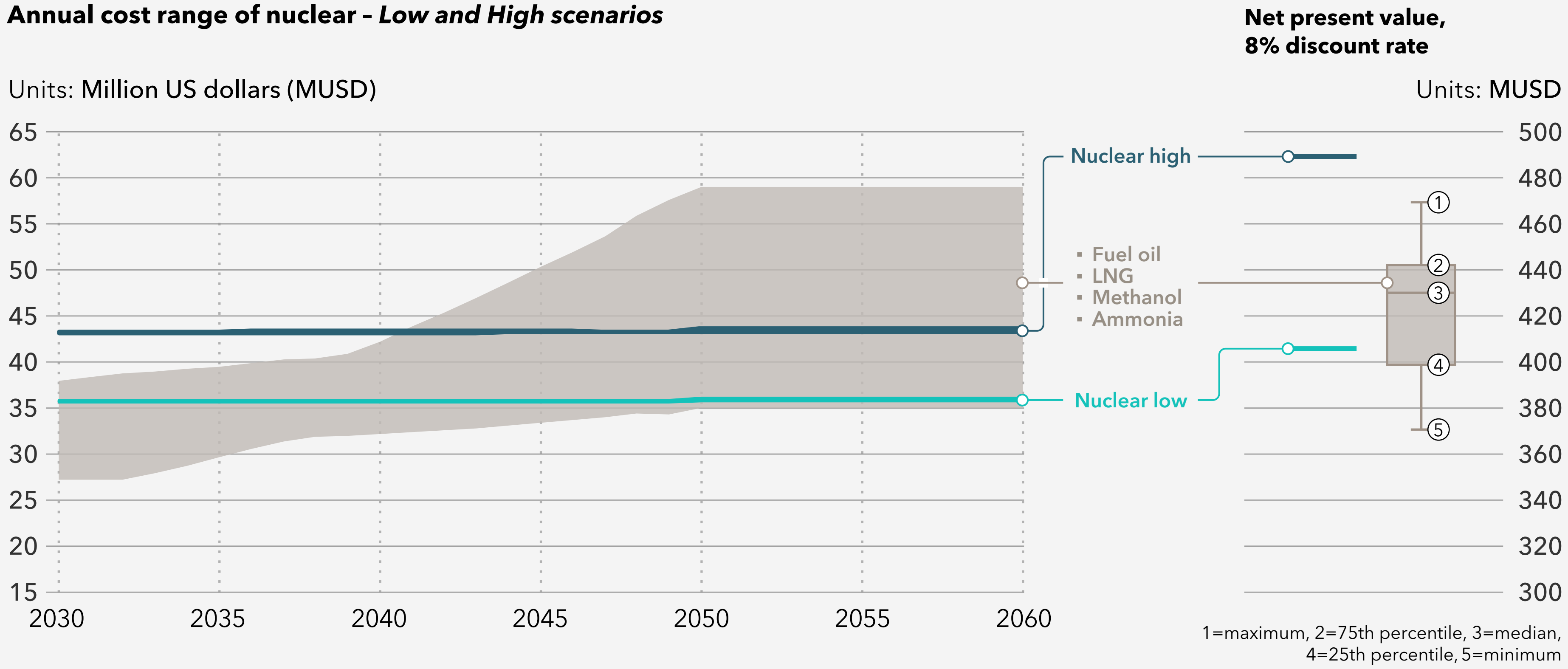
Annual cost range of onboard carbon capture and storage – *Low and High scenarios*



1=maximum, 2=75th percentile, 3=median, 4=25th percentile, 5=minimum

FIGURE 1-3

Annual cost range of nuclear – *Low and High scenarios*



1=maximum, 2=75th percentile, 3=median, 4=25th percentile, 5=minimum

In addition to the lack of supply of carbon-neutral fuels, there are other important barriers to decarbonizing shipping. Examples include lack of infrastructure, novel safety risks, lack of competence, immature technology and high costs.

This report presents an outlook on green shipping corridors. These can accelerate uptake of carbon-neutral fuels by allowing barriers to be identified and overcome in a more targeted and practicable way than on a global scale. We provide a three-step approach for stakeholders within the value chain aiming to establish green shipping corridors. It is based on DNV's experience over a decade with already existing green shipping corridors in Norway.

At the approach's core is identifying barriers to achieving viable business cases for green shipping corridor partners.

A shipowner navigating these uncharted waters should consider all available decarbonization options, focusing on reduced energy consumption and fuel flexibility in the short term, while also considering a long-term fuel sourcing strategy.

The 2020s is a decisive decade for shipping and the quality and effectiveness of plans put in place now will dictate how successful the maritime industry is in reaching its decarbonization goals over the coming decades.

FIGURE 1-4

Estimated supply of carbon-neutral fuel

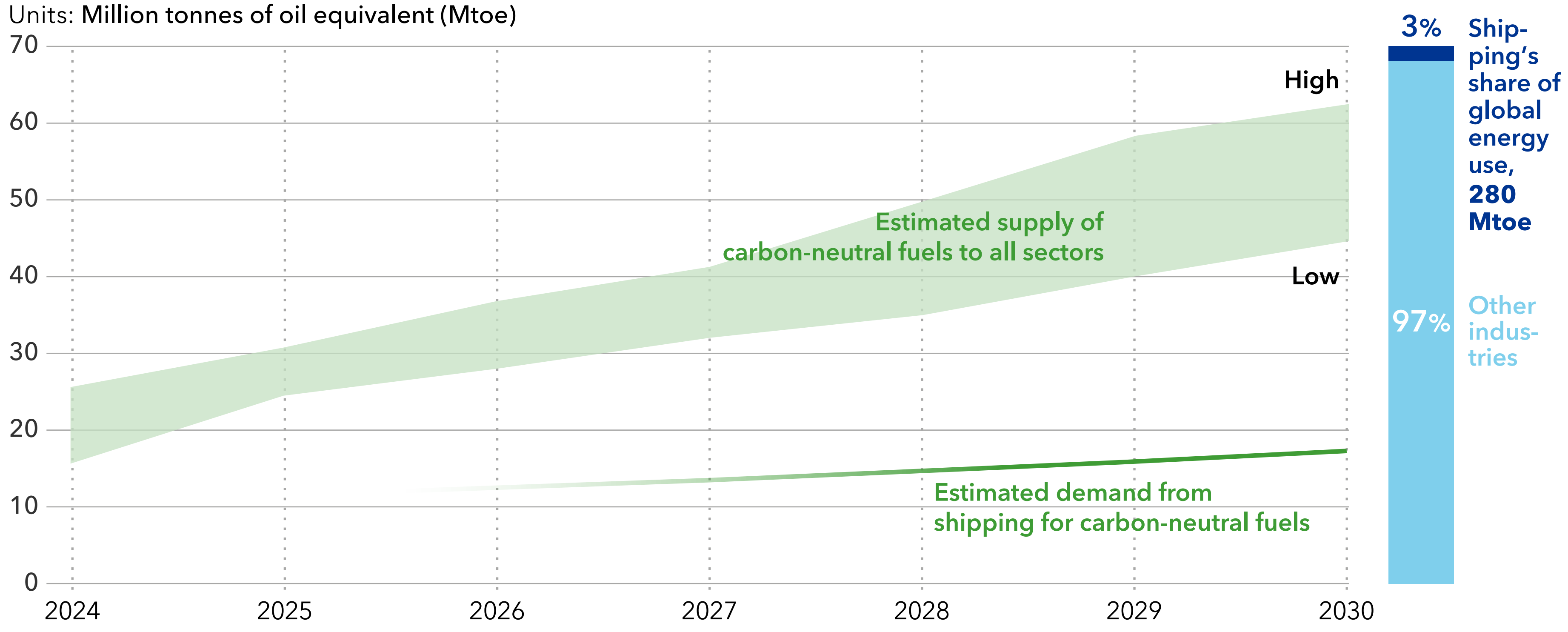
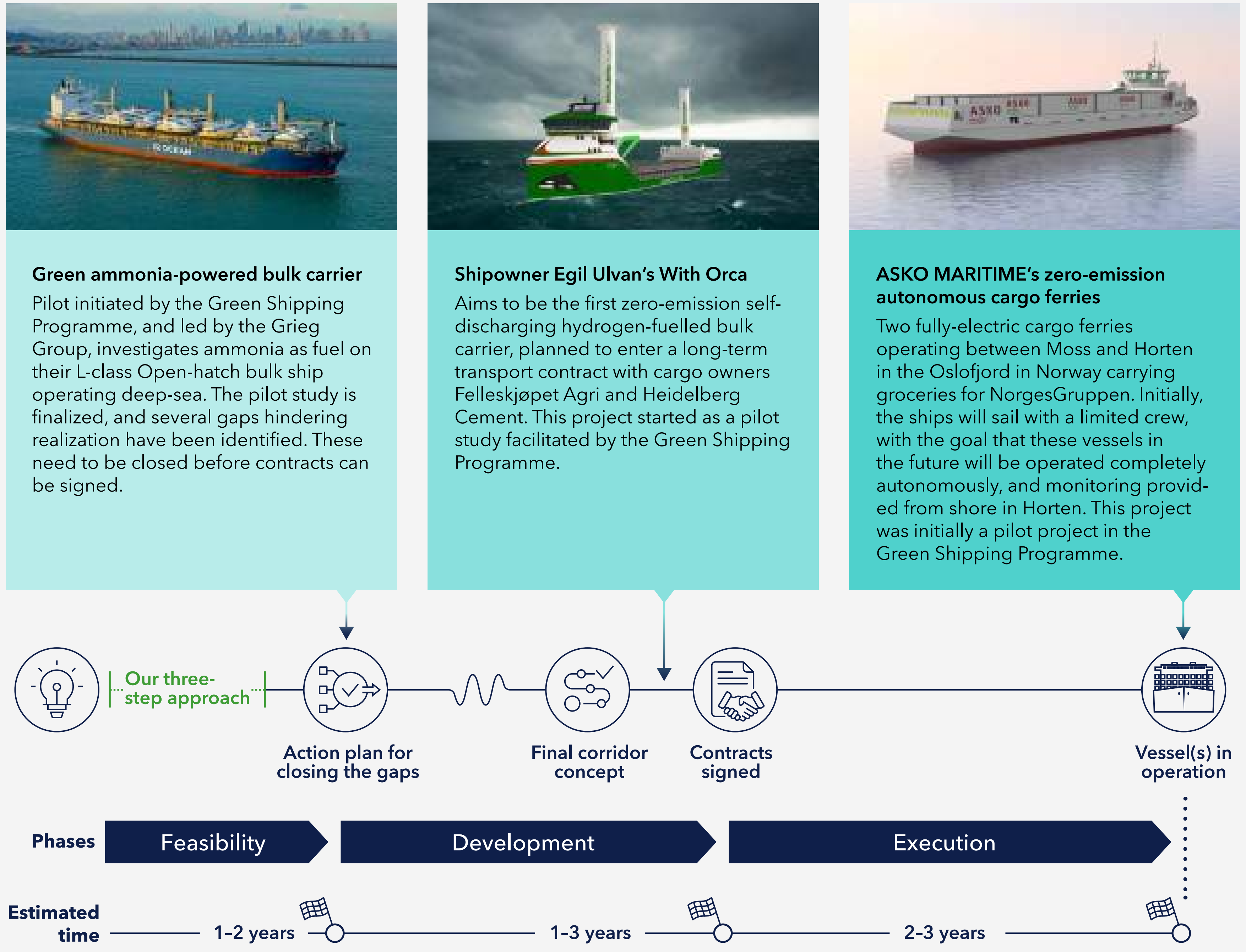


FIGURE 1-5

Main phases from initial idea to realization of a green shipping corridor



Green ammonia-powered bulk carrier
Pilot initiated by the Green Shipping Programme, and led by the Grieg Group, investigates ammonia as fuel on their L-class Open-hatch bulk ship operating deep-sea. The pilot study is finalized, and several gaps hindering realization have been identified. These need to be closed before contracts can be signed.

Shipowner Egil Ulvan's With Orca
Aims to be the first zero-emission self-discharging hydrogen-fuelled bulk carrier, planned to enter a long-term transport contract with cargo owners Felleskjøpet Agri and Heidelberg Cement. This project started as a pilot study facilitated by the Green Shipping Programme.

ASKO MARITIME's zero-emission autonomous cargo ferries
Two fully-electric cargo ferries operating between Moss and Horten in the Oslofjord in Norway carrying groceries for NorgesGruppen. Initially, the ships will sail with a limited crew, with the goal that these vessels in the future will be operated completely autonomously, and monitoring provided from shore in Horten. This project was initially a pilot project in the Green Shipping Programme.

2

INTRODUCTION

2 INTRODUCTION

This publication is part of DNV's 2023 suite of Energy Transition Outlook (ETO) reports. This latest Maritime Forecast to 2050 provides an independent outlook of shipping's energy future and examines how the technology and energy transition will affect the industry. We investigate fuel production, technology, and green shipping corridors to tackle the shift to carbon-neutral fuels. We also provide a valuable mapping of present and planned production of carbon-neutral[1] fuels.

The pressure to decarbonize is rising as people and governments increasingly acknowledge the challenges from anthropogenic climate change. This year, for example, the IMO has increased its ambitions for reducing GHG emissions from shipping. Next year, the EU will implement a carbon price for shipping.

New technologies and fuel production need to be developed for shipping to meet its decarbonization goals. In addition, standards for fuel production and well-to-wake emissions are required to avoid shifting emissions to other sectors.

With this in mind, this report starts by presenting an updated outlook on drivers and regulations, focusing on the new IMO ambitions and well-to-wake GHG emissions (Chapter 3). It proceeds with updated outlooks on ship technologies and fuels for decarbonization; the availability of competence (Chapter 4); and on fuel production and infrastructure, estimating the future availability of carbon-neutral fuels (Chapter 5). We present calculations illustrating the necessity of forthcoming well-to-wake GHG regulations and fuel production standards (Chapter 6). We also describe a case study of a large container vessel using two selected technologies, nuclear propulsion and onboard carbon capture (Chapter 7). Finally, we present a practical approach for establishing green shipping corridors (Chapter 8).

3

OUTLOOK ON DRIVERS AND REGULATIONS FOR DECARBONIZATION

Highlights

We analyse new IMO and EU regulatory changes as well as US and Chinese policies that may impact maritime globally, finding that:

- 2023 has seen significant regulatory developments by the IMO, with the goal of reaching net zero by 2050, and by the EU, with new legislation. Policies in the US and China may impact the maritime sector globally.
- Well-to-wake greenhouse gas emissions and fuel sustainability credentials become important to avoid unintended emission increases in other sectors.
- Some shipping companies now offer net-zero emission services in response to cargo owners needing to decarbonize their operations.
- A book-and-claim system could speed uptake of carbon-neutral fuels, enlarging the market by allowing those with no access to physical fuel products to buy reduction claims.

2023 has seen major decisions regarding GHG ambitions and regulations. The IMO has revised its GHG Strategy, strengthening the ambitions for international shipping. The new targets include a 20% reduction in emissions by 2030, a 70% reduction by 2040 (compared with 2008 levels), and the ultimate goal of achieving net-zero emissions by 2050. New regulations are expected to enter into force around mid-2027. The EU has agreed to include shipping in its Emission Trading Scheme (EU ETS) from 2024 and on setting requirements on well-to-wake GHG emissions (FuelEU Maritime) from 2025.

We expect three key fundamentals – regulations and policies, access to investors and capital, and cargo-owner and consumer expectations – to drive ship decarbonization through the 2020s and beyond (Figure 3-1). They are supported by frameworks and standards specifying sustainability evaluation criteria and targets, GHG emission calculation methods, and reporting requirements.

Regulations and policies remain the key drivers for decarbonization of shipping through direct requirements for ships and shipping companies. The last year has seen the inclusion of shipping in the EU ETS and a well-to-wake GHG requirement (FuelEU Maritime). Net-zero emission shipping services are being offered as a response to cargo owners' requirements to decarbonize their own operations, creating a market pull for sustainable biofuels. Well-to-wake fuel standards are maturing, setting the necessary framework for producing and using sustainable fuels in shipping.

This chapter first presents upcoming regulations on GHGs from the IMO and the EU, then discusses shipping-relevant policies in the US and China, representing two major global economies. Other international agreements will also contribute to drive developments, among them the Clydebank Declaration for green shipping corridors (see Chapter 8), but are not discussed further in this chapter. We then take a closer look at the framework and standards for calculating well-to-wake GHG emissions, before outlining how shipping companies offer net-zero emission services and the need for book-and-claim systems.

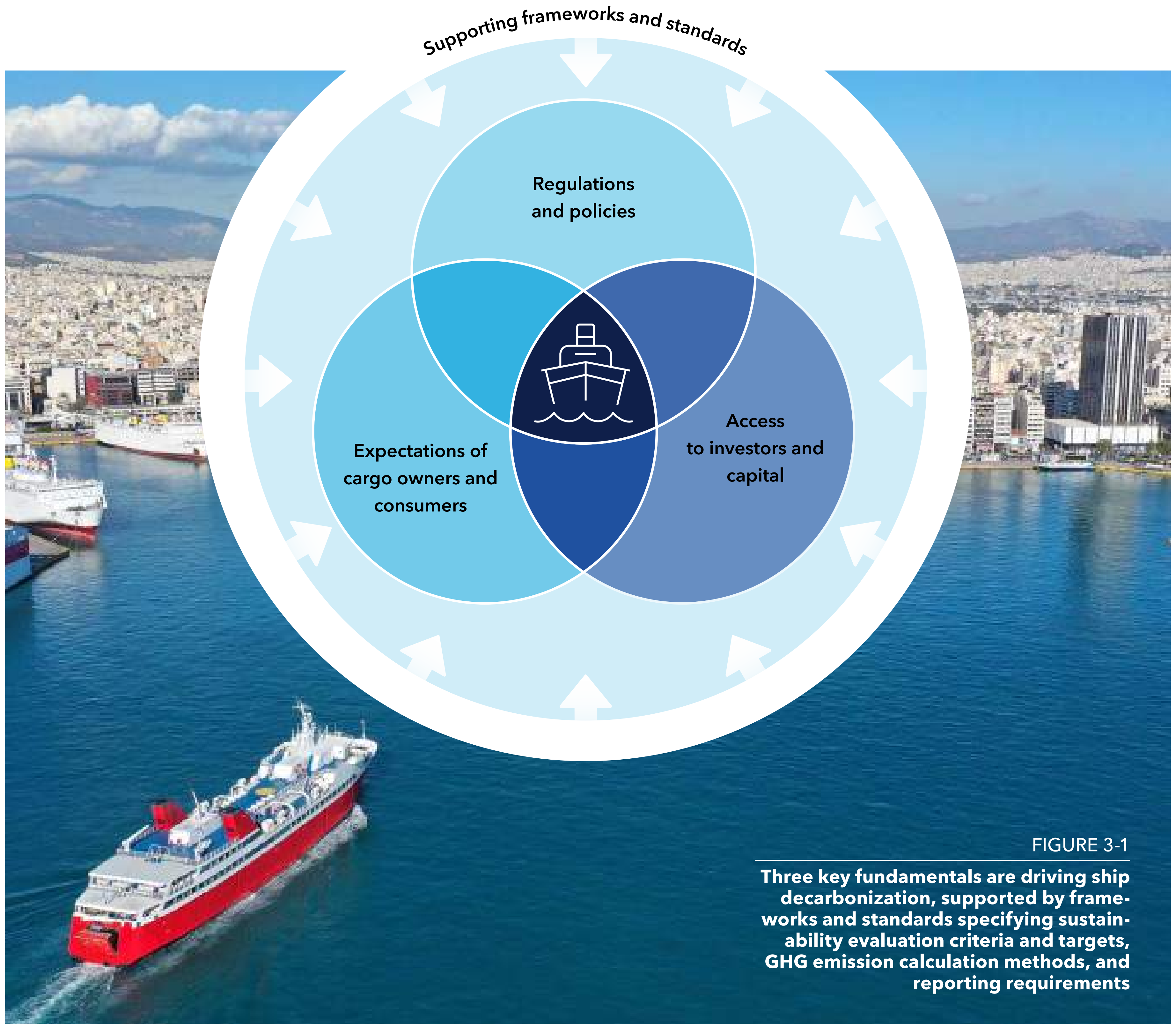


FIGURE 3-1

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

3.1 Regulatory developments

3.1.1 International Maritime Organization

In July 2023, the IMO completed the first revision of its GHG strategy.[2] It significantly strengthened the ambitions for international shipping compared with the initial strategy's ambition for a 50% GHG reduction by 2050. The revised strategy outlined in Figure 3-2 and taking 2008 as a baseline now aims to reduce well-to-wake GHG emissions by 20% in 2030, while striving for 30%; then for 70% by 2040, while striving for 80%; and to reach net-zero 'by or around, i.e. close to, 2050'. There is also a 2030 target to achieve an uptake of zero or near-zero GHG emissions technologies, fuels and/or energy sources, representing at least 5% of the energy used by international shipping, while striving for 10%.

The GHG strategy now also addresses lifecycle GHG emissions from shipping, with the overall objective of reducing GHG emissions within the boundaries of the energy system of international shipping and preventing a shift of emissions to other sectors.

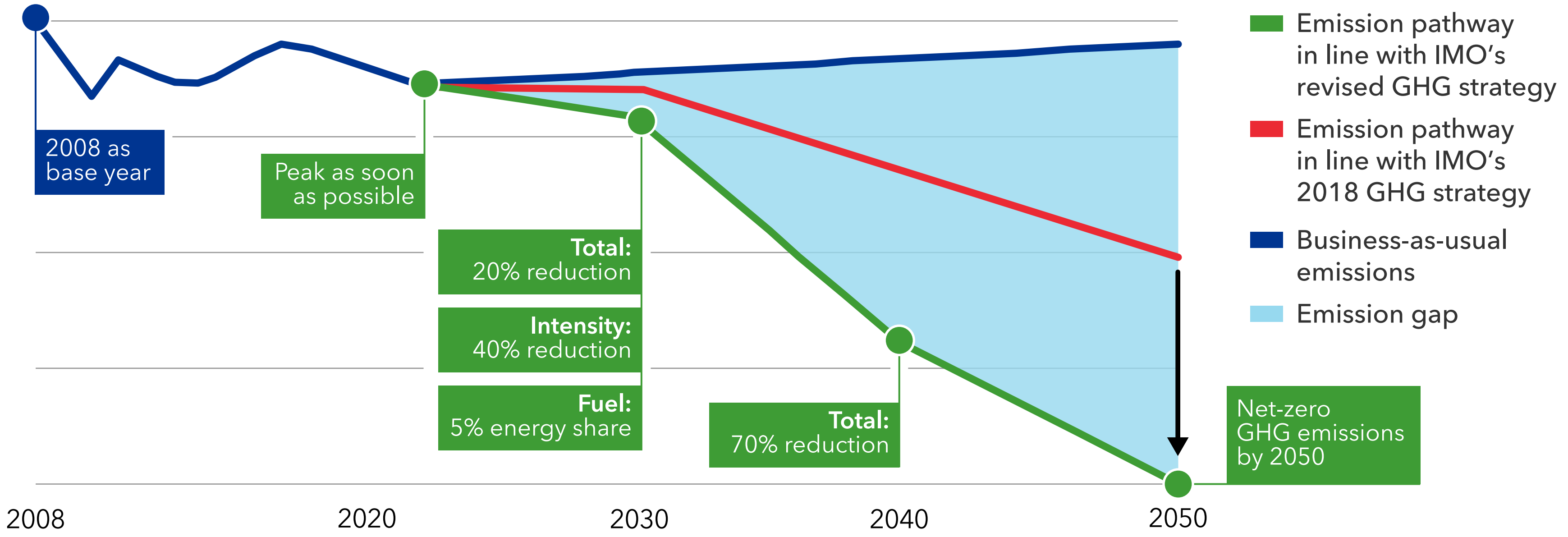
To ensure that shipping reaches these ambitions, the IMO has decided to implement a basket of measures consisting of two parts. First, a technical element which will be a goal-based marine fuel standard regulating the phased reduction of marine fuel GHG intensity. Second, an economic element which will be some form of maritime GHG emissions pricing mechanism, potentially linked directly to the GHG-intensity mechanism. The development of the measures will continue at the IMO and will, according to the agreed timeline, be adopted in 2025 and enter into force in around mid-2027.

The implementation of the Carbon Intensity Indicator (CII), Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Existing Ship

FIGURE 3-2

Outline of ambitions and minimum indicative checkpoints in the revised IMO GHG strategy

Units: GHG emissions



Total: Well-to-wake GHG emissions; **Intensity:** CO_2 emitted per transport work; **Fuel:** Uptake of zero or near-zero GHG technologies, fuels and/or energy sources

> For any emission reduction to be recognized, it is important to have assurance that the CO_2 is delivered to a facility that ensures that it is permanently stored. An internationally recognized certification scheme is likely to be needed.

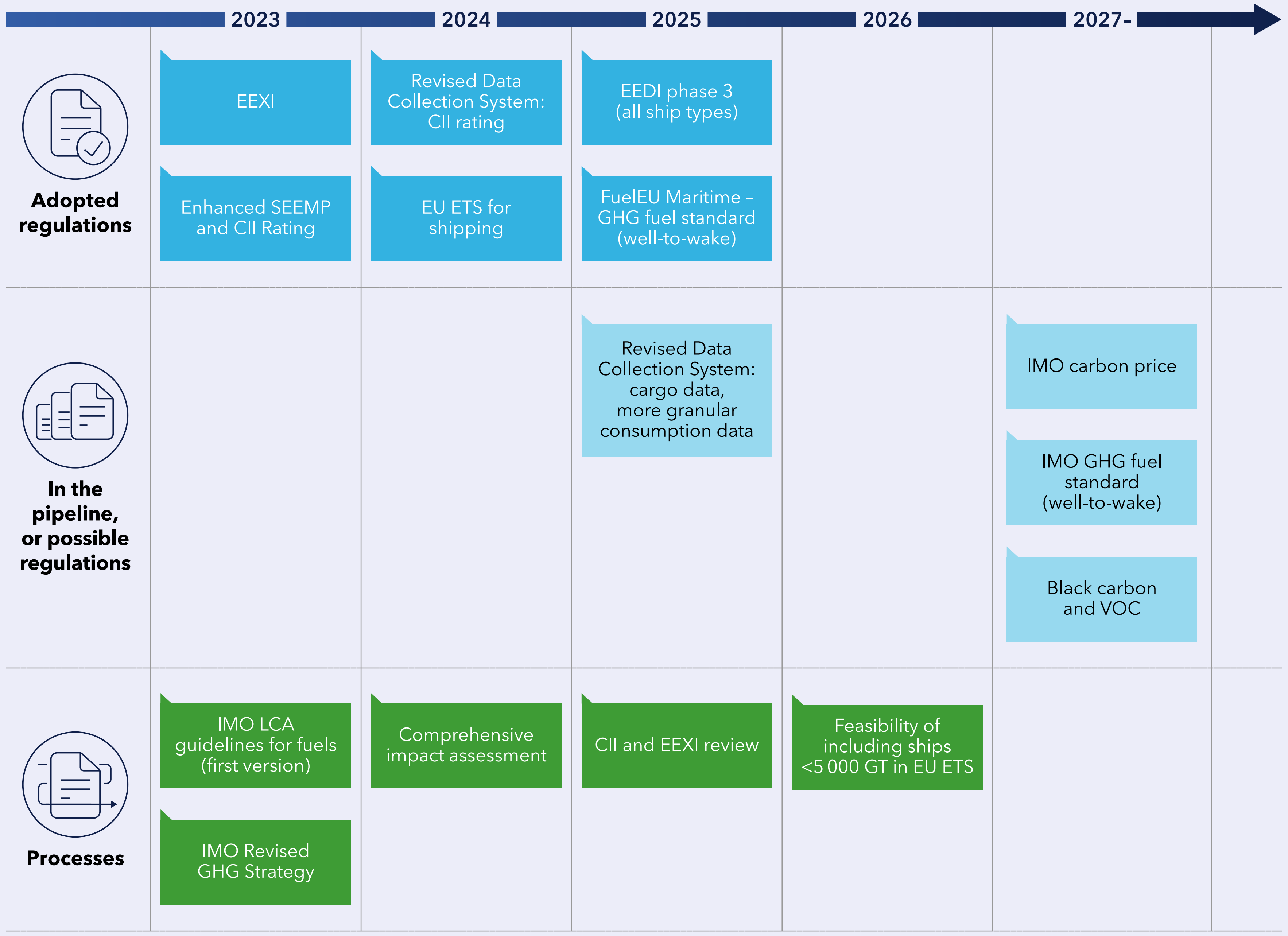
Index (EEXI) is well underway, and the last year has seen only minor updates on related guidelines. Recognizing the significant interest in the use of biofuels, the IMO also agreed that certified sustainable biofuels with at least 65% less well-to-wake GHG emission compared with fossil fuel can use a reduced CO_2-emission factor under the Data Collection System (DCS) and CII.[3] Several challenges with the CII – related in particular to ships with long period of waiting, port stay, and stationary operations – have been identified, but no further updates to the CII framework will be made at this time. The review of the regulation will be completed by the end of 2025.

Onboard carbon capture and storage (CCS) has seen increased interest as a possible solution for decarbonizing shipping. Section 4.3.5 provides a detailed outlook on the technology. Today, there are no incentives to use onboard carbon capture as it does not count against any IMO requirements. The application of onboard carbon capture will be incorporated in the IMO Lifecyle Assessment (LCA) guidelines, though further discussions are needed to address regulatory barriers, in particular those related to the fate of the captured carbon. The climate effect will depend on the amount of carbon captured and permanently stored. For any emission reduction to be recognized, it is important to have assurance that the CO_2 is delivered to a facility that ensures that it is permanently stored. An internationally recognized certification scheme is likely to be needed.

Figure 3-3 summarizes the regulatory timeline towards 2030 that is described in this chapter.

FIGURE 3-3

GHG regulatory timeline towards 2030



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)

3.1.2 European Union

The EU has through the European Climate Law[4] set legally binding targets to reduce emissions by 55% in 2030 relative to 1990 and to become climate-neutral by 2050. The EU also sees this as an opportunity to decouple economic growth from resource use to create opportunities for industry in clean technology and solutions. The Green Deal is a blueprint for the change required to reach these ambitions, and the Fit for 55 legislative package proposed in 2021 is a key part of this plan.[5]

Two of these pieces of legislation, the EU ETS and FuelEU Maritime, set specific requirements for ships. The EU has adopted a revision of the EU ETS which will include shipping from 2024.[6] It is an emission cap-and-trade system where a limited amount of emission allowances – the cap – is put on the market and can be traded. The cap is reduced each year, in line with the EU's 2030 target for a 55% emissions reduction relative to 1990, and with climate-neutrality by 2050. A ship above 5,000 gross tonnage (GT) transporting cargo or passengers for commercial purposes in the EU will be required to acquire and surrender emission allowances for its GHG emissions from 2024 as reported through the Monitoring, Reporting and Verification (MRV) scheme. By the 31st of March each year, starting in 2025, a verified company emissions report needs to be submitted to the administering authority of the company. The company emission report aggregates the emissions within the scope of the EU ETS, reported and verified for each ship under the responsibility of the company during the reporting period (i.e. the calendar year). By the 30th of September each year, the required number of allowances must be transferred to the account of the administering authority. Companies that fail to surrender allowances are liable to an excess emissions penalty of EUR 100 per tonne of CO_2 (tCO_2) and are still liable for the surrendering of the required allowances. A company that fails to comply for two or more consecutive periods may be denied entry into the EU for all ships under its responsibility. This will be the first time that ships in international trade are subject to a carbon price, and the EU ETS is expected to have a significant financial impact.

