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WHEN TRUST MATTERS

Energy Transition Outlook 2024

MARITIME FORECAST TO 2050

A deep dive into shipping's decarbonization journey

FOREWORD

Maritime decarbonization is the greatest challenge of our time but our industry's ingenuity and innovation can carry us forward.

The stage is set. Driven by regulations, the IMO's decarbonization goals, pressure from cargo owners, financing terms, and societal trends, shipping's historic voyage towards full decarbonization is underway.

IMO targets are clear: full-scale decarbonization by or around 2050, a 20% emissions reduction by 2030, and a 70% reduction by 2040.

The question now is, how do we get there?

Many in the industry are still waiting to see what happens but now is the time for leaders across the industry to step up. This means making smart decisions now which can accelerate the maritime green transition.

Full decarbonization will require large-scale transition to carbon-neutral fuels and the industry is continuing to embrace diverse fuel technologies like LNG, LPG, methanol, and ammonia. Production of green fuels is also underway but large-scale supply remains elusive and today's reality is that 93% of the world fleet is still running on conventional fossil fuels.

In this latest edition of the Maritime Forecast to 2050, we explore how this can be turned around through pathways involving operational and technological solutions. We examine how shipowners and other stakeholders can ensure that fleets meet emissions targets and regulations, while remaining competitive.

With a range of uncertainties, we accept that this transition will not be rapid, and the challenge must be faced with pragmatism. Simulations in Maritime Forecast to 2050 reinforce how energy-efficiency measures are essential to operating profitably into the 2030s and 2040s until cost and supply of carbon-neutral fuels become more feasible. Indeed, one of the few things which we do know for certain now is that investing in energy saving technologies and reducing fuel consumption creates significant savings for shipowners and should be a central part of any future business strategy.

We estimate that operational and technical energy-efficiency measures can reduce fuel consumption by 4% to 16% by 2030. Some can be achieved quite easily through encouraging operational efficiencies which can minimize fuel consumption and emissions. Achieving more requires a range of technological solutions: onboard carbon capture and storage, fuel cells, wind-assisted propulsion, and waste-heat recovery systems are among technologies already proven to deliver considerable emissions reductions.

Furthermore, energy efficiency is being significantly enhanced by digitalization. The Maritime Forecast to 2050 shows how this can help to unlock operational efficiencies, while also enabling smooth and reliable emissions reporting and facilitating contractual arrangements.

The estimated range of efficiency gains translates into varying demand for carbon-neutral fuels, and for CO_2 storage for onboard carbon capture, when measured against the IMO's 2030 goals. Depending on efficiency gains, ship demand for carbon-neutral fuels in 2030 is estimated at 7 to 48 million tonnes of oil equivalent, with demand for CO_2 storage between 4 and 76 million tonnes per year.

Two big takeaways result from these estimates. First, the greater predictability and affordability of energy efficiency measures should make this a top priority for shipowners. Second, shipping should work with fuel and carbon capture developers to secure carbon-neutral fuel supply, and with key ports to develop the carbon capture and storage capacity and infrastructure that it needs.

Changes to the technological and regulatory landscape are reflected through significant updates to this year's GHG Pathway Model. Examples include GHG fuel intensity regulation requirements with or without ship pooling, well-to-wake emission factors, FuelEU Maritime, onboard carbon capture, liquid organic hydrogen carriers, and nuclear propulsion.

We explore scenarios for achieving decarbonization (biofuels and onboard carbon capture, methanol, ammonia, and hydrogen), investigating conditions under which uptake of fuel types or technologies will accelerate by 2050. In all scenarios, onboard carbon capture emerges as an important technology after 2030, reducing demand for carbon-neutral fuels. However, no single fuel or technology dominates in any scenario, emphasizing the complexity of choice that the industry will continue to face.

Decarbonizing shipping will come at a cost. Maritime Forecast to 2050 estimates that to achieve the IMO's final and intermediate reduction ambitions in well-to-wake emissions, costs per tonne-mile could increase significantly compared to business-as-usual. Increased freight rates will have to be passed through the value chain, with consumers likely to pick up most of the tab.

In conclusion, the headwinds are strong, and a cloud of uncertainty still obscures how a fully decarbonized global fleet will look in 2050.

Nonetheless, buoyed by a proud tradition of maritime ingenuity, bravery, and innovation, and a spirit of collaboration, both within and beyond the industry, we can steer towards our goals with confidence.

Knut Ørbeck-Nilssen
CEO Maritime
DNV

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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 the technologies and fuels of shipping's energy future. We present an analysis of the future availability of carbon-neutral fuels and carbon storage, as well as estimates on how much shipping can reduce its energy consumption.

Spurred by a wave of decarbonization regulations, shipping is in a phase of unprecedented innovation with a wide range of new technologies being developed, tested, and implemented. Overall, the new technologies and fuels necessary for decarbonization increase costs of seaborne transport and these costs must be moved through the value chain to the consumer as an increase in the price of goods.

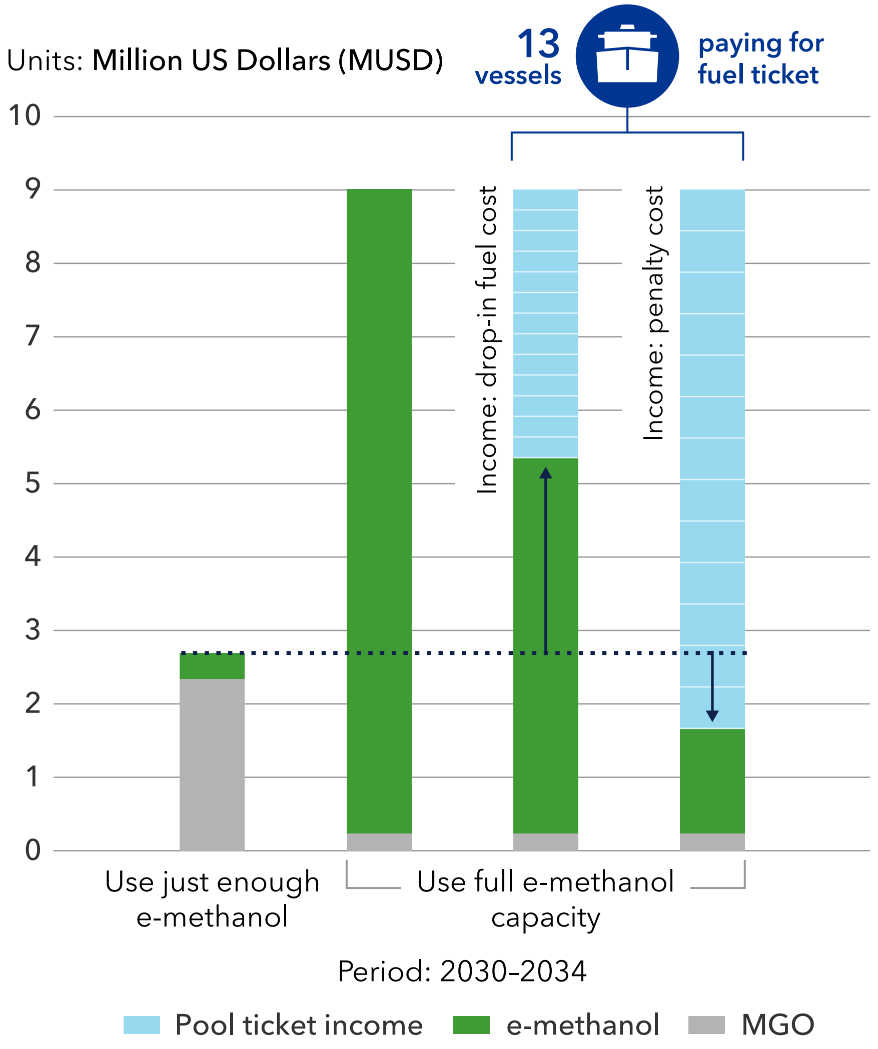
We present ongoing discussions in the IMO and an outlook on the upcoming changes in maritime regulations. This is the first year where ships trading in the EU are subject to the EU Emissions Trading Scheme (EU ETS), which has required a revision of regulatory responsibility and contracts to ensure the allowance costs are passed through the supply chain to the responsible company.

IMO negotiations are ongoing, developing what is called a basket of measures which can consist of two parts: a technical element, which will mandate reduced greenhouse gas (GHG) intensity of marine fuels, and an economic element, which will be a GHG emissions pricing mechanism.

The EU's FuelEU Maritime Regulation (Regulation (EU) 2023/1805) coming in 2025 is imposing a well-to-wake GHG intensity requirement on energy used during a year, effectively forcing the use of qualified low GHG fuels. Another feature of FuelEU Maritime, and something that is under discussion in the IMO, is the option to pool compliance across several ships from the same or different companies. This means that each individual ship does not need to achieve the required fuel GHG intensity but can rely on other ships to achieve a combined level of fuel GHG intensity that is below the requirement.

FIGURE 1-1

Annual fuel expenses including pool ticket income for a methanol-capable vessel in a FuelEU Maritime compliance pool



Pooling of compliance can incentivize shipowners to invest in technologies to use alternative fuels, as they can receive 'pool ticket income' from ships joining their pool. Measured in total cost per tonne of GHG emission reductions, DNV estimates that including a pooling mechanism can reduce the cost of decarbonization by 6%.

The decarbonization of shipping will also require a transition to carbon-neutral fuels, and hence the construction of vessels that can run on these fuels. The trend of larger ships being ordered with dual-fuel propulsion capabilities is continuing. This does not apply just for liquefied natural gas (LNG). Many methanol and liquefied petroleum gas (LPG) fuel-capable ships are in the order book, while ammonia fuel capability is also emerging.

Increasing global carbon-neutral fuel production is necessary to reach the IMO's ambition of a 20% reduction in total CO_2 emissions from shipping by 2030, relative to 2008 levels. We estimate that 44 to 63 million tonnes of oil equivalent (Mtoe) of carbon-neutral fuels will be available by 2030 for all economic sectors, and that shipping will need 10% to 100% of this to reach IMO targets.

As implied above, shipping has started on a fuel technology transition – in different directions towards LNG, LPG, methanol and ammonia. The production of carbon-neutral fuels, those with low well-to-wake (WtW) emissions, is also underway and being planned. As there are significant uncertainties around several factors influencing the transition, we present exploration scenarios for the development of the world fleet fuel mix where shipping achieves decarbonization. Rather than predicting a future fuel mix, we investigate the conditions under which the uptake of certain fuel types may accelerate. A new addition in this year's Marine Forecast to 2050 is that the scenario results now include fossil fuels with onboard carbon capture, nuclear propulsion, and hydrogen-powered fuel cells.

With limited supply of several carbon-neutral fuels, and the transition to an alternative-fuelled fleet taking time, other decarbonization solutions are required. Energy-efficiency technologies and measures provide cost-efficient and predictable pathways to emissions reduction while also reducing demand for carbon-neutral fuels. The business cases for using energy-saving technologies may now be better when evaluated against the cost of alternative rather than conventional ship fuels.

Energy-efficiency technologies and measures provide cost-efficient and predictable pathways to emissions reduction while also reducing demand for carbon-neutral fuels.

Technical and operational energy-efficiency measures can be underpinned by growth in the presence and sophistication of digital technologies and systems. Digitalization can add much needed transparency on vessel performance, providing vital data that can measure the impact of energy-saving measures and helping to design and operate the next generation of energy-efficient ships. In a new age of emissions reporting, digital verification tools can help to create an infrastructure of trust, boosting industry-wide collaboration and facilitating new contractual arrangements incentivizing energy-efficiency measures.

Carbon capture and storage (CCS) from continued use of fossil fuels can also contribute significantly to the decarbonization of shipping but infrastructure for handling and storing CO_2 needs to be developed. The estimated demand for carbon storage from shipping in 2030 is 4 to 76 $MtCO_2$, while the esti-

FIGURE 1-2

Growth of the number of ships capable of using selected alternative fuels, excluding LNG carriers, as of May 2024

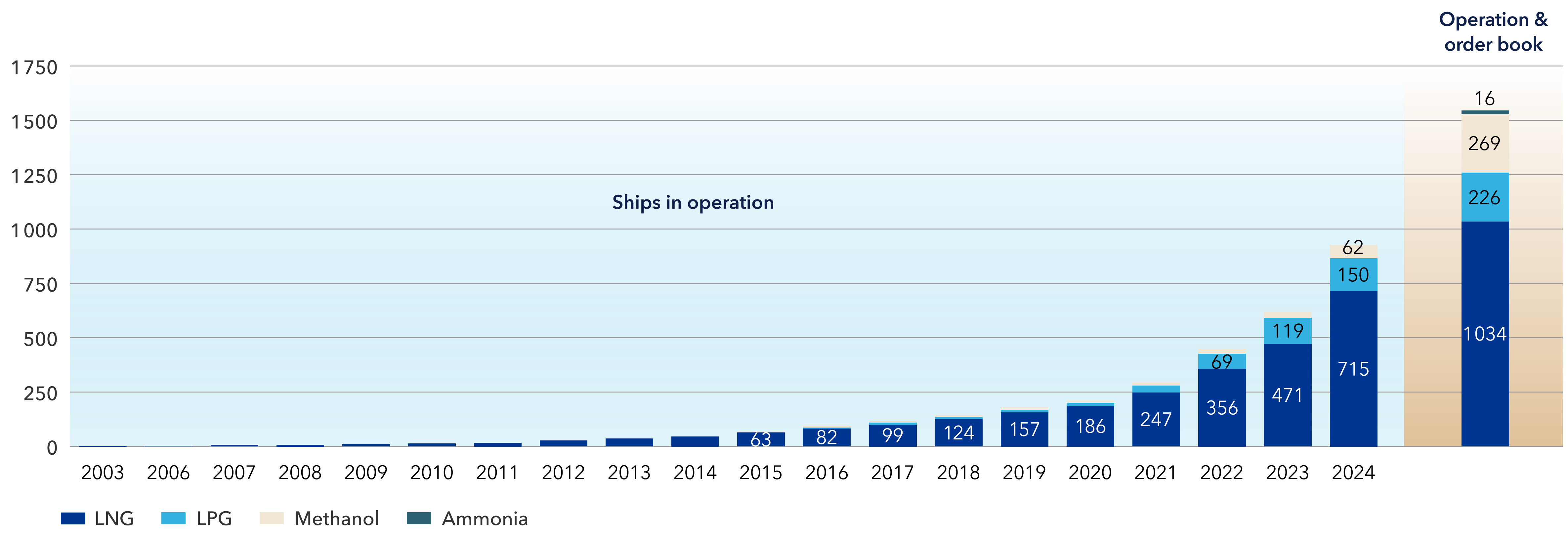


FIGURE 1-3

Estimated supply of carbon-neutral fuels to all sectors

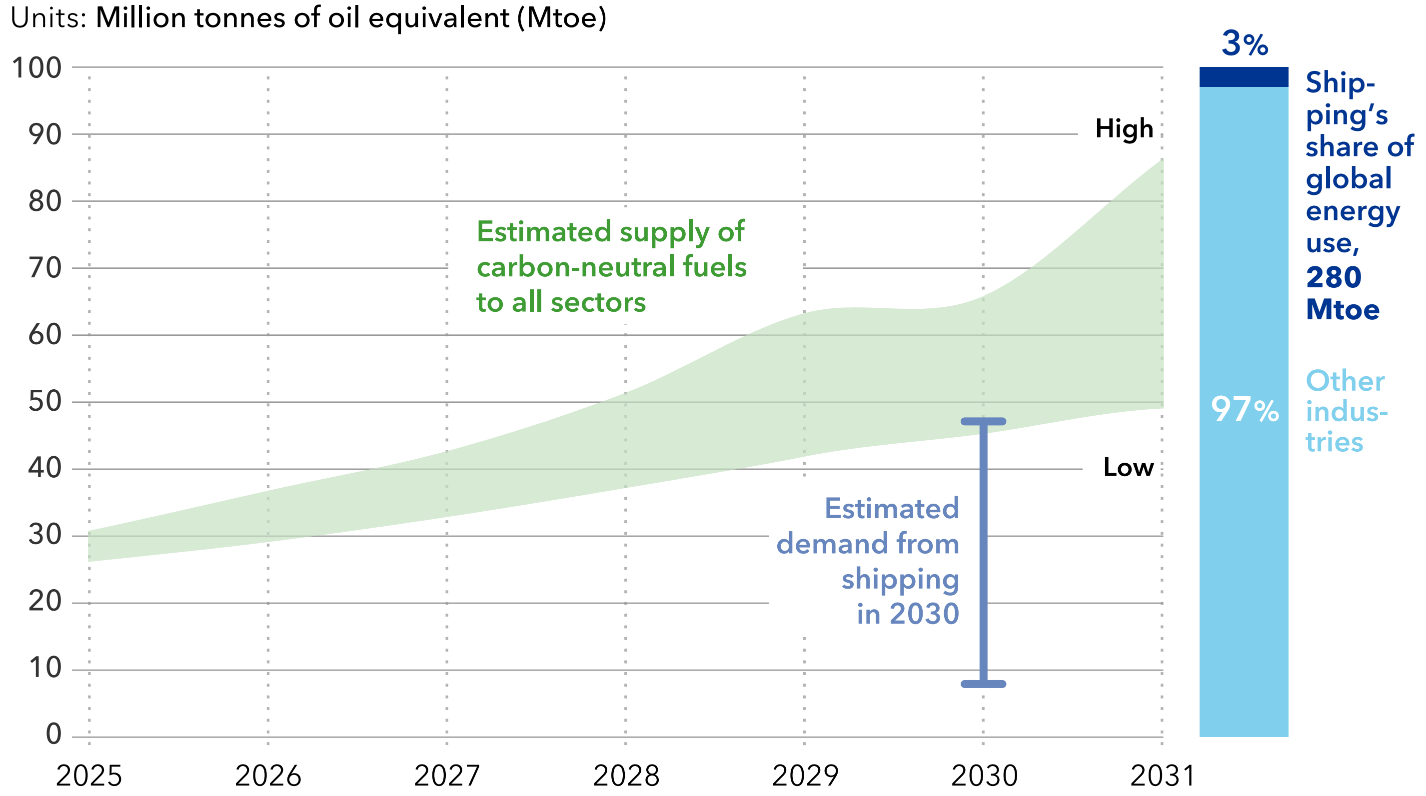
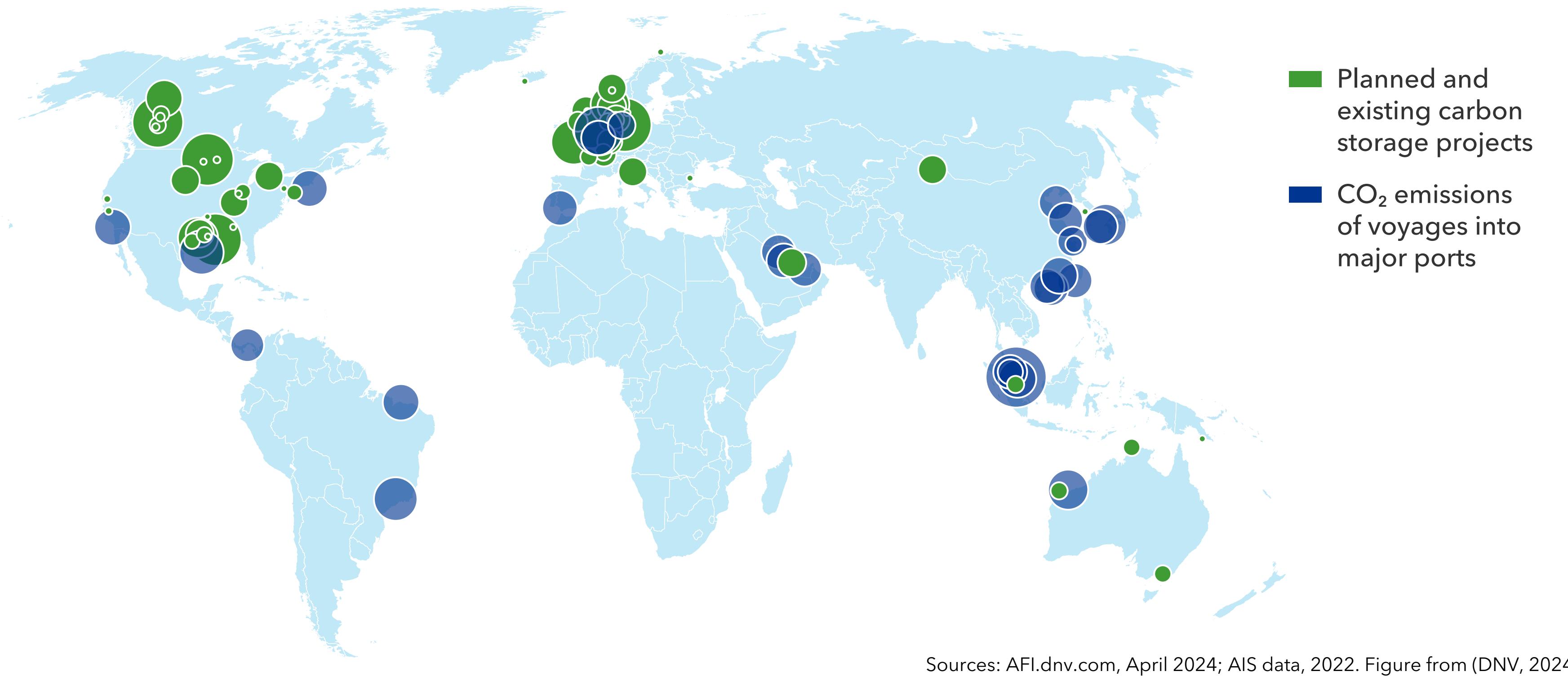


FIGURE 1-4

Planned and existing carbon storage projects, excluding enhanced oil recovery (EOR), by capacity (size of bubble) and location as well as voyage-based estimates of CO_2 emissions from direct voyages into major shipping ports, by annual tonnes of CO_2 emissions and location



Sources: AFI.dnv.com, April 2024; AIS data, 2022. Figure from (DNV, 2024b)

mated global carbon-storage capacity in 2030 is 47 to 67 $MtCO_2$.