The scopes of the MRV and ETS will be gradually expanded in the coming years (Figure 3-4). From 2024, methane (CH_4) and nitrous oxides (N_2O)[7] must be reported, and the emissions will be included in the ETS from 2026. Offshore ships will be required to start reporting from 2027 and those above 5,000 GT will be included in the ETS from 2027. The MRV will also be expanded to general cargo and offshore shipping between 400 and 5,000 GT from 2025, which will be evaluated in 2026 for inclusion in the ETS at a later stage. Other cargo and passenger ships between 400 and 5,000 GT will be evaluated for inclusion in MRV and the ETS in 2026 as well.

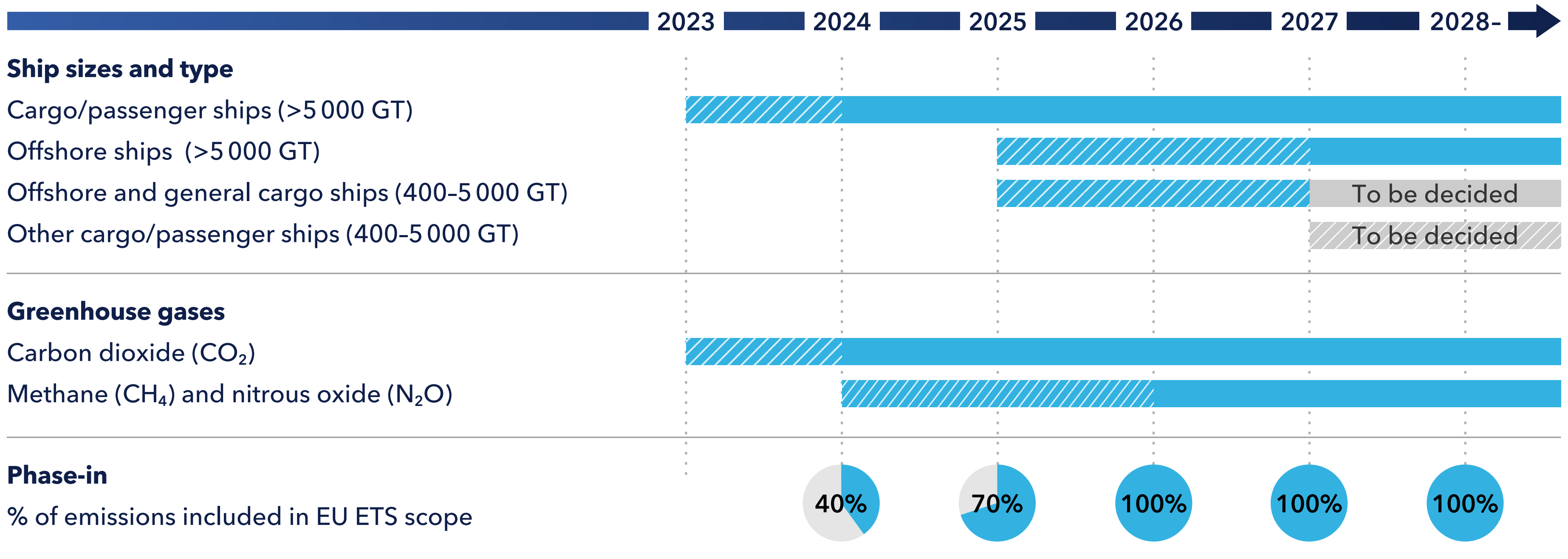
Overall, the EU ETS will have a significant impact on operations, costs, and contractual agreements. As of May 2023, the ETS emission allowance price was around EUR 90 per tonne of carbon dioxide. This would add EUR 290 to the cost per tonne of fossil fuel combusted, representing an almost 50% rise in fuel costs when operating in the EU, assuming a fuel cost of about EUR 600 per tonne. However, in the short term the price is unlikely to be sufficiently high to incentivize a fuel shift by itself. In its impact assessment, the EU considers that most of the GHG emission reduction will come from other sectors.[8] The number of allowances put on the market will be reduced by 4.2% per year, which means that the price can be expected to increase further when the abatement measures with lowest cost have already been implemented.

Although it is the shipping company (i.e. the ship manager) that is responsible for acquiring and surrendering emission allowance, all stakeholders through the transport supply chain will have to make sure that the costs are covered through contracts between ship managers, owners, charterers and cargo owners.

The EU has also adopted the FuelEU Maritime regulation to increase the share of renewable and low-carbon fuels in the fuel mix of international maritime transport in the EU.[9] The regulation sets requirements on annual average well-to-wake GHG emissions per unit of energy used by the ship. The requirements take effect from 2025 and will over time set more stringent limits on the GHG intensity. The reduction requirement is set relative to the average well-to-wake fuel GHG intensity of the fleet in 2020 of 91.16 gCO_2e per megajoule (MJ), starting at a 2% reduction in 2025, increasing to 6% in 2030, and accelerating from 2035 to reach an 80% reduction by 2050. The regulation also allows for compliance across a group of ships, meaning that one vessel in a pool of ships can over-achieve on the well-to-wake GHG intensity, allowing for the other ships to continue to use fossil fuels. It is also possible to bank and borrow compliance units for subsequent periods. From 2030, containerships and

FIGURE 3-4

Timeline for the phase-in of ship types, sizes and additional GHGs in the EU MRV and EU ETS



Key: Methane (CH_4); carbon dioxide (CO_2); European Union Emissions Trading System (EU ETS); European Union Monitoring, Reporting and Verification (EU MRV); nitrous oxide (N_2O)

passenger ships are required to connect to shore power when at berth for more than two hours in a TEN-T port.[10] From 2035, the requirement applies to all ports where shore power is available. The electric energy supplied to the ship from shore is also included for the calculation of the annual GHG intensity but is considered as having zero well-to-wake emissions.

The EU ETS includes provisions for the use of CCS, linked to the EU's CCS Directive (2009/31/EC). However, it remains to be seen how this will work specifically for onboard carbon capture in shipping. FuelEU Maritime includes a provision for reviewing onboard carbon capture and other new technologies and fuels by the 1st of January 2027.

In March 2023, the EU presented a proposal for a Net-Zero Industry Act. The aim is to develop and strengthen Europe's industrial capacity and to ensure that demand for net-zero technologies and solutions to a larger extent can be met through European production.[11] By 2030, the EU aims to both produce 10 million tonnes (Mt) and import 10 Mt per annum of clean hydrogen[12], and to reach an annual storage capacity of 50 Mt of carbon dioxide[13]. A wide range of policy incentives already exists to support research and development (including in shipping) such as the Horizon Europe programme[14] and the Innovation Fund[15] which is funded by proceedings from auctioning part of the ETS emission allowances.

3.1.3 United States

The US has not enshrined a climate target in its national laws, but when re-joining the Paris Agreement in 2021, the country committed to achieve a 50% to 52% reduction in net GHG emissions by 2030. The US State Department and the White House have issued a long-term strategy[16] committing to achieving net-zero emissions by 2050, focusing among other things on investments in renewable energy production and reduced methane emissions, as well as increased natural and technological removal of carbon dioxide.

Several US federal agencies have joined in developing a roadmap for reducing emissions from the transport sector, including maritime, which was released in January 2023.[17] The roadmap for maritime outlines actions on research and innovation, international and domestic stakeholder engagement and infrastructure investment, and improved design and planning.

The US is unlikely to impose additional requirements on international ships sailing to US ports or in its waters in the near term. We may see state requirements, such as in California, which has imposed mandates for increased use of shore power at berth since 2014 for cruise vessels, containers, and reefers for major ports, and will extend the mandates to tankers and vehicle carriers in the coming years.[18] On the federal level, the US works through the IMO to revise its GHG strategy to aim for phasing out GHG emissions from international shipping to zero no later than 2050. The US has also initiated several key shipping initiatives such as the First Movers Coalition[19] in 2021 and, together with Norway, the Green Shipping Challenge[20] in 2022. As part of the Green Shipping Challenge, the US has committed itself to facilitate green shipping corridors and to create a US National Action Plan for reducing shipping GHG emissions.

The US has several policy initiatives that aim to support renewable energy production, support for manufacturing advanced-technology vehicles, including ships[21], and development of maritime infrastructure. The Inflation Reduction Act (IRA) adopted in 2022 is a major policy instrument supporting the long-term strategy, which provides USD 369 billion direct investment aiming to ensure energy security, reduce carbon emissions and increase energy innovation, among other things.[22] Tax credits are provided for clean hydrogen production and for carbon capture and utilization or sequestering. The IRA includes a new USD 3 billion rebate and grant programme at the Environmental Protection Agency to provide funding for zero-emission port equipment or technology, along with technical assistance for electrification and emissions-reduction planning and port climate-action plan development. The US Department of Transportation announced more than USD 703 million to fund 41 projects in 22 states and one territory that will improve port facilities through the Maritime Administration's (MARAD) Port Infrastructure Development Program (PIDP).[23] The Infrastructure Investment & Jobs Act of 2021 authorizes USD 2.25 billion to MARAD for the PIDP for fiscal years 2022 through 2036.[24]

3.1.4 China

In September 2020, China announced its intentions to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, referred to as the '30–60' goals. This was followed in October 2021 by the Chinese State Council issuing the 'Action Plan for Carbon Dioxide Peaking Before 2030'.[25] Regarding the shipping sector, China has committed to work faster to upgrade old ships, develop ships fuelled by electric power and LNG, further promote the use of shore power by ships while in port, and make in-depth efforts to advance demonstration and utilization of green, smart ships along coastline and inland waterways according to local conditions.

Beginning from the top-level design, China's multi-level government agencies are taking actions to implement the carbon peak and carbon-neutrality action plan in the shipping sector during the 14th Five-Year Plan period (2021–2025). Among those agencies, China's Ministry of Transport published the 14th Five-Year Plans, one for the Development of Green Transport[26] and another for Waterway Transport[27] in Jan 2022. These plans encourage the application of new and clean energy including LNG, methanol, hydrogen, ammonia, and so on, as well as the increased use of shore power.

Besides the action plans, a draft amendment to the Marine Environment Protection Law[28] – which applies to all sea areas under China's jurisdiction – to include clauses on reducing GHG emissions in the shipping sector was submitted in December 2022 to the Standing Committee of the National People's Congress for review. The draft amendment again encourages the application of new and clean energies in ships and proposes compulsory requirement for shore power usage. The draft amendment also proposes to make it compulsory for coastal-region governments at county level and above to provide financial support and implement preferential policies to enable the upgrading and operation of shore power supply facilities, as well as the building of vessels powered by clean and new energies.

> For international shipping, the Chinese government encourages the Chinese shipping industry to promote green transformation via active exploration, innovation, and international collaboration.

China's national policy on shipping decarbonization mainly addresses the green and low-carbon development of domestic shipping. For international shipping, the government encourages the Chinese shipping industry to promote green transformation via active exploration, innovation, and international collaboration. The regulation on Energy Consumption Data and Carbon Intensity of Ships[29], effective from December 2022, requires all ships of 400 GT and above, regardless of flag, entering or leaving Chinese ports to report energy consumption data of their last voyage to the China Maritime Safety Administration (MSA).

Regarding market-based measures, China's national ETS started operating in 2021 and is presently covering power production only. The planned expansion of the ETS into seven new sectors does not include shipping. However, the national market has been built on the successful experience of the local pilot markets. The Shanghai ETS market has included local shipping companies and ports in its carbon emission allowance management unit list[30] since 2021, indicating that the national ETS could be further expanded as well.

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

Achieving significant GHG emission reduction in shipping requires transition to zero or near-zero GHG emissions technologies, fuels and/or energy sources. A key premise in the revised IMO GHG strategy is that this transition should not lead to increased GHG emissions in other sectors. For example, switching from a conventional fossil fuel oil to ammonia would lead to near-zero GHG emissions from the ship (uncertainty remains on N_2O emissions); but depending on the production pathway of the ammonia, there can be significant upstream or well-to-tank emissions. For some high-GHG-intensity fuel production pathways, such as methane reforming without CCS, the total emissions may even be higher than producing and combusting fossil fuels.

Biofuels is another possible set of fuels. Although combusting biofuels on a ship releases CO_2 emissions in the same way as fossil fuels, the carbon in the CO_2 was recently removed from the atmosphere through the growing or cultivation of the biomass, and the CO_2 emissions from combustion can be considered to have a neutral climate impact. However, significant upstream emissions can occur due to direct and indirect land-use change, which is also a sustainability issue, in connection with cultivation and growth of the biomass (Ricardo, 2022a). If using biomass from waste products, these issues can be avoided, though emission for production remains.

> A key premise in the revised IMO GHG strategy is that this transition should not lead to increased GHG emissions in other sectors.

For this reason, we expect regulations that will take into account the emissions in a well-to-wake perspective, starting with the FuelEU Maritime from 2025 and later possibly by the IMO's GHG fuel standard and a carbon pricing scheme. Ship-specific calculation methods for well-to-wake GHG emissions of marine fuels are maturing. The main challenges in establishing such methods are related to how to account for direct and indirect land-use emission from biofuels; the GHG intensity of electricity used for fuel production; CCS; the use of recycled captured carbon in the fuel; and how to certify the well-to-tank emissions.

For FuelEU Maritime, the EU builds on the methods and certification requirements in the Renewable Energy Directive (RED)[31] when detailing the calculation methods, standard factors, and how to use specific certified values. Under FuelEU Maritime, unless a fuel fulfils certain sustainability and GHG-saving criteria according to RED, it is considered as having GHG emissions equal to the least favourable fossil

pathway. To be considered sustainable, a biofuel needs to achieve at least a 50% to 65% GHG emission reduction, while renewable fuels of non-biological origin (RFNBO) and recycled carbon fuels (RCF) need to achieve a 70% reduction threshold.

Until now, the RED has mainly been concerned with biofuels; but in 2023, the EU agreed on a revised RED as well as delegated acts detailing how to account for GHG emissions reductions for RFNBO and RCFs. Requirements have been set out for when hydrogen produced from electricity can be considered zero-emission, and how to account for captured carbon reused in the fuel (e.g. for e-methanol). Initially (to 2036 or 2041, depending on source), captured carbon from a wide range of sources is considered to be contributing to GHG emission reduction provided the CO_2 is subject to effective carbon pricing. In the long term, the only carbon that can be recycled in a fuel will be from sustainable sources. For example, carbon captured from the air or from combustion of sustainable fuels, such as biofuels, RFNBOs, or RCFs.[32]

The IMO, in July 2023, approved guidelines for calculating lifecycle GHG emissions for marine fuels, including sustainability aspects[33]. These guidelines do not include any provision for application or requirements but are intended to support the GHG Fuel Standard under development. The IMO guidelines will be kept under review and developed further in the coming years, focusing in particular on default emissions factors, sustainability criteria, and fuel certification.

Current emission requirements such as the EEDI/EEXI, CII and the EU ETS which only cover tank-to-wake emissions also need to consider how to provide consistent incentives to fuels that contribute to reducing well-to-wake GHG emissions. For example, the EU ETS recognizes that CO_2 emissions from biofuels, RFNBOs and RCFs fulfilling the same criteria as described above for FuelEU Maritime can be considered as zero without having to surrender allowances. The IMO in July 2023 decided on a similar provision for the DCS and CII where sustainable biofuels can be assigned a lower CO_2 conversion factor.

The regulatory focus on lifecycle GHG emissions and sustainable production implies that marine fuels will be subject to production standards certification to verify their origin. Certification schemes already exist for biofuels, such as those from International Sustainability & Carbon Certification (ISCC)[34] and the Roundtable on Sustainable Biomaterials (RSB)[35]. In addition to their own standards, ISCC and RSB provide certification according to the International Civil Aviation Organization's (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 scheme[36], the China Hydrogen Alliance[37] and the EU's CertifHy[38]. Appendix A.1 provides a list of production standards and their emission thresholds.

Work is ongoing on adapting the RED certification processes to also work for FuelEU Maritime. It is also expected that the IMO's lifecycle analysis (LCA) guidelines will apply a similar model where certification schemes for marine fuels are recognized according to IMO requirements. These regulations and supporting standards provide calculation methods for well-to-wake emissions which can also be used outside regulatory requirements, such as setting and measuring the progress on net-zero emissions targets, ESG reporting, and GHG Protocol Scope 3 reporting requirements set by cargo owners and other companies.

In Section 6.2, we project the impact on well-to-wake GHG emissions towards 2050 with and without considering production standards and shipboard requirements, considering a Decarbonization by 2050 pathway.

> The regulatory focus on lifecycle GHG emissions and sustainable production implies that marine fuels will be subject to production standards certification to verify their origin.

3.3 Net-zero emission shipping services

Some cargo owners are setting ambitious targets for decarbonization of their operations, both for direct emissions from own operations (Scope 1 – see fact box below) and for their supply chains (Scopes 2 and 3), through net-zero emissions[39] targets. For a cargo owner with significant transportation needs, achieving targets for Scope 3 emissions requires access to low- and zero-emission shipping services. Shipping customers are increasingly willing to pay a premium for such services.[40] Shipping companies have started responding to this demand. Several of what can generally be termed 'net-zero emission services' are already available in the market from first movers. We expect this growth will accelerate in the coming years to meet demand from cargo owners.[41] Currently, net-zero emissions are achieved through the use of certified biofuels, but electrofuels and blue fuels could also be options when they become available.

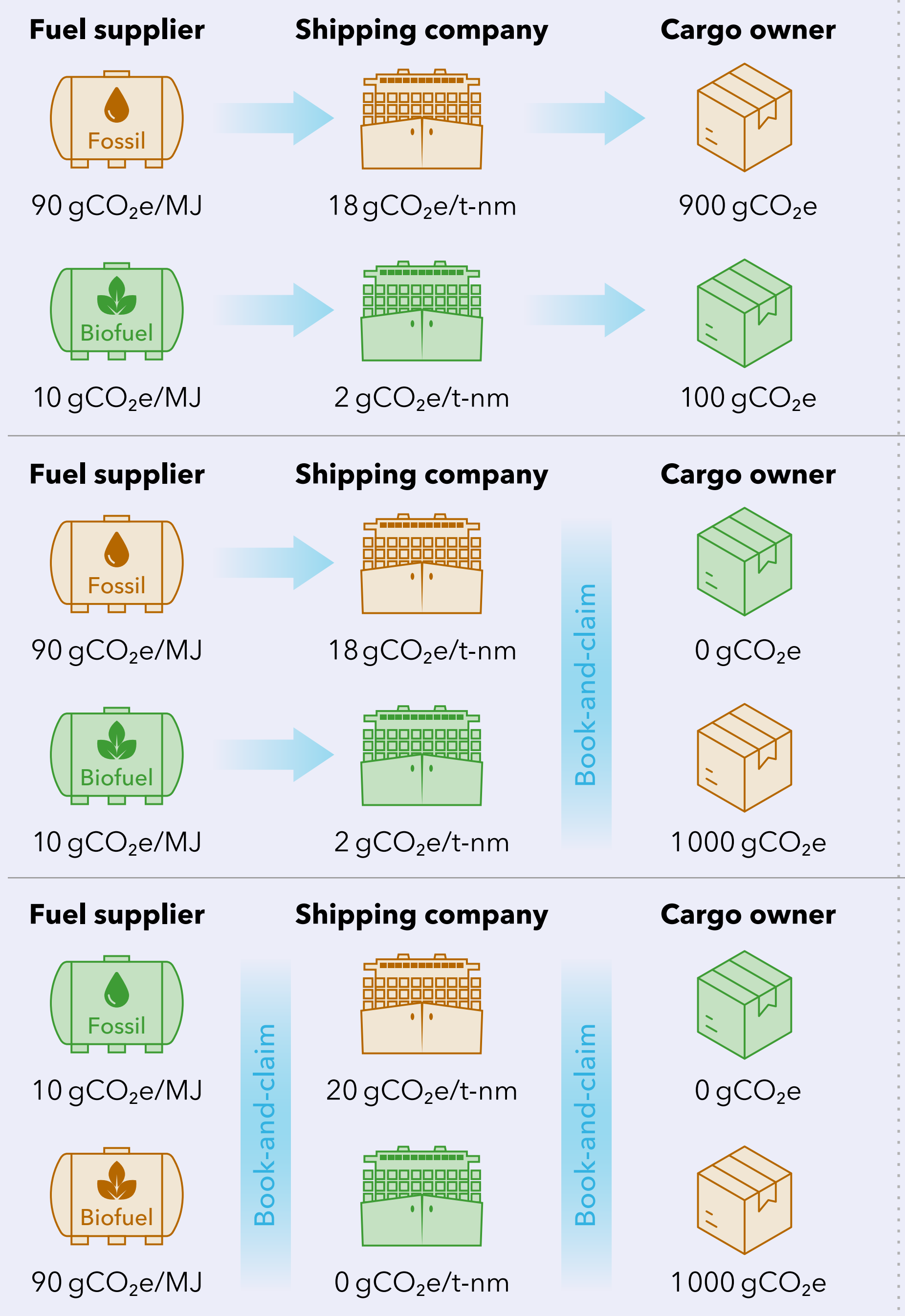
Net-zero emission services can also be considered a form of carbon insetting. Carbon insetting is a specific variant of carbon offsetting and occurs where a company's climate impact is reduced through actions within the company's supply chain leading to reduction of Scope 3 emissions. Carbon offsetting is disconnected from the activities of the company and its supply chain but can be used to achieve a GHG emission-reduction target. Carbon offsetting has received criticism that it does not lead to actual emission reduction and is a form of greenwashing.[42] The benefit of carbon insetting is that it is tangible, and a company can also claim it as part of Scope 3 emission reduction, as opposed to offsetting which can be reported but not as part of any of the scopes.

It will not always be possible to physically link the use of a biofuel, or other carbon-neutral fuels, to a specific service for a specific cargo owner. The fuel may not be available in all places, and transporting it could be costly. The willingness to pay a premium for a zero-emission product may also not be limited to a specific trade and may only cover part of a ship's transport work. Instead of transporting and distributing the fuel to specific ships, the emission reduction is calculated based on the total use of biofuel in the company's fleet, and the cargo owner can buy a transport service with a zero-emission claim. To avoid double-counting and greenwashing accusations, rigid control of claims and verification are needed to ensure the total amount of claims for the zero-emission services sold by a ship company does not exceed the actual reduction from the use of biofuels or other fuels. Figure 3-5 shows a conceptual outline disconnecting the GHG intensity for services and the physical assets, which can be done both for the fuel supply and for the transport service.

Applying such a book-and-claim system could accelerate uptake of carbon-neutral fuels as those that do

FIGURE 3-5

Conceptual outline of disconnecting the GHG-intensity performance of the physical assets and the service offerings for bunker supplier and shipowner



Physical link between fuel and transport service where the carbon footprint of the cargo is determined by the emissions of the ship transporting the cargo, and the emissions of the ship are determined by the fuel it uses and its energy efficiency.

Under FuelEU Maritime, the shipping company can pool compliance using the average GHG intensity per MJ of fuel. For CII, the rating applies to the individual ship.

The shipping company offers a zero-emission service by disconnecting the actual emission performance of the ship from the claimed footprint of the transport service. Part of the cargo can be delivered with zero emission footprint – i.e. even lower than the ship using the biofuel – but the emission footprint for the remaining cargo increases.

Verification is needed to ensure that the total footprint of the shipping company remains the same.

The fuel supplier can also disconnect the emissions claim from the physical product it sells. The fossil fuel can be sold as if it were a biofuel, while the actual biofuel then has to be sold as fossil fuel.

Verification and a central register are needed to ensure that the buyer of the actual biofuel, but sold as fossil fuel, does not claim any emission reduction.

This approach is currently not supported by regulations such as FuelEU Maritime, EU ETS and CII.

The GHG intensity for the fuel under the fuel supplier is the well-to-wake GHG emissions. The ships are assumed to use 0.2 MJ fuel per tonne-mile, and the cargo transported is 10 kg over 5 000 nm, which is 50 tonne-miles; Key: Carbon dioxide equivalent (CO_2e); Carbon Intensity Indicator (CII); European Union Emissions Trading System (EU ETS); tonne-nautical miles (t-nm).

not have access to the physical product can buy the claim. However, this approach has little recognition in regulatory schemes and other voluntary standards for the time being.

FuelEU Maritime builds on the calculation method and certification process under the EU's renewable energy directive (RED). The directive requires a mass balancing approach to certify a biomass chain of custody[43], and does not allow for a book-and-claim approach where a certified emission-reduction claim can be separated from the physical product. RSB is currently piloting a book-and-claim approach for sustainable aviation fuel (SAF).[44] FuelEU Maritime allows for pooling of compliance across a fleet of ships where the average GHG intensity in the pool for a calendar year needs to be below the required level.

The IMO is currently working on the certification requirements for fuels and has not started looking into which chain of custody model to apply. It is also possible that the GHG Fuel Standard will include a flexible compliance mechanism, for example by allowing for averaging across a fleet, or a surplus reward mechanism.

The GHG Protocol currently only allows for a physical or average-based approach for determining Scope 1 and 3 emissions, but has just started a revision of its guidelines, looking in particular at incorporating market-based accounting methods for Scope 1 and 3 emissions.[45] Under Scope 2, it is possible to apply a market-based method where a reduction claim – for example, through Renewable Energy Certificates or other contractual instruments – can be used to reduce Scope 2 emissions.

How are Scope 1, 2 and 3 emissions relevant for a shipping company?

The scopes are defined by the GHG Protocol framework that includes standards and tools to calculate GHG emissions for companies, supply chains, and countries. The framework is often used as basis for ESG (Environmental, Social, Governance) reporting, and has a global reach.

The framework divides the emission of a company into:

- **SCOPE 1**, the direct emissions from the company's operations
- **SCOPE 2**, the indirect emissions from production of electricity and heat generated elsewhere but used by the company
- **SCOPE 3**, other indirect emissions due to the operation of the company, upstream and downstream, and would include emissions from production of fuels used by the company.

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 CO_2 emissions from combustion of biofuels are not part of any of the scopes but should be reported in a separate memo. Emissions related to production of biofuels, including land-use, should be accounted for as part of Scope 3 as for fossil fuels. Scope 3 emissions would also include emissions from manufacturing 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.

4

OUTLOOK ON SHIP TECHNOLOGIES AND FUELS

Highlights

We report and discuss notable trends, developments, and prospects in the fuel technology transition underway, including:

- Half the ordered tonnage can use LNG, LPG or methanol in dual-fuel engines, compared with a third last year, but urgent action is needed for training in the use of new fuels.
- Wind-assisted propulsion and air lubrication are being installed on more vessels.
- Onboard carbon capture and, later, nuclear propulsion can reduce dependence on sustainable biomass and renewable electricity.

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. The expected adoption of energy-saving technologies and logistics, carbon-neutral fuels, and exhaust cleaning (see Figure 4-1) may fundamentally change how ships are designed and operated. Applying operational and technical efficiency measures could be sufficient to achieve shorter-term compliance with GHG regulations and thereby reduce the need for consumption of more expensive fuels.

It is worth stressing that the fuel technology transition is already in progress. For ships in operation, 6.52% of tonnage can operate on alternative fuels.[46] Dozens of large vessels have wind-assisted propulsion systems. Air lubrication systems are installed or ordered for hundreds of ships. So, what comes next?

Driven by the tightening regulations and commercial drivers described in Chapter 3, the increased cost of operating on carbon-neutral fuels will strengthen the drive for more efficient operation of the vessel fleet and simultaneously improve the business case for implementing energy-efficiency measures. Operational efficiency measures relate to the way in which the ship is maintained and operated, and therefore generally have low investment costs and moderate operating costs. They include measures such as optimized trim and ballasting, hull and propeller cleaning, improved engine maintenance, and optimized weather routing, scheduling, and vessel utilization. Operational measures do not require significant investment in hardware or equipment. Implementation of many of these measures will require execution of programmes involving changes in management and training.

Technical efficiency measures generally aim at either reducing the propulsion and auxiliary engine energy demand (e.g. increasing hull and propeller efficiency, reducing hotel load, shore power) or improving the energy production (e.g. waste-heat recovery, battery hybrid systems, and machinery-system optimization). There is potential for improvement in the areas of greatest energy loss; for example, by reducing hull friction and recovering energy from the engine exhaust and cooling water. These measures generally have a substantial investment cost and potentially significant emission-reduction effects. Many technical measures are limited to application on new ships, due to the difficulties or high costs of retrofitting existing ships. With the increased system complexity and the need for partially automated operation of several of these technologies, software and controls are becoming ever more important aspects of ship operation and design.

This chapter first presents the uptake status of alternative fuels in the world fleet, and then an outlook on the availability of competence for safe operation of the new technologies coming. Third, it gives an outlook on six selected technologies with potential impact on the decarbonization of shipping: solid oxide fuel cells, liquefied hydrogen, wind-assisted propulsion, air lubrication systems, onboard carbon capture, and nuclear propulsion.

FIGURE 4-1

Solutions that can contribute to decarbonize shipping, and their GHG reduction potential

LOGISTICS AND DIGITALIZATION	HYDRODYNAMICS	MACHINERY	ENERGY	AFTER-TREATMENT
Speed reduction Vessel utilization Vessel size Alternative routes	Hull coating Hull-form optimization Air lubrication Cleaning	Machinery efficiency improvements Waste-heat recovery Engine de-rating Battery hybridization Fuel cells	LNG, LPG Biofuels Electrification Methanol Ammonia Hydrogen Wind power Nuclear	Carbon capture and storage
>20%	5%-15%	5%-20%	0%-100%	0%-90%

4.1 Status of fuel technology transition

A review of the world fleet status and current order book with respect to the implementation of alternative fuel technology indicates an accelerated uptake compared with last year. LNG is still the most prominent alternative fuel technology choice, and can also be used in dual-fuel solutions with fuel oil. Furthermore, there has been an increase in the number of ships capable of using methanol as fuel in dual-fuel solutions. The gross tonnage of LNG-fuelled ships on order (excluding LNG carriers) is more than twice that of such vessels in the existing fleet. The order book for ships capable of using methanol as fuel is 20 times larger than the gross tonnage of methanol-fuelled ships currently in operation.

This indicates that the trend of ordering larger ships with alternative fuel propulsion highlighted in last year's Maritime Forecast is continuing, but at a greater pace. LNG is a popular fuel choice in the car carrier and containership segments, with 133 and 196 ships on order, respectively. Additionally, there has been a notable increase in the use of LNG for tankers (83) and bulk carriers (39). Out of the 1,376 ships currently on order with alternative fuels, 306 are LNG-fuelled LNG carriers, 523 are other types of LNG-fuelled ships, and 295 are using battery/hybrid propulsion.

Methanol has previously been a choice exclusively for tankers in the methanol trade, with 23 ships in operation and 14 new tankers on order. This year, the containership segment is dominating with 142 ships on order able to use methanol as fuel. Currently, 72 LPG carriers using LPG as fuel are sailing, while 93 LPG carriers and 4 ethane carriers have been ordered with LPG-burning capacity.

Figure 4-2 and Figure 4-3 present the status of the alternative fuel uptake in the world fleet and the order book (as of July 2023). Measured in gross tonnage, 6.5% of ships in operation and 51% on order can operate on alternative fuels (including LNG carriers), compared with last year's numbers of 5.5% and 33%, respectively. By number of ships, this year's figures are 1.8% and 26%, with 1,376 out of 5,258 ships ordered with alternative fuel capability.

Measured by number of ships, the uptake is dominated by battery/hybrid and LNG-fuelled ships. However, in gross tonnage terms, LNG fuel dominates, reflecting that battery/hybrid solutions are applied mostly on smaller vessels. Of the 1,079 ships in operation using LNG fuel, 659 are LNG carriers and 420 are ships of other types. The statistics also show a growing uptake of methanol and LPG, as well as the first hydrogen-fuelled newbuilds.

Although there are ongoing demonstration projects for ammonia-fuelled ships, there are none in the official order book. Using ammonia as a ship fuel

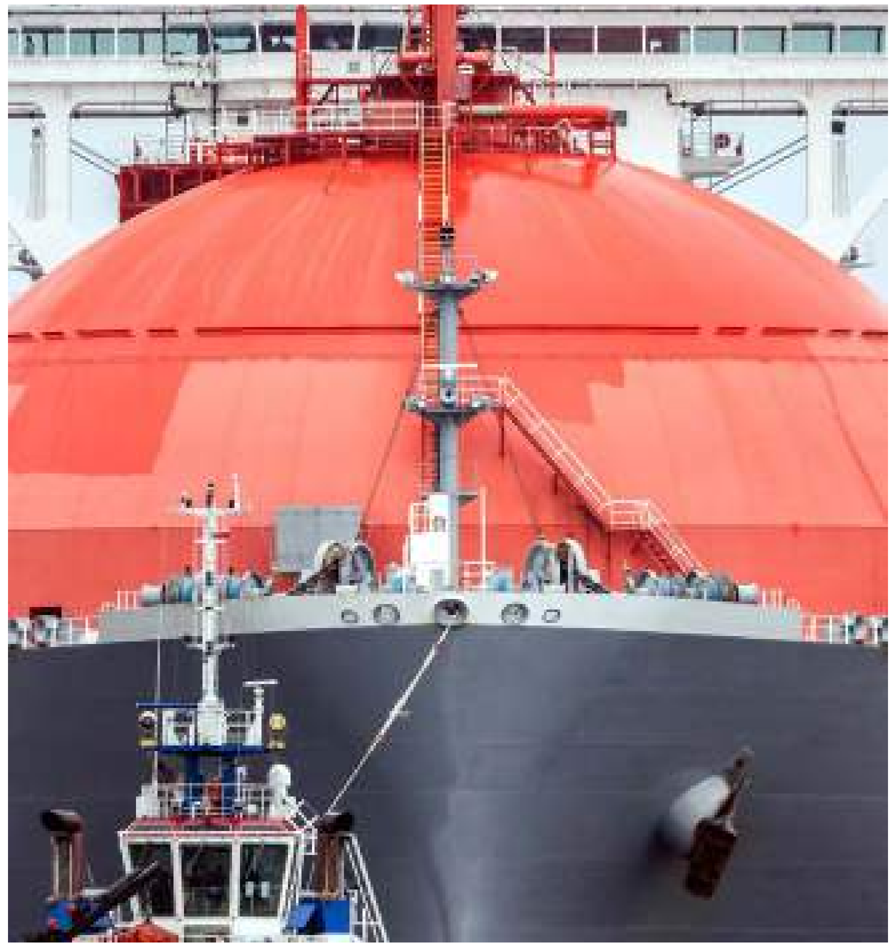
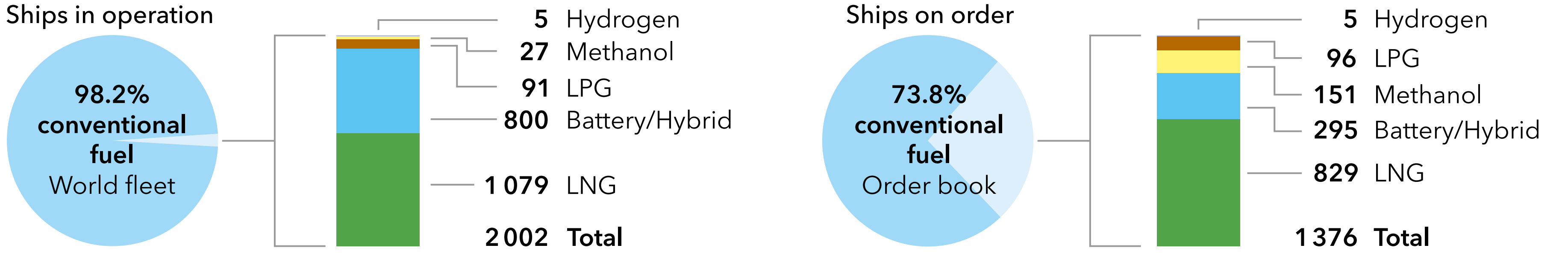


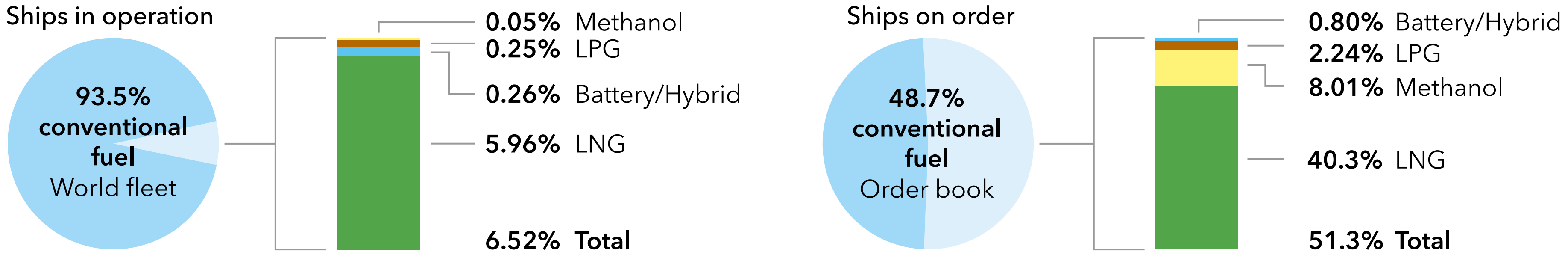
FIGURE 4-2

Alternative fuel uptake in the world fleet in number of ships (upper) and gross tonnage (lower), as of July 2023

NUMBER OF SHIPS



GROSS TONNAGE



Sources: IHSMarkit (ihsmarkit.com) and DNV's Alternative Fuels Insights for the shipping industry – AFI platform (afi.dnv.com) requires the continued development of suitable energy converter technology, which is still a few years into the future. Furthermore, the lack of prescriptive rules and regulations for handling ammonia is making it difficult to plan for its implementation on board. This lack of regulatory development is also causing issues for the adoption of hydrogen as a fuel. These implementation barriers come in addition to the challenges currently applicable to most carbon-neutral fuels: increased capital investment, limited fuel availability, lack of global bunkering infrastructure, additional training of crew, high cost of fuel, and additional demand for storage space on board. The uptake of vessels capable of operating with ammonia as fuel is expected to pick up once the technology becomes available, supported by the fact that 58 ships in DNV Class have been ordered as 'ammonia ready', implying that some preparation for potential conversion to ammonia propulsion has been done at the newbuild stage.

It should be noted that most of the ships which can use alternative fuels can also operate on fuel oils in dual-fuel solutions. Also, the alternative fuel may be derived from fossil energy sources, which emphasizes the need for requirements that address greenhouse gas emissions from well-to-wake.

There are currently 45 LNG bunker vessels operating to serve the fleet of LNG-fuelled ships. A third (15) of these vessels have a capacity of 10,000 m³ or more, making them suitable for serving, for example, the large LNG-fuelled container vessels. The order book shows that 11 new bunker vessels each with a capacity greater than 10,000 m³ will be delivered within the next few years.

> Challenges currently applicable to most carbon-neutral fuels: increased capital investment, limited fuel availability, lack of global bunkering infrastructure, additional training of crew, high cost of fuel, and additional demand for storage space on board.

FIGURE 4-3

Development of LNG, LPG and methanol fuel technology uptake by number of ships, excluding gas carriers[47]

FIGURE 4-4

Ship-to-ship bunkering in container port and at sea/anchorage

4.2 Outlook for the availability of fuel competence and readiness of safe operational practices

A technology change driven by transition to carbon-neutral fuels will have to coincide with a corresponding development of the fuel-specific knowledge in terms of seafarer and onshore organization competence, and in the maritime industry in general. Compared with conventional fuels, the safety risks arising from the properties of the alternative fuels – the gaseous nature of hydrogen, ammonia, and methane; the toxicity of ammonia and methanol; the low-temperature risks associated with methane, hydrogen, and ammonia; and the flammability of methanol, methane, and hydrogen – bring a new complexity to bunkering operations, onboard fuel storage, fuel distribution and maintenance.

Little or no operational experience with new fuels – urgent action needed for upskilling

The availability of seafarers with fuel-specific competence will be a critical factor when fuels presenting new operational safety challenges are introduced. Having a clear understanding of the hazards involved in fuel operations and during maintenance will be essential to be able to control and mitigate the risks.

While fuel-relevant competencies gained through decades of operating gas carriers and chemical carriers will be valuable in upskilling other shipping segments, this is a very limited resource considering the limited number of ships and seafarers in these segments compared to the world fleet.

The gradual introduction of LNG as a fuel, combined with decades of experience from LNG carriers and their use of cargo boil-off as fuel, have been important for the wider uptake of LNG as a fuel for deep-sea shipping seen today. It is a result of more than 20 years of learnings and experiences of designers, shipowners, seafarers, manufacturers, yards, flag states, and classification societies on how to safely integrate and operate onboard LNG fuel systems. The other relevant hydrocarbon gaseous fuel, LPG, is currently only used on LPG carriers where the crew is experienced with LPG handling. Relevant experience has also been gained for methanol through carriage and use as fuel on chemical carriers and as cargo on offshore supply vessels, as well as from the first methanol-fuelled ships.[48]

For ammonia, the picture is different. The maritime industry has experience with carriage of ammonia in gas carriers and as a refrigerant in refrigeration plants, but not as a fuel. Considering the urgency to decarbonize shipping, major deployment of ammonia as a fuel may happen faster than it did for LNG, which means additional focus should be put on the installation and safe operational practices by ship operators and regulators.

Hydrogen is not transported as a marine cargo apart from one pilot project in Japan[49], and the experiences using it as a marine fuel are currently limited to small-scale R&D projects. The entry into service of a ferry powered by proton-exchange membrane (PEM) fuel cells fuelled by liquid hydrogen in March 2023 marked a significant advance for what remains a largely untried technology.[50] The safety implications of storing and distributing hydrogen on ships are unclear. The general understanding of hazards and risks associated with hydrogen as a marine fuel, and particularly liquefied hydrogen, is limited (DNV, 2022c) (DNV, 2022e) (MTF, 2022).

No matter which fuels and technologies are ultimately being used, additional training for seafarers is essential to ensure their safety and that of the environment and local communities. This upskilling needs to be mirrored in the onshore organization.

A recent DNV study for the Maritime Just Transition Task Force points towards an immediate need to train seafarers (DNV, 2022d). The increase in newbuild orders for alternative fuels will increase the demand for seafarers with the required competence, challenging their availability in the near term. The number of seafarers expected to work on ships fuelled by LNG/LPG could increase by nearly 200,000 within the next five years. As many as 800,000 seafarers may require additional training by the mid-2030s to enable the fuel transition in shipping. However, the timing and type of training provided will depend on the ambition of decarbonization trajectories and the future fuel mix.

The ability to build up sufficient training capacity is currently subject to several constraints including:

- the lack of clarity surrounding alternative fuel options and decarbonization trajectories, along with slow regulatory development, making investment in seafarer training challenging
- the need to invest in training facilities and up-to-date equipment (e.g. simulators providing opportunities for hands-on learning experiences)
- the lack of qualified trainers
- the shortage of experienced seafarers.

The Maritime Technologies Forum (MTF)[51] identifies potential gaps for future safe use of alternative fuels within three existing Conventions/Codes in a recent study: The International Safety Management (ISM) Code, International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) and The Maritime Labour Convention (MLC). MTF makes recommendations on how to close the gaps related to safety management, crew training and safety culture (MTF, 2023).

The latest safety report from DNV and Lloyd's List Intelligence outlines what must be done to address safety concerns in the maritime sector – particularly given the challenges that come with digitalization and decarbonization (LLI, DNV, 2023). Digitalization supports the switch to alternative fuels. However, while digital tools can provide valuable insights and automate certain processes, human judgement, expertise, and decision-making are still essential. Crew and other stakeholders need to be vigilant, proactive, and well-trained to identify and address potential safety risks. Most of the global fleet of ships will continue to be operated by seafarers even if some vessels become fully autonomous over the next 10 or 20 years. Advances made in vessel operations technology over the past decade have already seen routine activity shifted from ship to shore. For this ship-shore partnership to work as it should, safety and security training of both seafarers and shoreside teams must be reassessed to ensure that safety will be in focus in all parts of the organization.

Safe operational practices – new safety challenges in bunkering operations

The introduction of new fuel technologies is expected to have a significant impact on maritime operations on ships and will require that practices are established to ensure continued safe and efficient operations during bunkering, onboard fuel storage, fuel distribution, and maintenance. This includes both normal operational procedures and emergency procedures in case of accidental fuel release.

Bunkering without interrupting other ship and cargo operations is the norm for conventional oil-fuelled ships with short port stays. It is also being established as the default bunkering mode for LNG-fuelled ships in these segments.[52] It is reasonable to assume that there will also be a commercial and operational drive towards continuing this practice for fuels like methanol, ammonia, and hydrogen.

The practice of refuelling while simultaneously performing other operations (simultaneous operations, SIMOPs) is typically reviewed on a case-by-case basis by ship operator towards local stakeholders. The purpose is to identify potential hazardous interactions between bunkering and other activities, regarding the receiving ship and the surrounding area, and to determine if any additional safety measures need to be implemented before the activity can proceed.

> In interviews with Nordic ports, nearly all reported safety and regulatory issues as key barriers against supplying hydrogen, ammonia, and methanol.

Performing SIMOPs safely requires co-ordination between the competent authority, terminal operator, fuel supplier, bunkering infrastructure owner, and receiving ship. The Society for Gas as a Marine Fuel (SGMF) is one organization providing guidance on how to determine which other ship and port operations may be conducted safely while an LNG-fuelled ship is being bunkered (SGMF, 2018). Similar guidance is relevant and needed for bunkering of methanol, ammonia, and hydrogen to evaluate the feasibility of performing other operations, such as loading and unloading cargo or having passengers on board, while bunkering these fuels. Depending on factors like proximity to populated areas, type of fuel to be bunkered, and type of bunkering facility, the risk may be considered too high to accept bunkering in certain locations or in parallel with other operations (Figure 4-4).

In interviews with Nordic ports regarding their views on barriers against supplying zero-carbon fuels, nearly all reported safety and regulatory issues as key barriers against supplying hydrogen, ammonia, and methanol (Menon, 2022). The safety aspects are perceived as more critical for ammonia than for hydrogen and methanol, illustrating the need for training for ports as well. Their concerns include, among others, how port operations may pose a threat or affect people living nearby, how to handle potential leakages, the additional space demand related to required safety zones, the lack of a regulatory framework, and uncertainty related to lengthy regulatory processes with authorities.

Safety studies examining the potential ramifications of large ammonia leaks indicate how key operational parameters, such as ammonia storage conditions, transfer flow rate, and release duration, can significantly affect the dispersion of ammonia, and the degree of reduction in affected area that can potentially be achieved by changing parameters (S. Dharmavaram, 2023) (DNV, 2021b) (Clara Kay Leng Ng, 2023). An important additional issue with ammonia, however, is that some leaks may be small enough not to be harmful, yet still be perceived as very dangerous (due to the potent ammonia smell) in surrounding areas, leading to potential major responses in public.

Irrespective of risk studies, it is clear that from a bunkering safety point of view, performing ship-to-ship ammonia bunkering at sea/anchorage would have a lower risk than refuelling while simultaneously performing other operations in port . Alternatively, shore-to-ship ammonia bunkering could be performed in designated areas where SIMOPS are not common practice, similar to how cargo is transferred between gas carriers and onshore gas terminals today (Figure 4-5). For ship types with short port stays, the need for performing bunkering operations at sea/anchorage or in designated areas without SIMOPs would have significant implications for operations, causing delays and additional costs.

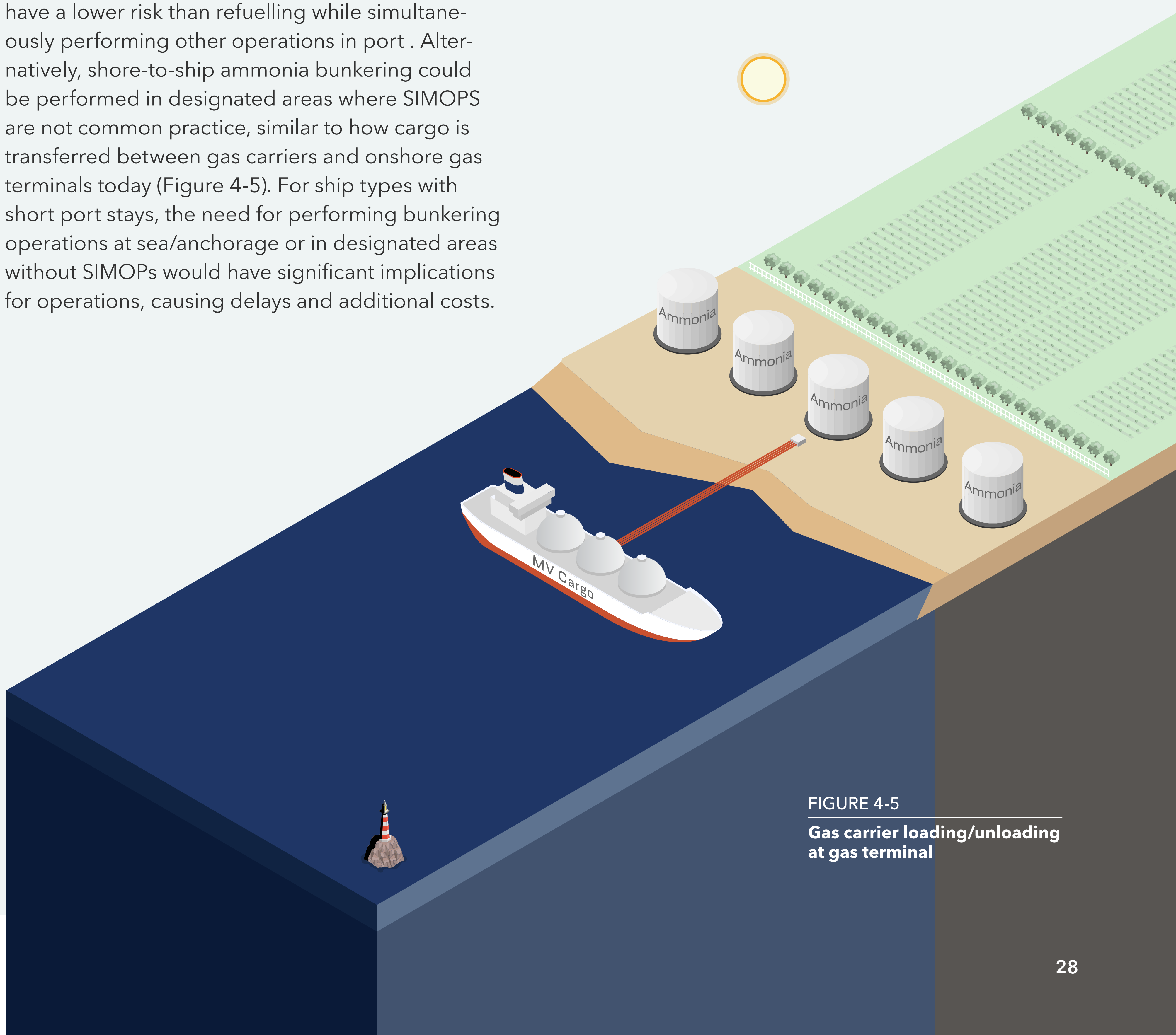
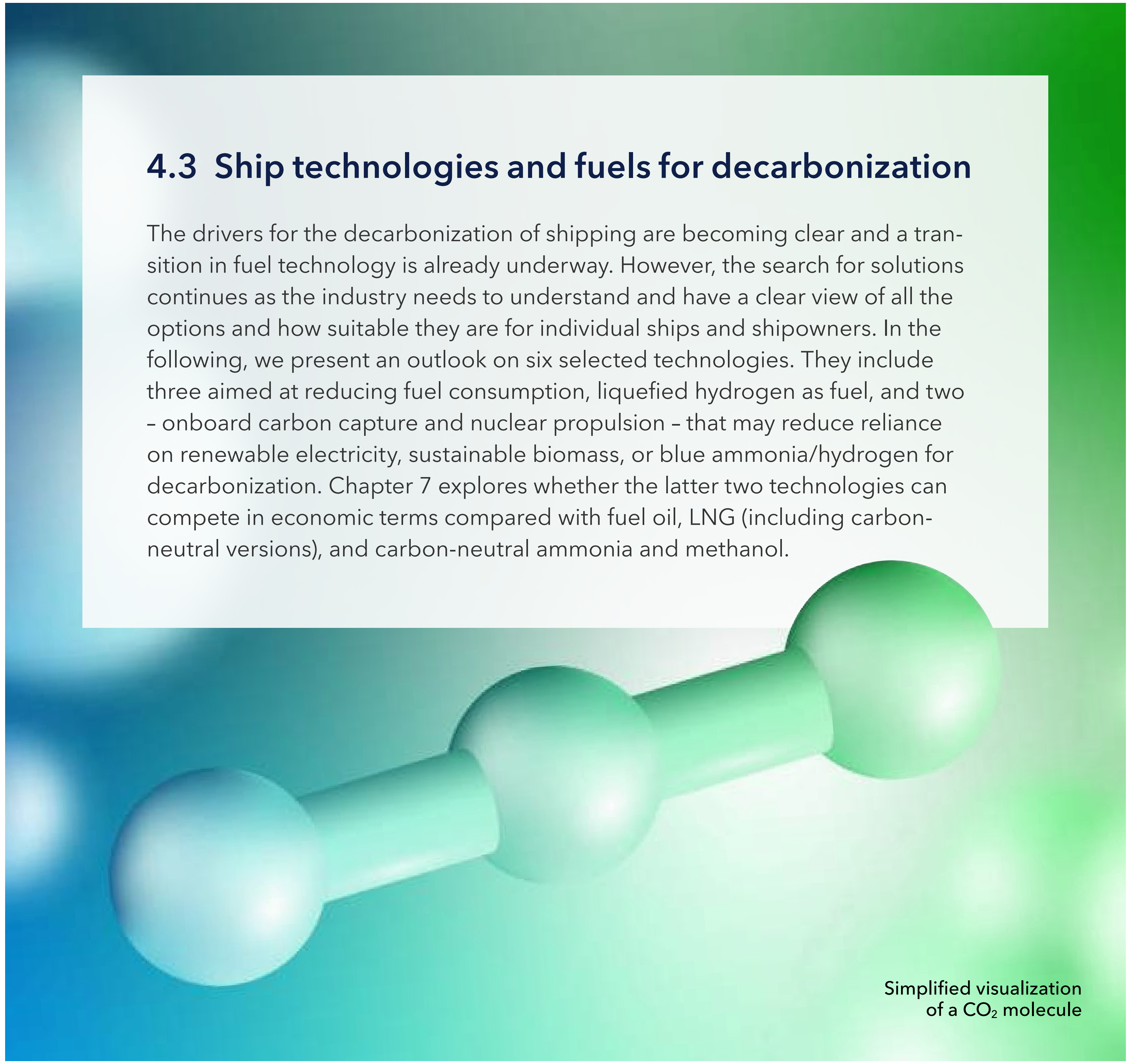


FIGURE 4-5

Gas carrier loading/unloading at gas terminal

4.3 Ship technologies and fuels for decarbonization

The drivers for the decarbonization of shipping are becoming clear and a transition in fuel technology is already underway. However, the search for solutions continues as the industry needs to understand and have a clear view of all the options and how suitable they are for individual ships and shipowners. In the following, we present an outlook on six selected technologies. They include three aimed at reducing fuel consumption, liquefied hydrogen as fuel, and two – onboard carbon capture and nuclear propulsion – that may reduce reliance on renewable electricity, sustainable biomass, or blue ammonia/hydrogen for decarbonization. Chapter 7 explores whether the latter two technologies can compete in economic terms compared with fuel oil, LNG (including carbon-neutral versions), and carbon-neutral ammonia and methanol.



Simplified visualization of a CO_2 molecule

4.3.1 Solid oxide fuel cell

New types of efficient onboard energy converters could reduce the GHG emissions compared to combustion engines. One such converter technology is the solid oxide fuel cell (SOFC), which has raised interest in the market due to the ability to convert fuels like ammonia, LNG, methanol, and hydrogen to electricity with a potentially higher energy efficiency compared to internal combustion engines.[53]

SOFC is characterized by its use of a solid oxide material as the electrolyte used to conduct negative oxygen ions from the cathode to the anode. The fuel cell is made up of ceramic layers, a few millimetres in thickness, stacked together and connected in series to form a SOFC stack. The ceramics used do not become active until they reach very high temperatures, which is why SOFC power plants are typically run at temperatures between 500°C and 1000°C. The high operating temperature is making it possible for some SOFCs to internally reform fuels like ammonia and light hydrocarbons into hydrogen at the anode without the need for external fuel reformers. If the heat given off by the exothermic electrochemical oxidation of the reformed hydrogen within the fuel cell can be recovered from the exhaust and utilized on board, a higher energy yield and corresponding reduction in GHG emissions could be achieved compared to current dual-fuel engines. Additionally, SOFCs fuelled by natural gas do not have issues with methane slip, and the concentrated CO_2 in the exhaust can be beneficial if used in combination with onboard carbon capture and storage, as high concentrations of CO_2 allow for less energy to be used for the capture process. The potential of using SOFCs with LNG as fuel has been explored in, for example, (Georgopoulou, et al., 2021), where DNV and Euronav found that if an SOFC system with waste-heat recovery through steam turbines could achieve 60% electrical efficiency, then the fuel consumption of an LNG-fuelled very large crude carrier (VLCC) could be reduced by 33% using this fuel-cell system.

> Solid oxide fuel cell can convert fuels like ammonia, LNG, methanol, and hydrogen to electricity with a potentially higher energy efficiency compared to internal combustion engines.

Apart from the potential efficiency increase, fuel cells have other potential benefits such as reduced noise, reduced maintenance needs, modular and flexible

> Apart from the potential efficiency increase, fuel cells have other potential benefits such as reduced noise, reduced maintenance needs, modular and flexible design, and improved part-load operation efficiency.

design, and improved part-load operation efficiency. However, fuel cells come with significant disadvantages related to cost and durability. These challenges will need tackling before fuel cells can make a meaningful contribution to reducing emissions.

The ShipFC[54] project intends to demonstrate that ammonia-fuelled SOFCs can provide long-range zero-emission voyages on larger ships. The Eidesvik-owned offshore vessel Viking Energy will in late 2023 be retrofitted with a 2 megawatt (MW) ammonia fuel cell in a project hoping to demonstrate the ability to operate for up to 3,000 hours annually on ammonia only. The project also aims to ensure that a large fuel cell can safely and effectively be the sole provider of electric power to shipboard systems.

A consortium led by Shell[55] aims to design, manufacture, and install a 600 kilowatt (kW) SOFC auxiliary power unit on an LNG carrier for a year of testing in 2025. The trial seeks to test the technology's decarbonization potential, prove its scalability as a propulsion solution for shipping, and enable wider industry acceptance of fuel cells.

Additionally, several cruise ship owners are looking at the possibility of using SOFC with natural gas as fuel. MSC Cruises took delivery of MSC World Europa in October 2022. The ship is reportedly the world's largest LNG-fuelled cruise ship in operation and is fitted with a 150 kW SOFC demonstrator installation fuelled by natural gas.[56] MSC is also investigating other fuels on its vessels Explora V and Explora VI. In addition to LNG-fuelled propulsion machinery, these ships are planned to feature a containment system for liquid hydrogen which will power a 6 MW fuel-cell installation intended to deliver emission-free power for hotel operations and allowing for zero-emission operations in port, with the engines turned off.[57]

Currently, SOFCs involve about 10 times the CAPEX of internal combustion engines per kW installed, and have a much shorter lifetime.[58] Laboratory tests indicate that SOFCs can achieve significantly higher efficiencies than conventional engines, but this has not yet been demonstrated on a ship. Fuel cells must first be demonstrated to have a significantly higher efficiency than internal combustion engines in real operating conditions, in a real ship energy system, over the ship's entire operational profile. Once the promise of significantly reduced fuel consumption is decisively answered, SOFCs can be mass produced and work on improving cell lifetimes and reducing costs can begin in earnest. The pilot projects underway have potential to demonstrate SOFCs' real operational efficiency over the next three to five years.

4.3.2 Liquefied hydrogen

The direct use of liquefied hydrogen has seen its first use as a marine fuel for a ferry in Norway[59], where MF Hydra has installed 400 kW of PEM fuel cells and an 80 m^3 C-type tank for liquefied hydrogen[60]. The ferry is operated by Norled, on contract for the Norwegian Public Roads Administration (NPRA). This is yet another major contribution by the NPRA to the development and implementation of new technology, following the introduction of the first LNG-powered ferry MF Glutra in 2000, and the first electric ferry, MF Ampere, in 2014.

Liquefied hydrogen is also being investigated as a fuel for deep-sea shipping. In addition, plans are made for transporting liquefied hydrogen on ocean-going vessels[61] aiming to fulfil plans for importing hydrogen to, for example, the EU[62]. The transported hydrogen could be made from both renewable electricity and fossil energy with CCS. Four ports in Europe and one port in Japan are developing hydrogen import plans. The Suiso Frontier, a 1,250 m^3 liquefied hydrogen carrier prototype, completed its first international cargo voyage from Victoria, Australia to Japan in January 2022[63]. For an example of a new design for a liquefied hydrogen carrier, see Figure 4-6.

> A successful development of a large liquefied hydrogen carrier can entail new tank designs for the cryogenic hydrogen.

Challenges to using liquefied hydrogen as ship fuel include high fuel costs, currently expensive fuel cells and tanks, and lack of regulations for onboard use, due to safety concerns over flammability and explosion risk. A key economic barrier to using liquefied hydrogen as fuel in deep-sea shipping is the low volumetric energy density compared with other fuels, when also considering the fuel containment systems. The energy density for liquefied hydrogen is higher than for compressed hydrogen, which is being considered in several projects for short-sea shipping. This makes it imperative to include measures to reduce fuel consumption, not only to reduce the direct fuel costs, but also to reduce the space required for onboard storage. Applying technical and operational energy-efficiency measures, logistics optimization, and energy assistance (e.g. wind) will extend the operational range of the ship and reduce loss of cargo space.

Another challenge for the use of liquefied hydrogen is the successful development of fuel cells, discussed in the chapter above, though there is also ongoing development and use of hydrogen in internal combustion engines[64]. The technological improvements of LNG-fuelled SOFCs can in many respects be directly transferrable to using liquefied hydrogen as fuel. If the higher-end efficiencies seen in research literature for fuel cells can be achieved, the use of fuel cells can significantly reduce the fuel usage and necessary storage volumes for liquid hydrogen – for example, see (Georgopoulou, et al., 2021).