The accumulated volumes of CO_2 emissions in the busiest shipping locations are large, with combined annual emissions on the last voyage of vessels entering the ports of Singapore and Rotterdam amounting to 24 and 13 $MtCO_2$, respectively. The 10 largest announced projects for dedicated CO_2 storage, intended for use with other industries, have a planned capacity of 7.5 to 20 $MtCO_2$/year. For the largest ports, dedicated CCS infrastructure for shipping could be built and could contribute significantly to decarbonizing shipping.

Emissions reductions can also be obtained through using shore power. Up to 7% of the total energy consumption of ships could be covered this way while they are in port, if shore power capacity was sufficient and all ships had shore power capability. The well-to-wake emissions from producing electricity from onboard diesel generators are higher than the average GHG intensity from the grid in many countries, while electrofuels should only be produced from very low GHG intensity electricity.

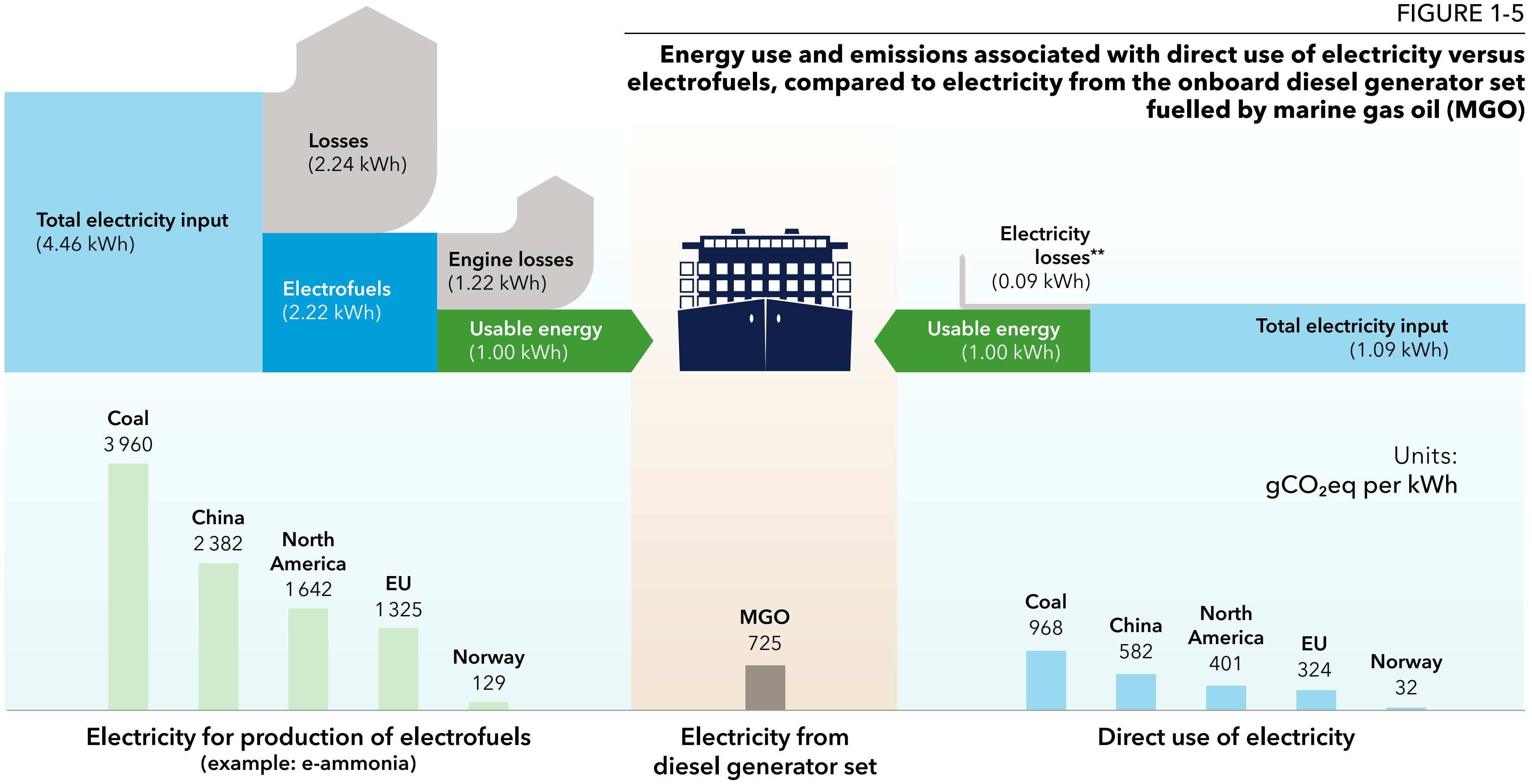
For a large set of scenarios for the IMO assessing the impact of coming GHG regulations on the world fleet, DNV simulations estimate that shipping could reduce fuel consumption in 2030 by 4% to 16% from operational and technical energy-efficiency measures, compared to a business-as-usual scenario. This results in a large variation in the estimated demand in 2030 from shipping for both carbon-neutral fuels and for CO_2 storage from onboard carbon capture. The estimated demand for carbon-neutral fuels is between 7 and 48 Mtoe in 2030, while the demand for CO_2 storage from using fossil fuels with onboard carbon capture is between 4 and 76 Mt of carbon dioxide.

Decarbonizing shipping will come at a cost. In this year's report, we present four scenarios where the increase in US dollar-denominated cost (capital expenditure, fuel cost, CO_2 price) per transport work (measured in deadweight tonne-miles, DWT-nm; or as twenty-foot equivalent unit nautical miles, TEU-nm) in a decarbonized 2050, compared to a business-as-usual scenario, was 69% to 75% for bulk carriers, 70% to 86% for tankers, and 91% to 112% for container vessels. With such a significant increase in costs for owning and operating ships, strategic fleet management is even more important, and the increased costs will have to be compensated for through an increase in freight rates, in order to move the increased costs through the value chain to consumers.

The decarbonization of shipping is a complex puzzle with many different solutions. Meeting the IMO's goal of zero-emission shipping by 2050 requires smart decision-making and strategic investments today to lay the foundations for significant emissions reductions in the future.

FIGURE 1-5

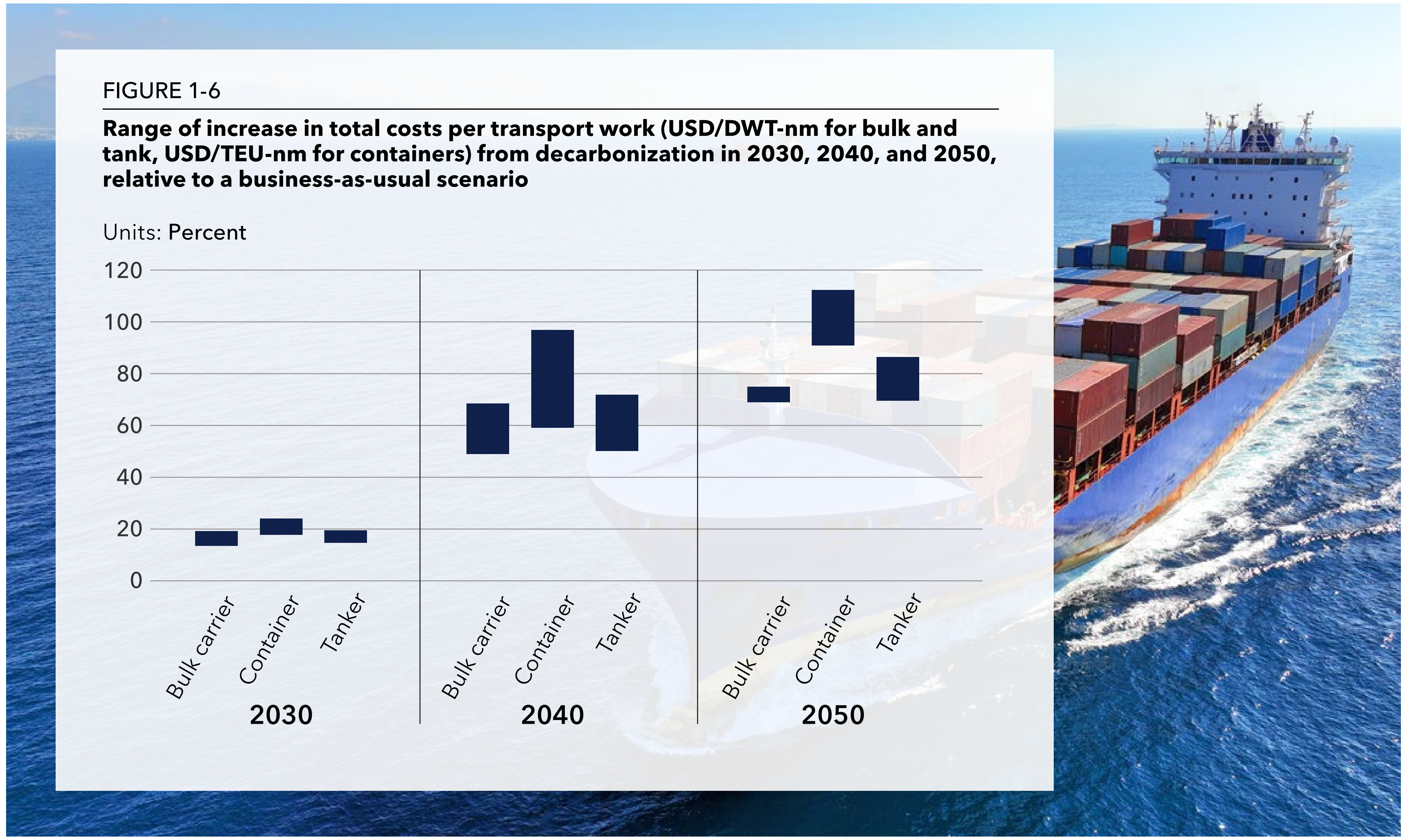
Energy use and emissions associated with direct use of electricity versus electrofuels, compared to electricity from the onboard diesel generator set fuelled by marine gas oil (MGO)



Key assumptions
Energy efficiencies: electric grid (92%); electrolysis (68%); H-B synthesis (69%*); onboard generator (45%)
Electric grid GHG intensity in gCO_2eq per kWh: North America (368); EU (297); China (534); Norway (29); coal power (888)
MGO WtW GHG intensity in gCO_2eq per kWh: WtT GHG (52); TtW GHG (274), based on FuelEU Maritime default emission factors
*includes loss of hydrogen and electrical energy; **excludes any losses related to battery charging

FIGURE 1-6

Range of increase in total costs per transport work (USD/DWT-nm for bulk and tank, USD/TEU-nm for containers) from decarbonization in 2030, 2040, and 2050, relative to a business-as-usual scenario



2 INTRODUCTION

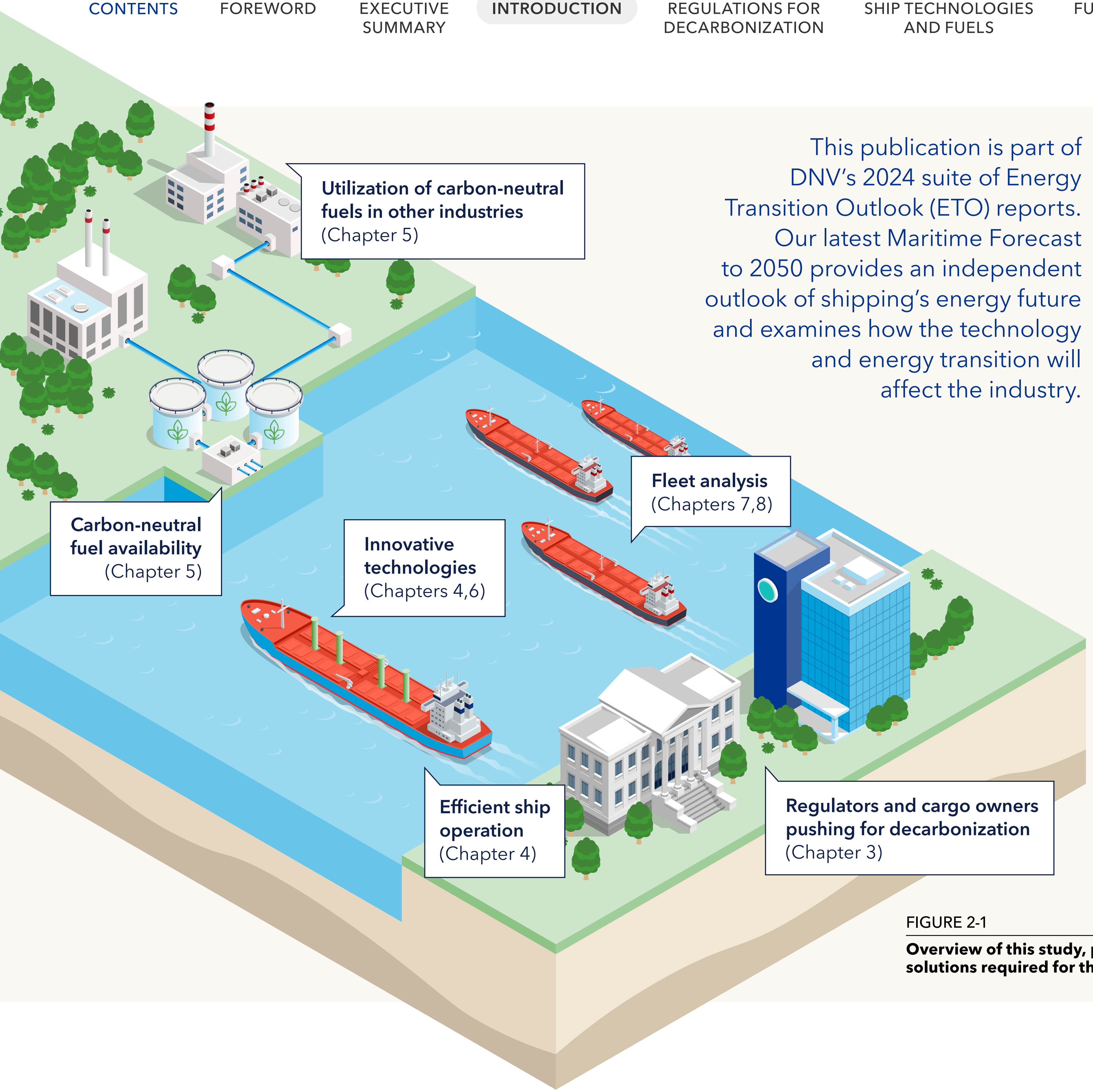


FIGURE 2-1

Overview of this study, providing an outlook on the drivers and solutions required for the decarbonization of shipping

This publication is part of DNV's 2024 suite of Energy Transition Outlook (ETO) reports. Our 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.

The course and speed are set for the maritime decarbonization transition, where compliance becomes tougher and ship emissions will cost. In this year's report we aim to provide understanding of the maritime transition driven by regulations and drivers, leading to technology changes and development in the world fleet and land-based industry providing energy for ships. The IMO aims to have reduced well-to-wake greenhouse gas (GHG) emissions by 20% in 2030 relative to 2008, far beyond the 3.6% reduction achieved by 2023 (DNV, 2024a). Achieving the IMO's updated ambition of zero-emission shipping by 2050 will require shipowners to identify, evaluate, and use technologies, fuels, and solutions that help minimize energy consumption and decarbonize ships. Many ships contracted in the coming years may still be in operation in 2050, and to retain their commercial attractiveness, asset value, and profitability for the following decades, new ships need to consider future demands for lowering energy use and GHG emissions in their design and operation. Net-zero emissions from shipping will not be reached in 2050 without making the right decisions and investments today.

Shipping is indeed facing an unprecedented wave of decarbonization regulations (Chapter 3) that not only affect technology choices and operation of ships (Chapter 4), but also impact the development of shoreside infrastructure and energy industries by creating demand from shipping for increased production of renewable or nuclear electricity, sustainable biomass, carbon storage and various alternative 'energy carriers', and fuels (Chapter 5).

The increasingly complex interplay between shipping, energy, and fuel production on land, impacts the strategies of shipowners and fuel producers, as well as society as a whole as it plans for broader decarbonization goals. With the ramping-up of production and competition from other sectors, the amounts of carbon-neutral fuels – from renewable electricity, sustainable biomass, and fossil sources with carbon capture and storage – that will be available for shipping are still uncertain. Therefore, it is crucial to not only focus on such alternative[1] fuels, but also to make increasing use of emerging technologies that can reduce emissions without using the limited carbon-neutral[2] fuels (Chapter 6).

The coming regulations allowing pooling of compliance between ships (Chapter 7) can drive uptake of high capital expenditure (CAPEX) solutions to decarbonization in the short to medium term. The driving force of regulations, the development of ship technologies, and the build-up of fuel infrastructure/production will impact and change the future fuel mix of shipping (Chapter 8). In these early stages of the transition, there is still uncertainty over exactly which technologies shipping will use in the future, but the first steps are being taken in several different directions.

3 OUTLOOK ON REGULATIONS FOR DECARBONIZATION

Highlights

We review the status and outlook for regulations impacting ship decarbonization, including:

- The EU Emissions Trading Scheme being implemented and the advanced preparations for FuelEU Maritime.
- The need for bunker suppliers to provide certified low-emission fuels when delivering to ships trading in the EU.
- FuelEU Maritime introducing the option to pool compliance across a fleet of ships.
- The IMO considering a GHG fuel intensity requirement and a GHG emission pricing mechanism.
- Ongoing negotiations on future IMO requirements, expected to conclude in 2025.

2024 is the first year where ships trading in the EU are subject to the EU Emissions Trading System (ETS), which has required a revision of regulatory responsibility and contracts to ensure the allowances costs are passed through the supply chain to the responsible company. Coming soon in 2025 FuelEU Maritime will impose a well-to-wake GHG intensity requirement on energy used during a year, effectively forcing the use of qualified low GHG fuels. In this chapter, we review the status of and provide an outlook for these and other regulations for the decarbonization of shipping.

We expect three key fundamentals – regulations and policies, access to investors and capital, and cargo-owner and consumer expectations (Figure 3-1) – to drive ship decarbonization through the 2020s and beyond. 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 the decarbonization of shipping through direct

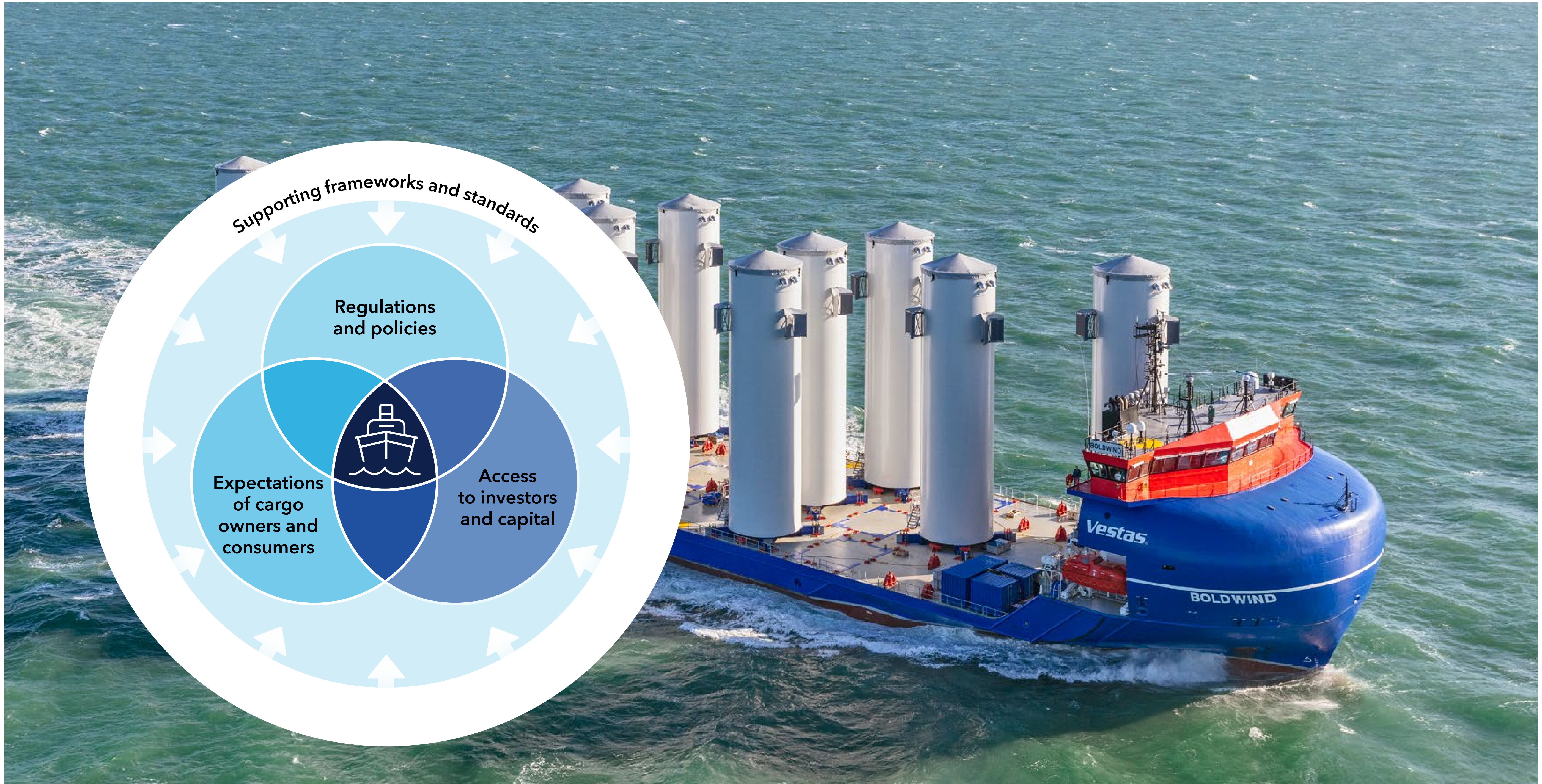


FIGURE 3-1

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.

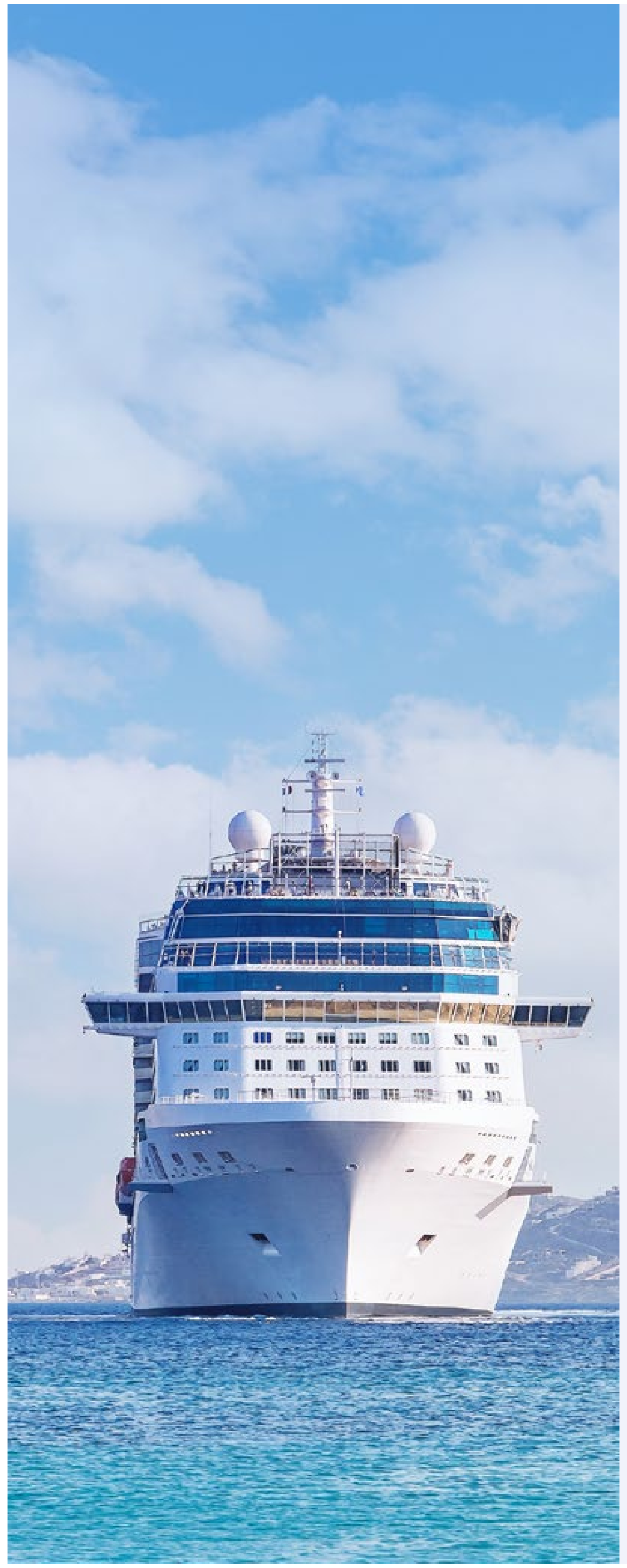
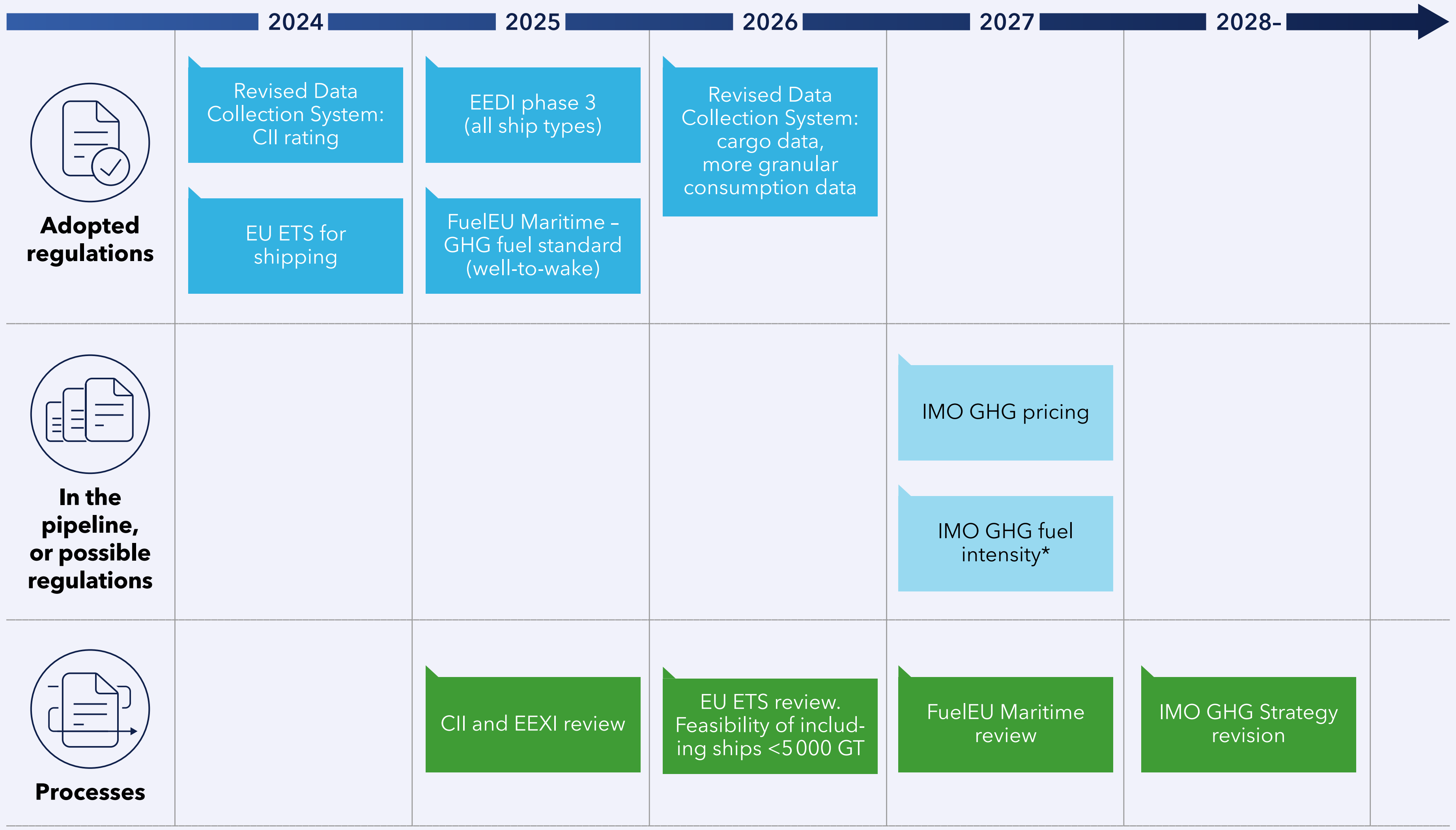


FIGURE 3-2

GHG regulatory timeline towards 2030



*taking into account well-to-wake Key: Carbon Intensity Indicator (CII); Energy Efficiency Design Index (EEDI); Energy Efficiency Existing Ship Index (EEXI); Emission Trading System (ETS); Ship Energy Efficiency Management Plan (SEEMP)

requirements and incentives for ships and shipping companies. These drivers are in focus in this chapter, while there are developments in the other key drivers, namely expectations of cargo owners and access to investors and capital.

One important aspect of both the EU ETS and FuelEU Maritime is the concept of qualified fuels which can be used to reduce GHG emissions. Bunker suppliers delivering fuels to ships trading in the EU need to provide documentation that the fuel adheres to the required standards. Another feature of FuelEU Maritime is the option to pool compliance across several ships, including with ships from other companies. For further discussion see Chapter 7.

This chapter presents the latest status on upcoming regulations on GHGs from the IMO and the EU, and Figure 3-2 summarizes the regulatory timeline towards 2030 that we describe. The solutions being investigated for decarbonizing shipping and complying with the coming regulations are discussed in Chapters 4 (ship technologies), 5 (alternative fuel production and demand), and 6 (emerging technologies to reduce demand for carbon-neutral fuels).

Regulations and policies remain the key drivers for the decarbonization of shipping through direct requirements and incentives for ships and shipping companies.

3.1 International Maritime Organization

The IMO is now working on implementing the GHG strategy to ensure that shipping follows the indicative checkpoints – reducing total GHG emissions by 20%, striving for 30% in 2030 and then 70%, and striving for 80% in 2040, all compared to 2008 – and that it reaches the revised ambition to 'reach net-zero GHG emissions by or around 2050'.[3] This implies zero well-to-wake GHG emissions, although negotiations are ongoing to determine how this is defined and implemented (see below). As of MEPC 81 in March 2024, the IMO has agreed on an overarching structure, the 'IMO net-zero framework', for the needed regulatory amendments in MARPOL Annex VI.[4] This is intended to form the basis for refined proposals. The development of regulations will continue at the IMO and will, according to the agreed timeline, be adopted in 2025 and enter into force about mid-2027.

Ongoing negotiations are developing what is called a basket of measures, which can consist of two parts:

- A technical element, which will be a mandate on reduced GHG intensity of marine fuels.

- An economic element, which will be a GHG emissions pricing mechanism, linked directly to the technical fuel GHG intensity mechanism or as a stand-alone mechanism. It can also be a flexibility mechanism on the fuel GHG intensity requirement.

The GHG strategy states that the GHG reduction ambitions should take into account well-to-wake (WtW) emissions. This can be done in different ways, either by setting a requirement on the total WtW GHG intensity of energy used, or by using TtW (tank-to-wake) GHG emissions, but adjusted based on WtT emissions and other sustainability aspects. Regardless of the agreed scope, to support the regulatory measures the IMO is developing lifecycle assessment (LCA) guidelines, detailing how the well-to-tank and tank-to-wake emissions of marine fuels should be calculated and certified. More work is needed to complete these guidelines and a scientific working group has been established to consider new default fuel pathway values, certification of actual well-to-tank and tank-to-wake emission factors, and more general methodological LCA issues.

Onboard carbon capture has seen increased interest as a possible solution for decarbonizing shipping, see Chapters 6 and 8 for more details. The IMO has started developing a workplan on the development of a regulatory framework, including both safety and environmental regulations, for the use of onboard carbon capture systems. The application of onboard carbon capture will be incorporated in the LCA guidelines, though further discussions are needed to address other regulatory barriers, particularly those related to the fate of the captured carbon. The climate effect of onboard carbon capture 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 or carbon is delivered to a facility that ensures that it is permanently stored. Internationally recognized certification schemes are likely to be needed.

Independently of the development of the new basket of measures, the Carbon Intensity Indicator (CII) and Energy Efficiency Existing Ship Index (EEXI) regulations are required to be reviewed by the end of 2025. The review has started with data gathering, and the analysis begins in October 2024. The review will conclude with proposed revisions to the regulations and associated guidelines in spring 2025. This will likely include CII reduction requirements from 2026 to 2030, new and amended correction factors, and/or additional metrics. It could possibly also include a revised enforcement mechanism, and application of LCA guidelines to take into account non-fossil fuels.

3.2 EU

The EU ETS[5] took effect from 1 January 2024 for ships trading in the EU. Shipping companies are required to buy and surrender emission allowances for TtW CO_2 emissions within EU and European Economic Area (EEA) ports, emissions on voyages between such ports, and 50% of emissions on voyages into or out of them. The first deadline for surrendering allowances is in September 2025 based on emissions in 2024. From 2025, general cargo vessels from 400 to 5,000 gross tonnage (GT), and offshore vessels from 400 GT are required to report GHG emissions but are not subject to the ETS for the time being. Offshore ships above 5,000 GT will be subject to the ETS from 2027, while the general cargo and offshore ships between 400 and 5,000 GT will be considered for inclusion only after a review in 2026. As of July 2024, the EU has not provided a definition of offshore ships. Methane and nitrous oxide emissions are required to be reported from 2024, and from 2026 these emissions are also included in the scope of the EU ETS. The EU ETS also takes into account the permanent storage of carbon.

A key challenge has been the allocation of the company responsibility for compliance. Contrary to other shipping requirements, as a default the registered shipowner is responsible for compliance, including surrendering of allowances, and can only transfer this responsibility to the ISM company[6] through an explicit mandate. This has in many cases meant updates of contracts to ensure a timely financial settlement based on an agreed reporting of emissions.

FuelEU Maritime[7] is under implementation, and from 1 January 2025 ships above 5,000 GT transporting cargo or passengers for commercial purposes are required to meet annual well-to-wake GHG emissions intensity requirements. The GHG intensity can be reduced by using fossil LNG or LPG, qualified low GHG intensity fuels (including a reward factor for Renewable Fuels of non-Biological Origin), shore power or by wind assisted propulsion. Wind assisted propulsion can reduce the GHG intensity by up to 5%. The reduction is based on design criteria and does not take into account the use of the system.

A novel feature of FuelEU Maritime is the option for banking and borrowing compliance balance toward the following year, and to pool compliance balance with other ships – this is covered in Section 4.3. Ships that do not meet the required GHG intensity and have a negative compliance balance even after banking, borrowing and pooling, must pay a penalty which increases for each consecutive year with a negative compliance balance.

As opposed to the EU ETS, the ISM company will always be responsible for compliance, and this cannot be shifted to another entity. It is also the ISM company which, on 31 December, is responsible for compliance for the full year, even if it took over the ship during the year. This implies that when taking over ships, ISM companies should ascertain the GHG intensity of the ship from the previous manager to ensure that any negative compliance balance is compensated for. It also means that there can potentially be two different companies responsible for the EU ETS and FuelEU Maritime for the same ship. For the time being, the regulation does not include either offshore ships or ships that use onboard carbon capture and storage. This will be considered during a review in 2027.

Both the EU ETS and FuelEU Maritime rely on the fuel certification framework of the Renewable Energy Directive[8] (biofuels, Renewable Fuels of non-Biological Origin, and Recycled Carbon Fuel) and the recast Gas Directive[9] (Low Carbon Fuels) for ensuring that only sustainable fuels with at least 50% to 65% (biofuels) or 70% (all other fuels) GHG saving compared to fossil fuels give emission or GHG intensity reductions. Ships using such fuels should ensure that the Bunker Delivery Note is accompanied with a Proof of Sustainability or similar documentation from the fuel supplier. See also Section 5.5.