Furthermore, a successful development of a large liquefied hydrogen carrier can entail new tank designs for the cryogenic hydrogen. Most storage of liquefied hydrogen today is done in smaller pressurized tanks, and it is to be expected that the cost of storage per unit of transported energy will be significantly reduced in a successful large tank design. Decreasing the cost of a liquefied hydrogen carrier vessel will not only help towards make transporting liquefied hydrogen economically feasible, it will also reduce the final cost of delivered liquefied hydrogen to the end consumer, as will a potential decrease in the energy needed for liquefaction of hydrogen (IRENA, 2022). These ongoing technological developments could decrease the cost of supplied liquefied hydrogen as an energy carrier and bunker fuel relative to other fuels.[65]

To illustrate the effect of reduced hydrogen fuel and equipment cost from potential new technological innovations on the future fuel mix, we have performed a sensitivity study on fuel price and CAPEX input in the Pathway Model that we use to simulate the future fuel mix of the world fleet. For this latest Maritime Forecast to 2050 we have not run a new set of scenarios, but have rerun two of the 24 scenarios published in the 2022 edition, with the only changes being reduced CAPEX and fuel price for liquefied hydrogen. These two scenarios (numbers 17 and 21 on page 63 in (DNV, 2022a)) represented a Decarbonization by 2050 trajectory, and very low electrofuel prices (scenario 17) and very low blue fuel prices (scenario 21). With a 25% reduction in liquefied hydrogen fuel price and a 25% reduction in additional CAPEX for a liquefied hydrogen ship, we see uptakes of 17% (very low electrofuel prices) and 39% (very low blue fuel prices) for liquefied hydrogen fuel in 2050. We have assumed that all vessels have a suitable arrangement for operation on liquefied hydrogen, which may not be the case for all ships due to space restrictions[66].

FIGURE 4-6

Concept design of liquefied hydrogen carrier, *courtesy of Shell Plc*

4.3.3 Wind-assisted propulsion systems

Wind-assisted propulsion system (WAPS) technologies have gained significant attention as a means of reducing ship fuel consumption and emissions. In generating aerodynamic forces, they use wind power to supplement vessel propulsion. WAPS could significantly improve the efficiency of shipping operations and contribute meaningfully to decarbonizing the industry, as wind is an inexhaustible, free, and carbon-neutral energy source.

> Wind-assisted propulsion has already delivered yearly fuel savings of between 5% and 9% for certain ships, and is claimed to have the potential to reach 25%.

Unlike alternative fuels, wind-assisted propulsion – because it uses wind energy to directly provide additional thrust to a ship – is categorized as a technology that reduces the propulsion power in the energy efficiency indices of EEXI/EEDI. In other words, wind in this terminology is not an alternative fuel that is bought and bunkered. Wind-assisted propulsion has already delivered yearly fuel savings of between 5% and 9% for certain ships, according to vessel owners and operators, and is claimed to have the potential to reach 25%. Potentially, the gains can be higher if newbuilds are specifically designed to carry sail systems. By combining wind-assisted propulsion technology with weather routing algorithms and logistics optimization (e.g. allowing for lower speed), the advantages of sailing can be enhanced by generating optimal routes for individual vessels. Transition to carbon-neutral fuels will typically imply increased fuel costs and reduced energy storage capacity/range. In this context, wind combined with energy optimization measures and, potentially, a small share of fossil fuels, may be just what is needed to successfully implement a near zero-emission concept.

The renewed interest in wind power will probably not lead to a renaissance of the sailing tall ships which served worldwide trade in previous centuries, but wind power can be a supplement to bunkered alternative fuels. Current wind-assisted propulsion technology relies on a combination of advanced aerodynamics, automation, computer modelling and modern materials to unlock a new generation of innovative sail systems for ocean-going ships. Most modern systems utilize state-of-the-art intelligent control and automation systems to operate safely, without the requirement for additional crew.

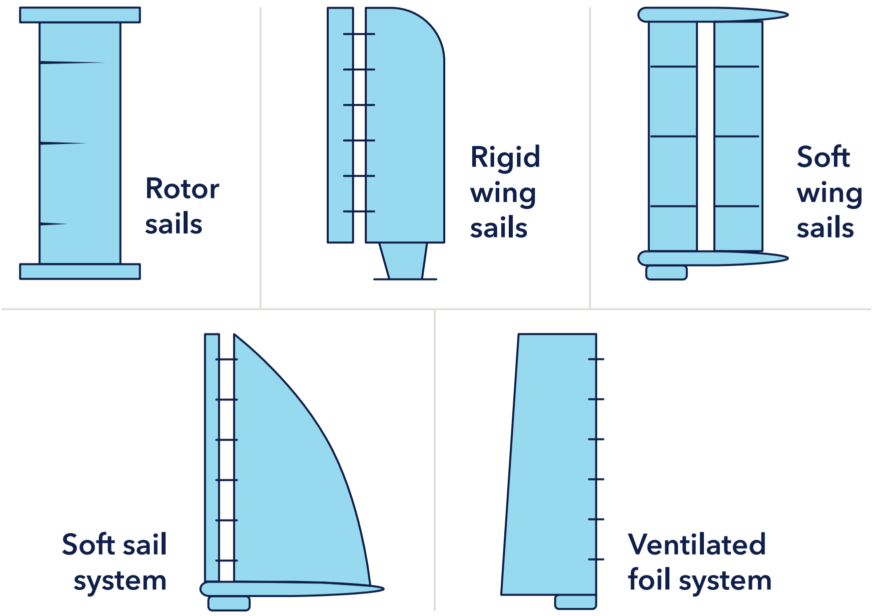
Several different sailing technology concepts have been or are being developed, including rigid or soft wing sails, rotor sails, ventilated foils, and kites, see Figure 4-7.

Alongside the potential benefits of wind-assisted propulsion technologies there are challenges to widespread adoption. One key challenge is to ensure the reliability of technologies that can operate effectively in a variety of conditions.[67]

Currently, 28 large commercial vessels have installed wind propulsion systems[68] representing more than one million tonnes of deadweight[69]. Rotor sails account for half of the current installations. Looking at publicly announced projects, these numbers are expected to double over the next year.[70]

FIGURE 4-7

Wind-assisted propulsion system technologies supported by DNV Standards[67]



An example of a large commercial vessel project utilizing wind power is the Orcelle Wind, for which Wallenius Wilhelmsen and project partners have secured Horizon Europe funding totalling EUR 9mn to support the building of a RoRo sailing vessel[71] over the next five years.

Sea-Cargo has installed two tiltable rotor sails on its vessel SC Connector and reports gaining a substantial propulsion effect and improved operational ability from the installation. It has estimated that 21% of the energy consumed by the vessel in 2021 was renewable energy.[72]

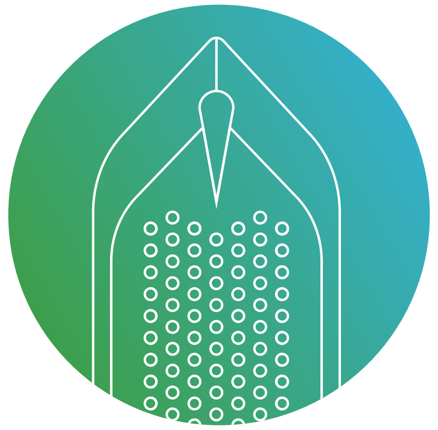
Sea-Cargo's SC Connector is fitted with two Norsepower tiltable rotor sails *(Image Sea-Cargo)*

4.3.4 Air lubrication systems

Air lubrication systems (ALS) can reduce energy consumption by lowering the resistance between the hull and seawater through injecting air along the flat bottom area of a ship. A vessel's resistance to motion through the water consists of multiple components, of which the frictional resistance is the dominant one. For low-speed displacement vessels, frictional resistance can reach 85% of total resistance. The skin friction resistance is proportional to the wetted surface of the hull and the cruising speed, and even small decreases in skin friction can have large impacts on the fuel consumption when the vessel is travelling at speed.

Air lubrication systems inject air along the flat bottom area of a ship to reduce the frictional drag. Due to the turbulence in the boundary layer, an air and seawater mixture is established. When a sustained air layer in this mixture can be generated over a large portion of the ship bottom, drag reduction is greater than if the air layer breaks up into patches or if the patches further break up into large bubbles.

The reduction in frictional drag depends on the homogeneity of the air and seawater mixture and the rate of air flow across the width of the bottom over the length of the ship, making the distribution of the air release units discharging the air an important factor.



Air lubrication systems inject air along the flat bottom area of a ship to reduce the frictional drag.

Some systems apply multiple rows of air release units in the ship's longitudinal direction, while all have several air release units placed transversely. Much effort is put into the design of the air outlets to improve the efficiency of the air injection. The aim is to get the maximum reduction of frictional viscous resistance with a minimum of required air pressure and volume.

Laboratory tests have been performed with full-scale air release units to optimize the air outlets. In these tests the water inflow speed is similar to the vessel's speed and the viscous turbulent boundary layer behaves like on the vessel, but the ambient pressure of the full-scale ship typically cannot be met. Extrapolating test results from limited models to actual ship conditions is challenging, but more feasible than conducting experiments under full-scale conditions with a prototype.

Model tests with scaled models have been used, but the results are also difficult to extrapolate to full-scale. Traditional towing tank tests for calm water resistance rely on a rather complex extrapolation procedure, which reflects the physical processes involved. With air lubrication applied, the validity of these extrapolation procedures is compromised, making performance improvement predictions uncertain.

Full-scale measurements can be used to quantify the effect of air lubrication technology. The ability to turn the systems on and off provides an excellent opportunity for verification. Collecting a set of system-on and system-off measurements during stationary conditions has been shown to provide accurate estimates of the increased vessel speed and reduced engine power.

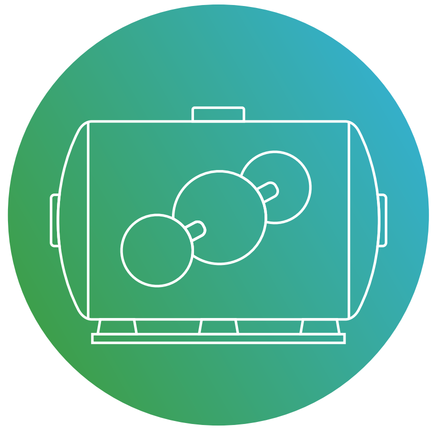
The net power savings of an air lubrication system will be the savings from the reduction of the hull frictional resistance, adjusted for the additional power needed to run the air compressors and auxiliaries of the system. Typical values for net power savings, as provided by system manufacturers, are in the range of 4% to 7% at normal operating weather conditions (up to Beaufort scale 5) without large roll motions or large trim.


AIDAperla is fitted with air lubrication system

Air lubrication is presently seeing a high rate of uptake, particularly in the container and gas carrier segments, but is still in early days of implementation. By June 2023, more than 347 vessels either equipped or retrofitted with an air lubrication system have been reported as contracted or delivered.[73] In total, the three large Korean yards Hanwha Group, HD Hyundai, and Samsung Heavy Industries have 137 vessels equipped with air lubrication systems in their reference lists, comprising 105 LNG carriers, 26 container vessels, and 6 container/RoRo vessels. The UK company Silverstream Technologies has 110 vessels equipped with ALS in its references, comprising 19 LNG carriers, 53 containerships, 20 cruise ships, 6 bulkers/tankers, and 12 RoRo vessels. More vessels equipped with the Finnish company Foreship's air lubrication system and with the Mitsubishi Air Lubrication System (MALS) are reported in service or on order.

Future research will likely improve the performance of air lubrication systems significantly, and the ability to maintain a stable air layer for a larger distance downstream is a key research topic. New types of hull coating may be part of the solution. Another important element is optimization of the ALS control system and usage, considering the effect of changing vessel draft, trim, and speed, or waves and wave-induced vessel motions.

4.3.5 Onboard carbon capture and storage



Onboard carbon capture enables carbon-neutral operation without being dependent on blue fuels or fuels made from sustainable biomass or renewable electricity.

The concept of onboard carbon capture and storage (CCS) is based on technology that captures the carbon in the fuel before CO_2 is emitted to the atmosphere through the exhaust. This requires onboard CO_2 storage capacity as well as a value chain that can receive and store the CO_2 permanently away from the atmosphere. Onboard carbon capture allows for continued use of carbon-rich fossil energy directly on individual ships (but with significantly reduced CO_2 emissions), as opposed to the industrial transformation of fossil energy to carbon-free blue fuels (ammonia or hydrogen) with centralized carbon capture on land. Hence, onboard carbon capture enables carbon-neutral operation without being dependent on blue fuels or fuels made from sustainable biomass or renewable electricity.

Onboard carbon capture and storage systems will therefore be dependent on a developed infrastructure for shore-based CCS, as onboard capture will be the starting point of a long logistics chain. The ship will require: carbon capture facilities to remove CO_2 from the exhaust; process plant to transform captured CO_2 to a state suitable for storage; and storage and offloading facilities enabling discharge to shore or transport ship. Once captured and ready for discharge, successful permanent CO_2 storage requires the development of a reception infrastructure connected to a transport network of pipelines or ships to get the CO_2 to permanent storage sites. Carbon pricing is expected to be the primary driver for this onshore development. An example could be the EU ETS already in place for land-based industry. It is reasonable to assume that the shore-based CO_2 capture industry will drive the development of much of this logistic chain, as the volumes that will be captured ashore are estimated to be much larger than for shipping. Shipping emits around 1,000 million tonnes of CO_2 per year. Forecasted global CCS capacity in net-zero policies' 2050 scenarios ranges from 4,000 to 8,400 $MtCO_2$ stored annually, part of which could be made available for CO_2 captured from shipping (Ricardo; DNV, 2023).

There are several potential methods for reducing the CO_2 content in industrial flue gases, while for shipping, the post-combustion method, capturing CO_2 from the exhaust after the fuel has been burned, seems to be the method of choice. Post-combustion capture technologies for onboard use can be based on different principles like chemical absorption, membrane separation, or cryogenic capture technologies. The chemical absorption process using amine solvents currently seems to be the most popular option. This technology is considered mature for shore-based applications, and several companies are working to prove its usability for ships.

From a ship perspective, the costs of onboard carbon capture will to a large degree depend on:

- the installation cost of carbon capture and storage facilities on the ship
- the additional operating costs and additional fuel consumption required to run the carbon capture and storage process on board
- the cost of delivering captured CO_2 to reception facilities.

Solvang and Wärtsilä intend to use Clipper EOS for full-scale testing of onboard carbon capture and storage *(Photo rendering by courtesy of Wärtsilä and Solvang Shipping)*

A shipowner considering onboard carbon capture and storage as a decarbonization strategy will be faced with several technical challenges regarding system integration and optimization. For retrofitting on existing ships, it should be noted that both the carbon capture technology and storage facilities for CO_2 demand space and will add considerable weight.

Extra energy is needed – referred to as 'the fuel penalty' – for exhaust cleaning and processing, which may require installing additional auxiliary power. The fuel penalty, typically estimated to be between 10% and 40%, will depend on the type and size of the system, the fuel consumption deciding the exhaust flow into the capture system, and the CO_2 capture rate. Higher capture rates will require more input energy and/or additional equipment, and at some point, such increases may not be defensible. The ability to use waste heat from the ship systems in the capture process will also be a determining factor for the fuel penalty. For a newbuild, integration of the CCS plant and the required auxiliary power increase will be easier to manage, but for both newbuilds and retrofits there will be more exhaust emissions to clean due to the energy demand of the onboard carbon capture system.

The effectiveness of onboard carbon capture and storage systems in purifying exhaust depends on various factors, such as the type of capture system, rate of absorption, capture system size, fuel type, fuel consumption rate, and CO_2 concentration in the exhaust gas. For example, lighter fuels have a higher CO_2 concentration and less sulphur oxides (SO_X) and particulate matter (PM).

A 100% CO_2 capture rate does not seem to be a realistic goal for an onboard carbon capture plant, while manufacturers indicate that 90% could be achieved technically. The design CO_2 capture rate should be aligned with the ship's GHG ambitions over its lifespan, the CO_2 storage capabilities, and the CO_2 offloading frequency. It should also be optimized to combine with carbon-neutral fuel use, if the carbon reduction requirements exceed the capabilities of the capture system. Capturing CO_2 while running on carbon-neutral fuels will remove CO_2 from the global carbon cycle.

The Norwegian shipowner Solvang ASA is one of the early movers within onboard carbon capture. Solvang and Wärtsilä have signed a Letter of Intent[74] to do a full-scale testing of a Wärtsilä carbon capture plant onboard Clipper EOS, which is on time charter to Marubeni Corp, Tokyo. The goal is to demonstrate that CO_2 can be captured from heavy fuel oil (HFO) combustion and stored aboard in deck tanks, and to gain experience on operational aspects of the process, energy consumption, and maintenance needs.

EverLoNG[75] is a three-year EU research initiative involving the maritime, R&D, and engineering sectors and co-funded by the ERA-NET ACT3 programme. The project aims to encourage the uptake of onboard carbon capture and storage by demonstrating its use on LNG-fuelled ships and moving it closer to market readiness. The work tasks include demonstrating onboard carbon capture and storage effectiveness by installing test installations on two LNG-fuelled vessels, evaluating the cost of onshore logistics, and developing a roadmap proposal for a European CO_2 offloading network.

4.3.6 Nuclear propulsion

Nuclear propulsion is a zero-emission, zero-carbon, and carbon-neutral alternative for shipping, and industry actors are considering nuclear-powered merchant shipping. Nuclear propulsion provides the ship's main energy needs from an onboard nuclear reactor in which controlled fission of nuclear fuel produces heat that is extracted using a coolant. The heat is used to generate power – for example, by generating steam to drive turbines, either to generate electricity for electric propulsion or to drive a shaft for mechanical propulsion. In addition to the advantage of inherently carbon-neutral operation, a nuclear-powered ship is less exposed to risks related to price fluctuations and availability of carbon-neutral fuels, as well as possible changes in emission regulations and emission costs. Furthermore, such ships have long bunkering intervals, possibly aligning with the dry-docking schedule or even with the lifetime of the ship.

Nuclear propulsion still has implementation barriers to overcome, the most significant being non-proliferation issues, preventing nuclear accidents, need for international regulatory development[76], and public perception of the technology.

Approximately 700 nuclear reactors have been used on ships and submarines since the first nuclear-powered ship, the American submarine Nautilus, was introduced in 1955. As of today, 160 ships with 200 reactors are in operation (Maritime Nuclear Application Group, 2022). The majority of marine nuclear reactors have been used in naval surface ships and submarines, and Russia has built 12 icebreakers with nuclear propulsion, of which 7 are still in operation[77]. Three experimental merchant ships have been outfitted with nuclear propulsion (Schøyen & Steger-Jensen, 2017): Savannah in the US (1962–1972), Otto Hahn in Germany (1968–1979), Mutsu in Japan (1990–1992), as well as the Russian merchant ship Sevmorput, which is still in operation.

For economies of scale, the size of nuclear reactors on land have over time increased to an installed capacity of around 1 gigawatt (GW) or more, reducing the operation and maintenance costs per output. The economy of scale would be reduced for smaller nuclear power reactors, but it may be offset by the economy of multiples through standardization and subsequent mass production. In a centralized plant, small nuclear reactors can be manufactured in modules for installation at other sites, allowing for standardization, reduced regulatory burdens, improved quality control, and shortened construction times. In this way, the process avoids making each power plant's construction a first-of-its-kind. Typically, the designs aim to improve safety performance to achieve public acceptance and to reduce operating costs. These types of reactors are known as Small Modular Reactor (SMR) and have up to 300 MW of electric output.

> Small modular reactors have some qualities that fit well with shipping, approximately matching the power output of larger ships.

Otto Hahn was one of three experimental merchant ships that were equipped with nuclear propulsion

Small modular reactors have some qualities that fit well with shipping, approximately matching the power output of larger ships. Several of the SMRs are claimed to be of inherently safe design by not requiring active control to avoid nuclear accidents. This would be a significant benefit in shipping by not requiring a large and specialist crew to operate the nuclear reactor, while serial production would reduce the regulatory burden and thereby the costs.

At least 70 SMR designs are being proposed (IAEA, 2020), with three in operation and three under construction (IEA, 2022c). These are based on both existing and new technologies and are defined within different reactor categories: land-based water-cooled, marine-based water-cooled, high-temperature gas-cooled, liquid metal, and molten salt. When the reactor output is less than 20 MW, they are classified as microreactors. Six of the designs listed in (IAEA, 2020) are for marine application, all of which are based on water-cooled reactors. However, other companies are working towards the maritime sector. For example, Ulstein[78] has a concept ship design, while Seaborg[79] and Core Power[80] are both developing molten salt reactors.

A molten salt reactor (MSR) is a class of nuclear fission reactor in which a molten salt either performs a primary cooling function for the reactor and/or the fuel is a molten salt mixture with the nuclear fuel (uranium or thorium) dissolved in the salt. ORNL in the US operated an MSR reactor successfully from 1965 to 1969, and a significant effort was put into solving corrosion challenges.[81] The salt typically has a melting point around 400°C and boiling point at 1,400°C, enabling the reactor to operate at low pressure at around 700°C compared to water-cooled reactors which typically operate at temperatures of about 300°C and pressure of about 150 bar. When molten salt is used as reactor fuel, the nuclear reactivity decreases with higher temperature, making the process self-regulating and preventing thermal run-aways. As an additional safety feature, separate, cooled drain tanks are placed underneath the reactor where the radioactive fuel can be drained to in accident scenarios as a passive safety measure or for regular maintenance. Draining the fuel-salts from the core into this tank renders the reactor subcritical, due to the shape of the draining tank.[82] In case of loss of electric power a freeze plug would melt, automatically draining the fuel-salts into the draining tank. Once in the draining tank the fuel-salts would undergo natural decaying, releasing only decay heat. The use of molten salt instead of zirconium-based fuel rods also prevents the formation of hydrogen gas as is the case in water-cooled reactors, thus eliminating the risk of hydrogen explosions.

A sub-category of SMR is microreactors with capacities up to 20 MW. One such microreactor is the 5 MW reactor eVinci by Westinghouse[83], which is intended to be fitted in shipping containers for transporting to the power production site and back to the manufacturer for refuelling or replacement (after about three years). The eVinci is based on a micro-pipe cooling with sodium without moving parts, a solid moderator (metal hydride), and a nuclear core that is sub-critical (i.e. with decreasing rate of fission) without utilizing movable neutron reflectors around the core. The reactor container is also planned to come with built-in shielding.

Nuclear reactors are CAPEX-intensive, giving rise to the concept of shipowners leasing a nuclear reactor for the lifespan of a ship[84]. Chapter 8 investigates which annual leasing costs for nuclear propulsion – with corresponding interest rates and CAPEX – could compete with other proposed solutions for decarbonizing the case-study ship, a 15,000 TEU container vessel.

US nuclear-powered aircraft carrier USS Gerald R. Ford sailing into the Oslofjord, Norway, May 2023
Copyright Hendrik W. Brinks

5

OUTLOOK ON ALTERNATIVE FUEL PRODUCTION AND DEMAND

Highlights

We assess the future for carbon-neutral fuels for which shipping will compete with other sectors, concluding that:

- The estimated demand from shipping to achieve emission-reduction goals in 2030 is 30% to 40% of the total world supply of carbon-neutral fuels.
- Competition means production of carbon-neutral fuel alternatives must accelerate if emission-reduction goals are to be met.
- Price fluctuations due to supply uncertainty while production of carbon-neutral fuels ramps up mean fuel flexibility will be key for shipowners during the transition period.

The availability of carbon-neutral fuels is one main concern for the shipping industry striving towards decarbonization. Demand for carbon-neutral fuels for all sectors will increase as local, regional, and global regulations are tightened and cargo owners require low- to zero-emission services to fulfil their own decarbonization targets. The current fuel market for shipping is about 280 Mtoe[85] per year, mainly fossil fuel, and towards 2030 the energy industry is ramping up production of carbon-neutral fuel alternatives. Our analysis shows that if 30% to 40% of the total expected world supply of carbon-neutral fuels in 2030 is allocated to shipping, that will be sufficient to cover the annual demand from the industry. However, as shipping will compete with aviation and road transportation, and with other industries, production of carbon-neutral fuel alternatives needs to accelerate if the emission-reduction goals are to be met.

The target for shipping industry decarbonization can be achieved by combining various measures. Reducing speed and implementing a wide range of energy-efficiency measures will reduce the need for energy, but the final step will rely on carbon-neutral fuel.

This chapter presents an overview of shipping's current consumption of fossil fuels, and a simulation of demand for carbon-neutral fuels to meet emission targets. We also reflect on supply and infrastructure for carbon-neutral fuels towards 2030.

5.1 Existing fuel-supply chain

To estimate today's fuel consumption we use published IMO and IEA data, as well as finally considering activity-based studies using automatic identification system (AIS) data. We estimate that shipping today consumes about 280 Mtoe of fuel annually.

For 2021, the reported fuel oil consumption for ships of 5,000 gross tonnage (GT) or more in international trade was 209 Mtoe according to (IMO, 2022). Almost all (99.9%) the fuel that was reported was either heavy fuel oil (HFO), light fuel oil (LFO), marine gas oil (MGO) or liquefied natural gas (LNG). Beyond the fuel consumption reported by the IMO (2022) for ships above 5,000 GT (see Figure 5-1), there is an additional amount consumed by ships of less than 5,000 GT.

The total bunker volume sold to ships in international trade was 213 Mtoe in 2019, according to sales figures from IEA. In addition to ships in international

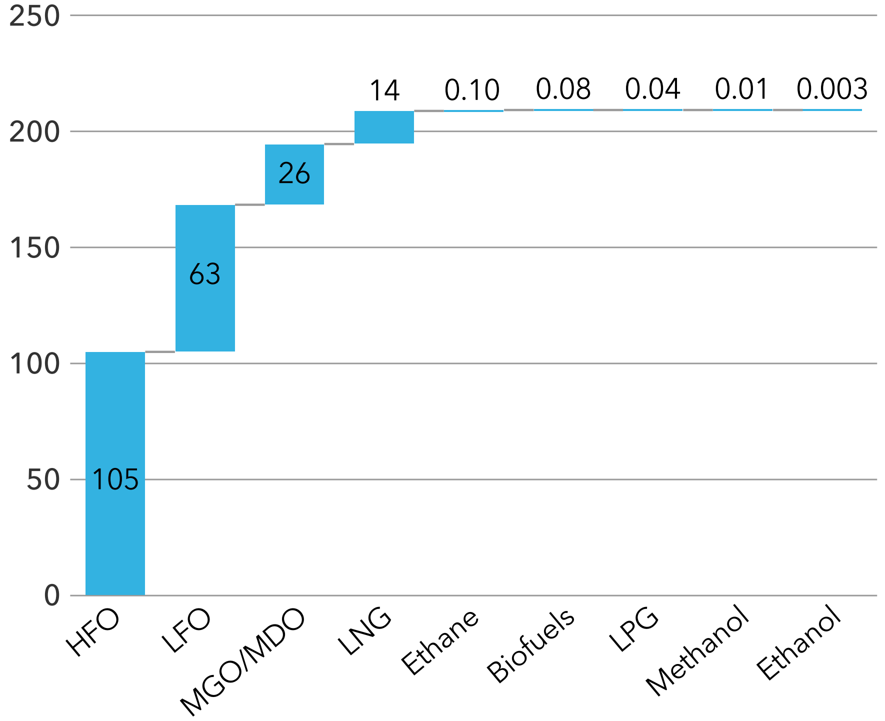
trade, there is also fuel consumption by the domestic and fishing fleet, reported by IEA as a further 57 Mtoe in 2019 (IEA, 2019). LNG consumption rose from 12.0 Mtoe in 2019 to 14.5 Mtoe in 2021 (IMO, 2022), and LNG comprises about 7% of the total fuel consumption in 2021 for ships above 5,000 GT. However, more than 95% of the LNG consumption is boil-off from the cargo on gas carriers and therefore not bunkered as fuel.

Among carbon-neutral fuels, biofuel is the most widely used in shipping today and often used as a blend-in with fossil fuels. Biofuels can be blended in with a variety of different marine fuels, such as MGO, marine diesel oil (MDO), high sulphur fuel oil (HSFO), very low sulphur fuel oil (VLSFO), and so on. The typical blending ratio of biofuel is currently in the range 20% to 30% but is also available as 100% biofuel. The bio-blended fuels represent an available decarbonization option, as it is possible to use the infrastructure in the same way as for conventional marine bunkering fuel today. Additionally, biofuels already have an established infrastructure due to their use in multiple sectors (IRENA, 2021). For example, Port of Rotterdam sold more than 500,000 tons of bio-blended fuels in 2022 and Port of Singapore reported a sale of 140,000 tons bio-blended fuel, distributed over 90 bunkering operations[86]. Overall, the sales of bio-blended fuels increased by more than 70% between 2021 and 2022.

FIGURE 5-1

Fuel consumption for ships >5,000 GT based on reported DCS data to IMO (2021) (IMO, 2022)

Units: Million tonnes of oil equivalent (Mtoe)



Source: IMO (2021, 2022). Key: Heavy fuel oil (HFO); liquefied natural gas (LNG); liquefied petroleum gas (LPG); marine diesel oil (MDO); marine gas oil (MGO); light fuel oil (LFO)

5.2 Demand for carbon-neutral fuels in shipping

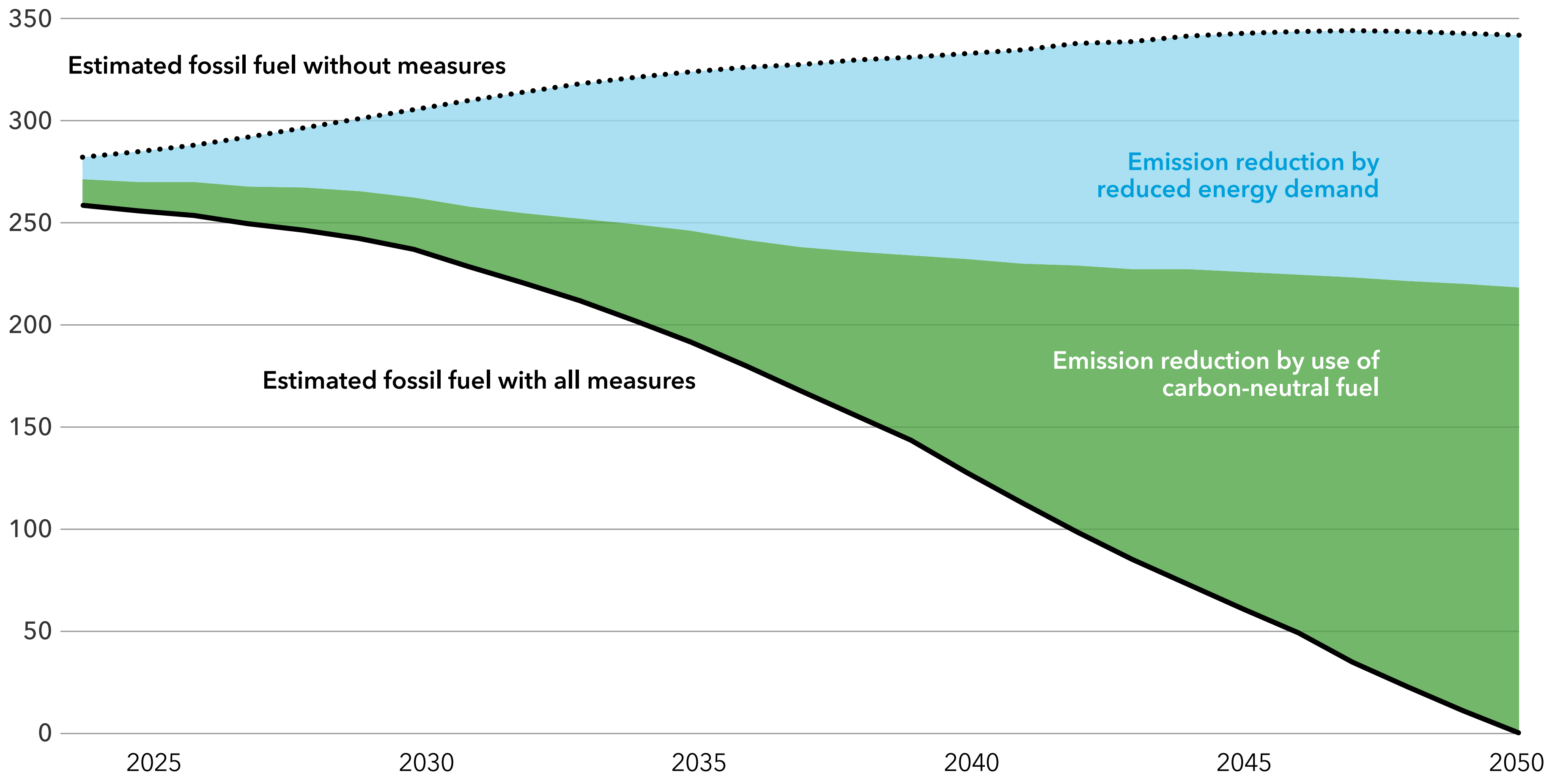
Demand for carbon-neutral fuels in shipping will be driven by GHG regulations and policies such as carbon pricing (see Chapter 3), expectations of cargo owners and consumers, and access to investors and capital. The demand for carbon-neutral fuels is therefore strongly dependent on global, regional, and national regulations.