The EU ETS and FuelEU Maritime include review provisions. For the EU ETS, this is due by the end of 2026 and will in particular consider whether ships below 5,000 GT should be included in the scheme. The FuelEU Maritime review is due by the end of 2027 and could in addition to smaller vessels also consider inclusion of offshore vessels and allow for onboard carbon capture when calculating the WtW fuel GHG intensity. Both regulations also include provisions that they will be reviewed if the IMO adopts similar measures.

3.3 Fleet compliance pooling

One particular feature of FuelEU Maritime, which is also being considered by the IMO for its GHG intensity requirement, is the option to attain compliance across a fleet of ships, even if they belong to different companies. This means that each individual ship does not need to achieve the required fuel GHG intensity but can rely on other vessels to achieve a combined level of fuel GHG intensity which is better than the requirement.

A key element in a fleet compliance mechanism is for each ship to calculate a compliance balance which indicates how far the ship is above or below the required GHG fuel intensity (GFI) in terms of absolute GHG emissions. A ship with an attained GFI below the required GFI will have a positive compliance balance, and a ship with an attained GFI above the required GFI will have a negative compliance balance. In other words, if an attained GFI is below the required level, the ship emits less GHG than the requirement, and is said to have positive compliance balance.

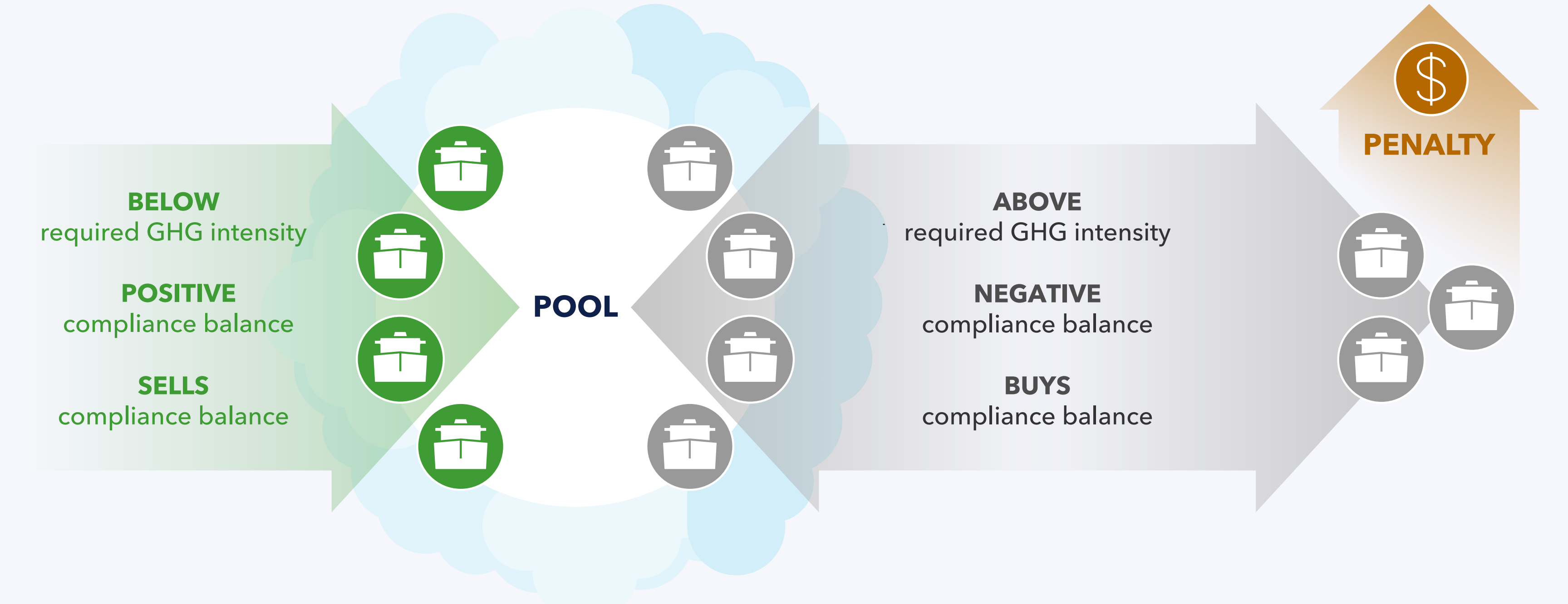
Fleet-level compliance can then be implemented in several ways. One is to establish an explicit exchange of emission units – for example, a tonne of CO_2eq – where ships with a positive compliance balance can sell excess emission units to ships with a negative compliance balance (Figure 3-3). A variant of this is a pooling mechanism, used in FuelEU Maritime, where ships with positive and negative compliance balances can declare a pool where all ships are considered compliant if the total compliance balance of the ships in the pool is equal to or greater than zero.

Regardless of the variant chosen, we expect that for a fleet of ships from different companies, or even in the same company operating in different trades and with multiple charterers and/or owners, there will be a need to agree on financial settlements. The emission unit exchange price would be set bilaterally between the parties in the fleet. The IMO is also considering the option to buy or sell emission units to a central body which would in effect set a floor and ceiling on emission units' prices in the market. The FuelEU Maritime penalty is similarly a ceiling on the cost of compliance.

> Fleet-level GHG compliance allows for taking full advantage of using alternative fuel technologies. Capital costs can be distributed across a larger GHG emission reduction.

FIGURE 3-3

Pooling of compliance in the FuelEU Maritime to avoid penalty



Compliance balance measured in tonnes CO_2eq

The two main benefits of fleet-level GHG compliance can be summarized as follows:

- There is no need to supply each individual ship with a certain amount of low GHG emission fuels. This is particularly beneficial in a phase of developing production and bunkering infra-structure. The required amount of such fuels in the compliance fleet can be used where it is available.
- It allows for taking full advantage of using alter-native fuel technologies. A ship that invests in ammonia, methanol, or onboard carbon capture and storage would be able to fully utilize the capacity of that technology and sell emission units to other ships. This means that capital costs can be distributed across a larger GHG emission reduction than if the ship only needed to comply individually. See further analysis in Chapter 7.

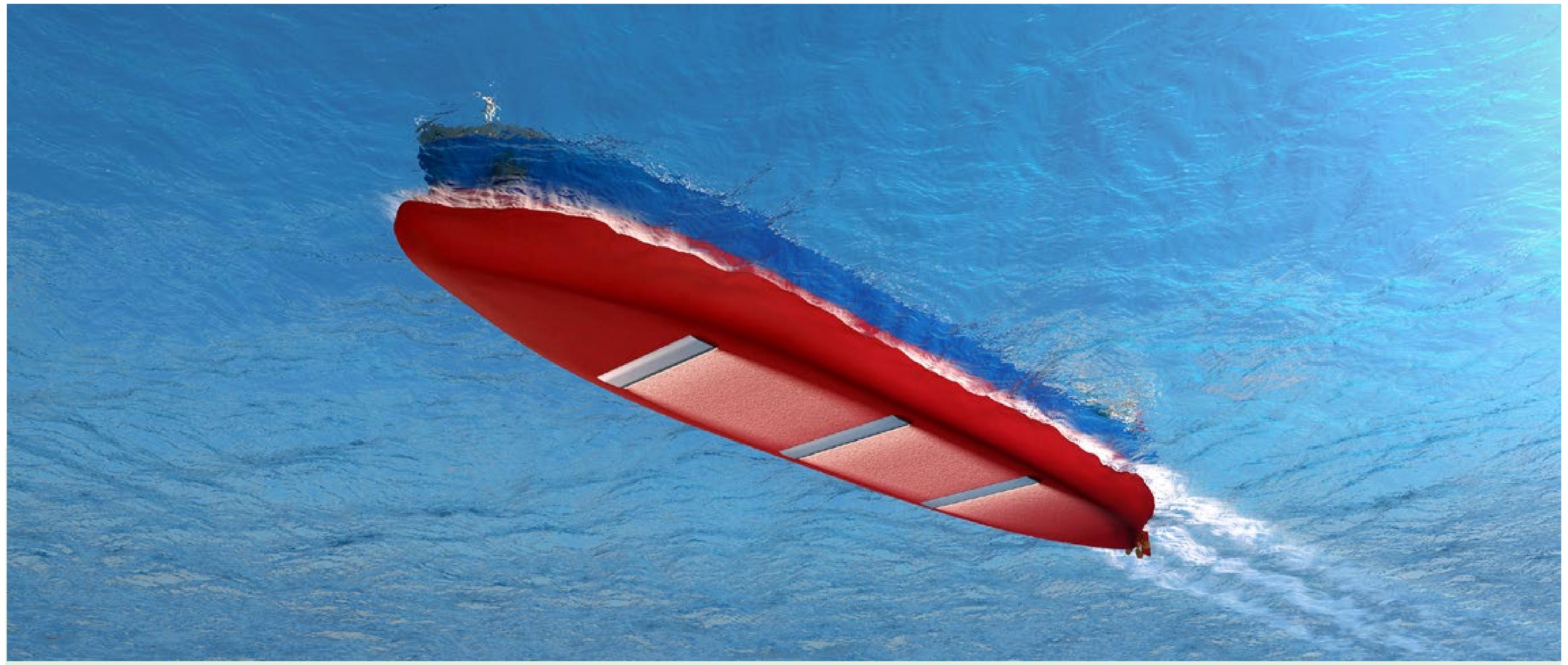
4 OUTLOOK ON SHIP TECHNOLOGIES AND FUELS

Highlights

Our tracking of technology uptake for reducing ship energy consumption and using new fuels finds:

- 92.6% of tonnage in operation can only use fuel oils, but half the tonnage on order will have alternative fuel capability.
- The number of ships that can run on LNG keeps rising and orders include many methanol and LPG-fuelled ships and the first ammonia-powered vessels.
- Nearly 1,000 ships today use batteries alone or in hybrid systems, with 400 more on order.
- By sharing costs and gains among parties, data sharing and verification in new contracts can unlock low-cost operational measures for emission reduction.

Achieving the IMO ambition of net-zero emission shipping by 2050 will require shipowners to identify, evaluate, and use technologies, fuels, and solutions that help minimize energy consumption, decarbonize ships, and meet other environmental requirements. The maritime decarbonization course and speed are set, with additional regulations in the pipeline, where compliance becomes tougher and ship emissions will cost (Chapter 3). It will be essential to understand the current emission status and to develop robust decarbonization strategies for ships. This will involve implementing energy-efficiency strategies in the near term while preparing fuel-change strategies in the longer term.

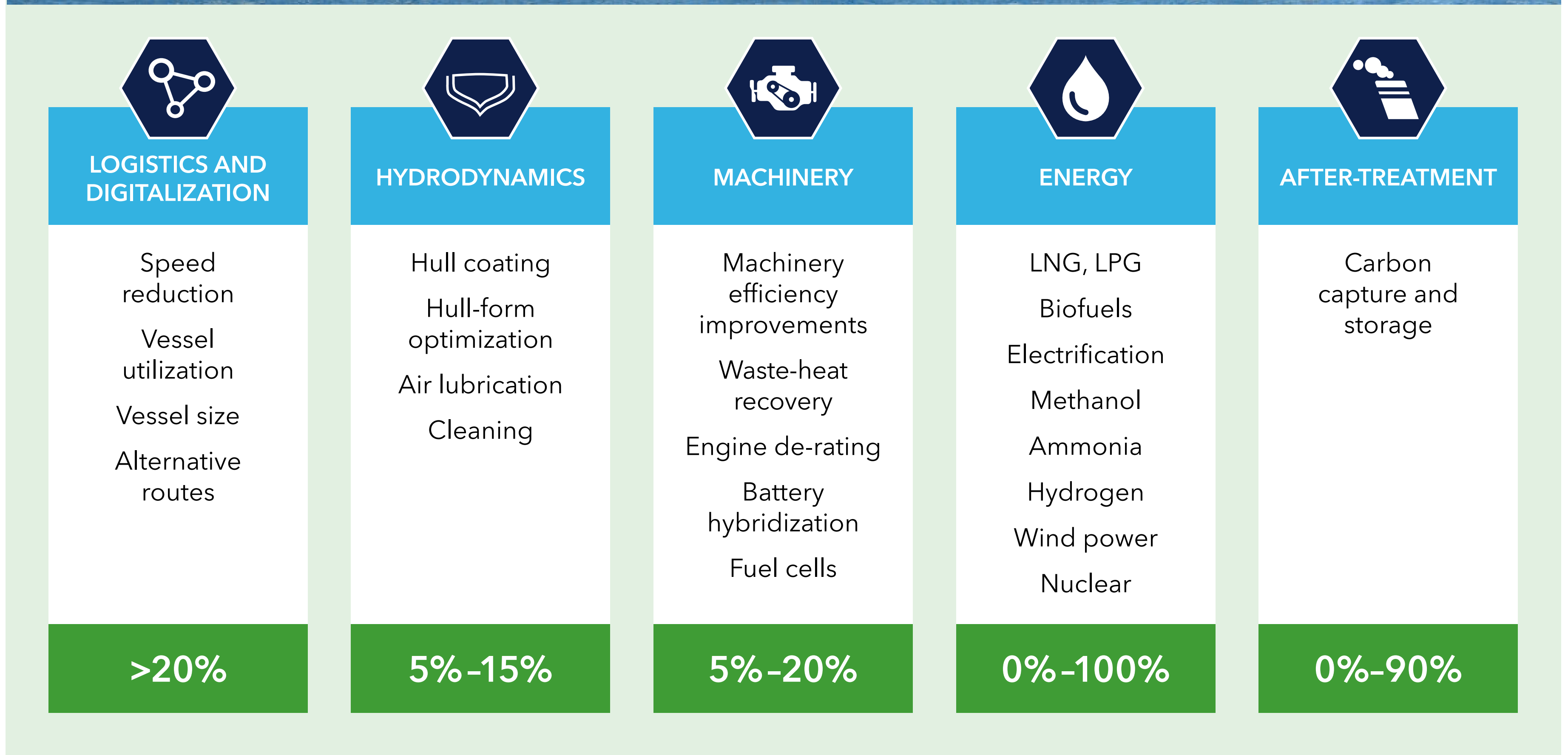


Decarbonizing shipping will predominantly require new fuels but also greater energy efficiency, improved logistics, and the uptake of onboard carbon capture and storage. Digitalization will be a key enabler for decarbonizing shipping and improving ship design, operations, and fleet utilization. There are many solutions (Figure 4-1) that can reduce emissions to meet GHG regulations, reduce penalties, and ensure the long-term profitability of shipowner assets, each solution having different barriers to its implementation and use. Many of the technologies that are required to meet the IMO goals of making shipping carbon-neutral by 2050 are still under development, so more effort is needed to test and validate new technologies and solutions. In addition, carbon-neutral fuels are not available today in sufficient quantities, are much more expensive than conventional fuels, and require more onboard space. Additionally, new fuels introduce novel safety risks, requiring new design solutions and large-scale training of seafarers.

In this chapter, we first discuss the status of the fuel technology transition (4.1) and give an outlook on the readiness of main engines for alternative fuels (4.2), then move on to reducing ship energy consumption by technical measures (4.3) and by implementing digital solutions for optimizing ship operation (4.4).

FIGURE 4-1

Decarbonization solutions that can contribute to reducing a ship's energy consumption and emissions from energy use, and their GHG reduction potentials



4.1 Status of fuel technology transition

The trend of larger ships being ordered with dual-fuel propulsion capabilities is continuing, indicating that the fuel technology transition is progressing (Figure 4-2). As illustrated, the uptake of LNG is continuing, but what is new in the order book is a large number of methanol and LPG-fuelled ships and the emergence of ammonia as fuel.

Figure 4-3 presents the status and details of the uptake of alternative fuel technologies in the world fleet and the order book as of June 2024. Measured in gross tonnage, 7.4% of the ships in operation can now operate on alternative fuels. In the order book, 49.5% of the tonnage can operate on alternative fuels. This compares to last year's numbers of 6.5% and 51.3%, respectively. Measured in number of ships, the percentages are lower, 2% in operation and 27.1% for the order book, indicating that larger ships are going for dual-fuel solutions. This shows that the fuel technology transition is continuing, with an increasing number of ships capable of operating on alternative fuels, where large ships capable of burning methanol will enter the fleet towards 2030.

Reviewing the fuel technology choices for ships in operation and on order, we find that:

- In the world fleet, 92.6% of the tonnage in operation can only use fuel oils, whereas half the tonnage in the order book is without alternative fuel capability.
- LNG-fuelled ships represent 6.7% of the tonnage for ships in operation, while 36% of the tonnage in the order book can use LNG as fuel. It remains a popular fuel choice in the containership segment (171 ships on order) and car carrier segment (157 ships on order), with significant uptake also in tankers (93), bulk carriers (16) and cruise ships (22). LNG carriers

FIGURE 4-2

Growth of the number of ships capable of using selected alternative fuels, excluding LNG carriers[10], as of May 2024

The trend of larger ships being ordered with dual-fuel propulsion capabilities is continuing, indicating that the fuel technology transition is progressing.

ordered, respectively. See Section 5.2 for details on methanol consumption capacity in the existing fleet and order book.

- Following the Norwegian ferry MF Hydra which has been operating on liquefied hydrogen since 2023, the ferry operator Torghatten will take delivery of two 120-metre ferries fuelled by compressed hydrogen in 2025. Dutch logistics solution provider Samskip has ordered two 700 TEU containerships at the Cochin shipyard in India, intending for them to be provided with hydrogen-fuelled fuel cells. There are also numerous hydrogen initiatives for smaller vessels.

- Despite the low maturity of ammonia energy converter technology, we have recently started to see the first orders of ammonia-fuelled ships. Belgian shipowner CMB has ordered a series of eight bulk carriers with main engines capable of using ammonia as fuel. As expected, there are also first movers in the ammonia carrier segment, with Exmar LPG BV ordering two, and NYK one, mid-size gas carriers capable of burning ammonia as fuel. In total, there are 25 ammonia-fuelled ships on order.

In addition to ships capable of using alternative fuels, 940 ships in operation use batteries for propulsion or in a hybrid power system, and 433 of the ships on order will use them. Fully electric propulsion systems are only used on smaller vessels with limited range.