To meet defined regulatory requirements, shipping companies will seek the most economically favourable GHG emission-reduction measure at any given time. It is therefore assumed that a combination of speed reduction and energy-efficiency initiatives will ensure individual vessel compliance in the short term. Based on results from the 2022

FIGURE 5-2

Simulated results for future demand of carbon-neutral fuels in shipping

Units: Million tonnes of oil equivalent (Mtoe)



edition of Maritime Forecast to 2050 (DNV, 2022a), we estimate demand for carbon-neutral fuels towards mid-century in a Decarbonization by 2050 scenario, see Figure 5-2. The estimated demand for carbon-neutral fuels takes into account an expected increase in shipping activity, as well as the fleet-wide impact of speed reduction and implementation of energy-efficiency measures. This simulated scenario requires about 17 Mtoe of carbon-neutral fuels for shipping in 2030.

FIGURE 5-3

Map of planned and existing projects in the database for products that can be used as carbon-neutral fuels by ships, by capacity (size of bubble) and location

5.3 Supply of carbon-neutral fuels

When the shipping industry is looking ahead to 2030, two central questions are: How much of the different carbon-neutral fuels will be produced, and how much will be available for shipping? Today the supply of carbon-neutral fuels is very limited for all industries, including shipping. The estimates we present here are therefore based on a comprehensive mapping of ongoing projects and initiatives for carbon-neutral versions of fuel oil, methane, methanol, ammonia, and hydrogen. These fuel types can be used as carbon-neutral fuels for ships but can also be used as fuel by other sectors or for other industrial purposes. For example, the hydrogen derivate ammonia can be used for fertilizer production and methanol in the chemical industry. We therefore do not focus only on projects aiming to provide fuel for ships, but all projects aiming to produce a product that can be used as a carbon-neutral fuel. The comprehensive database for future fuel production has been compiled from several other databases[87] and other studies, for example (DNV, 2023a) and (DNV, 2023b). The number of projects for production of carbon-neutral fuels is high: more than 2,200 relevant projects are mapped and populated into our database, see Figure 5-3. However, most of these projects have not yet started construction or even reached an investment decision.

There are already biofuels available in the market today, see (DNV, 2023a), and many new projects are identified. However, only advanced biofuels[88] are included in our results here. We do not present results for different types of fuels, as both the production plans for each fuel and the competition with other sectors are uncertain. The focus has been on identification of the total amount of carbon-neutral fuel that can be supplied, focusing on the short-term availability, which is constrained by existing and planned production capacity.

It is expected that the lead time for new production facilities for carbon-neutral fuels is long, depending on the type of fuel and the size of the plant. As an example, in (Wappler, et al., 2022) the lead time is estimated to be 6 to 10 years for green hydrogen projects over 1 GW. It is therefore expected that only a few projects that are not already announced will be operational before 2030. Even if the database is comprehensive, it cannot be regarded as complete, as some projects are not disclosed to the public for various reasons.

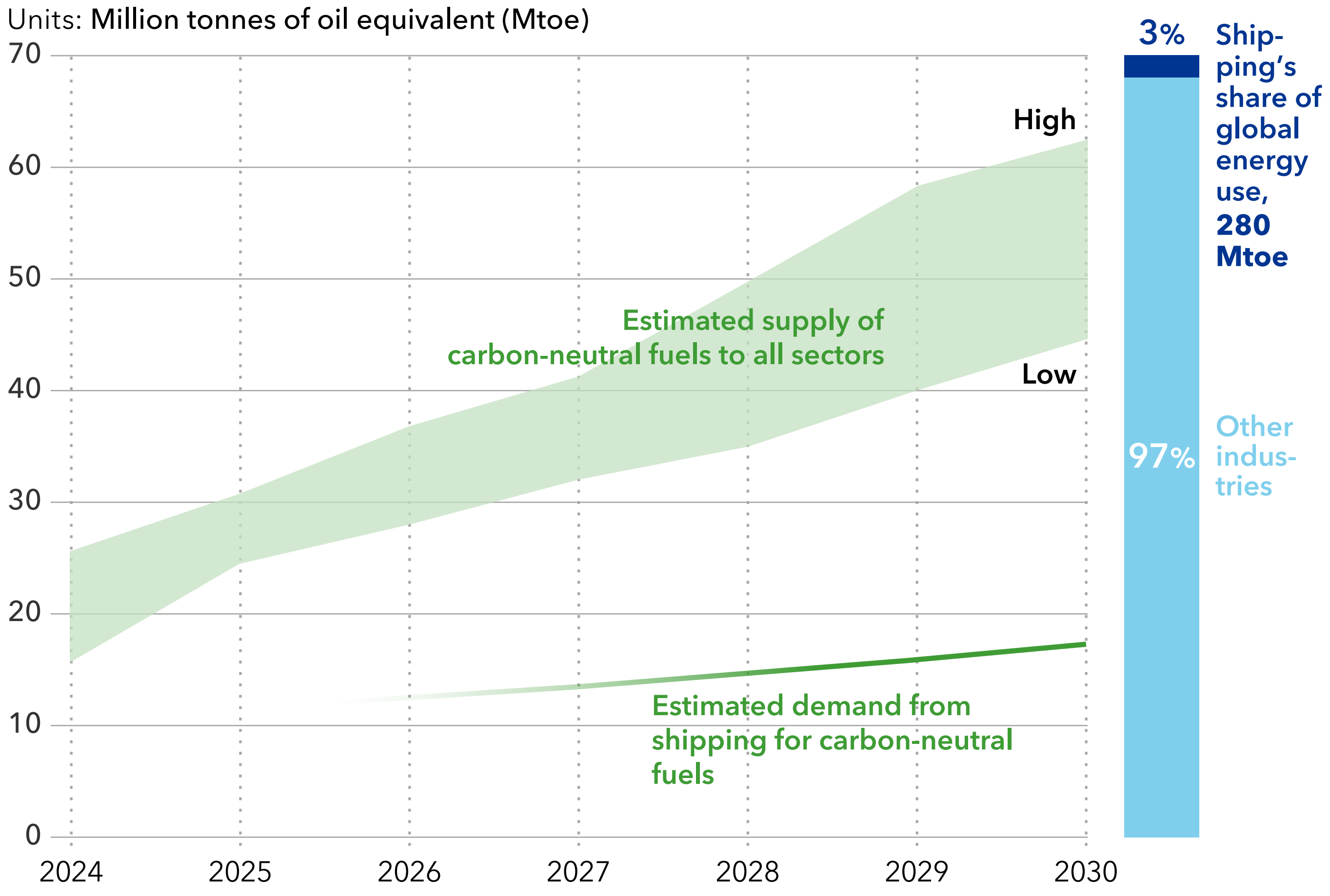
To estimate the amounts that can be produced in each of the coming years, we have assigned a likelihood to each project being completed. The likelihood is based on the project's current development stage, categorized as concept, pre-investment, investment decision, implementation or in operation. In addition, we have added a delay to the planned finish date of all projects, using this to define two different scenarios:

- High Availability scenario – high probabilities of completion, and one-year delay
- Low Availability scenario – low probabilities of completion, and two-year delay

The available fuel in the High Availability and the Low Availability scenarios is derived as the sum of planned output finished by a given year, weighted

FIGURE 5-4

Cross-sector supply of carbon-neutral fuels vs. total shipping demand



by the assigned probability of completion. Looking towards 2030, Figure 5-4 shows our high and low estimates for supply of all carbon-neutral alternatives (for all industries) that also can be used as carbon-neutral fuels for shipping, compared with the estimated demand for carbon-neutral fuels from the shipping industry.

If all the produced carbon-neutral fuels in 2030 end up being available to the shipping industry, the supply would cover the demand with a margin. The challenge is that the energy demand from shipping represents approximately 10% of the energy demand in the transport sector, and less than 3% of the total energy demand in the world.

Furthermore, other industries use ammonia and methanol as feedstock for industrial production (for example in the fertilizer and chemical industries). These industries are currently consuming a total volume of ammonia and methanol equivalent to 120 Mtoe per year, representing more than 40% of the total fuel consumption from shipping today of about 280 Mtoe. This methanol and ammonia are currently produced from fossil sources with GHG emissions, and these industries will most likely compete for the same carbon-neutral methanol and ammonia towards 2030.

To supply carbon-neutral fuels to shipping, a large-scale build-up of production facilities over many years is needed. In this period, the limiting factor for available carbon-neutral fuels will be the production capacity, and not the theoretical upper limit to production. Even for sustainable biofuels (see Appendix A.3 and (DNV, 2023a)), there will be a long phase of expansion of production capacity before the potential is reached. At the same time as sustainable biofuel production is increased year-by-year, renewable electricity production, electro-fuels production, blue ammonia and blue hydrogen production will also be ramped up.

A central question for the shipping industry is what the future fuel market will look like. What fuels will be made available for shipping and at what price? Fuel producers need to consider which fuel type(s) to make, and for which markets. This is decided by factors such as access to energy feedstocks and other inputs, such as sustainable CO_2 and the availability of storage and distribution infrastructure. Another key aspect is which markets will demand carbon-neutral fuels, and their willingness to pay. The price elasticity – in other words, the change in demand because of a change in price – can be expected to vary between shipping, aviation, power production and other sectors as well as between each shipping segment. The fuel suppliers also need to relate to production standards and other policy incentives and requirements which can be general or sector specific, impacting the cost, GHG intensity, and quality requirements of production.

Shipping companies will on their side have individual demands for certain fuels, based on price, availability, technical readiness on each vessel as well as on a fuel's GHG intensity. Their decisions are also impacted by various policy requirements (e.g. CII rating, EU ETS, FuelEU Maritime) and expectations from cargo owners, finance institutions, and others. The increasing cost for carbon-neutral fuels due to competition with other industries can also make other alternatives more competitive, such as onboard carbon capture (medium term) and nuclear propulsion (longer term), see Chapter 7 for a case study on these alternatives.

Policymakers need to consider how to use the limited renewable resources across different sectors. Ideally, energy should be used in such a way as to provide the largest global GHG emission reduction as early as possible, a relevant question both for biofuels and for low-GHG-intensity electricity production. To accelerate the use of electrofuels in shipping, FuelEU Maritime provides an additional incentive for the use of renewable fuels of non-biological origin (RFNBO), even though the renewable energy could be better used to initially replace fossil fuels for producing grid electricity.

5.4 Outlook on infrastructure for carbon-neutral fuels

It is essential to have sufficient infrastructure in place for distribution and bunkering, see Figure 5-5. Some biofuels and electrofuels can use existing fuel oil infrastructure (bio-MGO, e-MGO) while carbon-neutral liquefied methane (bio-LNG, e-LNG) can use existing LNG infrastructure. Assuming availability for such fuels, the bunkering infrastructure, distribution, and storage capabilities must be prepared for further expansion in line with demand development.

In addition, there is already a significant shipping network for the transport of ammonia and methanol, annually transporting in the order of 50 million tonnes (Mt) in total. About 18 Mt to 20 Mt of ammonia are transported annually by ship, and about 170 ammonia carriers are in operation, of which 40 ships carry ammonia on a continuous basis (IRENA and AEA, 2022). The seaborne transport of methanol was about 30 Mt in 2018, and methanol is already available in more than 100 major ports today, where 47 of those ports have storage facilities in excess of 50,000 tonnes[89]. The map in Figure 5-6 shows the locations of ammonia and methanol terminals globally, where the clusters indicate number of terminals in that area. In total there are around 210 existing ammonia terminals and around 130 existing methanol terminals with storage infrastructure. 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 cost.

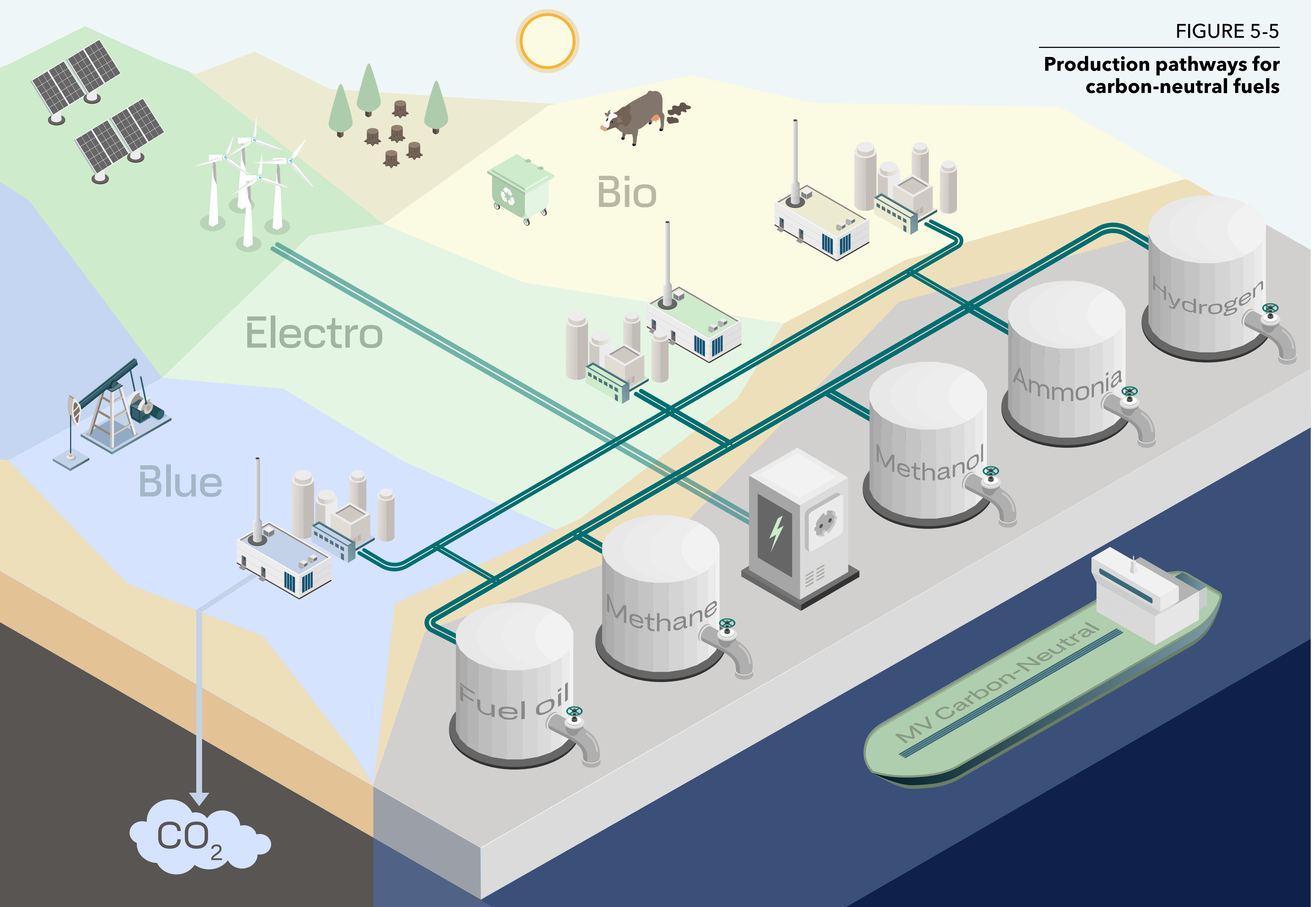


FIGURE 5-5

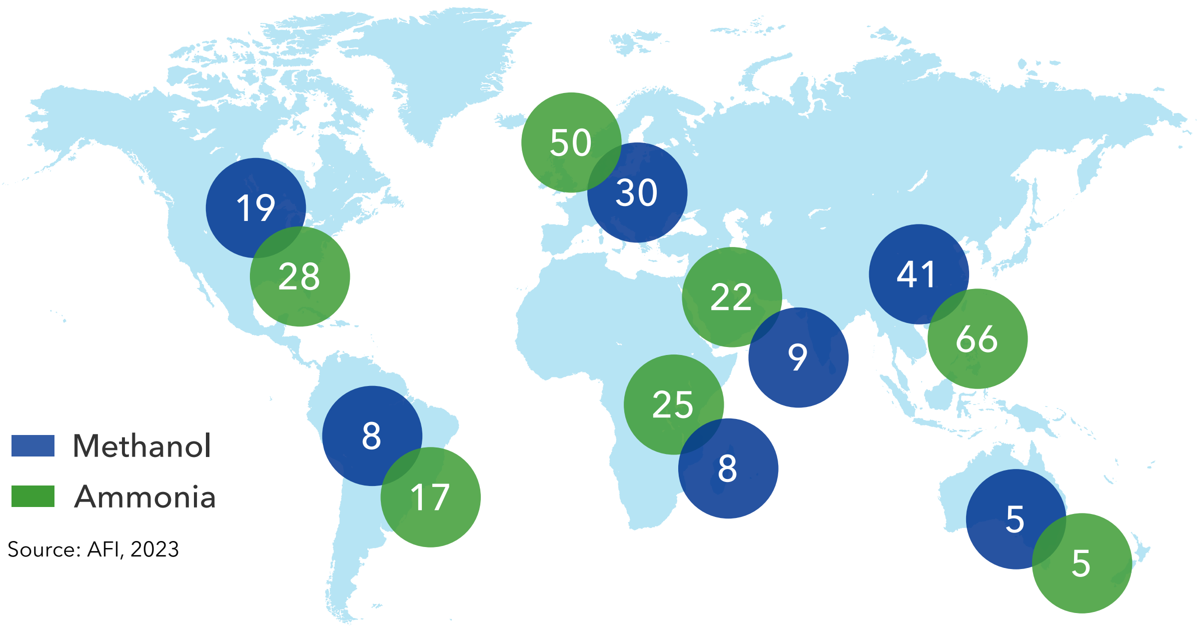
Production pathways for carbon-neutral fuels

To take advantage of the existing infrastructure, carbon-neutral methanol and ammonia could be mixed with the fossil variants. Certification schemes should be in place enabling selling and using the carbon-neutral variants from the storage even if the physical products are mixed; for example, the Green Gas Certification Scheme[90].

For hydrogen, the distribution network is not developed, only small-scale transportation of hydrogen exists today. However, liquefied hydrogen has been transported at sea as a test[91] and several projects are in the pipeline for transporting compressed hydrogen, either in bulk, or in pressurized containers[92]. In 2021, the world's first ship-to-ship methanol bunkering took place in the Port of Rotterdam[93], and another ship-to-ship bunkering operation was completed in the Port of Gothenburg in January 2023[94].

FIGURE 5-6

Map showing the geographical distribution per area of existing ammonia and methanol terminals



Source: AFI, 2023

6

A LIFECYCLE PERSPECTIVE ON SHIPPING EMISSIONS TAKING INTO ACCOUNT FUEL PRODUCTION

Highlights

We evaluate coming requirements to measure lifecycle or well-to-wake emissions of marine fuels and run some numbers, revealing that:

- Well-to-wake emissions from shipping in 2020 were estimated at more than 1 billion tonnes of CO_2e, 16% of it emitted during fuel extraction, production, and distribution.
- Without fuel production standards and ship-specific policies for such emissions, GHG emissions from shipping could shift to production of fuels and may not reduce shipping’s total GHG impact.
- Future biofuels, electrofuels, and blue fuels for ships are expected to adhere to emerging production standards, and to support full decarbonization of shipping.

Taking into account the lifecycle or well-to-wake emissions of marine fuels is needed to ensure that decarbonizing shipping does not shift emissions to other sectors. Requirements on well-to-wake GHG emissions are being introduced, starting with FuelEU Maritime from 2025 in the EU, and later globally by the proposed well-to-wake GHG fuel intensity requirement in the IMO. Ship-specific calculation methods for well-to-wake GHG emissions of marine fuels are maturing, as well as standards and policy incentives for fuel production.

In this chapter, we first provide an assessment on how well-to-tank emissions from fuel production will develop and be addressed through emerging fuel standards and requirements. We then calculate the current well-to-wake GHG emissions from shipping, and how they can develop with and without requirements addressing lifecycle GHG emissions.

6.1 Addressing GHG emissions from fuel production

Lifecycle emissions related to fuels generally include emissions related to cultivation (of biofuels), extraction (of fossil fuels), production, distribution and onboard use. A wide range of studies and papers have provided lifecycle assessments and estimated well-to-wake GHG emissions for various fuel types and production pathways in combination with onboard energy converters – see, for example, (Brynolf, et al., 2023; Ricardo, 2022b). The studies show large variations due to different assumptions and setting of system boundaries. Most of these studies estimate the upstream emissions based on very specific production pathways and circumstances. For example, for the well-to-tank emissions for electrofuels which are based on hydrogen from electrolysis, some studies assume that all electricity is provided from renewable sources with zero GHG emissions (e.g., (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021; MMMCZCS, 2022)), while others use the GHG intensity of the electricity provided to the grid (e.g. (Brynolf, et al., 2023)).

The expansion of renewable electricity production will happen gradually and take time (DNV, 2022b). A large part of this renewable electricity would be used for replacing existing electricity production based on fossil fuels. Excess renewable electricity in the grid, or standalone renewable electricity, could be used to produce zero-emission electrofuels. However, this renewable electricity may not be available all the time and may need to be supplemented by grid electricity to maintain a steady load, or production would need to be reduced.

Emerging fuel standards, incentives and requirements (see Section 3.2 and list in Appendix A.1) support this approach and do no not require or incentivize only fuels that are based on 100% renewable sources and have zero well-to-tank GHG emissions. The current GHG emission thresholds, measured as gCO_2e per unit of energy, across various standards and policy instruments are about 50% to 70% below the fossil fuel references of 89 to 96 gCO_2e/MJ. The thresholds apply to both hydrogen from electrolysis and from reforming of natural gas with CCS, as well as biofuels. We expect that production of biofuels, electrofuels, and blue fuels will all adhere to these standards, with some regional variations, setting an upper boundary for well-to-tank GHG emissions from carbon-neutral fuels.

We also expect that the standards and supply requirements will gradually be strengthened towards 2050 to support decarbonization targets in shipping and other sectors. This implies that some production pathways that are viable with current GHG thresholds may be phased out and replaced with production pathways with even lower emissions.

Similarly, the question remains whether requirements on the ship side will require zero well-to-wake GHG emissions. FuelEU Maritime ultimately requires an 80% reduction of well-to-wake GHG emission from current fossil fuels in 2050, while the IMO has stated that lifecycle emissions should be taken into account, but has not explicitly set an intensity target for fuels.

6.2 Projection of well-to-wake emissions to 2050

In last year's edition of Maritime Forecast to 2050 (DNV, 2022a) we presented 24 different scenarios for decarbonization and the energy transition in shipping. The decarbonization targets were assumed to be achieved with carbon-neutral fuels defined as having no net GHG emissions.[95] However, and as discussed in the previous section, decarbonizing the fuel-supply chain will take time. We do not expect the majority of fuels supplied to the shipping sector to be fully carbon-neutral before closer to 2050. In addition, there will also be emissions of methane (CH_4)[96] and nitrous oxide (N_2O) – both potent GHGs – during onboard use, which needs to be considered.

To show the impact of addressing well-to-wake GHG emissions of energy, we consider two scenarios and estimate the total well-to-wake GHG emissions for the world fleet to 2050, assuming that shipping follows a Decarbonization by 2050 trajectory. Note that this trajectory is not fully in line with the 2030 and 2040 checkpoints in the strengthened IMO GHG Strategy.

No requirements on well-to-wake emissions: This is a worst-case scenario on emissions where the IMO and other regulators and stakeholders do not set requirements on sustainability or well-to-wake GHG emissions of fuels, and there are no production standards. To achieve the decarbonization targets, shipping uses conventional biofuels, electrofuels made from grid electricity, or grey fuels made from fossil sources without onboard carbon capture. The well-to-wake GHG intensity is set to an average of 91 gCO_2e/MJ for all the alternative fuels, which is the reference used in FuelEU Maritime.

80% reduction of well-to-wake GHG intensity: This is a scenario where there is a ship-specific well-to-wake GHG-intensity requirements trajectory in combination with regional and national general (i.e. not specifically targeting shipping) fuel production standards. As carbon-neutral fuels, shipping uses advanced biofuels; electrofuels made primarily from renewable sources; blue fuels with at least 90% capture rate; or a fossil and biofuel blend with onboard carbon capture, all having well-to-wake emissions according to current fuel standards starting at a 70% reduction (27 gCO_2e/MJ) in GHG intensity relative to fossil fuels (91 gCO_2e/MJ) in 2023 and strengthened gradually to an 80% reduction (19 gCO_2e/MJ) in 2050 in line with the ship-specific requirements in FuelEU Maritime.

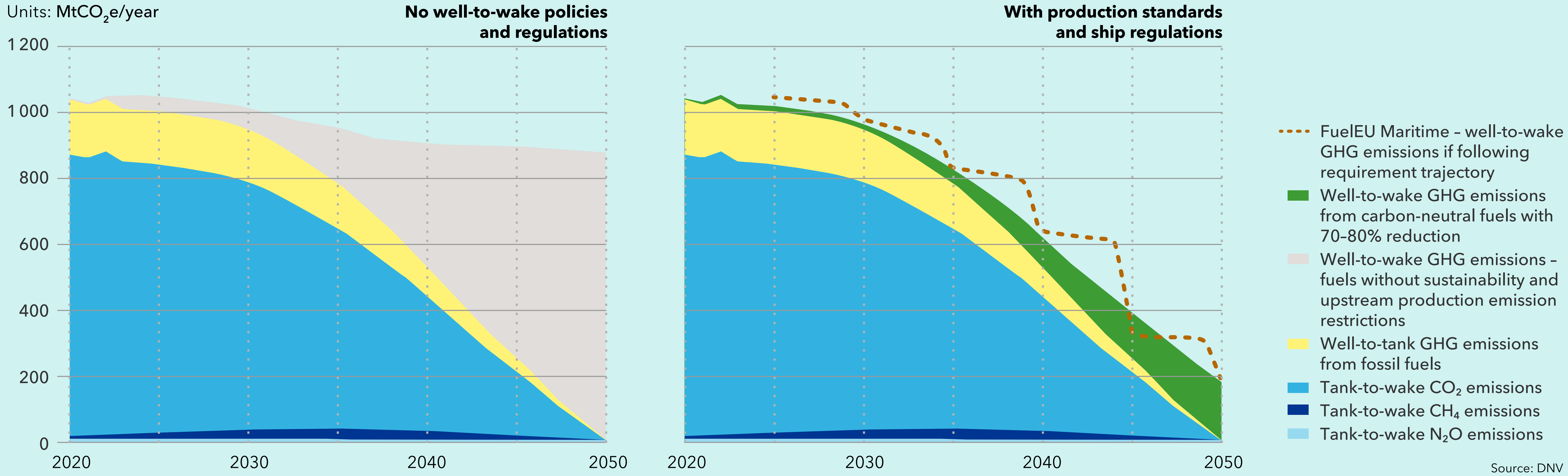
The assumptions and conversion factors for the well-to-tank fuel production emissions, and the tank-to-wake ship emissions for fossil fuels, are provided in Appendix A.2. We use the share of carbon-neutral fuels from scenario 19 from the 2022 edition of Maritime Forecast to 2050, but we do not make any assumption on which fuel type will be used. The share of carbon-neutral fuels does not vary significantly between the scenarios. The results of the calculations are shown in Figure 6-1.

The CH_4 emissions in 2020 are estimated to have been 9.4 $MtCO_2e$, 0.9% of the total tank-to-wake GHG emissions, and the N_2O emissions to have been 11.2 $MtCO_2e$, 1.3% of total GHG emissions. Due to the increased uptake of LNG on newbuilds, CH_4 emissions are projected to increase to a peak of 33.4 $MtCO_2e$ in 2034, 4.1% of the total GHG emissions from shipping at that point. However, the total GHG intensity of fossil fuels decreases towards 2050 when including CO_2 and N_2O emissions.

The estimated well-to-tank GHG emissions were 164 $MtCO_2e$, 16% of the total well-to-wake GHG emissions in 2020. As shown in the left panel of Figure 6-1, unless there are restrictions on sustainability and well-to-tank GHG emissions of fuels, the well-to-tank emissions could be shifted upstream to other sectors producing the fuels, thereby cancelling the emission-reduction gains achieved to 2050. This scenario assumes that the alternative fuels have well-to-wake emissions similar to current fossil fuels. Both conventional biofuels and grey electrofuels can have higher well-to-wake emissions than current fossil fuels (for example (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021)), and our projection could underestimate the well-to-wake GHG emissions.

FIGURE 6-1

Comparing well-to-wake GHG emissions in a scenario without policies and regulations (left) and with production standards and ship regulations (right). For fossil fuels the emissions are split into well-to-tank GHG emissions (i.e. extraction, production, and transport) and tank-to-wake CO_2, CH_4 and N_2O emissions (i.e. onboard energy conversion and slip). For other fuels we show the total well-to-wake GHG emissions. On the right-hand panel we also compare with the GHG emissions if all ships globally follow the requirement trajectory in FuelEU Maritime, showing that it is generally in line with our scenario with fuel production standards.



Source: DNV

The right panel of Figure 6-1 shows that the well-to-wake GHG emissions can be substantially lower if GHG emissions and sustainability requirements are set, ensuring that shipping uses carbon-neutral fuels. This can be achieved with production standards and with ship emission requirements such as FuelEU Maritime. It can also be possible to reduce emission beyond 80% reduction, as assumed in this scenario, with further restrictions. In the right panel, we compare the scenario results with the well-to-wake GHG emissions if all ships globally follow the requirement trajectory in FuelEU Maritime. These requirements increase in steps every five years, but in general this trajectory compares well with our scenario with fuel production requirements.

Carbon-neutral fuels can also include use of fossil fuels in combination with onboard carbon capture. To achieve zero well-to-wake emissions, a fossil fuel would need to be blended with advanced biofuels or electrofuels, where the stored biogenic carbon offsets any uncaptured CO_2 emissions (Ricardo; DNV, 2023). For example, if the capture rate is 70%, a 30% biofuels or electrofuels blend would achieve close to zero well-to-wake GHG emissions, and a further increase in the blend could give negative emissions.

7

TECHNO-ECONOMIC EVALUATION OF ONBOARD CARBON CAPTURE AND NUCLEAR PROPULSION

Highlights

We assess if onboard carbon capture and nuclear propulsion could be significant for decarbonizing ships, finding that:

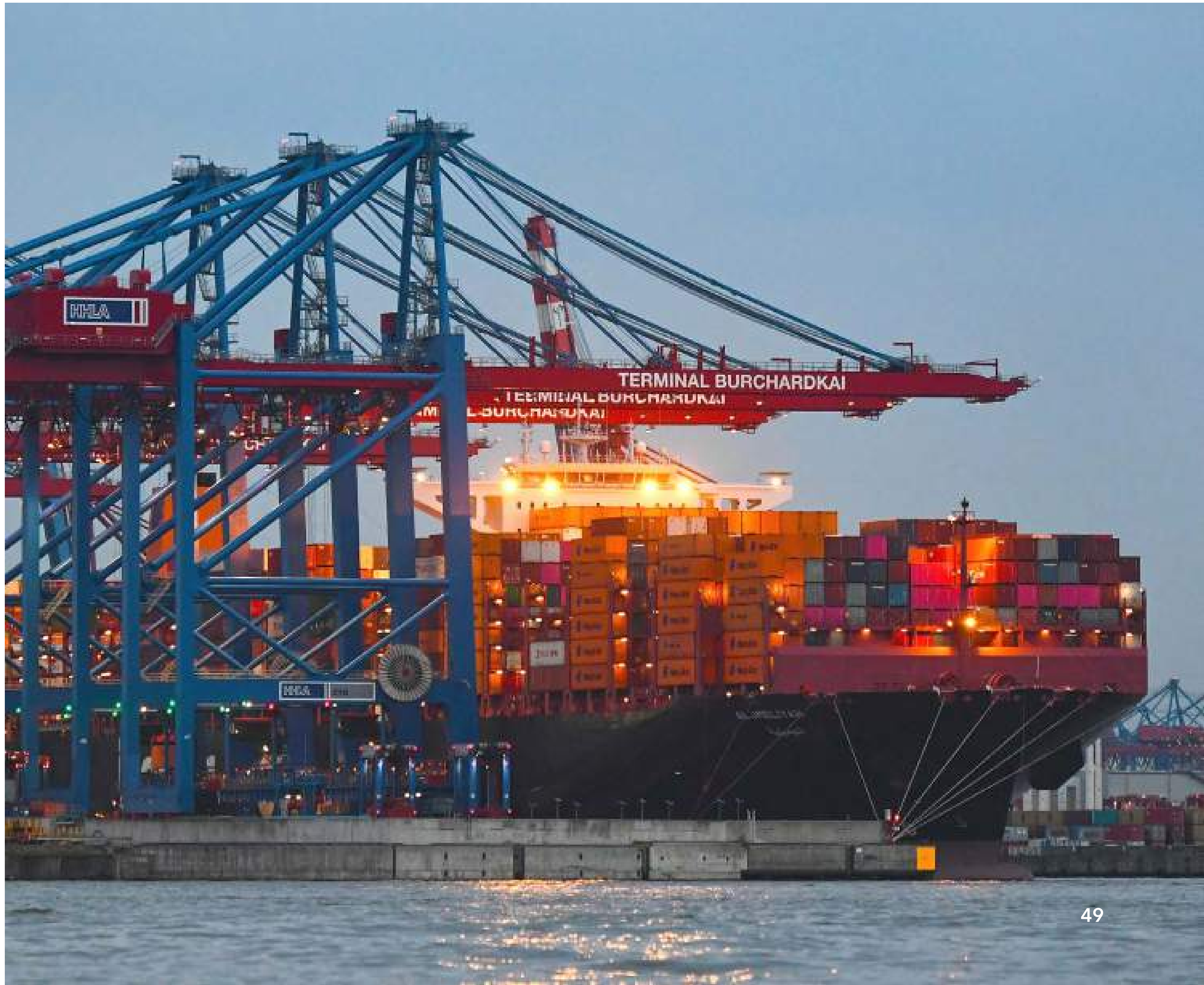
- Onboard carbon capture can be operationally feasible for our case-study ship, a 15,000 TEU deep-sea container vessel.
- Onboard carbon capture and nuclear propulsion can compete with other decarbonization strategies.
- Nuclear propulsion can compete with other decarbonization strategies if reactor costs are in the lower range of historical capital expenditure for land-based nuclear power plants.

Industry actors are, as noted in Chapter 4, exploring onboard carbon capture and nuclear propulsion for reducing GHG emissions to comply with the forthcoming GHG regulations discussed in Chapter 3. Both technologies can have advantages over other decarbonization solutions when it comes to the likely cross-industry competition for carbon-neutral energy described in Chapter 4. Neither onboard carbon capture nor nuclear propulsion require a shift to energy carriers made from highly sought-after renewable or bio-based energy sources.

To assess the feasibility of onboard carbon capture and nuclear propulsion having a significant uptake in shipping, we have performed a case study of a relevant large deep-sea ship: a 15,000 TEU container vessel. The first goal of the case study was to assess whether the use of these technologies is operationally realistic. The second aim was to compare the lifetime costs of other commonly discussed fuel strategies with onboard carbon capture and nuclear propulsion.

By establishing a benchmark range of costs with four different fuel strategies called fuel oil, LNG, methanol and ammonia, we investigate how onboard carbon capture and nuclear propulsion can compete economically. To do this, we have evaluated the financial performance of these technologies for the case-study ship built in 2030 over five different fuel-price scenarios.

This chapter first presents the 15,000 TEU containership case study's benchmark fuel strategies; showing a large variation in annual costs. We then present one high-cost and one low-cost scenario for onboard carbon capture, showing that it is operationally feasible, and one high-cost and one low-cost scenario for nuclear propulsion, and compare the lifetime costs with the baseline fuel strategies.



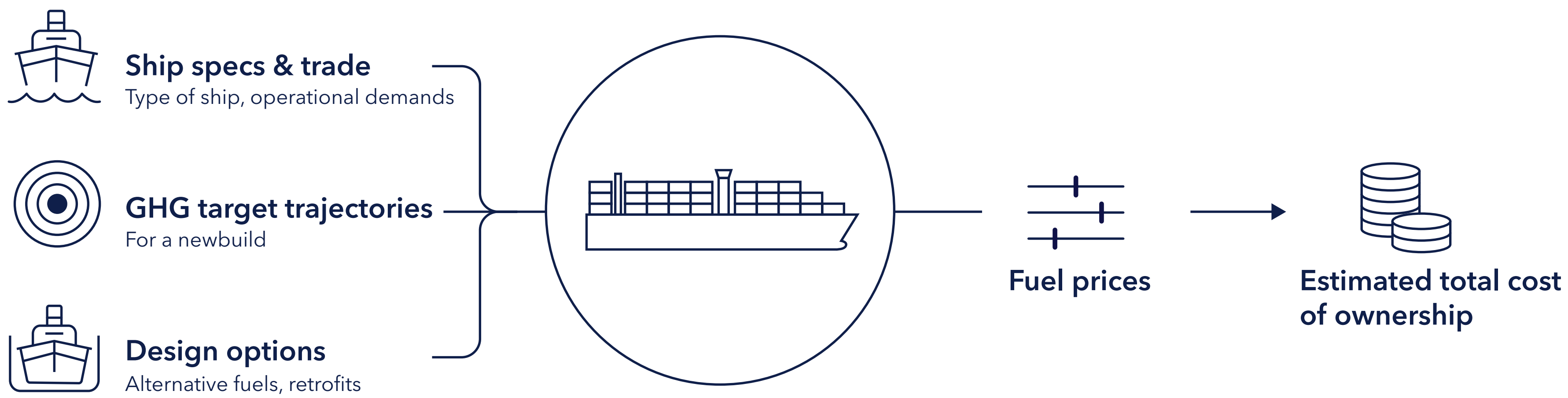
7.1 Case study – 15,000 TEU container vessel

The case-study ship represents a frequently used size for a container vessel plying the trade between Western Europe and the Far East. The baseline case-study ship is of modern design, intended to represent the average of vessels of the same type and size built between 2015 and 2018.

To explore the financial performance of onboard carbon capture and nuclear propulsion we have used the FuelPath model described in the 2021 edition of Maritime Forecast to 2050 (DNV, 2021a) and used in the FuelSelector service[97], see Figure 7-1.

FIGURE 7-1

The FuelPath model



In the box we describe the main assumptions defining the case-study ship and which are used as input for the FuelPath model.

Our case study assumptions are as follows

Capacity: 15,000 TEU

Installed power: 68 MW (main engine and gensets)

Annual energy demand: 24,500 tonnes of VLSFO equivalent, 67 tonnes per day (annual average).[98]

Annual sailing distance: 94,000 nautical miles (nm)

Operation: The ship operates from 2030 to 2060 between Europe and the Far East with approximately 4.5 round trips per year. We assume 35% of annual energy is used in EU waters.

GHG trajectory: We have applied a GHG trajectory going towards zero in 2050. The CII reference line for container vessels has been used to set the starting point of the GHG trajectory.

CO_2 price: We assume a CO_2 price in EU waters only, using a modelled carbon price from our Energy Transition Outlook (DNV, 2022b).

Interest rate: We assume that the CAPEX is covered by an annuity loan with 8% interest, with equal annual payments over the ship's lifetime.

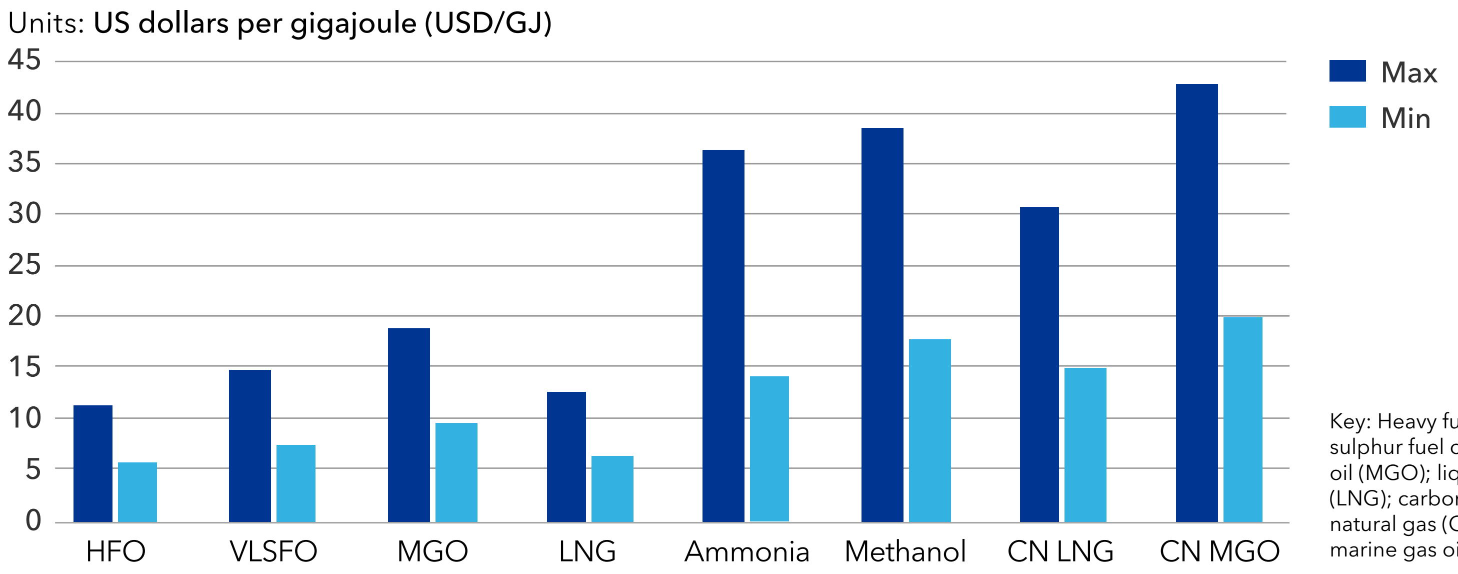
Benchmark fuel strategies: Each fuel strategy is capable of using several different fuels to satisfy both pilot fuel requirements and GHG target trajectories:

- **Fuel oil**, compatible fuels are VLSFO, MGO, carbon-neutral MGO
- **LNG**, compatible fuels are LNG, MGO, carbon-neutral LNG, carbon-neutral MGO
- **Ammonia**, compatible fuels are MGO, fossil ammonia, carbon-neutral ammonia, carbon-neutral MGO
- **Methanol**, compatible fuels are MGO, fossil methanol, carbon-neutral methanol, carbon-neutral MGO

Fuel prices: We have used our Marine Fuel Price Mapper model (DNV, 2022a) to create relevant fuel-price scenarios. These scenarios have been used in commercial FuelSelector projects and are based on the scenarios presented in the 2022 edition of Maritime Forecast to 2050 (DNV, 2022a). We use five different scenarios with prices given for every fuel for each year, with the range of values seen in Figure 7-2.

FIGURE 7-2

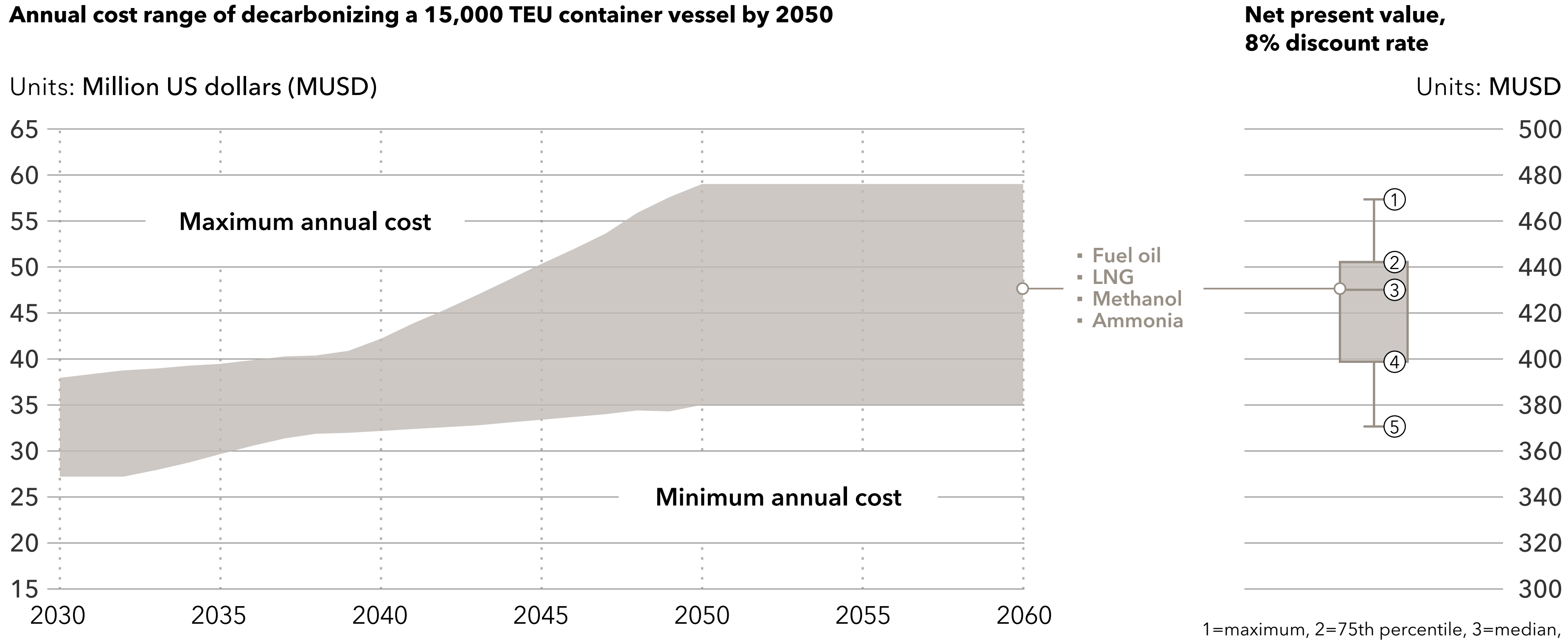
Estimated high and low prices for fuels 2030-2060



Key: Heavy fuel oil (HFO); very low sulphur fuel oil (VLSFO); marine gas oil (MGO); liquefied natural gas (LNG); carbon-neutral liquefied natural gas (CN LNG); carbon-neutral marine gas oil (CN MGO)

FIGURE 7-3

The benchmark span of annual costs and net present value for the case-study ship with fuel strategies using fuel oil, LNG, ammonia and methanol as well as carbon-neutral blend-in for compliance



1=maximum, 2=75th percentile, 3=median, 4=25th percentile, 5=minimum

Provided with the above input, the model evaluates the economic performance of all the available design options related to fuel over the lifetime of the vessel, expressed in terms of total cost of ownership, and other relevant economic parameters. To make this evaluation, the vessel's GHG performance is assessed year-by-year and compared against the chosen GHG target trajectory. If the GHG intensity exceeds the target, all measures available to reduce emissions are assessed, and the least costly is selected. Thus, the model minimizes the fuel cost (including CO_2 cost) of the ship for each year of operation, under the constraint that the ship cannot exceed the carbon intensity of its GHG target trajectory.

In Figure 7-3 we present the span of annual costs of the fuel oil, LNG, methanol and ammonia fuel strategies under the different price scenarios, to be used as benchmark. The annual costs are calculated from the annual payments on CAPEX, the fuel costs, CO_2 price and operating expenditure. With 4 fuel strategies and 5 price scenarios, we get 20 different results for annual cost for the years 2030 to 2060, but present here the annual cost range as well as the minimum, 25th percentile, median, 75th percentile and maximum levels of the net present values (NPV).

The annual costs for the fuel oil, LNG, methanol and ammonia fuel strategies increase towards 2050[99], when the GHG trajectory requires an increasing share of carbon-neutral versions of these fuels.

7.2 Onboard carbon capture

In Section 4.3.5 we described the onboard carbon capture technology, and in this chapter we compare the possible economic performance of a ship with onboard carbon capture with the benchmark cost range. The case-study ship will run on HFO and, in addition to the CO_2 capture unit and storage tanks, the system will also have a scrubber for SO_X and pre-treatment of the exhaust. There are several uncertainties in the economic performance of onboard carbon capture, like CAPEX and OPEX, and to address the uncertainty of the costs, two different cases for an onboard carbon capture system are evaluated. We have chosen to look at two parameters that we assess to have the greatest impact on the final performance of onboard carbon capture, the fuel penalty (the extra energy used for operating the capture unit) and the CO_2 deposit cost (the sum of the CO_2 transport and storage costs).

Assumptions for onboard carbon capture case-study ship

CCS industry: Carbon offloading infrastructure, CO_2 transportation and permanent storage facilities exist and can be used by shipping.

Cargo capacity: Assuming the same cargo carrying capacity for all fuel strategies.

CO_2 purity: Purity levels of captured CO_2 are aligned with storage provider's requirements.

GHG compliance: Can use captured and stored CO_2 to reduce carbon intensity for regulatory compliance. To get to net-zero emissions, carbon-neutral drop-in fuels will be used in addition to carbon capture.

Carbon price: Carbon pricing regulations like the EU ETS do not count captured CO_2 as emitted.

Compatible fuels: HFO, MGO, carbon-neutral MGO

CAPEX: 20 MUSD[100] additional CAPEX (12.5% increase) for scrubber, CO_2 capture unit, and storage tanks.

OPEX: 5% of CAPEX (1 MUSD) in additional OPEX per year compared to fuel-oil benchmark ship. The additional OPEX is expected due to maintenance and replacement of solvents used in the capture process.

Fuel penalty: The fuel penalty is the additional energy used to capture CO_2 when operating at the design maximum annual carbon capture rate. These two numbers are based on a review of CCS studies and discussions with industry actors.

- **High**, 30% additional energy consumption
- **Low**, 15% additional energy consumption

CO_2 deposit cost: Based on studies (IEA, 2020) and discussions with industry actors, we use two different costs for depositing the captured CO_2. This CO_2 is discharged from the ship, transported, and stored in a geological storage site at the given deposit cost per tonne of carbon dioxide.

- **High**, 80 USD/tCO_2
- **Low**, 40 USD/tCO_2

CO_2 storage on board: Assume tanks for liquefied CO_2 with storage volume of 4,000 m³. For comparison, an LNG-powered 15,000 TEU vessel could have 12,000 m³ of LNG for fuel, equivalent to the energy of 6,700 m³ HFO.

Capture rate: Without carbon-capture fuel penalty and carbon-neutral fuels, the ship would emit 8,400 tCO_2 per trip from east to west, or west to east. With a high fuel penalty of 30%, the total CO_2 produced is 10,920 t per trip. We assume **a maximum annual capture rate of 70%**, for a total of 7,644 tCO_2 captured per trip. Net-zero can be achieved with approximately 30% blend-in of carbon-neutral MGO, with the remaining emissions from the fossil fuel cancelled out by the negative well-to-wake emissions from the carbon-neutral fuel.

Offload frequency: The CO_2 storage capacity of 4,000 m³ means that we assume the ship will have to offload CO_2 **twice each trip** (e.g. from east to west) to reach a 70% capture rate.[101] The ships used as the basis for the case study typically have several port calls on each trip, hence simultaneous operations combining loading/offloading of containers and offloading of CO_2 could be considered.

We construct **two scenarios** for the ship with onboard carbon capture with variations in fuel penalty and CO_2 deposit costs:

- **High CCS**
  - High fuel penalty (30%)
  - High CO_2 deposit cost (80 USD/t)
- **Low CCS**
  - Low fuel penalty (15%)
  - Low CO_2 deposit cost (40 USD/t)

> If carbon capture ship technologies can reach low fuel penalties and a CCS industry can offer the low CO_2 deposit costs used here, there can be an economic case for onboard carbon capture.

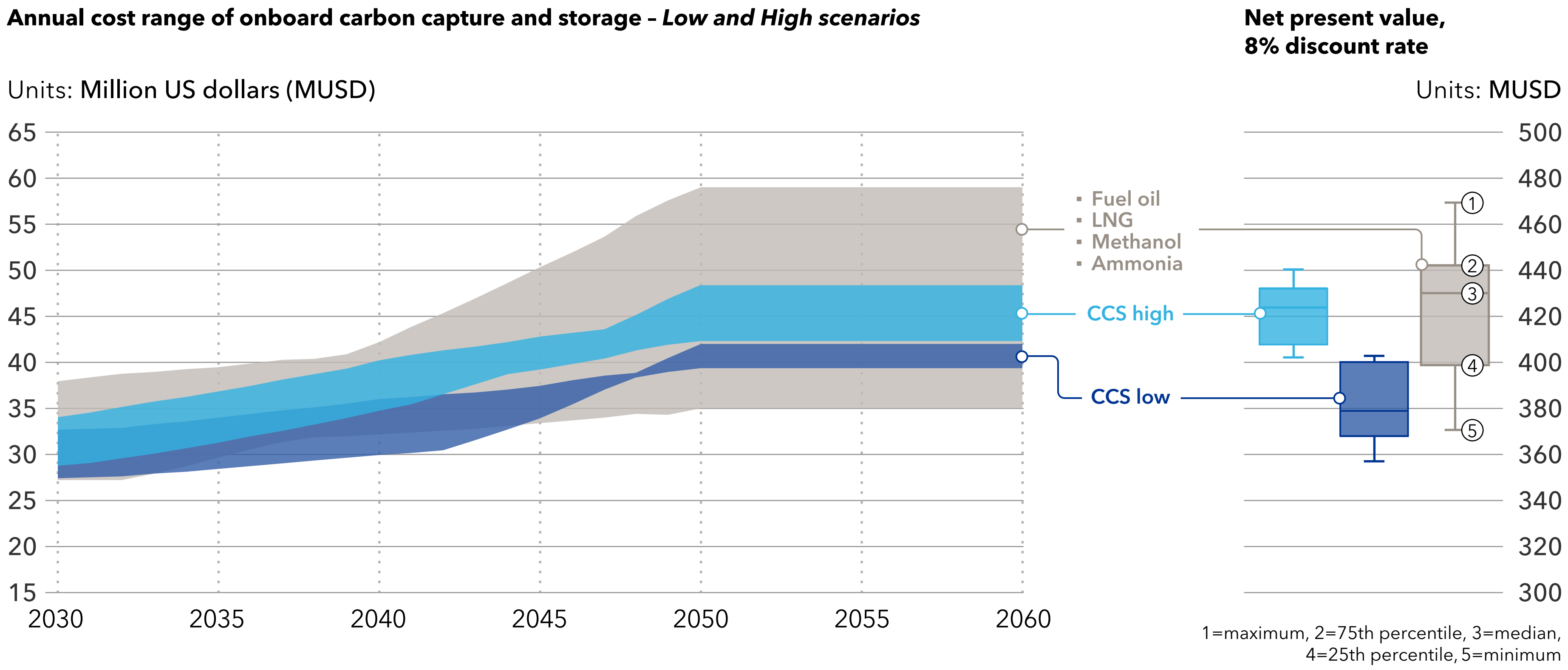
Due to variations in the fossil-fuel prices (HFO) and the carbon-neutral fuel prices (bio-MGO and e-MGO) over the five price scenarios, the two onboard carbon capture scenarios have a range of annual costs similar to the benchmark cost range seen in Figure 7-3. In Figure 7-4 we overlay the bands of annual costs for the High CCS and Low CCS scenarios over the benchmark band of annual costs, in addition to comparing the net present value (NPV) ranges for the CCS scenarios with the benchmark fuel strategies.

The Low CSS scenario performs well compared with the other fuel strategies in this case study. This can in part be explained by the comparatively low price of HFO used in the scenarios, and in part by the costs of operating the onboard carbon capture unit and depositing CO_2 compared with the cost of buying a larger share of carbon-neutral fuels. The High CCS scenario performs around the middle of the strategies considered. When looking at the net present values of the fuel oil, LNG, methanol and ammonia strategies and comparing them with onboard carbon capture cases, the High CCS case end up close to the mean of NPV for the other strategies, while the Low CCS case performs better than three-quarters of the fuel oil, LNG, methanol and ammonia strategies.

By comparing the total costs of supplied energy for the most commonly discussed carbon-neutral fuels with these two scenarios for onboard carbon capture, we see that if carbon capture ship technologies can reach low fuel penalties and a CCS industry is developed that can offer the low CO_2 deposit costs used here, there can be an economic case for onboard carbon capture.

FIGURE 7-4

Range of case study annual costs (left) and net present value (right) for Low CCS and High CCS onboard carbon capture scenarios compared to the benchmark


Annual cost range of onboard carbon capture and storage – *Low and High scenarios*

Net present value, 8% discount rate

1=maximum, 2=75th percentile, 3=median, 4=25th percentile, 5=minimum

Onboard carbon capture can drive demand for specially built CO_2 tankers

7.3 Nuclear propulsion

In Section 4.3.6 we discussed nuclear propulsion for ships, and in this chapter we compare nuclear propulsion for our case-study ship to the four fuel strategies described in Section 7.1 in the case-study box. The CAPEX for a nuclear reactor propulsion system is uncertain, though it is likely to be high, perhaps one to two times the CAPEX of the ship itself. Leasing of nuclear reactors is being discussed to alleviate issues with financing, cash flow, and risk for the shipowner. For the nuclear-powered ship we therefore assume a leasing solution for the reactor with related systems and services. Due to the uncertainty in reactor costs for merchant vessels, we construct High Nuclear and Low Nuclear scenarios for the costs of the case-study ship with nuclear propulsion. The reactor costs in these scenarios are based on literature (Houtkoop, Visser, & Sietsma, 2022) (Lovering, Yip, & Nordhaus, 2016) (Eide, Chryssakis, & Endresen, 2013) and discussions with industry actors.

For land-based nuclear power plants, the CAPEX varies significantly between countries and over different periods (Lovering, Yip, & Nordhaus, 2016). Many US nuclear power plants were under construction when the Three Mile Island accident occurred, generally resulting in extensive project delays, and US plants have had CAPEX[102] ranging from 2,000 USD/kW to almost 11,000 USD/kW. South Korean nuclear power plants built between 2000 and 2010 had CAPEX around 2,000 USD/kW, presumably due to standardization and a predictable regulatory regime. There will be cost differences between reactors for land and sea. For example, ship reactors will typically be smaller than reactors in existing nuclear power plants on land, which could lead to higher specific CAPEX, while there could be lower licensing costs for a nuclear reactor for a ship if produced as part of a series of identical small modular reactors (SMRs).

Due to the high costs and lengthy procedure for licensing a given reactor design (i.e. obtaining required regulatory approval), there can be a smaller range of reactor sizes than engine sizes for a ship designer to choose from. Designs should then be optimized for revenue in addition to costs, for example by installing a larger and more costly reactor allowing for higher speeds and higher revenue. In this case study we only look at costs and omit this aspect.

Our assumptions for the case-study ship with nuclear propulsion are as follows

Regulatory and public acceptance: The ship is allowed to trade in enough ports and waters that it can have the same revenue as the other case-study fuel strategies.

Cargo capacity: The same cargo carrying capacity as the benchmark fuel strategies.

Energy conversion system: The reactor will cover most of the energy demand. In addition to the reactor, the system will have auxiliary engines for peak loads and take-me-home capabilities, fuel tanks for the same purpose, battery, steam generator, steam turbines and electromotors for electric propulsion.

- **Nuclear reactor:** 42 MW, providing 98% of annual energy to the ship. Estimates for volume and weight of the reactor point to decreased installed volume and weight compared with the other fuel strategies.
- **Gensets:** 24 MW
- **Batteries:** 2 MW
- **Electric motors:** 56 MW

Compatible fuels: MGO, nuclear fuel, carbon-neutral MGO

CAPEX: 14.5 MUSD additional CAPEX (9% increase), without the reactor, compared with mono-fuel (MF) VLSFO.

OPEX: Additional OPEX assumed and included in leasing costs,

Nuclear reactor costs: We construct a High Nuclear and a Low Nuclear scenario, by assuming a cost for the 42 MW reactor (including initial fuel), then we calculate a leasing cost based on an annuity loan over the ship's lifetime with 8% interest for the CAPEX, with an additional 2.5 MUSD in OPEX. The OPEX[103] includes refuelling, remote monitoring, decommissioning fund, extra crew costs and more. The annual leasing cost, including both CAPEX and OPEX, is then used in the FuelPath model to calculate the case study economics.

- **High Nuclear scenario**
  - Specific CAPEX, 6,000 USD/kW
  - CAPEX, 252 MUSD
  - Annual cost for CAPEX 22.2 MUSD, and for OPEX 2.5 MUSD
  - Annual leasing cost high, 24.7 MUSD
- **Low Nuclear scenario**
  - Specific CAPEX, 4,000 USD/kW
  - CAPEX, 168 MUSD
  - Annual cost for CAPEX 14.8 MUSD, and for OPEX 2.5 MUSD
  - Annual leasing cost low, 17.3 MUSD

The results for the High Nuclear and Low Nuclear scenarios are shown in Figure 7-5. The graph on the left side shows the annual costs, including annualized CAPEX, annual OPEX, fuel cost and carbon cost, while the net present value is shown to the right.