It is important to note that most ships that have the capability to use alternative fuels have dual-fuel solutions. Battery-electric ships almost always have

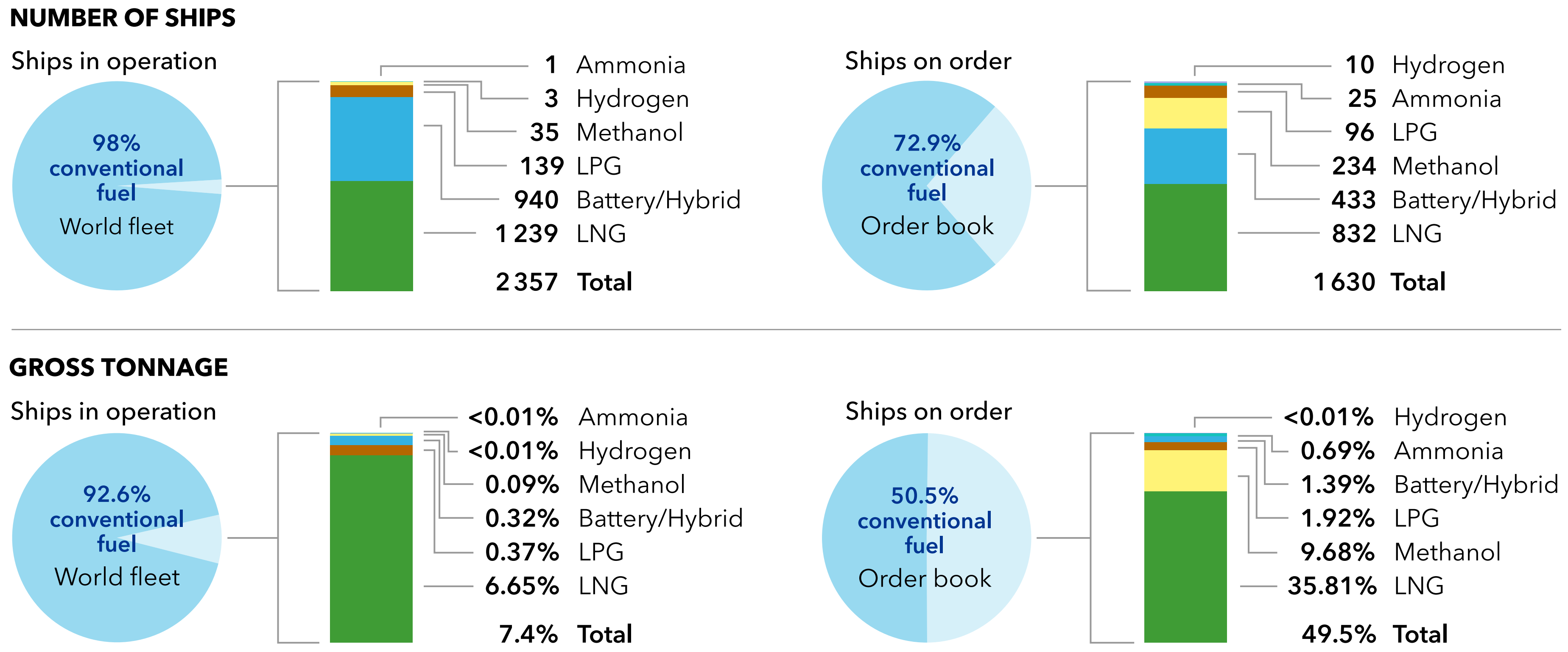
using their natural gas cargo as fuel constitute 687 of the LNG-fuelled ships in service, while another 339 are on order. In total, 1,239 LNG-capable ships are currently sailing, while 832 are on order.

- 139 LPG carriers using LPG as fuel are currently sailing, representing 0.37% of the world fleet tonnage. With 96 LPG carriers on order, 1.9% of the order-book tonnage has LPG-burning capacity. Two ethane carriers with dual-fuel engines are also on order.

- Methanol-fuelled ships represent 0.09% of the world fleet tonnage in operation but 9.68% of the tonnage ordered. The containership segment saw a considerable increase in methanol-fuelled ship orders last year. This trend is still ongoing, with 173 methanol-capable containerships on order. Bulk carriers and car carriers are new ship types in the methanol statistics, with 24 and 20 ships being

FIGURE 4-3

Alternative fuel uptake in the world fleet in number of ships (upper) and gross tonnage (lower), as of June 2024



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

oil-fuelled generator sets as back-up. Furthermore, the alternative fuel may still originate from fossil energy sources, emphasizing the necessity for regulations that address GHG emissions from a well-to-wake perspective.

Development of the bunkering vessel fleet

The number of LNG bunker vessels serving the existing fleet of LNG-fuelled ships grew from 42 to 53 ships over the last year, with new vessels sized to fit the fuel carriage capacity of large ships. The order book shows that 11 new LNG bunker vessels will be delivered in 2024. Bunkering infrastructure development supporting methanol is also reflected in the order book, with 8 methanol bunkering vessels.

According to DNV's Green Shipping Corridor Database (as of June 2024), there are currently 60 green shipping corridors announced with various degrees of maturity. These initiatives include plans for operation on low GHG emission intensity fuels and are expected to be important for developing bunkering infrastructure/energy hubs for new fuels.[11] Already in the Baltics, there have been trials for operation one day a week.[12]

Conversion of existing ships

Converting ships to run on new fuels is technically complex and costly. Retrofit expenses are substantial and vary depending on the fuel and ship type, conversion scope, and degree of preparedness. Therefore, the number of conversion candidates will be limited by factors such as asset value, remaining lifetime, design implications, and availability of main engine fuel conversion kits. When considering a retrofit, the techno-economic analysis should consider factors such as duration of conversion/off-hire cost, remaining lifetime, fuel prices and cost of emissions, as well as the actual cost of engine and ship conversion. We have observed that several container operators are mulling over retrofits, with several shipowners considering the methanol conversion route for their ships. Maersk is embarking on a programme to convert 11 of its 15,000 TEU ships to dual-fuel methanol operation[13], while the Seaspan and Hapag-Lloyd fleets have agreed to a delivery of 15 MAN B&W S90 retrofit solutions to dual-fuel ME-LGIM, with an option for 45 additional deliveries.[14] COSCO[15] and CMA CGM[16] are also reporting on ongoing methanol conversion programmes for their containership fleets.

Zero-emission pilot projects

The Global Maritime Forum has been tracking the development of zero-emission pilot and demonstration projects annually for the last four years. According to the fourth edition of the Forum's study[17], the portfolio has increased to 373 projects, up from 203 in the previous year. More than a third of registered projects have achieved a significant development milestone since the third edition of the study, with over 30 ship technology projects receiving Approval in Principle. The two most frequent subject fuels in all project categories are hydrogen and ammonia, indicating the continued need to develop these fuel options. The study found an increase in the number of projects focusing on ammonia as a fuel, while the number centred on hydrogen has remained stable. Around 40% of all projects are publicly funded, most of which are supported by European organizations.

4.2 Outlook for the readiness of onboard fuel technologies

It is important to recognize that many ships contracted in the coming years may still be in operation in 2050. New ships need to consider future demands for lowering energy use and GHG emissions in their design to retain their commercial attractiveness and asset value for the following decades. Any built-in flexibility in design will be beneficial if a conversion to other fuel types becomes necessary to stay compliant. We find that allocating sufficient space for fuel storage and balancing the limitations of safety requirements, while minimizing the impact on cargo carrying capacity or passenger space, are the main design challenges for a newbuild. Implementation of design features towards this goal at the newbuild stage may eliminate showstoppers and reduce cost and time spent at the conversion yard (DNV, 2021).

Most ships use diesel engines for propulsion and power generation, and the large deep-sea ships are typically propelled by slow-speed 2-stroke engines. A DNV study found that the 25,000 largest ships, 30% of the world fleet, accounted for 80% of the CO_2 emissions (DNV GL, 2019). A change to carbon-neutral fuels for these ships is essential for the fuel transition and would significantly reduce shipping's total emissions.

Currently, engine makers are working to provide new engines and retrofit packages for operating on alternative fuels. Shipowners are increasingly investing in fuel flexibility – by ordering ships with dual-fuel engines which can run on alternative fuels in addition to conventional fuel oils. There are also engine makers following a strategy of providing fuel-ready engines for later conversion. Figure 4-4 illustrates the available main engine technologies for the use of alternative fuels available for main ship types and sizes, covering both 2-stroke engines for large ships and 4-stroke technologies used in small to medium-sized ships (and for auxiliary power for all ships).

While methane and methanol engines are generally available in a wide power range, the first ammonia engines, which will become available in the next two to three years, are sized for use in large bulk carriers and gas tankers. For hydrogen, development plans for marine engines seem to be aimed at the lower power ranges (see textbox). It may be expected that technologies and power ranges serving the segments of high demand will be available first, followed by retrofit options and an expansion in product range depending on market development and regulations.

Outlook on engine availability for alternative fuels (Figure 4-4)

Engine types are typically characterized by their combustion cycle (2- or 4-stroke) and rotational speed, where slow-speed 2-stroke engines are used by larger cargo ships for direct or geared mechanical propulsion. Medium-speed 4-stroke engines are commonly used for propulsion and auxiliary power generation and dominate the marine industry by the number of engines installed. High-speed 4-stroke main engines are typically used in smaller vessels. Carbon-neutral fuel alternatives can be used in combustion engines when the engines are designed for them or retrofitted accordingly. In the following, we provide background on the dual-fuel engine availability for alternative fuels:

Methane

LNG-fuelled engines are becoming a mature technology with a global uptake for most ship types. Currently, there are both high- and low-pressure 2-stroke engines available. Smaller 4-stroke engines, both dual-fuel and gas-only, are also available. LNG engine design has been steadily improving as the technology becomes more widely adopted, with increases in efficiency and reductions in methane slip emissions.

Methanol

2-stroke dual-fuel engines using methanol as fuel have almost reached maturity, with many engines on order in the container segment, and 4-stroke engines are developing quickly.

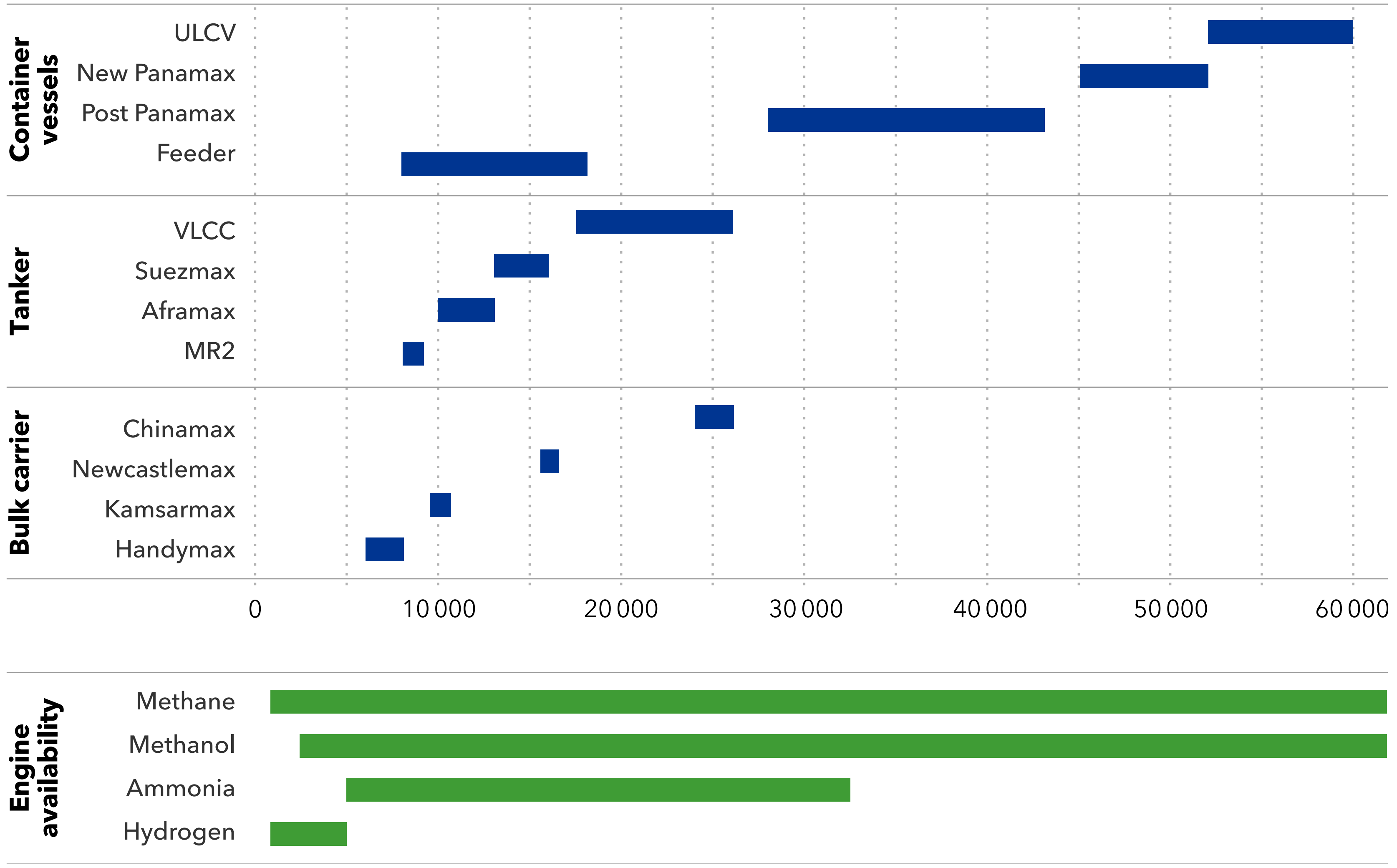
The first MAN B&W ME-LGIM engines came into service in 2016 and have accumulated more than 600,000 running hours on methanol. This low-speed engine operates with an injection of liquid methanol and pilot fuel at the top of the stroke and is currently available with 50, 80, and 95 cm bores covering the power range from 5.4 to 82 MW (with a different rpm range for each engine type). WinGD is developing a multi-fuel strategy for its 2-stroke engines, flexible in terms of working principle. When operating on methanol, their engines are expected to follow the diesel principle, at least for the upper load levels.

The 4-stroke engines currently available are medium-speed engines operating with the injection of liquid methanol and pilot fuel at the end of the compression stroke. This principle is already available from Wärtsilä (Wärtsilä 32 Methanol) and HiMSEN (H 32 DF LM). The engines available in the market have a 32 cm bore and cover the power range from 3,500 to 5,220 kW at 750 rpm.

FIGURE 4-4

Main engine specified maximum continuous rating in kW for typically installed engines as a function of ship size for the largest ship segments: bulk carriers[18], tankers[19], and containerships[20]. Compared with available main engines for the use of methanol, methane, ammonia, or hydrogen as fuel.

Units: Main engine specified maximum continuous rating in kW



Fortescue Green Pioneer became the first oceangoing vessel to be fuelled by ammonia after completing a set of trials in Singapore in May 2024.

Ammonia

No commercial vessels are operating on ammonia as fuel yet, but the first orders for ammonia dual-fuel engines have been signed for delivery from 2025.[21] The converted supply vessel Fortescue Green Pioneer became the first ocean-going vessel to be fuelled by ammonia after completing a set of trials in Singapore in May 2024.

MAN, J-Eng, and WinGD are currently investigating the 2-stroke diesel principle. MAN started testing on its 2-stroke ammonia engine in June 2023 in its test centre. The MAN B&W 7S60ME ammonia engine will be installed in a 200,000-DWT class bulk carrier being built for a joint venture between K Line, NS United, and Itochu Corporation in 2024. MAN plans to be ready to offer ammonia-powered engines to its clients after 2027, using time for thorough testing and demonstration[22] on selected projects. WINGD is currently offering 2-stroke ammonia engines from 5 MW to 31 MW. The WinGD 6X72DF-A has been ordered for a series of bulk carriers with delivery dates between 2025 and 2027, while the 6X52DF-A 1.0 shall be delivered to two gas tankers and a containership in the same period. An NYK ship, which will be delivered in 2026, will use a Japan Engine Corporation (J-Eng) ammonia engine. J-Eng plans to complete its first 50-bore ammonia engine in 2025 and to follow up with a 60-bore engine after 2026.

4-stroke medium and high-speed engines can operate with a high-pressure injection of liquid or vaporized ammonia and pilot fuel at the top of the stroke, or with an injection of vaporized ammonia upstream of the inlet valves or directly into the cylinder early in the stroke. Wärtsilä is reportedly testing both principles in the development work with an ammonia-fuelled engine.

Hydrogen

No commercial oceangoing ships are operating on hydrogen engines yet, but development is ongoing.

BeHydro, J-Eng, VOLVO, Bergen Engines and IHI Power Systems are developing engines that will run on a mix of conventional fuel and hydrogen, with a later aim of 100% hydrogen. These engines will range from 750 kW to 5,000 kW, indicating an intended use for smaller vessels.

4.3 Reducing onboard energy losses by technical energy-efficiency measures

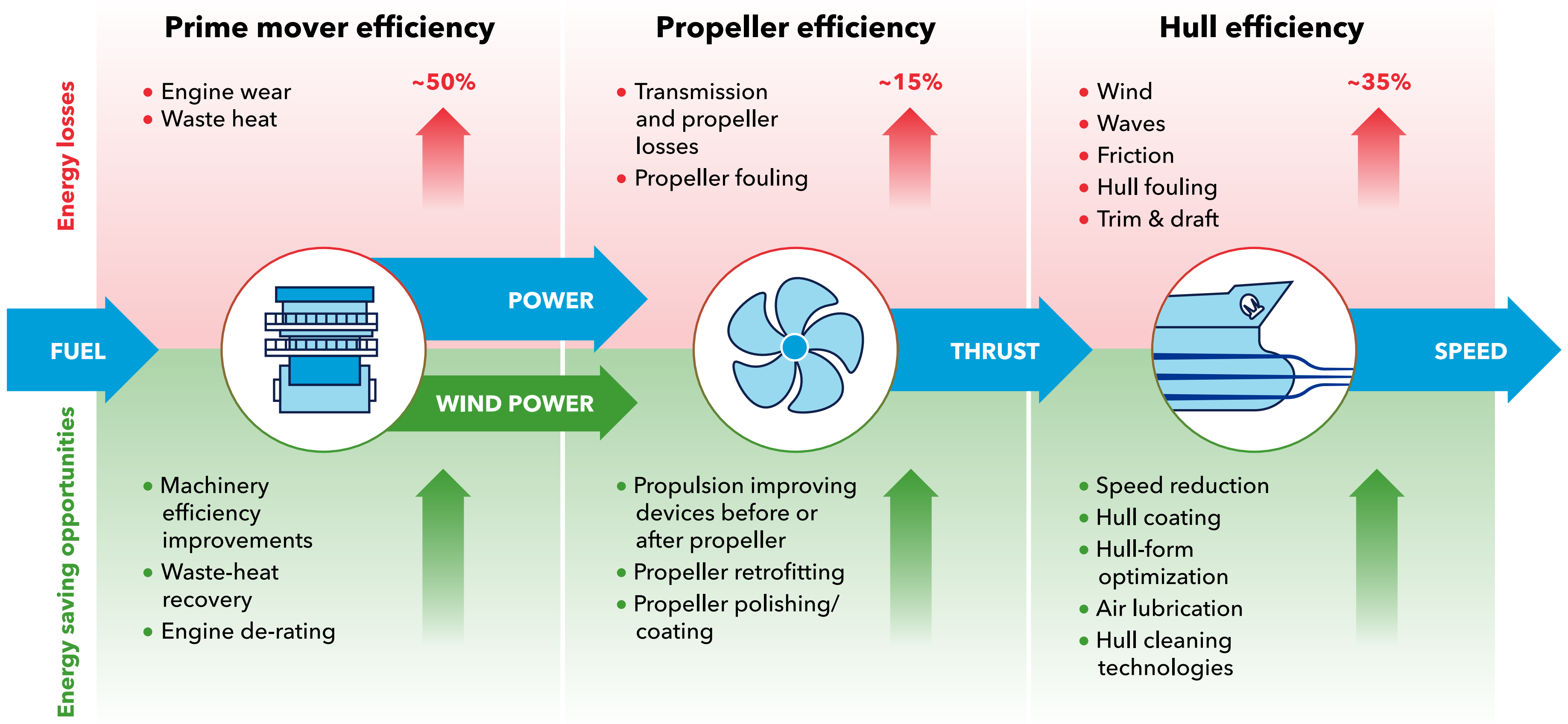
The future changes in fuel and technology must be accompanied by increased energy efficiency of ships – doing the same amount of useful work but using less energy. While 'first movers' implement alternative fuel solutions, a logical initial step for most operators will be to apply operational and technical efficiency measures to meet near-term GHG regulations and lower the demand for more expensive fuels. Current literature on energy-efficiency potential suggests that at least 15% of emissions from shipping could be reduced through energy-efficiency measures, saving 40 Mt of fuel[23] and 120 MtCO_2 emissions.[24,25] This would be equivalent to operating the 55,000 smallest ships (above 400 GT) or the 2,500 largest ships with carbon-neutral fuel (DNV GL, 2019).

Fuel costs make up a large part of the total cost of ownership of a ship, and technical energy-efficiency measures that were not previously considered commercially viable may gain in significance when GHG emissions come at a price and the use of carbon-neutral fuels increases the fuel cost. Reducing onboard energy use is also important because most carbon-neutral fuels have a much lower volumetric energy density than fuel oil. This means that storing fuel will require more space or that the operational distance will need to be shorter, or possibly both. Technical measures that improve energy efficiency will count towards increasing operational range or reducing the fuel tank size, freeing up more space for cargo or passengers.

As shown in Figure 4-5, onboard energy losses are substantial. Only about half the fuel energy is converted into shaft power, and the rest is lost in the engine exhaust or as heat. After accounting for

FIGURE 4-5

Converting fuel energy to ship speed – typical energy losses for large ships and the opportunities for energy savings (Inspired by Glosten, 2016)



After six month of operation with hard sails, Cargill reported average fuel savings of 14%.

the losses in the propeller and transmission, only about a third of the energy from the fuel produces propulsion thrust to overcome the resistance to move the hull through the water. As indicated in Figure 4-5, there is a range of technologies that can help reduce the losses.

Prime mover efficiency

The areas of highest energy loss offer opportunities to enhance efficiency, for instance, by recovering waste energy from the engines. Waste Heat Recovery (WHR) systems capture the heat generated by the engine and convert it into electricity used to power the ship's systems. Steam can be produced by high-temperature heat sources and converted to electricity with steam turbines, while an organic Rankine cycle (ORC) process can recover waste heat from low- to medium-temperature heat sources. Compared to water, the selected ORC fluid has a lower boiling point with a lower specific heat of vaporization. This makes it possible to exploit waste heat of lower-temperature sources like heated cooling water and lubricating oil, thereby improving the overall energy efficiency of the power plant.

Various wind-assisted propulsion arrangements, such as sails, kites, fixed-wing, and Flettner rotors, have been tested on merchant ships, and interest in these technologies has increased significantly in recent years. Savings can typically range between 3% and 15% of the main engine consumption, but higher savings are also reported. The Kamsarmax bulker Pyxis Ocean, retrofitted with two BAR Technologies WindWings hard sails, has been testing the system for six months. Cargill has the ship on a five-year time charter and reports that the system has performed according to expectations, providing an average fuel saving of 14%.[26]

Onboard energy losses are substantial. Only about half the fuel energy is converted into shaft power, and the rest is lost in the engine exhaust or as heat. A range of technologies can help reduce the losses.

Propeller and hull efficiency

The shape of a ship's hull affects how efficient it is at different speeds and drafts. The drag created by the friction between the hull and water is a significant area of energy loss. Several technologies have been developed to improve hull efficiency. Efforts to optimize the hull shape typically focus on the fore and aft ship, and to improve how the water flows over rudders and propellers. Hydrodynamical measures such as propeller ducts and rudder bulbs are already well-established in the market. A fast-growing measure to reduce hull friction is the use of air lubrication systems (ALS). These inject air bubbles to create a layer of air between the hull and the water to reduce the hull's resistance. Another approach is to apply low-friction hull coatings to reduce hull roughness and drag.

Regular hull cleaning will reduce the hull resistance and, in turn, the fuel consumption. Minimizing biofouling growth on the hull and propeller of the ship over the lifetime is currently one of the most effective ways to reduce GHG emissions. It can be achieved by establishing good biofouling management practices, including the use of high-performance anti-fouling paints, proactive and reactive hull and propeller cleaning, and using ultrasonic anti-fouling systems. The benefits of good biofouling management practices will differ depending on the operational area and operational profile of the ship. Factors such as seawater temperature, salinity, and whether the ship is moving influence biofouling growth.[27]

Progress in uptake of waste-heat recovery, air lubrication, and wind technologies

There are 72 waste-heat recovery systems on order, which will double the number in existence. Out of those on order, 22 are for containerships, and 19 are for multi-purpose product (MPP) ships.[28]

166 air lubrication systems are already installed and more are ordered for approximately 280 newbuilds, mainly large containerships and LNG carriers.

The International Windship Association estimates that around 90 large vessels could have wind-assisted propulsion systems at the end of 2024, compared with 31 systems at the beginning of the year. 17 bulk carriers and 11 RoRo ships are among the vessels receiving the new systems.

With the increasing demand for energy-efficiency measures, we see an increased focus on maturing, improving, and commercializing the technologies, and an increased uptake. DNV's Abatement Insight database provides further information on energy-efficiency measures together with several recent review studies on the subject.[29]

As we search for ways to reduce energy waste and 'harvest' energy, we expect that advanced simulation and optimization models will help assess various abatement options relevant to designing the next generation of energy-efficient ships.[30]

4.4 Unlocking energy-saving potential through digital-enabled optimization

Digital-enabled energy savings on voyages will come through learning from the past; real-time optimization of key parameters; minimizing system degradation; maintaining high performance via optimized cleaning/maintenance; benchmarking; and through setting performance targets. In the effort to make ship operations more efficient, digital ship technologies have an increasingly important role to play in realizing energy-saving potential through optimization, an important factor that must be considered in addition to alternative fuel technologies and ship technology energy-efficiency measures. Currently, the maritime industry is undergoing a digital shift as modern ships transform into sophisticated sensor hubs, generating data with increased connectivity through satellites (see Figure 4-6), from a situation where the majority of ships are non-digital and rely on manual reporting through the captain's noon reports.[31] Upgrading older ships to the required level of digital capability can be challenging and costly. In this section, we discuss how improved vessel performance and voyage planning can lead to emissions reductions, how contractual structures in shipping can be barriers to efficient operation, and how digital information handling is important for GHG emissions reporting.

Digital ship technologies

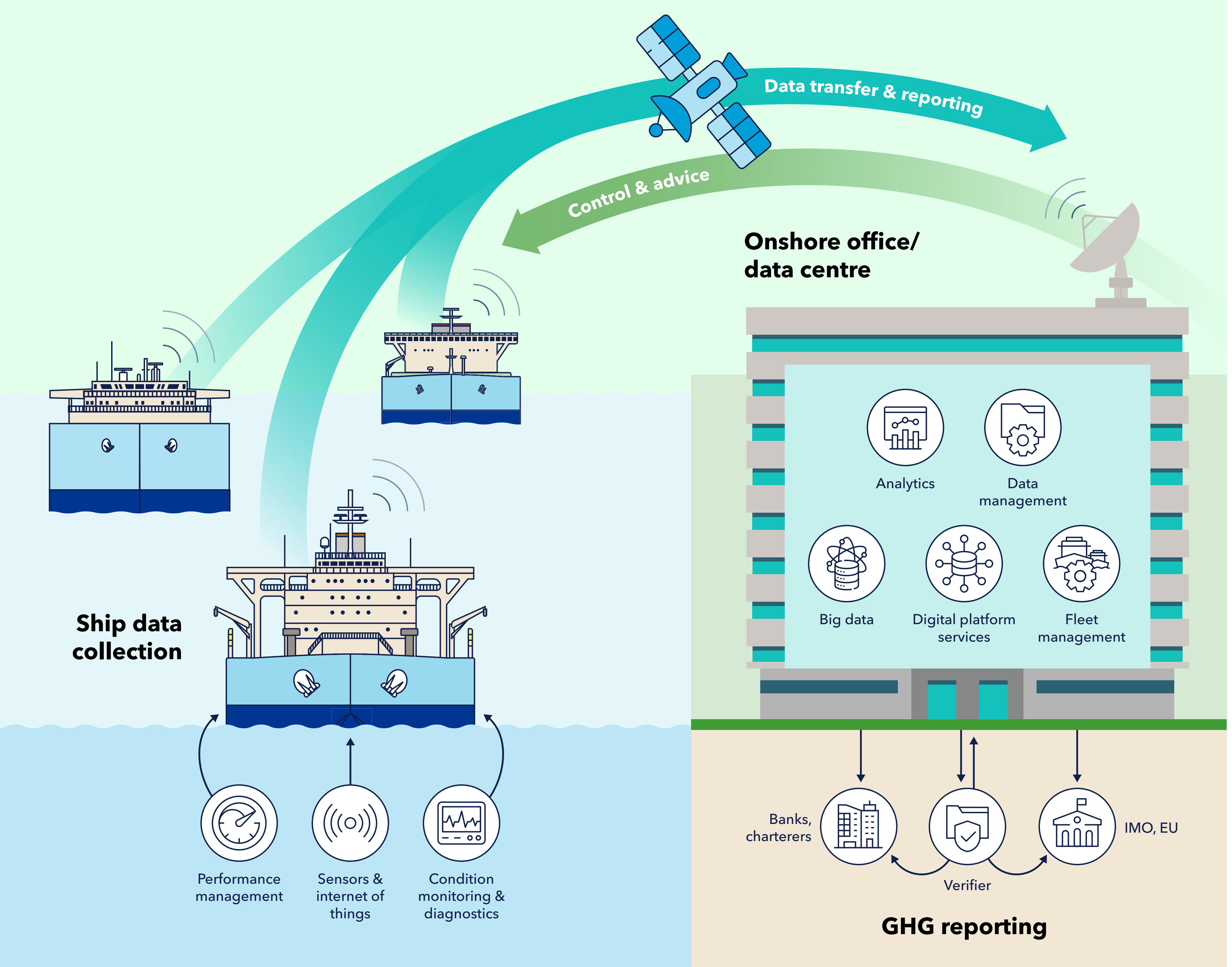
New ships, their systems, and their components are being increasingly linked to the internet and onshore operation centres, making them accessible from anywhere and part of a network of online maritime assets. This is giving the industry access to real-time data, enabling increased automation, decision-support, remote monitoring, and overall boosts to performance. The data is stored in the cloud and used to create digital twins and other simulations for operation, design, and construction.

Numerous digital tools have been developed in recent years to optimize and decarbonize operations, either independently or in conjunction with other digital technologies. Artificial intelligence (AI) and its subset machine learning (ML), the Internet of Things (IoT), connectivity, and computer-based simulation and optimization platforms have progressed rapidly. These digital technologies can be grouped into four types – sensing technologies, enabling technologies, data handling technologies, and decision-making technologies (Figure 4-7) – and their interaction is needed to optimize shipping through digitalization.

While decarbonization and digitalization are the dominant transforming drivers in shipping, maintaining an acceptable safety level is a prerequisite when introducing new technologies and solutions. The maritime industry uses numerous industrial platforms without standardized interfaces. The responsibility for the integrated software systems is

FIGURE 4-6

Key elements in a digital system with the ship in focus. Digital ship technologies can help improve vessel performance and voyage optimization. Integration and communication between ships, shore offices and ports enable further increased fleet utilization. Digital ship technologies will also significantly improve GHG management and reporting.



distributed among vendors and sub-suppliers. This lack of system integration, coupled with a general lack of understanding of holistic risk, makes it challenging to manage the design, construction, operation and maintenance of a software-controlled vessel (DNV, 2021). A human-centric approach to design and operation is essential when developing new technologies, automated processes, and systems to ensure they are focused on the end user, so that their potential can be realized in a safe and sustainable manner for the transformation of shipping.

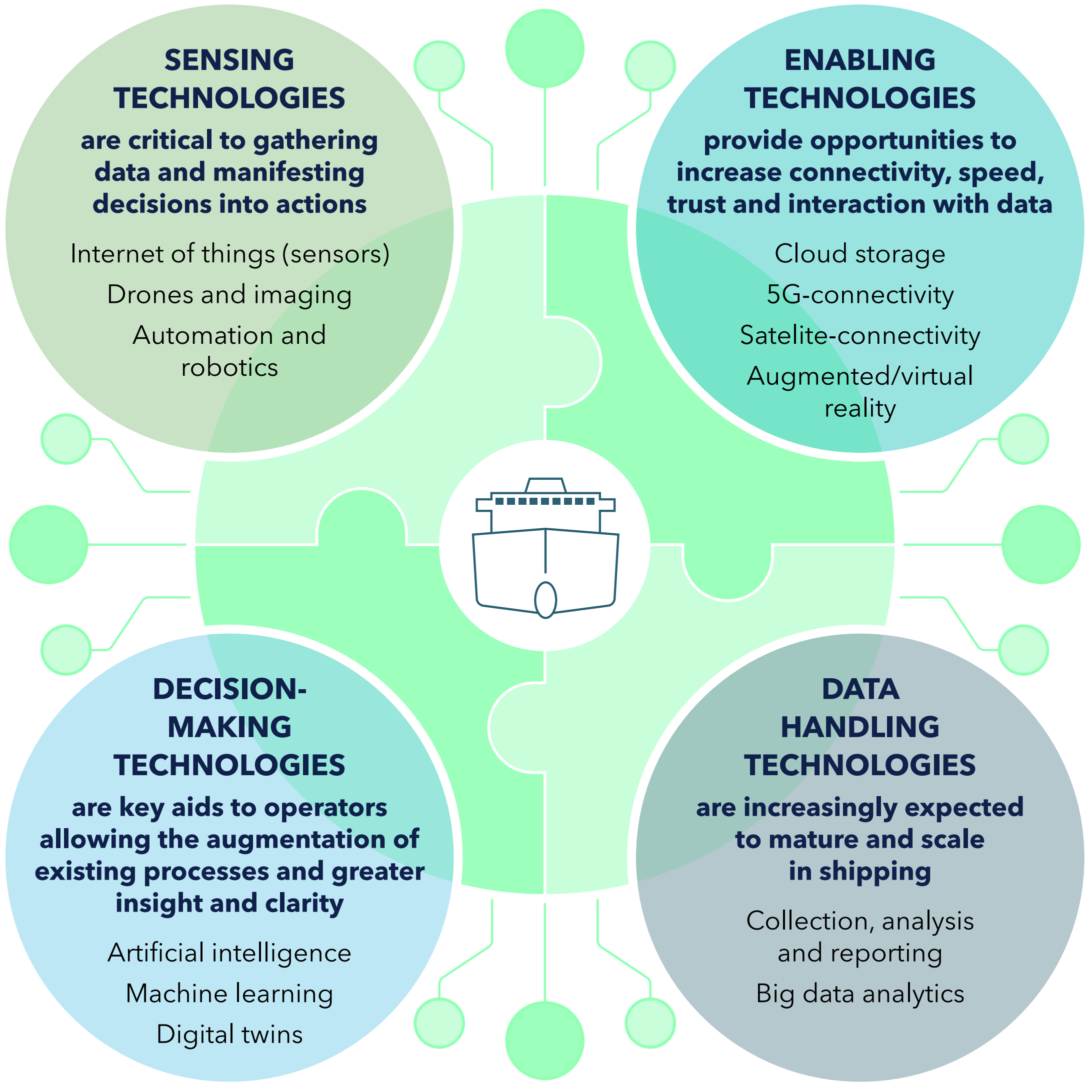
Improving vessel performance and voyage planning

Factors such as machinery condition, hull and propeller fouling, and the efficiency of machinery and systems affect a ship's fuel consumption, and hence its GHG emissions (Figure 4-5). Fuel consumption over a voyage is also influenced by dynamic factors such as weather conditions, speed, route and currents.

The harnessing of data from the vessel and its systems, combined with sophisticated weather data and the increased ability to process large data sets, can be utilized for voyage optimization. In addition to applying weather routing, using the optimal propulsion power in different environmental conditions can reduce fuel consumption. Methods are explored to predict and control the optimal propulsion power in real time, accounting for the environmental conditions ahead (Kai Wang, 2016) (Liu, Gao, Yang, & Hu, 2022).

FIGURE 4-7

Four types of digital technologies that can be applied together (inspired by World Economic Forum)[32]

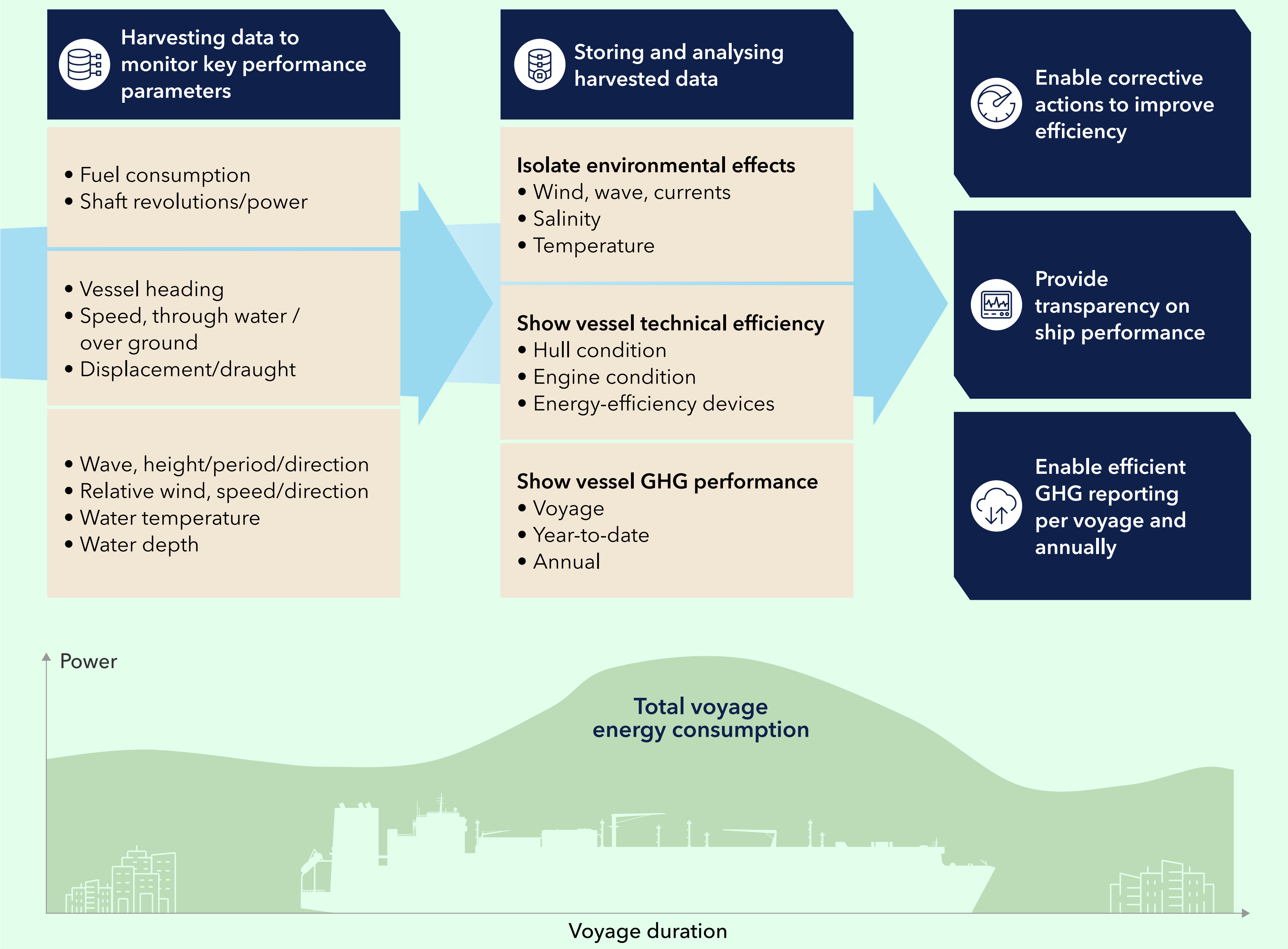


As illustrated in Figure 4-8, regular sampling of relevant parameters enables analysis of fuel consumption and identification of key factors influencing fuel consumption in various operational and environmental conditions. Advanced models comparing power/speed curves against known benchmarks can assist in identifying issues with marine fouling. Observation of main engine performance trends and generator engine loading and running hours can support decisions on maintenance needs, machinery parts replacement, and overhauling.[33]

DNV Recommended Practice DNV-RP-0675 Technical ship performance (September 2023 edition) is one proposed tool for how to measure, evaluate and verify the technical ship performance for hull and propeller, including quantifying its uncertainties. This recommended practice offers an accurate and transparent method for measuring, evaluating, and verifying the technical performance of ships in service.[34] DNV-RP-0675 introduces a Vessel Technical

FIGURE 4-8

Regular sampling of relevant parameters enables analysis of fuel consumption to support corrective actions to optimize efficiency and maintenance, provide transparency, and enable efficient GHG reporting



Index (VTI) showcasing a ship's technical performance relative to its initial state, thereby eliminating the influence of external operational factors. In addition, the recommended practice includes a novel approach to assessing the relevant sources of uncertainty, enabling the users to make informed decisions based on the VTI calculations.