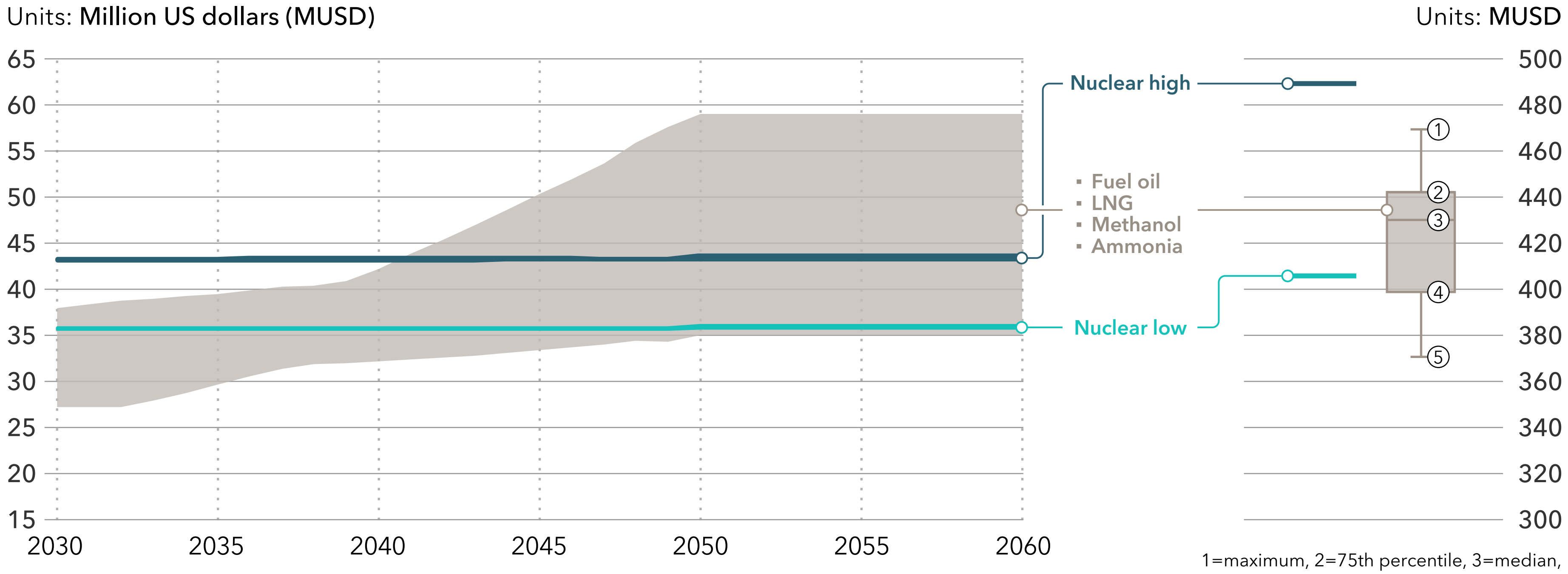
Figure 7-5 shows the annual costs for nuclear propulsion compared with the four benchmark fuel strategies based on fuel oil, LNG, methanol or ammonia as the ship is decarbonized. Nuclear propulsion will be increasingly competitive as the GHG limits are tightened, as can be seen from the more or less stable annual costs of nuclear compared with the benchmark cost range that increases from 2030 to decarbonization in 2050.

By comparing the total costs of supplied energy of the most commonly discussed carbon-neutral fuels with two scenarios for costs for nuclear propulsion, we see that if nuclear reactors are developed that can reach the lower range of cost levels described here, there can be an economic case for nuclear propulsion.

FIGURE 7-5

Annual costs and net present value for the High Nuclear and Low Nuclear scenarios

Net present value, 8% discount rate



1=maximum, 2=75th percentile, 3=median, 4=25th percentile, 5=minimum

8

GREEN SHIPPING CORRIDORS FOR ACCELERATING THE UPTAKE OF CARBON-NEUTRAL FUELS

Highlights

We suggest how creating green shipping corridors can be accelerated to speed uptake of carbon-neutral fuels, concluding that:

- Green shipping corridors can indeed boost uptake of carbon-neutral fuels.
- DNV's experience-based, three-step approach can assist relevant stakeholders getting started with green shipping corridors from early idea phase onwards.
- Green shipping corridors can support public policy goals and create opportunity for private stakeholders seeking to be in the forefront of green shipping and fuel supply.

By addressing and resolving barriers on a manageable scale, green shipping corridors can speed uptake of carbon-neutral fuels. The many barriers hindering uptake include, among others, risk, cost, and supply. By focusing on a specific green shipping corridor, the technical, practical, organizational, legal, political and financial barriers can be identified. They can be overcome by engaging and involving relevant stakeholders in a more practicable way than on a global scale. More than 25 green shipping corridor initiatives have already been announced. All are in the early planning phase, facing key issues such as the fuel cost gap, fuel supply, and the need for coordinated action among stakeholders. In this chapter, we provide guidance and a stepwise approach for stakeholders aiming to establish green shipping corridors.

The approach builds on DNV's experience over more than a decade with existing green shipping corridors in Norway, pilots in the Green Shipping Programme, pre-piloting work in the Nordic Roadmap project, and other large-scale joint industry projects.

To decarbonize shipping, the industry is developing more energy-efficient ships, technology to use new fuels (Chapter 4), and the infrastructure, including carbon-neutral fuel production (Chapter 5), needed to operate these ships. This is a great challenge, and a wide range of relevant policies, regulations, and R&D activities have been initiated across the globe. One such policy initiative is the Clydebank Declaration, in which more than 20 countries have committed themselves to develop at least six green shipping corridors by 2025, and many more by 2030.[104]

8.1 What is a green shipping corridor?

There are several definitions of green shipping corridors.[105] The Clydebank Declaration states that they are simply 'zero-emission maritime routes between two (or more) ports'. It further declares that fully decarbonized fuels or propulsion technologies should not lead to additional GHG emissions to the global system through their lifecycles. We interpret this use of 'zero-emission' as meaning that any carbon-neutral[106] fuel can be used in a green shipping corridor, such as carbon-neutral methanol, methane, diesel, ammonia and hydrogen, as well as battery-electric propulsion, onboard carbon capture and nuclear propulsion. It is also worth mentioning that the Clydebank Declaration recognizes that not all vessels sailing between ports in a green shipping corridor would be required to be carbon-neutral, or to participate in the corridor partnerships.

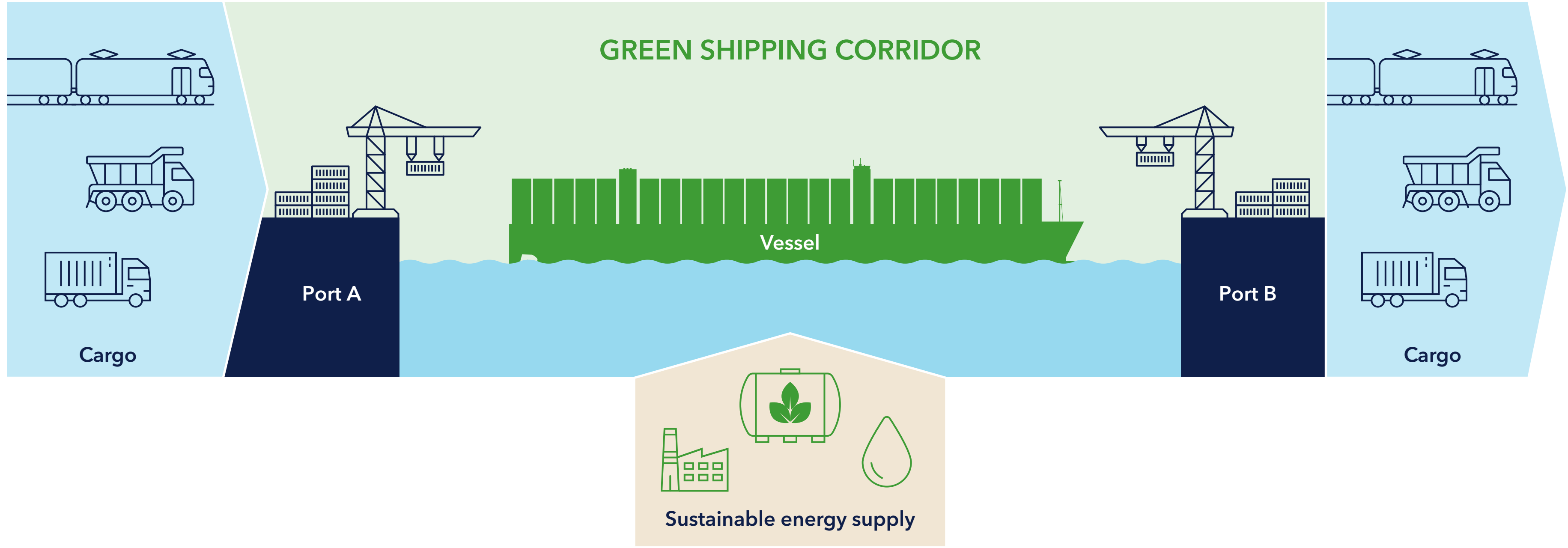
A green shipping corridor concept is sketched out in Figure 8-1. It involves an ecosystem of many actors such as cargo owners and charterers, ports, shipowners and operators, energy suppliers, financial institutions, authorities, and others that need to cooperate in a green shipping corridor.

Overview of announced green shipping corridors

The pledges made by Clydebank Declaration signatories signal a political will to help accel-

FIGURE 8-1

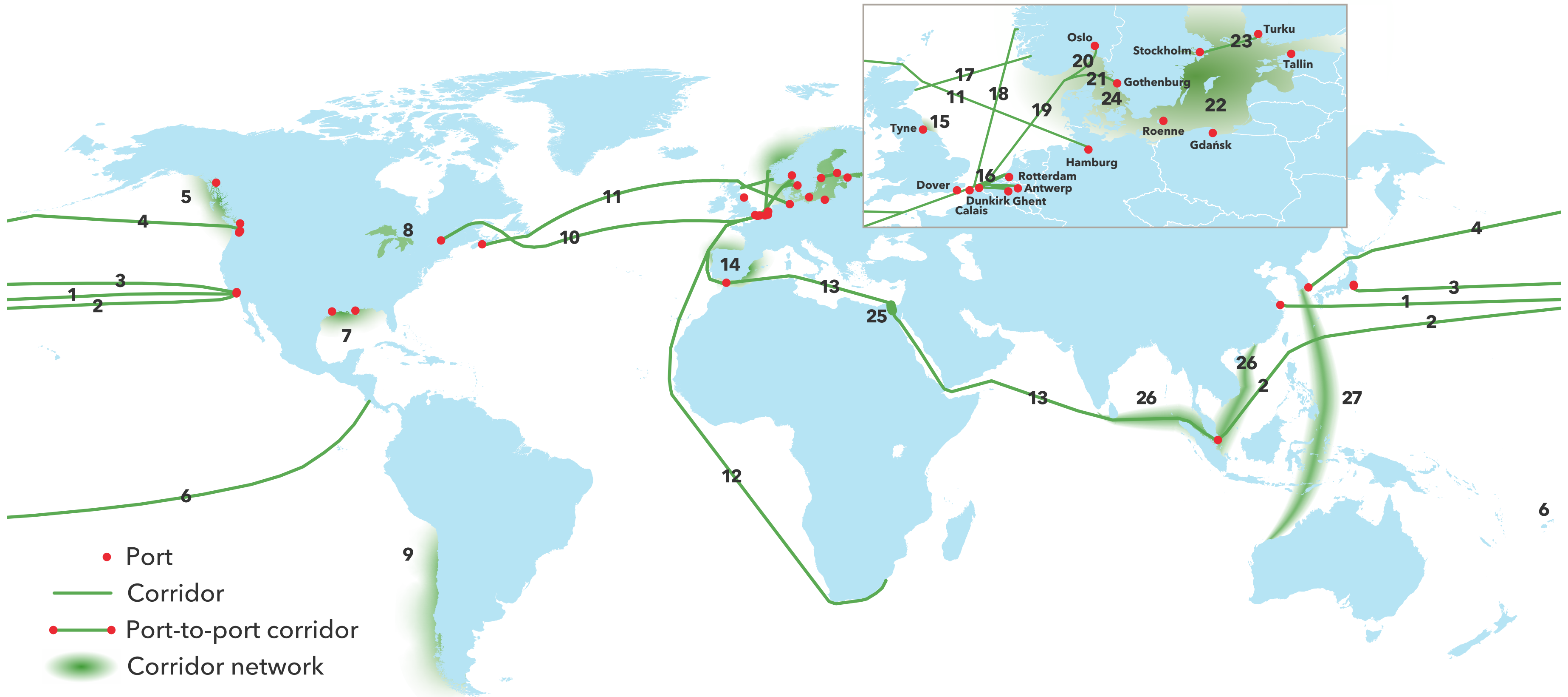
Illustration of a green shipping corridor from port to port



erate shipping decarbonization through the green corridors concept. To date, numerous plans to develop such corridors have been announced by different initiators, involving varied ship types, fuel types, and technologies. An overview of 30 green shipping corridors announced so far is illustrated in Figure 8-2. All are in the very early planning phase. However, they demonstrate the eagerness of

FIGURE 8-2

Thirty announced green shipping corridor initiatives as of June 2023, mapped as ports, corridors, port-to-port corridors, and corridor networks



1 Shanghai – Los Angeles (LA)
2 LA-Long Beach – Singapore
3 LA – Tokyo –Yokohama
4 Busan – Seattle/Tacoma
5 Pacific Northwest – Alaska
6 US – Fiji – Panama
7 Gulf of Mexico
8 Great Lakes – St. Lawrence
9 Chilean Green Corridor Network
10 Antwerp – Montreal
11 Halifax – Hamburg
12 South Africa – Europe Iron Ore Corridor
13 Singapore – Rotterdam
14 Green Corridors Spain
15 Clean Tyne Corridor
16 Dover – Calais and Dover – Dunkirk
17 H_2 powered North Sea Crossing
18 Rotterdam – West-Coast Norway
19 Gothenburg – North Sea Port
20 Oslo Fjord – Rotterdam
21 Gothenburg – Rotterdam
22 European Green Corridor Network
23 Turku – Stockholm (Decatrip)
24 Nordic Regional Corridors
25 Suez Canal
26 SILK Alliance
27 Australia – East Asia Iron Ore
28 Rotterdam – Algeciras*
29 QUAD Shipping Taskforce*
30 G7 Corridors*

*not shown in map Source: DNV, 2023

industry actors to follow up on these political ambitions. Undoubtedly, more green shipping corridors will be announced in the coming months and years. It remains a great challenge, however, to convert plans and ambitions into reality.

The initiators and goals of a specific green shipping corridor will vary from project to project. Figure 8-3 presents a simplified illustration of typical objectives (on top) and initiators (bottom) of green corridor projects. Note that such projects may represent a blend of what is presented in Figure 8-3.

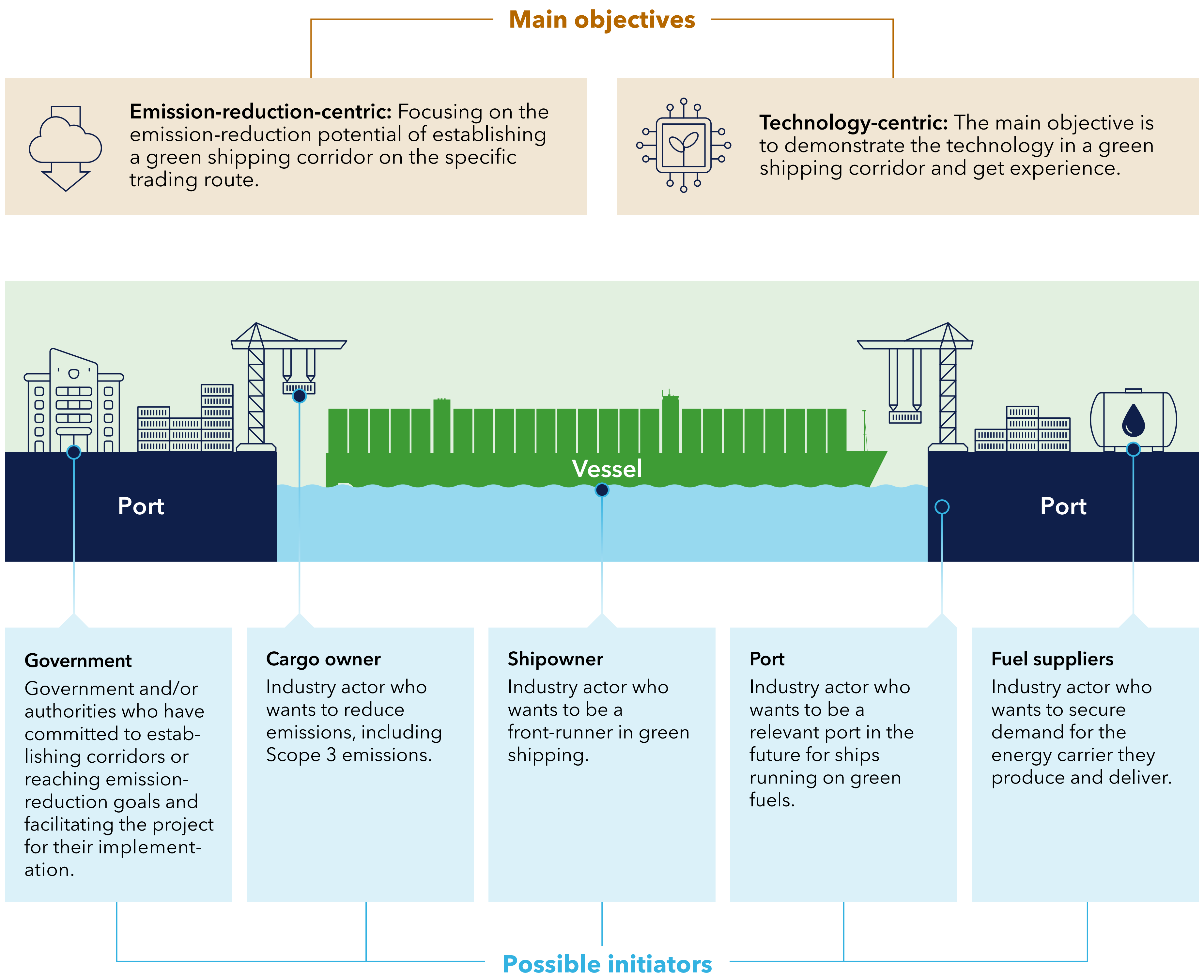
Every green corridor being realized aims to contribute to development steps along several different axes. Examples include increased fuel production and infrastructure development, technology maturity and cost reductions, accelerated development of rules and regulations for safety, development of new supporting policies, growing market demand for green shipping services and green contracts.

Moreover, succeeding with a set of green shipping corridors can also contribute directly to decarbonizing shipping, especially if the corridors are heavily trafficked and CO_2-intensive. However, the most important outcome of realizing green corridors will be indirect – through allowing for learning on critical issues and facilitating the reduction of risks and costs. These benefits can be generalized and applied on a regional and global scale, leading to scaling through a multitude of mechanisms, generally described as diffusion.[107]

Beyond decarbonization, green shipping corridors can impact on digitalization in the maritime industry. One good example is in the development of digital trade lanes and autonomous vessels, because a green shipping corridor will be a closed transport system in which barriers to autonomy and digitalization can be handled and resolved on a manageable scale. Autonomy will impact on fuel-saving potential as reported by (Ziajka-Poznańska, 2021), and also in enhancing the effectiveness of the logistics chain, including multimodal aspects (Tsvetkova, 2022). Some corridors, such as Rotterdam to Singapore, recognize the need to become not only green corridors but also digital corridors[108] facilitating seamless movement of vessels and cargo, and optimizing just-in-time arrival of vessels from port to port.

FIGURE 8-3

Simplified illustration of main objectives (boxes on top) and possible initiators (boxes at the bottom) of green shipping corridor projects



Emission-reduction-centric: Focusing on the emission-reduction potential of establishing a green shipping corridor on the specific trading route.

Technology-centric: The main objective is to demonstrate the technology in a green shipping corridor and get experience.

Government
Government and/or authorities who have committed to establishing corridors or reaching emission-reduction goals and facilitating the project for their implementation.

Cargo owner
Industry actor who wants to reduce emissions, including Scope 3 emissions.

Shipowner
Industry actor who wants to be a front-runner in green shipping.

Port
Industry actor who wants to be a relevant port in the future for ships running on green fuels.

Fuel suppliers
Industry actor who wants to secure demand for the energy carrier they produce and deliver.

8.2 DNV’s stepwise approach assists stakeholders starting out on green shipping corridors

To accelerate development of green shipping corridors we introduce a three-step approach. This builds on DNV’s experience over more than a decade with existing green shipping corridors in Norway (see boxes in Figure 8-5), pilots in the Green Shipping Programme[109], pre-piloting work in the Nordic roadmap project[110],and other large-scale joint industry projects.

The three-step approach builds on a concept paper (DNV, 2022f) developed as part of the Nordic Roadmap project.

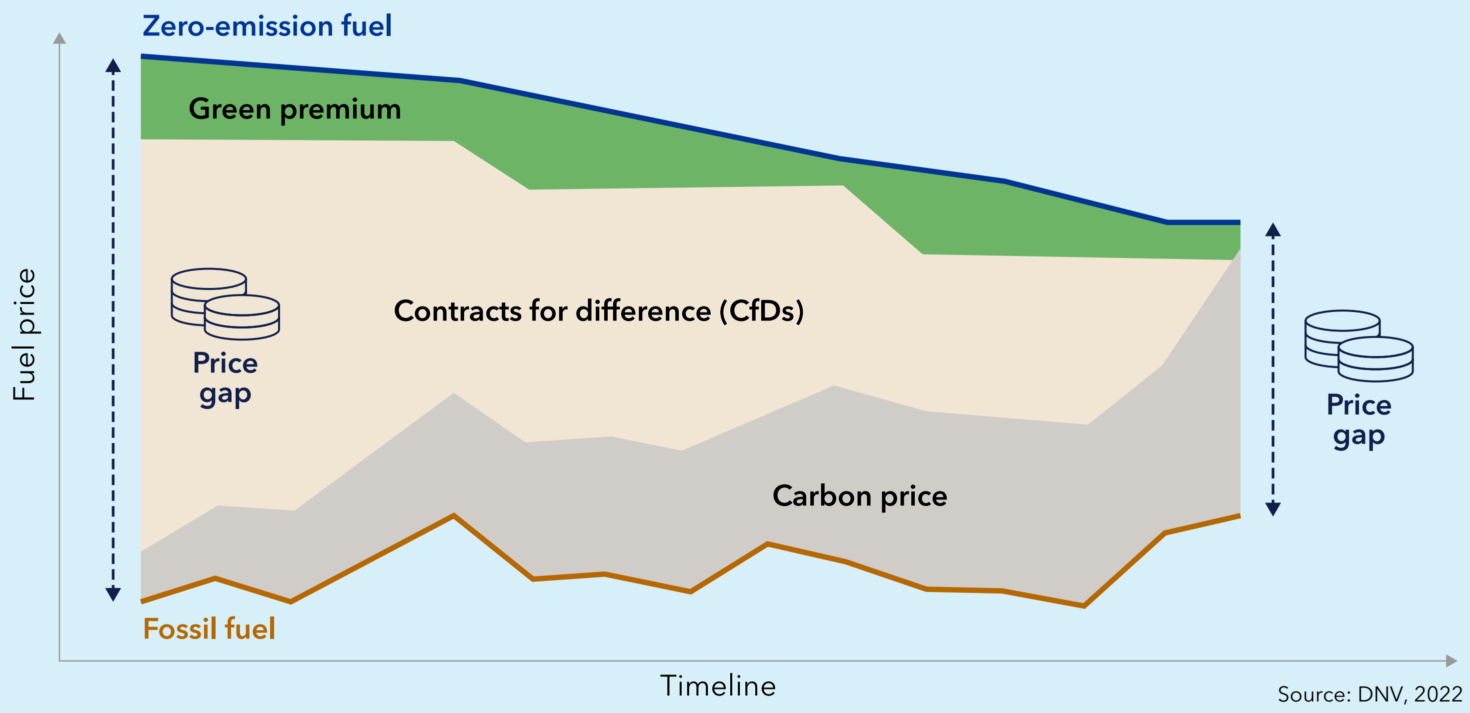
Moving from idea to realization will take time and involve several phases and milestones, as illustrated in Figure 8-5. In our experience, the way in which the start of the process is handled is critical. It is when stakeholders should strive to reduce the risk of unnecessary delays, establish momentum and, most importantly, identify cost gaps and cost-sharing mechanisms such as procurement policies, green financing, and government incentives, to bridge the cost gap.[111]

The purpose of the three-step approach is to accelerate the process by guiding relevant stake-

Finding ways to share risk and close the significant fuel cost gap is critical for realizing green shipping corridors. The EU’s adoption of shipping into the EU ETS, and the IMO’s work on market-based instruments, are policies for decreasing the cost gap (Chapter 3). However, they are not expected to be sufficient to create price parity with conventional fuels within this decade. Therefore, other cost- and risk-sharing mechanisms, such as Contract for Difference (CfD, see Figure 8-4) will be needed to support first movers developing green shipping corridors. If carbon prices or other measures are insufficient to reduce the price gap, stakeholders could have to pay a green premium for carbon-neutral fuel, a cost which most cargo owners are not expected to wish to cover.

FIGURE 8-4

Indication of how to close the price gap between carbon-neutral and fossil fuels. Without carbon price and CfDs, the whole price gap will be green premium



Source: DNV, 2022

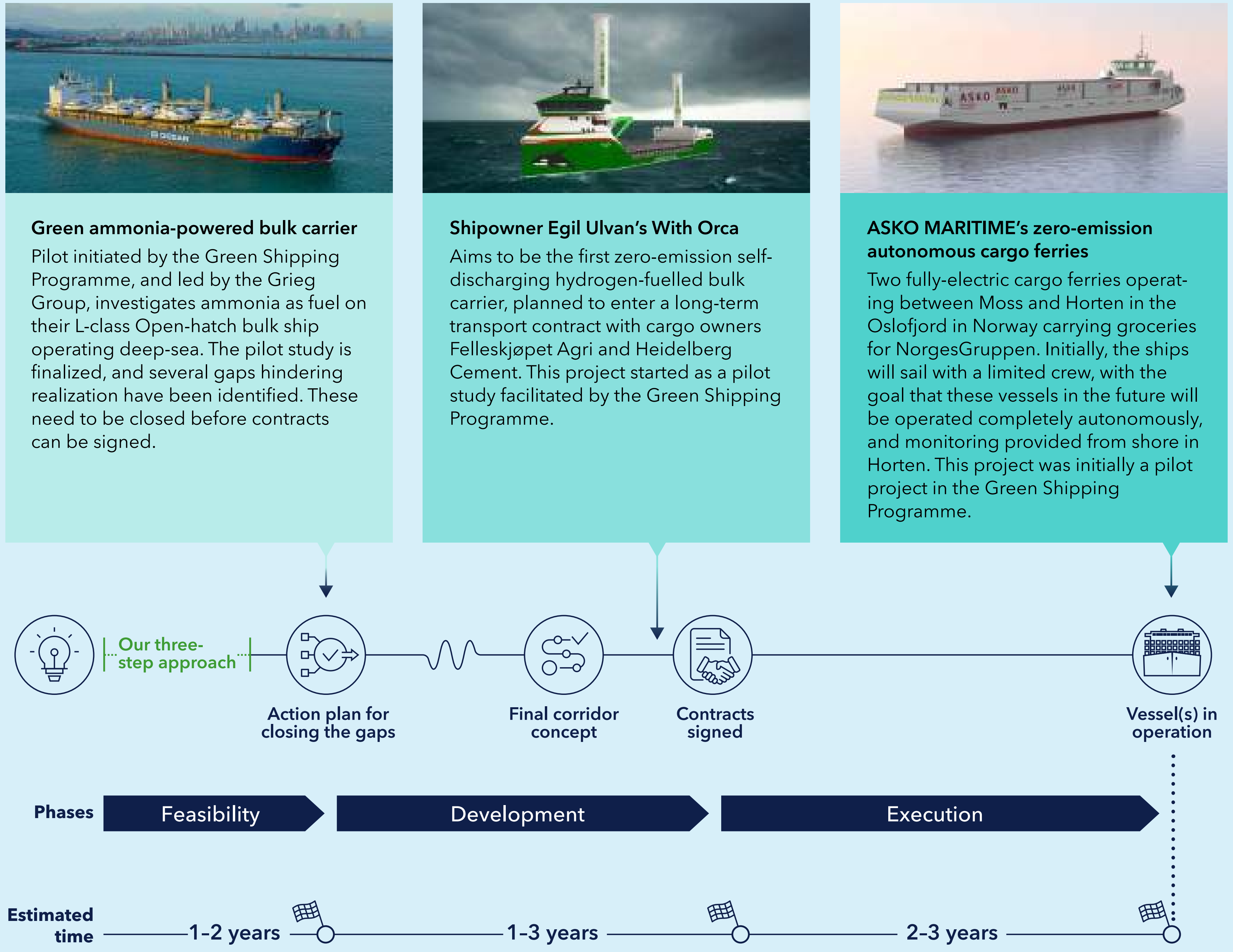
holders in the right direction from the initial idea phase, focusing on early identification of key barriers and actions for overcoming potential showstoppers. Importantly, starting with our three-step approach for investigating the feasibility of a green shipping corridor should be a low-hanging fruit and involve low costs for the stakeholders involved. While our approach covers only the initial feasibility phase (see Figure 8-5), we have experience guiding projects through the whole process. However, proposed approaches covering all phases from idea to realization exist.[112]

A large number of papers and studies address green corridors. For more information see the Nordic Roadmap Knowledge Hub.[113]

Our stepwise approach consists of three main steps as shown in Figure 8-6. Step one involves data collection and feasibility assessment of a specific green shipping corridor. Step two is the onboarding of relevant stakeholders. Step three is the building of business cases for each stakeholder and identifying bottlenecks for realization. The starting point for the stepwise approach is the assumption that one or several stakeholders have an idea of a possible green shipping corridor to explore. The framework is general and flexible and can be used for facilitating collaboration and exploring the feasibility of promising green shipping corridors. Note that the stepwise approach is technology-neutral, meaning that it can be applied to projects exploring all different fuel and technology options.

FIGURE 8-5

Main phases from initial idea to realization of a green shipping corridor



Green ammonia-powered bulk carrier

Pilot initiated by the Green Shipping Programme, and led by the Grieg Group, investigates ammonia as fuel on their L-class Open-hatch bulk ship operating deep-sea. The pilot study is finalized, and several gaps hindering realization have been identified. These need to be closed before contracts can be signed.

Shipowner Egil Ulvan's With Orca

Aims to be the first zero-emission self-discharging hydrogen-fuelled bulk carrier, planned to enter a long-term transport contract with cargo owners Felleskjøpet Agri and Heidelberg Cement. This project started as a pilot study facilitated by the Green Shipping Programme.

ASKO MARITIME's zero-emission autonomous cargo ferries

Two fully-electric cargo ferries operating between Moss and Horten in the Oslofjord in Norway carrying groceries for NorgesGruppen. Initially, the ships will sail with a limited crew, with the goal that these vessels in the future will be operated completely autonomously, and monitoring provided from shore in Horten. This project was initially a pilot project in the Green Shipping Programme.