Transparency of vessel performance data through digitalization can also be a motivating factor amongst seafarers to reduce fuel consumption and GHG emissions when the related cost is benchmarked on a regular basis. When a vessel's crew are engaged with and motivated by the issue of decarbonization, they are more likely to proactively implement operational measures to reduce vessel emissions on an ongoing basis. This could be encouraged by regular training of vessel shoreside management, sailing officers, and crew to promote an energy-efficiency culture. Recent studies indicate that energy awareness and incentives for the crew can unlock up to 10% of energy savings (Hui Xing, 2020). Bernhard Schulte Shipmanagement, in cooperation with Signol, ran a research project over four months where vessels were followed up through an app designed to encourage fuel-saving practices on board. They reported promising results, with a 12% fuel saving across the 28 participating ships over the course of the trial.[35]

Contractual structures are barriers against efficient operation

Today's contractual structures are widely recognized as a barrier to improving operational efficiency in shipping. Transparency of information, provided by sensors and digital communication, can be an important tool in making a necessary shift in the supply chain's incentive structure to encourage operational efficiency through changes in the legal agreements that the industry uses in the maritime transport of goods.

The technical applicability and commercial viability of technologies, fuels, and solutions will vary significantly for various ship sizes, types, and trades. Liner operators and cruise ship companies often have key decision-makers involved in ship design and operation decisions within the same organization, which makes it easier to coordinate goals and budgets related to ship design, customization, and the need for energy-efficient operations and fuel shift. As a result, these sectors are more likely to be early adopters of new technologies to reduce GHG emissions. The bulk and tanker segments tend to be more fragmented, and the issue of split incentives is more pronounced. With charterers paying the fuel

Transparency of information, provided by sensors and digital communication, can be an important tool in making a necessary shift in the supply chain's incentive structure to encourage operational efficiency.

bills and lacking a binding contractual framework to ensure energy-efficient performance, owners have less motivation to invest in new technologies.[36]

When chartering supply vessels, Equinor[37] incentivizes owners to apply new technologies and reduce fuel consumption. This includes using fuel consumption as a selection criterion for new vessels, requiring battery-hybrid operation for vessels on long-term contracts, and paying shipowners for fuel saved versus an agreed benchmark (and a surcharge for overconsumption). Being able to develop collaborative business models driven by transparency and sharing costs and benefits of increased energy efficiency in ship operations will be essential to enable the uptake of new energy-efficiency technologies and improve operational efficiency. When we can directly measure the impact of technologies on fuel consumption, shipowners may be more willing to invest, and operators may be willing to share the costs.

FIGURE 4-9

Cost allocation between shipowner and charterer in the different types of contracts (N. Rehmatulla, 2020)

	Spot charter	Contract of affreightment	Time charter	Bareboat charter
Remuneration	Per unit of cargo	Per unit of cargo over fixed duration and route	Per day	Per day
Cargo handling (stowage and storage)				
Voyage expenses (port and fuel costs)				
Operating expenses (crew wages, maintenance, repairs, store & supplies, insurance, overheads)				
Capital expenses (interest and capital repayment)				

Charterer

Shipowner

With cargo vessels generally spending up to 50% of their time in port or at anchorage, there is most likely a significant potential for the existing fleet to improve its effectiveness and utilization (DNV, 2018). Improving operational efficiencies is sometimes perceived as an easily achievable goal, but for many operators that may not necessarily be the case. The Global Maritime Forum (GMF) has published a series of 'insight briefs' that explore the possibilities and challenges for operational efficiencies and found that contractual and cultural issues are complicating many efficiency efforts.[38]

One example is the use of speed reduction, which is considered one of the most effective short-term operational actions to lower the GHG emissions from shipping. In Figure 4-9, we see which party typically pays for fuel and other expenses in different contracts. The chartering arrangements either incentivize shipowners to prioritize speed over efficiency (voyage charters) or disincentivize owners to optimize operations where the charterer is providing and paying for the fuel (time charter). Standard ocean shipping contracts require a chartered vessel to proceed at 'utmost despatch' to its destination port, even if it is almost certain that the vessel will have to dwell at anchor for several days before being admitted to a berth. More reliable, accurate, and transparent vessel performance data can enable more tolerances in speed warranties and pave the way for more aligned incentive structures in the charter parties between owners and charterers.

The berthing policies at many major ports, which admit vessels on a first-come, first-served basis, represent an additional incentive for the master to sail at full speed. The widespread utilization of these legacy contracts and berthing policies constitutes a major, and arguably unreasonable, driver of marine fuel consumption and harbour congestion. Given that the rate of fuel consumption of a vessel is approximately proportional to the cube of the vessel's speed, a more ingenious speed and berthing regime could result in substantial cost savings and a significant reduction of GHG emissions (J. Fernando Alvarez, 2010).

There are several opportunities for increased fleet utilization through digital-enabled optimization. For

Unlocking the full potential of operational energy-efficiency measures across the global fleet requires new ways of collaboration. Green and digital shipping projects enable scalable optimization trials.

example, improved synchronization allowing for just-in-time (JIT) ship arrival in ports will allow for fuel saving from slow steaming and reduce waiting time in ports. A recent IMO study demonstrates significant savings (up to 14.2%) through the implementation of JIT arrivals in the container sector, but much needs to be done to realize such potential (IMO, 2022). Collaboration between shipping lines, ports, and terminals to enhance the exchange of data and information required for the ship to optimize its voyage is critical to properly implementing JIT arrivals. JIT arrivals are most likely to be realized first for scheduled services such as container services, as there are fewer contractual barriers and, due to the nature of the trade, liner services have more predictable schedules than tramp services (IMO, 2020).

PSA International, one of the world's largest container port operators, has built a digital capability, Opti Arrive, creating a digital connection with vessels enabling the exchange of real-time data between ship and port so that the vessel can adjust sailing speed en route to Singapore and optimize fuel consumption to arrive just in time for berthing.[39] The Ports of Singapore and Rotterdam have signed a memorandum of understanding (MoU) to establish a Green and Digital Corridor to enable low- and zero-carbon shipping between them.[40]

Unlocking the full potential of operational energy-efficiency measures across the global fleet will require new ways of collaboration. Green and digital shipping corridor projects that involve the complete logistics value chain – including shipowners, charterers, shippers, ports and terminals – can provide opportunities to pilot scalable optimization solutions. In the future, this may also include the use of unmanned autonomous ships, learning from the current short-sea developments.[41]

Reporting on fuel consumption, GHG intensity and emissions, and other operational parameters

In addition to monitoring and managing fuel consumption, ship operators will increasingly need to manage GHG performance. Shipowners and operators are already required to report on fuel consumption through the IMO and EU, and are requested to share data through industry transparency initiatives like the Sea Cargo Charter and the Poseidon Principles. This includes making plans for reducing GHG emissions, monitoring those targets, and initiating corrective actions when necessary. In the ongoing fuel transition, it will be business-critical for actors in the whole value chain to have access to verified data on fuel consumption and emissions on a voyage, ship, and fleet basis, with the Emissions Connect[42] service as one part of the solution. New environmental, social and governance (ESG) reporting standards are taking effect and moving into legislation throughout the world, requiring robust fuel and decarbonization transition plans.[43] However, data collection and sharing remain challenging due to fragmented systems and a lack of global standards (Hüffmeier & Johanson, 2021).

To meet the increasing needs of emission reporting and operational optimization, advanced sensors capable of gathering and sharing relevant and reliable data at higher frequencies are required.

Implementing an open industry standard like Operational Vessel Data (OVD)[44] for reporting operational data brings significant benefits to the maritime industry, including improved efficiency, connectivity, and sustainability. It also serves as a foundation for digital solutions and supports the industry's decarbonization efforts. OVD data submitted through DNV's Veracity platform undergoes validation, structuring, and quality assurance processes, providing users with reliable and valuable insights.

5 OUTLOOK ON ALTERNATIVE FUEL PRODUCTION AND DEMAND

Highlights

We investigate carbon-neutral fuel production and alternative fuel infrastructure for shipping, finding that:

- Requiring between 10% and 100% of the world's carbon-neutral fuel production, the shipping industry must significantly cut its energy use to reduce fuel demand, to stand a chance of meeting the 2030 targets.
- In all potential fuel pathways, maritime will compete with other decarbonizing sectors for carbon-neutral fuels.
- Robust and trusted chain of custody models such as Mass Balance and Book and Claim are needed to certify the sustainability and GHG intensity of fuels.
- A book and claim model can reduce the need for separate infrastructure and transport of carbon-neutral fuels and increase their availability.

The availability of carbon-neutral fuels is a main concern for the shipping industry striving towards decarbonization. Increasing the global carbon-neutral fuel production is necessary to achieve the IMO's checkpoint of a 20%, striving for 30%, reduction in total GHG emissions from shipping by 2030, relative to 2008 levels. Sufficient infrastructure for distribution, storage, and bunkering of these fuels must also be developed. This chapter presents the latest developments in such production and infrastructure, setting shipping's demand for carbon-neutral fuels in the wider context of a decarbonizing world.

This holistic approach is essential as shipping is part of the global energy system in which it competes with other sectors such as land transport, aviation, and industry for carbon-neutral fuels and the feedstocks they are based on – sustainable biomass, renewable electricity, sustainable CO_2, and fossil energy with carbon capture and storage (CCS). Sustainable and carbon-neutral sourced diesel, methane, methanol, ammonia and hydrogen are today scarce resources, and Chapter 6 in this report therefore takes a closer look into emerging technologies that can be alternatives to these fuels.

5.1 Existing fuel supply

Conventional fossil fuels dominate the market for marine fuels, with LNG and biofuel blends increasingly being used, and shipping consumes about 280 Mtoe of fuel annually (DNV, Maritime Forecast to 2050, 2023).

The reported fuel oil consumption for ships of 5,000 GT or more trading internationally in 2023 was 213 Mtoe (IMO, 2023). Almost all this fuel was fossil, including heavy fuel oil, light fuel oil, and diesel/gas oil, which together constitute almost 95% of the total volume. LNG consumption was around 11 million tonnes (13 Mtoe) in 2022, slightly less than in 2021 and constituting around 5% of the total volume. In addition to ships trading internationally, there was fuel consumption by the domestic and fishing fleets, reported by IEA as 57 Mtoe in 2019 (IEA, 2019). It should be noted that the IMO Data Collection System (DCS) data includes consumption from domestic trades for ships that also trade internationally in the same year.

Biofuels are the most widely used carbon-neutral fuels in shipping today and can be blended in with a variety of different marine fuels.[45] In 2023, fuels blended with biodiesel accounted for more than 7% of the total bunker sales in the Port of Rotterdam[46] and around 1% in the Port of Singapore[47], totalling an estimated 0.4 Mtoe pure bio-based diesel, an increase from about 0.3 Mtoe in 2022 (DNV, 2023d). In addition, Rotterdam reported a sale of 750 tonnes of bio-methanol while Singapore reported a sale of 300 tonnes of bio-methanol.

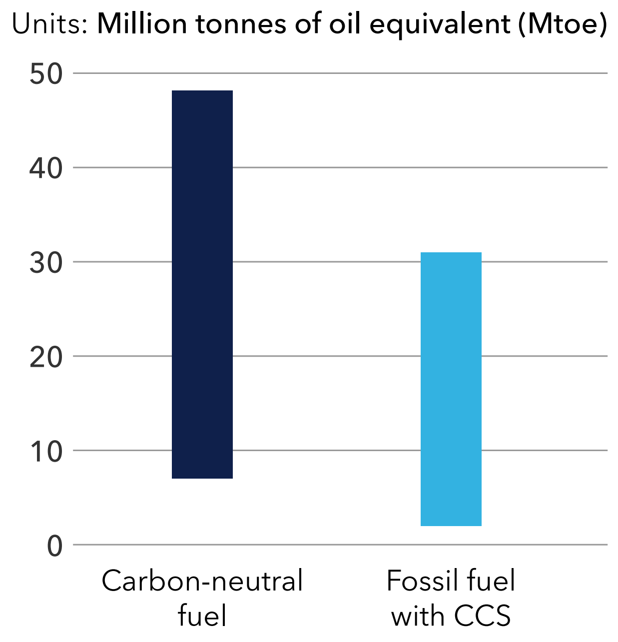
5.2 Demand for carbon-neutral fuels

In last year's edition of this report (DNV, Maritime Forecast to 2050, 2023) we presented simulation results from one scenario for the demand for carbon-neutral fuels for shipping in 2030 based on the ambition in the IMO GHG Strategy that the uptake of zero or near-zero GHG emission technologies, fuels, and/or energy sources should represent at least 5% of the total energy use. As part of the IMO's comprehensive impact assessment, DNV has estimated the required uptake of carbon-neutral fuels and onboard carbon capture across 16 policy combination scenarios to achieve the IMO's indicative checkpoint of 20% GHG emission reduction in 2030, compared to 2008 levels (DNV, 2024a).

To meet the target in 2030, taking into account the expected growth in seaborne trade, the well-to-wake

FIGURE 5-1

Range of estimated demand in 2030 for carbon-neutral fuel and fossil fuel with CCS (DNV, 2024a)



GHG emission has to be reduced either by using carbon-neutral fuels, using onboard carbon capture, or by reduction in energy use. The different policy combinations investigated had a significant impact on the uptake of energy-efficiency measures, reducing energy consumption compared to a business-as-usual scenario by between 4% and 16% in 2030. The greatest reduction in energy use came in scenarios with a high levy of 150–300 USD/tCO_2eq. This indicates both a significant potential for reduction in energy use and that large barriers need to be overcome to achieve this improvement.

With lower energy use, less carbon-neutral fuels and onboard carbon capture were used in the scenarios. The estimated demand for carbon-neutral fuels in 2030, achieving the IMO goals, ranged between 7 and 48 Mtoe, and demand for fossils fuels with CCS between 2 and 31 Mtoe (4–76 MtCO_2 captured), see Figure 5-3. The results indicate that by lessening the need for carbon-neutral fuels, energy-efficiency measures and onboard carbon capture can play an important and large role in achieving short-term emission reduction goals for shipping.

Competition for carbon-neutral fuels

Shipping is not the only industry exploring and learning more about the implications of each fuel. Aviation, road transport and several hard-to-abate industries require many of the same fuels to decarbonize to meet regulations and commitments, and will compete for the available resources. The relevance of different feed-

FIGURE 5-2

Relevance of feedstocks and carbon-neutral fuel types for different sectors

Feedstock	Fuel/ energy carrier	Maritime	Aviation	Road transport	Industry
Sustainable biomass	bio-methanol	Relevant	Relevant	Not relevant	Relevant
	bio-methane/ bio-LNG	Relevant	Not relevant	Relevant	Relevant to some degree
	bio-diesel	Relevant	Not relevant	Relevant	Not relevant
	bio-kerosene	Not relevant	Relevant	Not relevant	Not relevant
Renewable electricity	e-ammonia	Relevant	Not relevant	Not relevant	Relevant
	e-hydrogen	Relevant to some degree	Relevant to some degree	Relevant to some degree	Relevant
	Electricity	Relevant to some degree	Relevant to some degree	Relevant	Relevant
Renewable electricity + CO_2	e-methane	Relevant	Not relevant	Relevant	Relevant to some degree
	e-methanol	Relevant	Relevant	Not relevant	Relevant
	e-diesel	Relevant	Not relevant	Relevant	Not relevant
	e-kerosene	Not relevant	Relevant	Not relevant	Not relevant
Fossil + CCS	blue hydrogen	Relevant to some degree	Relevant to some degree	Relevant to some degree	Relevant
	blue ammonia	Relevant	Not relevant	Not relevant	Relevant

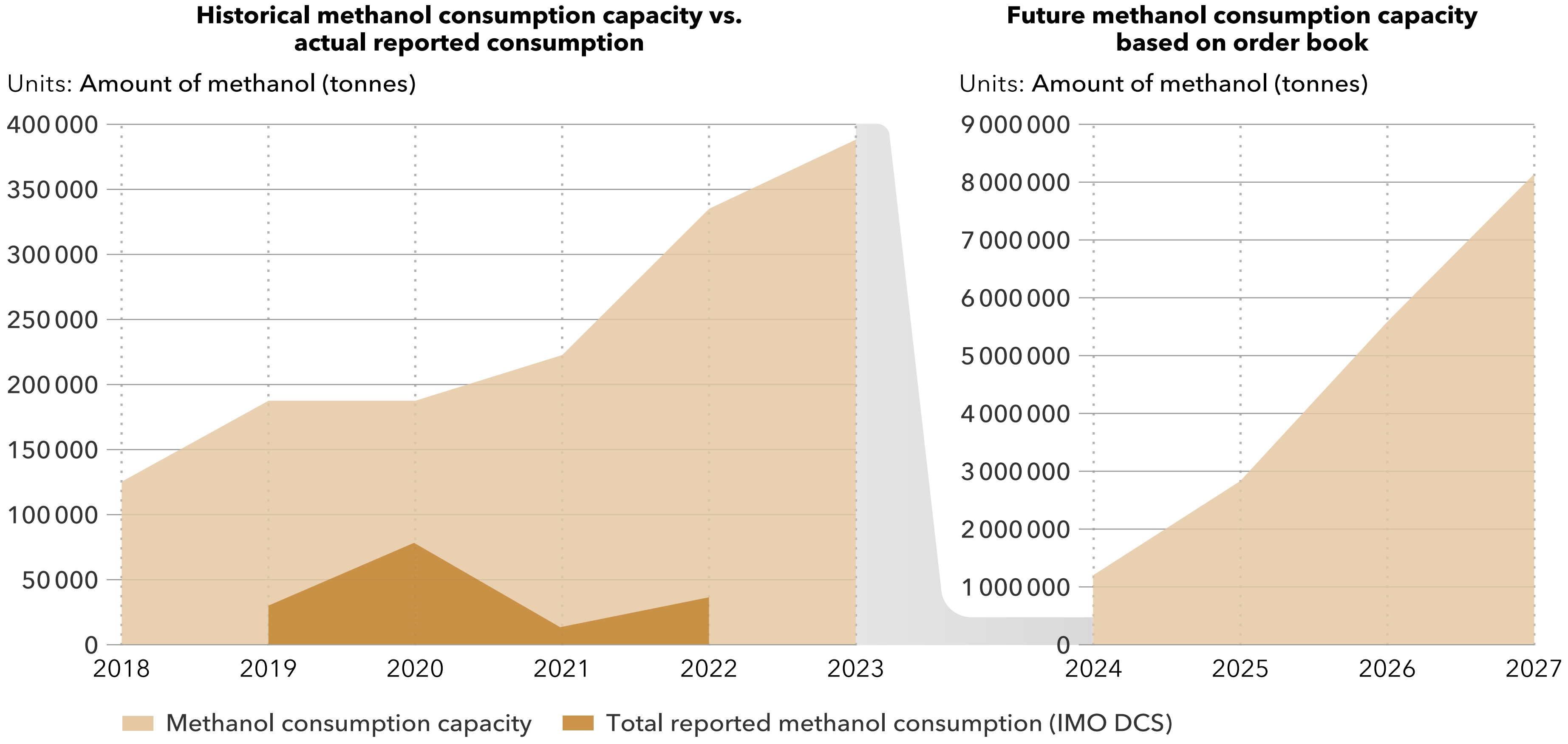
Relevant   Relevant to some degree   Not relevant stocks and carbon-neutral fuels for different sectors is shown in Figure 5-2, illustrating the potential competition between the maritime, aviation, road transport and industry sectors. We see that all fuels relevant for maritime decarbonization are also relevant to other industries and transport sectors for the same reason.