Step 1 – Data collection and assessment

Here, relevant data is collected and assessed for the five main elements required for defining a green shipping corridor: cargo type, volumes and frequency; design of transport system; onboard energy carrier; energy supply; and financial instruments and support mechanisms. In Figure 8-7, we further elaborate on each of these main elements, including key output.

Note that these main elements can vary in time. Hence, the assessment should consider the current status and possible future developments. As an example, larger trading volumes will potentially require more vessels, which again will result in a need for a greater energy supply.

The key output from this step is a set of relevant data collected and assessed for this specific green shipping corridor, such as specific transport system information (cargo type, volumes, frequencies), fleet mix, operational profiles, relevant energy carriers, mapping potential stakeholders to involve, and potential financial support schemes. In addition, we provide an initial high-level techno-economic assessment of the potential energy carriers and technologies to use on board the vessel(s). This is key information that forms the basis for initial discussions in Step 2, and further in Step 3.

Step 2 – Onboard relevant stakeholders

Next, we gather the relevant stakeholders and, based on the key findings in Step 1, try to motivate them to join the green corridor partnership. Having all stakeholders around the same table, as seen in Figure 8-8, facilitates early identification of barriers and actions for solving these. Typical bottlenecks are cost gaps, overly risky investments, lack of fuel supply and bunkering infrastructure, and low technological maturity. These barriers can be structured and mapped in a scorecard for each energy carrier (DNV, 2020) (DNV, 2023). Moreover, our experience is that barriers often occur in the intersection between the stakeholders. A key to solving these barriers will be close collaboration built on trust. The end point of this step is a common agreement between the necessary stakeholders to participate in this corridor partnership, and to further explore bottlenecks and develop business cases for each stakeholder, with the ultimate goal of producing an overall green corridor business case in Step 3.

Step 3 – Build business cases

In this step, each stakeholder investigates their business case, their 'reason' for participating in the green shipping corridor. Stakeholder perspectives on opportunities and concerns will differ. For any potential green shipping corridor, the following key issues are among those which are likely to need addressing:

FIGURE 8-6

DNV's stepwise approach for assisting relevant stakeholders getting started and to assess the feasibility of a specific green shipping corridor

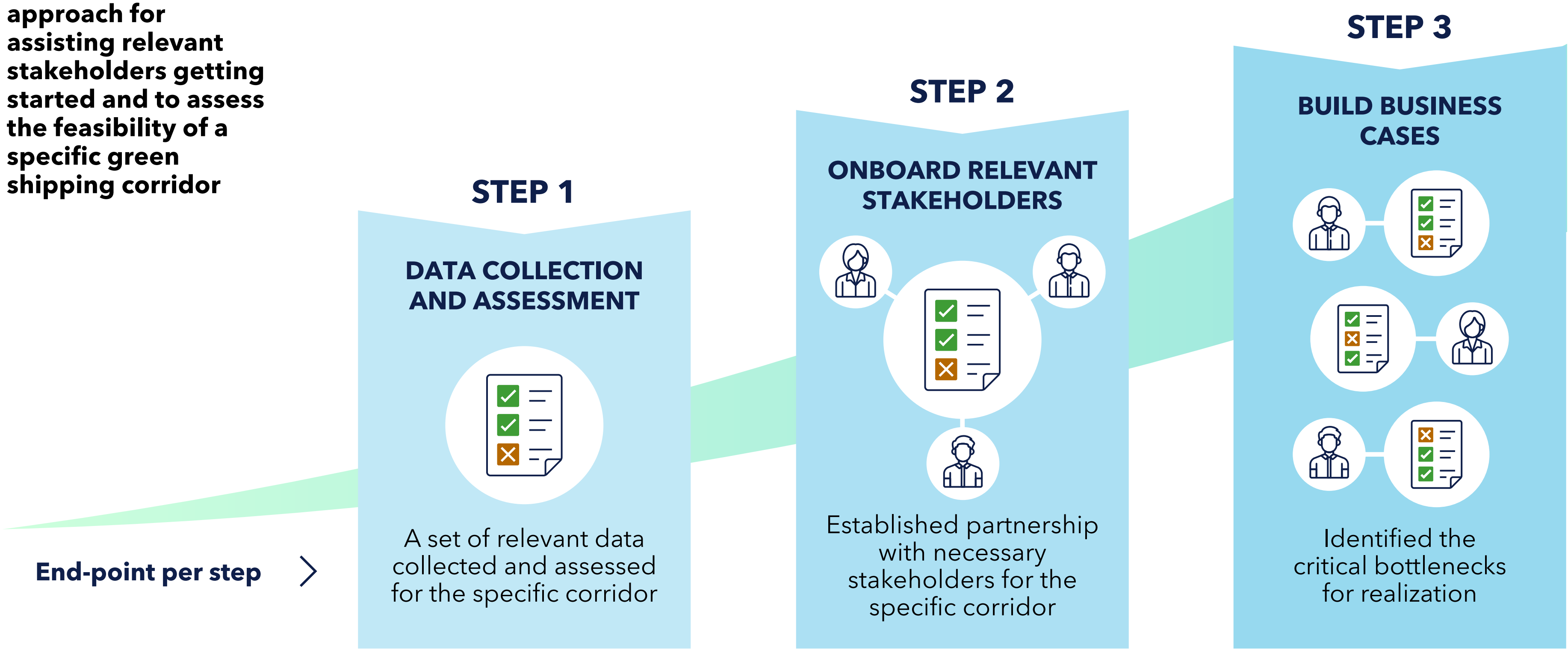


FIGURE 8-7

Main elements required for defining a green shipping corridor – not all stakeholders need to be involved in Step 1

Cargo type, volumes and frequency	The cargo owner(s) in the corridor have specific transport needs (cargo volume, passengers, etc.) with a certain frequency. Hence, in many ways, the transport need of cargo owners is the main boundary condition of the transport system. A key output from this element is collated data on past, present and future cargo types, volumes, and frequencies.
Design of transport system	With cargo types, volumes, and frequencies determined, the transport system can be designed. This includes defining the number of vessels needed to fulfill transport demand, vessel type(s), size, operational profile. For identifying synergies with other cargo owners to reduce ballasting and increase the utilization of the vessel(s), AIS data analysis can be used. A key output from this element is the energy demand for the vessel(s).
Onboard energy carrier	With the energy demand defined for the vessel(s), relevant energy carriers such as ammonia, hydrogen, methanol or batteries, and wind-assisted propulsion systems, and so on can be assessed for onboard use. One key aspect to consider is energy density, which varies significantly between the energy carriers. A key output will be data to use in an overall onboard barrier assessment for each relevant energy carrier, focusing on barriers such as energy density, technical maturity, costs, safety. Note that various energy carriers can have design implications that need to be considered.
Energy supply	A supply of relevant energy carriers is central for it to be a viable option. Hence, for each relevant energy carrier an assessment of the status for the fuel availability (production, distribution and bunkering infrastructure) is important. A key output will be data focusing on the onshore barriers for supplying the energy carriers, such as fuel availability, port readiness, cost, safety zones, and so on.
Financial instruments and support mechanisms	Critical for the realization of green shipping corridors will be to find ways for sharing risk and closing the significant investment and operational cost gaps. In this regard, early identification and mapping of financial instruments and supporting schemes relevant for the green shipping corridor is critical. A key output is an overview of the relevant supporting schemes in each country involved in the corridor, and cost-sharing possibilities among the corridor partners.

- Cargo owner – What will be the unit cost for transporting my cargo? What is my risk exposure? Does paying extra for green transportation make sense in my overall strategy? Are the customers willing to pay a green premium?
- Shipowner – What is the technical and economic feasibility of the potential fuels and technologies to be applied? Can my investment in this be justified? Will this increase my attractiveness in the market today and in the future? What happens if the relevant green fuel becomes unavailable or too expensive?
- Fuel supplier – What is the market outlook, and the business case for producing and distributing new fuels? What is the feedstock availability? Can this corridor support the needed investments? Does the corridor provide a stepping-stone to a wider market? What if the green fuel demand from specified ships turns out to be lower than expected?

FIGURE 8-8

Having all necessary stakeholders around the same table facilitates collaboration, early identification of bottlenecks, and a common understanding of each stakeholder's motivation for being in the corridor partnership

- Port – What is the market outlook, and the business case for supplying new fuels on my docks? Will my investment in infrastructure be profitable? Is the safety zone sufficient? What regulatory barriers are there? What policy incentives?
- Financial institutions – What is the Return on Investment in green fuels or green ships or new infrastructure? What is my risk exposure?
- Authorities – How can this corridor be implemented safely, onshore and onboard? Can financial support be justified? How can we be sufficiently predictable in our regulation of this new field? Can this corridor help us to reach our emission-reduction goals and support commitment to the Clydebank Declaration?

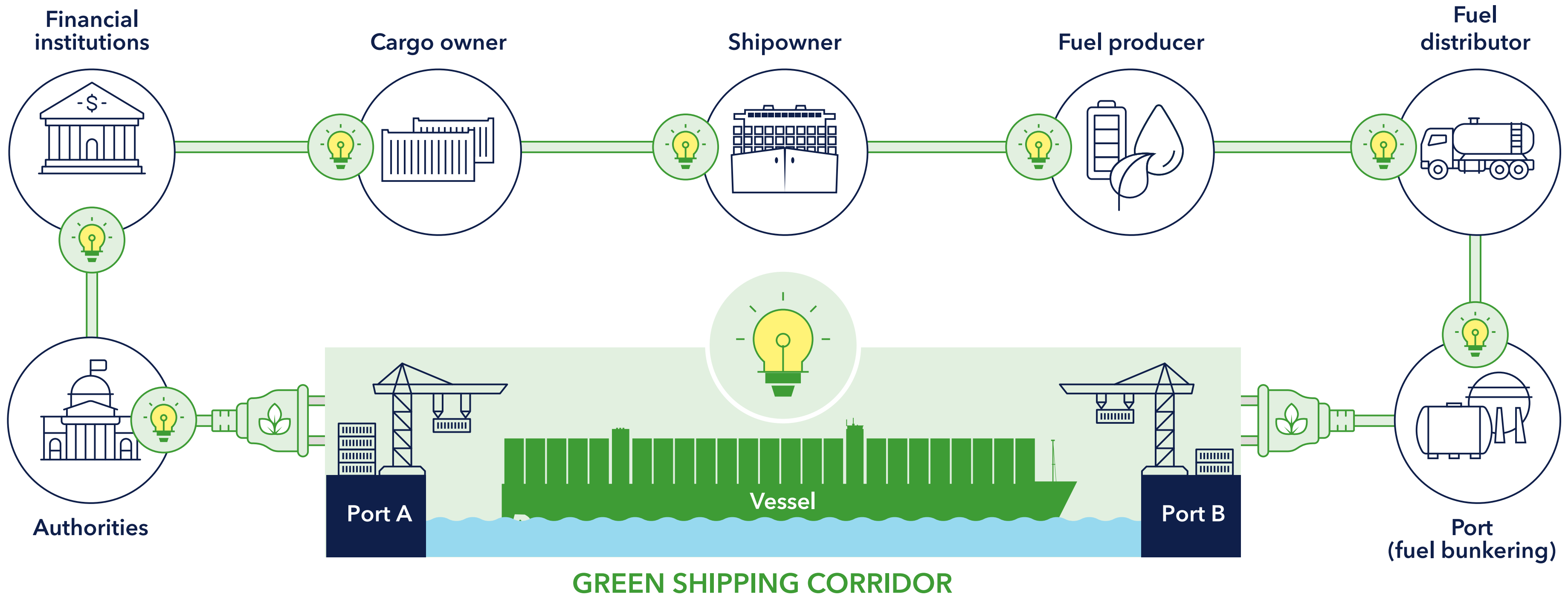
Importantly, these issues are interconnected. Resolving them in a green shipping corridor requires the whole value chain to act, jointly and concurrently, as individual stakeholders will be unable to resolve these issues on their own. This is illustrated by analogy in Figure 8-9. In such a system, 'breaking the circuit' at any point will cut the current through all components, and the lights metaphorically go out for all the lightbulbs. In the green corridor value chain, if one stakeholder fails to overcome their barriers and produce a sound business case, the business cases for all stakeholders will fail, and the green shipping corridor will not be established.

Balancing the perspectives and concerns listed above for the various stakeholders will be an iterative process. We recommend appointing an independent green corridor coordinator to facilitate this. The ultimate focus for the coordinator is to facilitate collaboration between stakeholders to define business opportunities and build an overall business case for the green shipping corridor. Finding proper cost- and risk-sharing mechanisms will be important for turning ambitions into actions.

From experience, typical bottlenecks for realization are economic, financial, and organizational barriers rather than technical issues (even if they will also be challenging). Our stepwise approach facilitates an initial assessment focusing on the real-life showstoppers for realization. It aims to identify critical stakeholders and what they need for establishing a sound business case in the green shipping corridor. As key stakeholders and bottlenecks are identified, the partnership can call attention to where actions are needed to move a green shipping corridor from idea to realization. Hence, the end point is a common understanding between the involved stakeholders on the main bottlenecks on which the rest of the project will have to work to realize the green shipping corridor.

FIGURE 8-9

Simplified illustration of interconnections between selected stakeholders in a green shipping corridor ecosystem – similar to a series electric circuit, all stakeholders are connected end-to-end, forming a single path for current to flow



APPENDIX

A.1 Fuel production standards

Regulations and standards set various definitions and requirement for fuels based on their production and use characteristics. Table A-1 provides a list of selected definitions and GHG emission thresholds in the US, EU, China, and by ICAO, compared to fossil fuels and to the shipboard requirements set out in FuelEU Maritime. Currently the IMO has not set any definitions or requirements for marine fuels.

TABLE A-1

Fuel definitions and production standards with GHG emission thresholds, compared to fossil fuels and to shipboard requirements under FuelEU Maritime

Name	Entity	Definition/note	Emission threshold
Fossil fuel reference	*Multiple*	*Fossil fuel reference values varies between standards*	*89–96 gCO$_2$e/MJ*
FuelEU Maritime	*EU*	*Well-to-Wake GHG intensity requirement for ships*	*89.3 gCO$_2$e/MJ (2025–29)* *85.7 gCO$_2$e/MJ (2030–34)* *77.9 gCO$_2$e/MJ (2035–39)* *62.9 gCO$_2$e/MJ (2040–44)* *34.6 gCO$_2$e/MJ (2045–49)* *18.2 gCO$_2$e/MJ (2050)*
Sustainable biofuels, Recycled Carbon Fuels (RCFs), Renewable Transport Fuels of non-Biological Origin (RFNBO)	*EU, Renewable Energy Directive (RED)*[115]	*Fuels complying with the sustainability and GHG saving criteria of the EU RED*	*28.2 gCO$_2$e/MJ for RFNBOs and RCFs* *32.9–47.0 gCO$_2$e/MJ for biofuels depending on when the installation started production*
Advanced biofuels	EU, Renewable Energy Directive	Biofuels that are produced from the feedstock listed in Part A of Annex IX of the EU RED, mostly waste products	No specific threshold
Low-carbon hydrogen	EU Hydrogen Directive (proposed)[116]	Hydrogen, the energy content of which is derived from non-renewable sources and which delivers at least a 70% reduction in greenhouse gas emission	28.2 gCO$_2$e/MJ
Low-carbon hydrogen	CertifHy[117]	Originating from non-renewable origin: nuclear or fossil energy using carbon capture and storage (CCS) and potentially carbon capture and utilization (CCU)	37.6 gCO$_2$e/MJ
Green hydrogen	CertifHy	Originating from renewable sources	37.6 gCO$_2$e/MJ
Renewable Fuel Standard / Advanced biofuels	US EPA[118]	At least 50% GHG emission reduction and for cellulosic biofuels at least 60% reduction	37.2–46.5 gCO$_2$e/MJ
Clean Hydrogen production standard (proposed)	US DoE[119]		33.3 gCO$_2$e/MJ (4 kgCO$_2$e/kgH$_2$)
Low Carbon Fuel Standard	California Air Resources Board (CARB)[120]		79.6 gCO$_2$e/MJ (2030 onwards)
Low-carbon hydrogen	China Hydrogen Alliance[121]		120 gCO$_2$e/MJ (14.5 gCO$_2$e/kgH$_2$)
Clean/renewable hydrogen	China Hydrogen Alliance		40.8 gCO$_2$e/MJ (4.9 gCO$_2$e/kgH$_2$)
Sustainable Aviation Fuel	ICAO	Renewable or waste-derived aviation fuels complying with ICAO's sustainability criteria, including a 10% reduction in net greenhouse gas emissions	80–86 gCO$_2$e/MJ

A.2 Well-to-wake emission factors

The well-to-tank and tank-to-wake emission conversion factors used in this report for fossil fuels are provided in Table A-2. The tank-to-wake factors for ships built to 2022 are calculated based on conversion factors from the Fourth IMO GHG study (IMO, 2020), with some adjustments due to availability of data. For CO_2, the conversion factors are a direct function of the carbon content of the fuel. For CH_4 and N_2O, the conversion factors are dependent on the engine type and engine load. For LNG-fuelled ships we distinguish between 4-stroke Otto cycle engines, 2-stroke low pressure Otto cycle engines, 2-stroke high pressure diesel cycle engines, and steam turbines. All auxiliary power is assumed to be produced by 4-stroke engines. No correction taking into account that emissions increase at low loads is applied.

For CO_2 and N_2O, the same conversion factors are also used for ships built from 2023. The CH_4 emissions for LNG- fuelled engines are improving, and for all ships built from 2023 and onwards we use a reduced emissions factor based on a report by Sphera (Sphera, 2021).

The well-to-tank GHG emissions factors are based on the default factors in FuelEU Maritime (European Union, 2023).

TABLE A-2

Well-to-tank (WtT) and tank-to-wake (TtW) emissions factors by fossil fuel and engine type

Fuel	Engine type	TtW CO_2	TtW CH_4 [gCH_4/kWh]		TtW N_2O [gN_2O/kWh]	WtT [gCO_2e/MJ]
		All	Built up to 2022	Built from 2023	All	All
HFO	All	3.114	0.01	0.01	0.031	13.5
LSFO/MGO	All	3.206	0.01	0.01	0.03	13.7
LNG	Otto 4-stroke	2.75	5.5	4.0	0.02	18.5
	Otto 2-stroke Low Pressure	2.75	2.1	1.0	0.02	18.5
	Diesel 2-stroke High Pressure	2.75	0.2	0.2	0.02	18.5
	Turbine	2.75	0.04	0.04	0.02	18.5

A.3 Biofuels

The two sections below are taken from a DNV whitepaper published in June 2023 (DNV, 2023a).

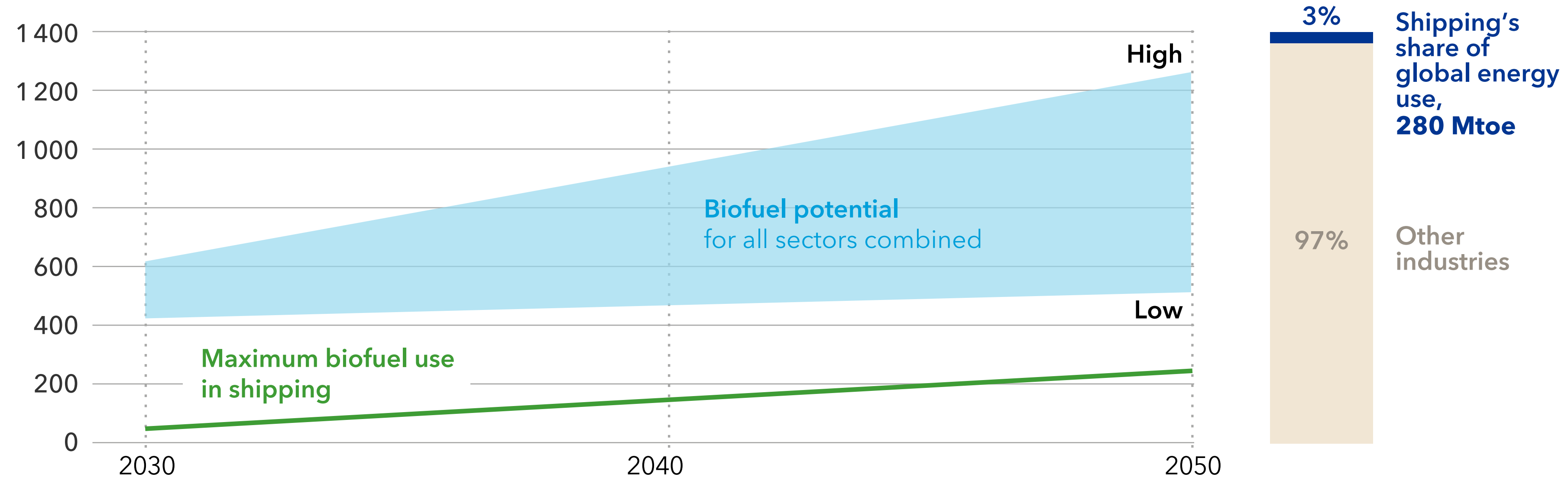
A.3.1 Potential biofuel supply

In (DNV, 2023a) the global potential supply of sustainable and economical biofuels was assessed. This potential is an estimate of the total global biofuel production capacity for all sectors, of biofuels that are both sustainable and economical. If shipping was to decarbonize fully by 2050 primarily using biofuels, 250 Mtoe of sustainable biofuels would be needed annually (DNV, 2022a). At the same time, using stringent sustainability criteria, we estimate a sustainable and economical potential supply of biofuels of 500–1,300 Mtoe by 2050. This is illustrated in Figure A-1. Current global production capacity of sustainable biofuels is around 11 Mtoe/year and our database indicates that this could grow to 23 Mtoe/year by 2026. Therefore, a major build-up of sustainable biofuel production capacity is needed before the full biofuel potential is reached.

FIGURE A-1

Potential of global supply for sustainable biofuel compared to maximum simulated demand from shipping

Units: Million tonnes of oil equivalent (Mtoe)



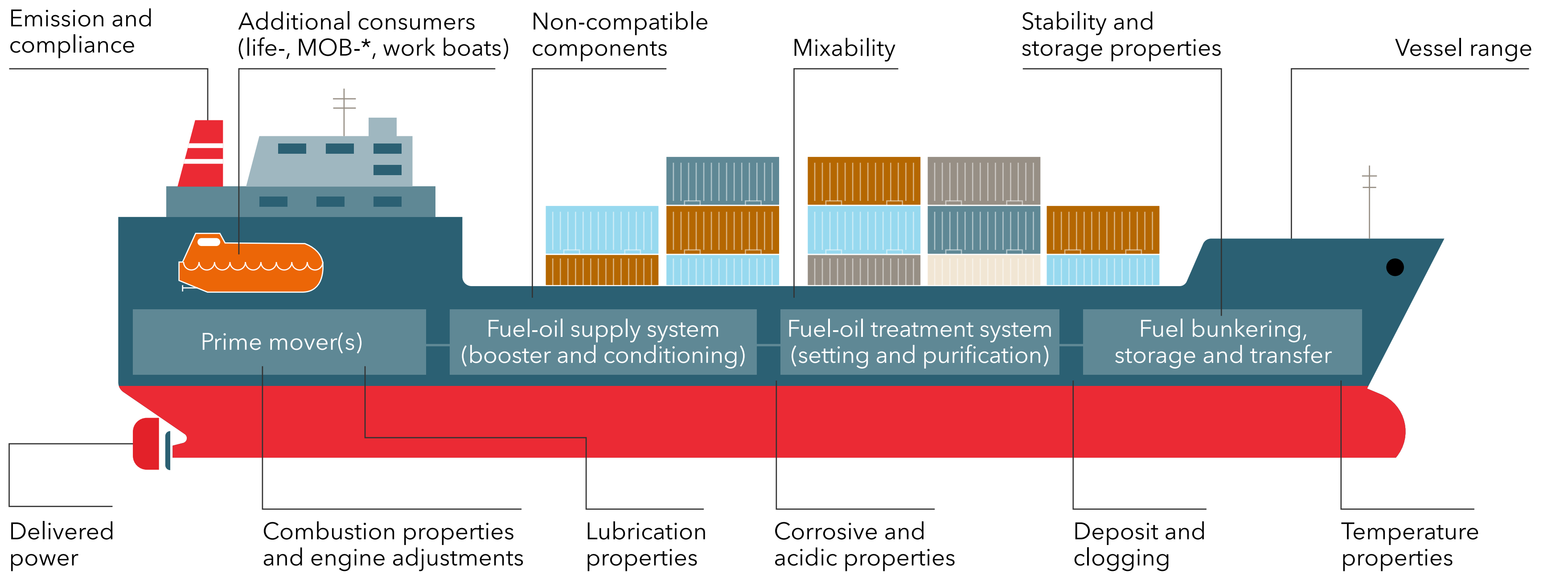
A.3.2 Practical considerations of biofuel use

A key reason why biofuels are seen as an attractive decarbonization pathway for vessels is their ability to be used on existing vessels without modifications (i.e. they have drop-in capability). This holds largely true for bio-methanol and bio-LNG if the correct onboard equipment is installed, since they have practically the same properties as their fossil-based counterparts. For biodiesels and bioliquids used to replace fuel oils and distillates, on the other hand, drop-in capability depends on factors such as what feedstock the biofuel is based on, the production process, and the storage time. It is therefore important to make sure that the fuel specification and quality are compatible with the intended applications on the vessel. Otherwise, there is a risk of damage to equipment and loss of power.

Due to lack of long-lasting trials, there is a shortage of experience with regard to biodiesels and bioliquids and their compatibility with existing onboard machinery. The most widely used liquid biofuels in shipping are FAME (Fatty Acid Methyl Esters) and HVO (Hydrotreated Vegetable Oil), each of which has its own characteristics which should be considered by users. For example, the oxidative stability of FAME is low, leading to degradation of the fuel during long-term storage. HVO, on the other hand, has

FIGURE A-2

Key parameters worth investigating when considering a transition to biodiesels and bioliquids



*MOB boat: man overboard rescue boat

high oxidation stability, and can be stored for long periods.

In the future, other biofuel types may emerge, and more specific guidelines will evolve and be established as more tests are conducted. Before transitioning towards use of biodiesels and bioliquids on vessels built to run on fuel oils, it is important to investigate some key parameters and areas on the vessel, see Figure A-2.

To minimize the risk of damage to equipment on the vessel, we recommend the actions and steps given in Figure A-3 before a transition to biofuels.

FIGURE A-3

Technical aspects of a biofuel transition process and relevant items recommended to consider for a shipowner

BIOFUEL TRANSITION PROCESS

Initial screening of biofuel alternatives

Risk assessment to map compatibility of relevant biofuel (e.g. HAZID)

Onboard preparation and modifications

Implementation and trialing

RELEVANT CONSIDERATIONS FOR SHIPOWNERS

Mapping of biofuel options:

- Potential involvement of third party to provide market intelligence and knowledge related to various biofuel options.

Ensure dialogue with relevant parties such as:

- Fuel supplier and/or laboratory (fuel specification and proper documentation).
- Engine maker (guidelines, recommended practice, compatibility statement, guarantee).
- Original equipment manufacturers of other relevant subsystems (guidelines, recommended practice, compatibility statement, guarantee).
- Flag (regulations, compliance, approvals, certification).

Training and knowledge sharing with relevant personnel (onboard crew).

Ensure proper follow-up, reporting and evaluation after implementation to capture the effects accompanying a fuel transition (long- and short-term effects of all affected systems).

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ENDNOTES

Click on an endnote number to navigate to the related page !

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43 Chain of custody is an auditing process that traces and verifies raw materials, such as biomass, throughout a supply chain to assure the sustainability credential of the end product.

44 https://rsb.org/book-claim

45 https://ghgprotocol.org/sites/default/files/Market-based%20accounting%20Survey%20Memo.pdf

46 Alternative fuels mean any fuel type beyond conventional fossil fuel oils and gas oils, such as LNG, LPG, methanol, ammonia, hydrogen. Alternative fuels may or may not be carbon-neutral depending on the primary energy source and production pathway. A dual-fuelled ship will have the capability of running on an alternative fuel, but both the conventional fuel and alternative fuel can be derived from fossil sources or be carbon-neutral.

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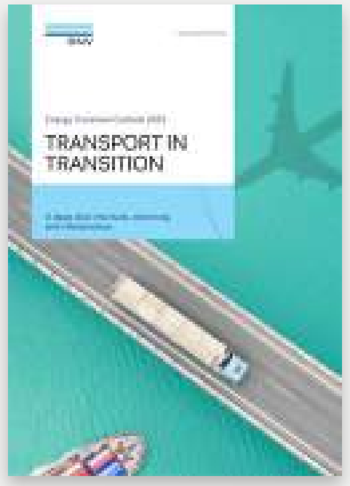
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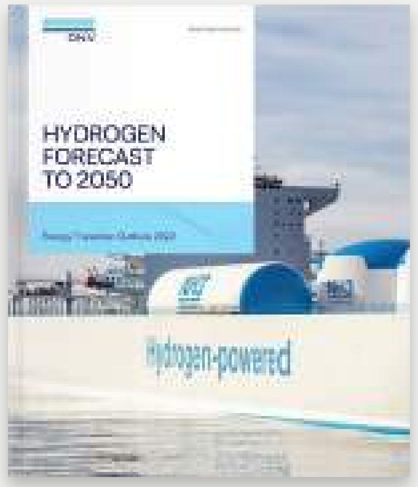
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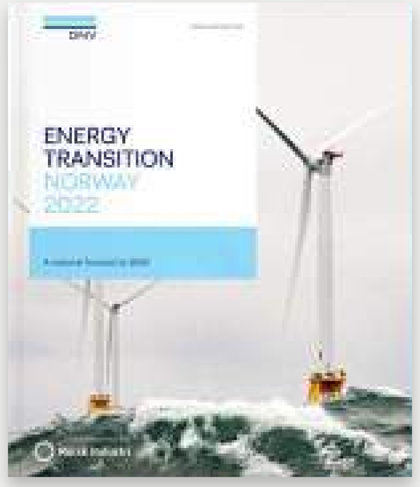
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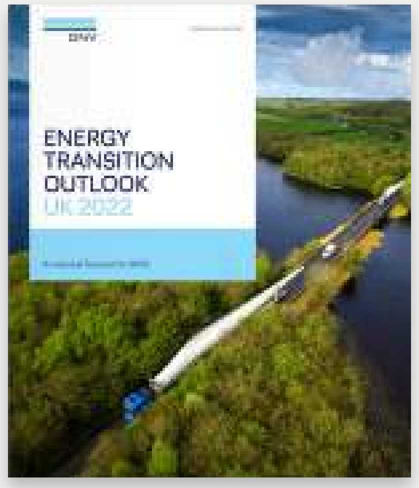
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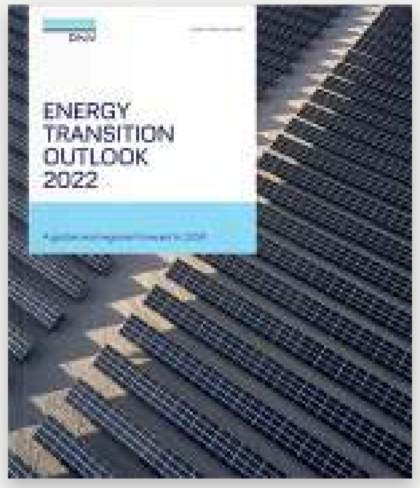
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Published by DNV AS.

Design: printprojekt, Hamburg.
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