Last year's Energy Transition Outlook (DNV, 2023a) estimated that energy from biomass could provide 25% of the total maritime energy demand in 2050, that this would constitute about a third of all biomass resources used for transport, and that aviation would use almost half of the total amount. Today, HEFA (hydro-processed esters and fatty acids) is currently the most commercially available biofuel for aviation, accounting for more than 95% of bio-based jet fuel, but there are concerns that the feedstock can meet only 10% to 15% of aviation's fuel demand.[48]

In a deployment analysis investigating the resource requirements to decarbonize aviation and shipping by 10% by 2030 using electrofuels (made from hydrogen produced by electrolysis), IEA[49] estimated that the resources required to produce enough electrofuels to cover 10% of fuel demand for aviation and shipping in 2030 were beyond the announced electrolysis capacity. The study found that about 330 GW of electrolysis capacity would be needed for aviation and 130 GW for shipping, even without including demand from other industries. In terms of low-emission electricity, IEA further estimated that decarbonizing 10% of aviation and shipping with electrofuels by 2030 could require more than 20% of the global growth of low-emission electricity between 2022 and 2030. However, based on company announcements, the electrolysis manufacturing capacity could reach up to 155 GW/year by 2030. Regarding CO_2 as feedstock, IEA estimated that there will be a limited availability of sustainable sources, such as biomass residues and waste, and that competition for these will increase in the future.

FIGURE 5-3

Historical methanol consumption capacity vs. total consumption by shipping as reported to IMO DCS (left); future consumption capacity based on order book (right)



A closer look at demand for methanol as fuel in shipping

Carbon-neutral methanol is an example of a fuel for shipping where production capacity is being developed due to demand from methanol-capable tonnage. The first methanol-fuelled vessel started operation in 2015, since when methanol-capable tonnage has grown significantly (see Section 4.1). These ships can use carbon-neutral or fossil methanol as fuel, but can also run on conventional fuel. The methanol capacity is how much methanol ships could potentially burn, not taking fuel availability or prices into consideration. In Figure 5-3 (left) we show the historical methanol capacity and the reported consumption, illustrating that these ships have mostly used conventional fuels.

Accounting for the methanol vessel order book, Figure 5-3 (right) shows annual methanol consumption capacity growing more than six-fold from an estimated 1.2 Mt (0.6 Mtoe) in 2024, to more than 8 Mt (3.8 Mtoe) in 2027.

The extent to which this capacity is utilized is expected to depend on factors such as regulations from the IMO and EU impacting fuel use; the fuel price and well-to-wake GHG intensity of grey methanol compared with conventional fuel oils; and the price of carbon-neutral methanol compared with carbon-neutral fuel oil.

China has the largest order book for carbon-neutral methanol production (Figure 5-5) and its leading shipowners are actively investigating the use of carbon-neutral methanol for their fleet's decarbonization journeys. By 2030, COSCO Shipping expects its green methanol consumption to reach a maximum of 0.3 to 0.4 Mtpa (0.14 to 0.19 Mtoe/year). In September 2023, COSCO Shipping, State Power Investment Corporation Limited, Shanghai International Port Group, and China Certification & Inspection Group jointly signed the Memorandum of Cooperation on the Construction of a Green Methanol Industrial Chain, which encompasses the production, transportation, refuelling, and certification of green methanol for ships.[50] Other Chinese shipping companies, including Shandong Shipping, CMES, and OOCL have also placed newbuild orders for methanol-capable tonnage.

5.3 Supply of carbon-neutral fuels

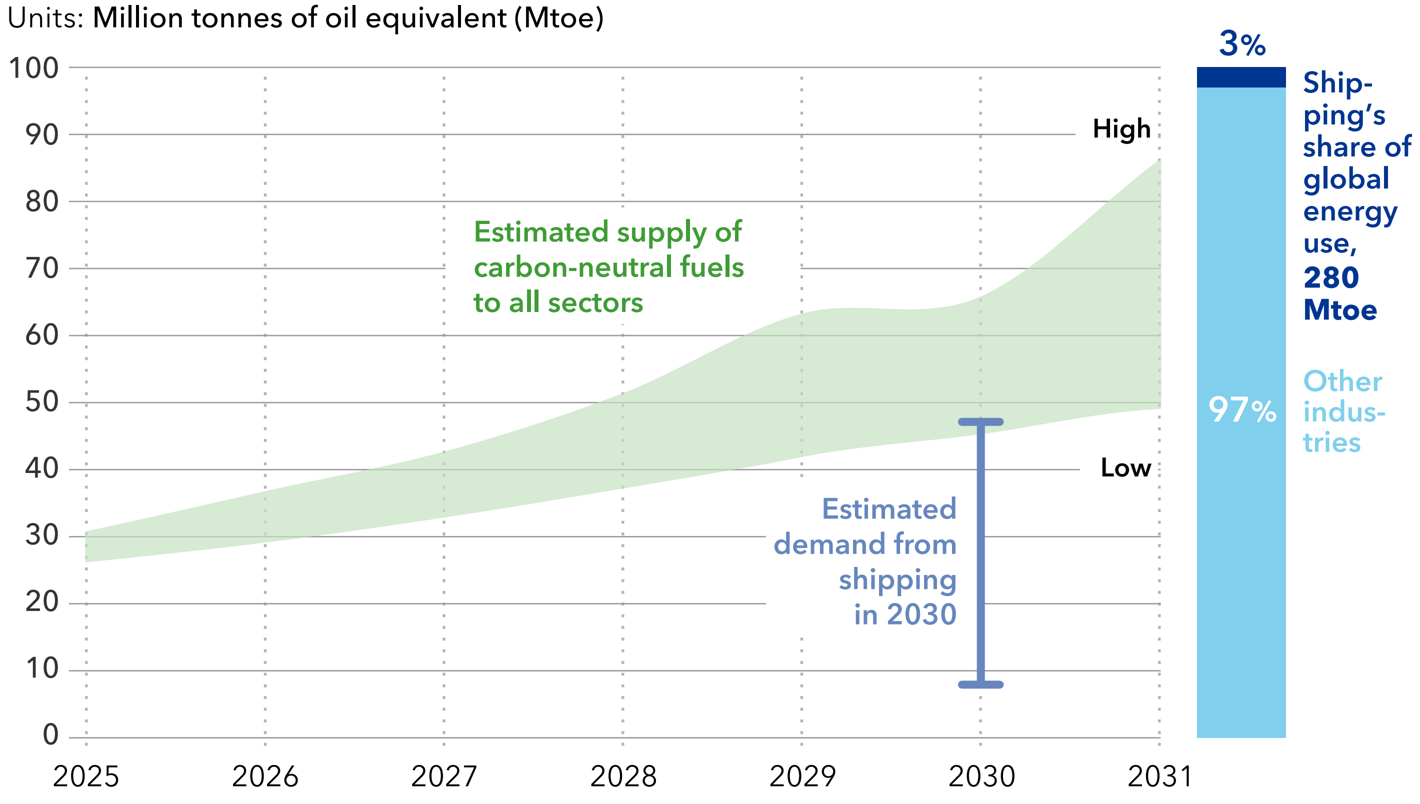
In this section we present the status of existing and planned production of all products – globally and across sectors – that can be used as carbon-neutral fuels by shipping, by which we mean electro-, bio- or blue versions of fuel oils, methane, methanol, ammonia and hydrogen.

Using the same methodology as in the previous edition of this report (DNV, Maritime Forecast to 2050, 2023b), we have comprehensively mapped ongoing and announced projects – globally and across sectors – for production of carbon-neutral versions of fuel oil, methane, methanol, ammonia and hydrogen. To estimate the potential fuel output for each year, we have assigned probabilities to individual projects based on their current development stage. Additionally, we have taken into account delays to the originally planned project completion dates. The available carbon-neutral fuel is calculated as the sum of planned output by a given year, weighted by the assigned probability of completion. This allows us to define two distinct scenarios, High and Low estimate (Figure 5-4). We compare these with an estimated range of demand from shipping for carbon-neutral fuels based on achieving the IMO's 2030 ambition of 20% GHG emission reduction compared with 2008, see Section 5.2.

Compared to last year's results (DNV, 2023a), the estimated cumulative capacity of ongoing or announced carbon-neutral fuel production capacities for 2030 has only marginal changes and is between 44 and 63 Mtoe. This compares with estimated demand from shipping, seen in Section 5.2, of between 7 and 48 Mtoe, with shipping needing between 10% and 100% of this to reach IMO targets. The increase in estimated supply from (DNV, Maritime Forecast to 2050, 2023) is predominantly due to new ammonia project announcements, with a leap in estimated production capacity from 63 Mtoe in 2030 to 83 in Mtoe in 2031 for the High-availability scenario.

FIGURE 5-4

Estimated supply of carbon-neutral fuels to all sectors



To scale up production of carbon-neutral fuels, reusing existing fossil-fuel refineries can be an important step. In Europe, companies such as Galp, CEPSA, ConocoPhillips, Preem, and Repsol have already been co-processing renewable feedstock in their refineries for several years.[51] Consideration should be given to co-locating new carbon-neutral fuel production plants with existing industry facilities to reduce environmental impacts, costs, and lead times (DNV, 2023c).

Common to all hydrogen-derived fuels is that most projects are in early development stages, working towards reaching final investment decisions. In the short to medium term, biofuels such as bio-methanol, various biodiesels, and biomethane appear to be more available and mature than hydrogen derivatives.

We estimate that supply of carbon-neutral methanol from China can significantly increase from 2025 onwards.

A closer look at carbon-neutral methanol production globally and in China

In this section, we look into the short-term status of production of carbon-neutral methanol[52], focusing on China, which is taking the lead in planned production capacity. According to Methanol Institute data[53], more than 70% of the total pipeline production capacity for carbon-neutral methanol is still in the feasibility stage of development, with no final investment decision taken. Accounting for the differing status and maturity of projects, Figure 5-5 shows the estimated supply of carbon-neutral methanol towards 2030. Current supply is modest, expected to be around 0.5 Mtpa (0.2 Mtoe/year) methanol by the end of 2024. However, we estimate a ramp-up in supply to 1.9–3.6 Mtpa (0.9–1.7 Mtoe/year) by the end of 2027, and 3.6–6.1 Mtpa (1.7–2.9 Mtoe/year) by the end of 2030.

While the carbon-neutral methanol production projects are in 25 different countries, the top 5 account for almost 70% of the total pipeline production capacity: China (43%), United States (14%), Spain (5%), Netherlands (4%), and India (4%). In particular, we estimate that supply of carbon-neutral methanol from China can significantly increase from 2025 onwards (see Figure 5-5), potentially from about 0.1 Mtpa (0.05 Mtoe/year) by the end of 2024, to 1.1–2.2 Mtpa (0.5–1.0 Mtoe/year) by 2027.

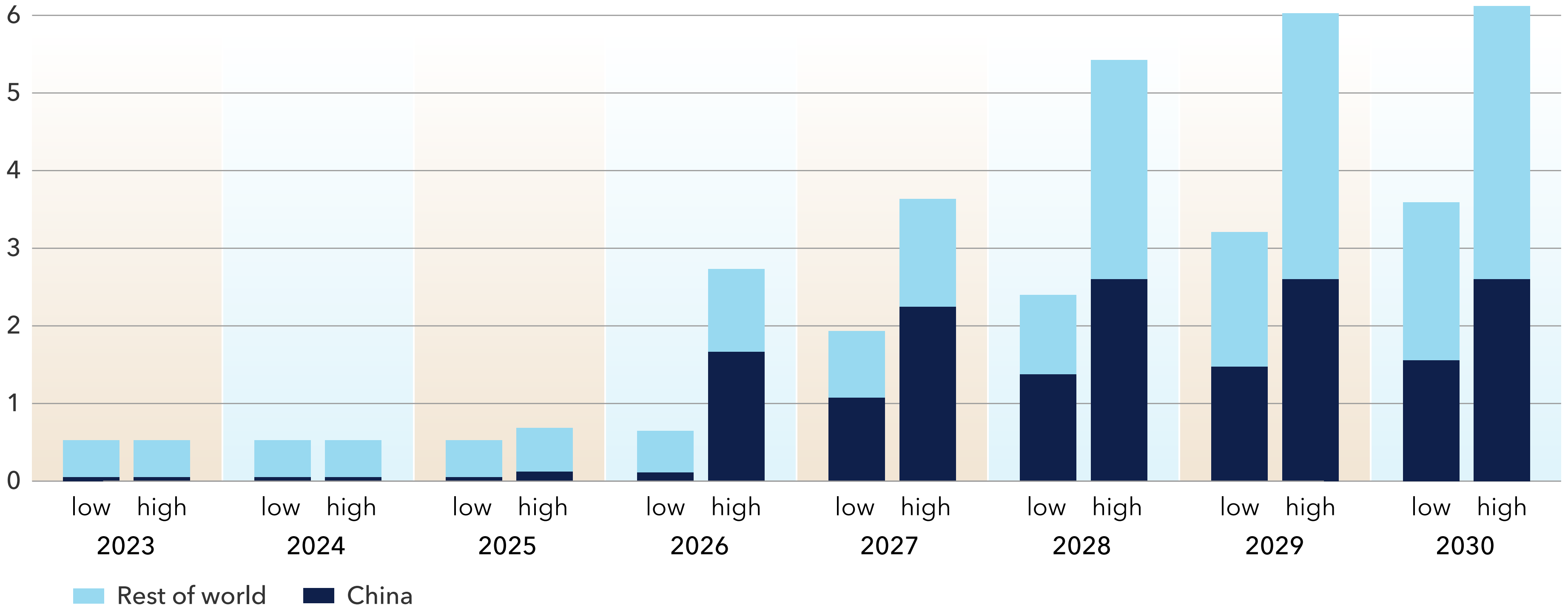
The total number of carbon-neutral methanol production projects in operation or announced in China is more than 40, with a production capacity ranging up to 0.6 Mtpa (0.29 Mtoe/year) for the largest projects. Some notable major projects with planned capacity above 0.5 Mtpa (0.24 Mtoe/year) include Mingyang Smart Energy, Yuanhuang Energy, CGN Wind Power, Goldwind Green Energy Chemical, and Liquid Sunshine Energy Technology. Mingyang Smart Energy and Yuanhuang Energy are currently at the engineering stage, with expected completion of phase 1 by 2025. China General Nuclear Power Group has signed agreements with local authorities and value-chain partners to produce green methanol via wind power, with an expected capacity of 0.6 Mtpa (0.29 Mtoe/year) by the end of 2025 and more capacity add-ons possible in the future.[55] An offtake agreement was also signed between Maersk and Chinese developer Goldwind for 0.5 Mtpa methanol (0.24 Mtoe/year), with first production expected in 2026.[56] The Liquid Sunshine Energy Technology methanol project plans production capacity of 0.5 Mtpa methanol (0.24 Mtoe/year) in phase 1, with start-up in 2026.[57] All the projects mentioned are located in the Inner Mongolia region of Northern China, utilizing the abundant solar and wind power resources for carbon-neutral methanol production.

Proman Stena Bulk methanol-fuelled tanker Stena Pro Patria

FIGURE 5-5

Estimated global and Chinese supply of carbon-neutral methanol, based on data from the Methanol Institute[54]

Units: Million tonnes methanol per year



5.4 Infrastructure for carbon-neutral fuels

In addition to increasing carbon-neutral fuel production, sufficient infrastructure for distribution, storage, and bunkering of these fuels is essential. Table 5-1 presents the results from a high-level screening of the readiness level of distribution, storage, and bunkering infrastructure for different fuel types. Some fuels like methanol, methane, and biodiesel can to some extent use existing distribution, storage, and bunkering infrastructure. The bunkering infrastructure of ammonia and hydrogen, on the other hand, is more immature.

By using or repurposing existing infrastructure, where possible, development of the required infrastructure can be made more time and cost efficient. One example is the repurposing of natural gas pipeline systems for hydrogen, which has expected construction costs of about 10–35% of new construction.[58] One of the leading initiatives in Europe is the European Hydrogen Backbone (EHB). A collaboration between 33 energy infrastructure operators, the EHB envisions a connected hydrogen network spanning industrial clusters, ports, and hydrogen production and storage sites.[59]

The World Ports Climate Action Program has developed a port readiness level (PRL) tool to allow ports to share their readiness for calls, bunkering, service, and maintenance of alternative fuels.[60] The tool offers a simple transparent way to share when a port is ready for a given fuel and the support they can offer. Specific readiness levels vary with each individual port and fuel.[61] An ongoing green corridor pilot study in the Nordic Roadmap project, with support from the Green Shipping Programme, will assess the port readiness level for hydrogen bunkering in the Port of Oslo.[62]

Ship-to-ship methanol bunkering has been proven by successful operations in the ports of Rotterdam[63], Gothenburg[64], and Singapore.[65] In December 2023, the Maritime and Port Authority of Singapore issued an Expression of Interest to gather proposals for the implementation of end-to-end methanol bunkering solutions in the port from 2025.[66] In March 2024, the world's first use of ammonia as a marine fuel was successfully conducted in the Port of Singapore, utilizing an existing ammonia facility.[67] Truck-to-ship hydrogen bunkering has also been demonstrated; for example, on the west coast of Norway[68] and in San Francisco Bay.[69]

TABLE 5-1

High-level screening of the readiness level of distribution, storage, and bunkering infrastructure for different fuel types (Ricardo; DNV, 2023): green - mature and proven; amber - solutions identified; red - barriers remain to be solved

Fuel type	Distribution and storage	Bunkering infrastructure
Fuel oils (e-diesel, biodiesel)	Can use existing distribution and storage facilities for distillate fuel.	Can use existing bunkering infrastructure for distillate fuel.
Gaseous fuels (e-methane, biomethane)	Can use existing (and still developing) distribution and storage facilities for LNG.	Can use existing (and still developing) bunkering infrastructure for LNG.
Methanol (e-methanol, bio-methanol)	Can build on existing distribution and storage facilities from global network of terminals, used for global methanol trading/transport.	Partially developed bunkering infrastructure at 90 ports worldwide. Demonstration of bunkering operations has been successful, ship-to-ship bunkering proven.
Ammonia (e-ammonia, blue ammonia)	Can build on existing distribution and storage facilities from global network of terminals, used for global ammonia trading/transport.	No existing bunkering infrastructure. Local bunkering operations have been demonstrated.
Hydrogen (e-hydrogen, blue hydrogen)	No existing distribution and storage infrastructure.	No existing bunkering infrastructure. Local bunkering operations have been demonstrated.

5.5 Chain of Custody – rules for fuels from production to ship

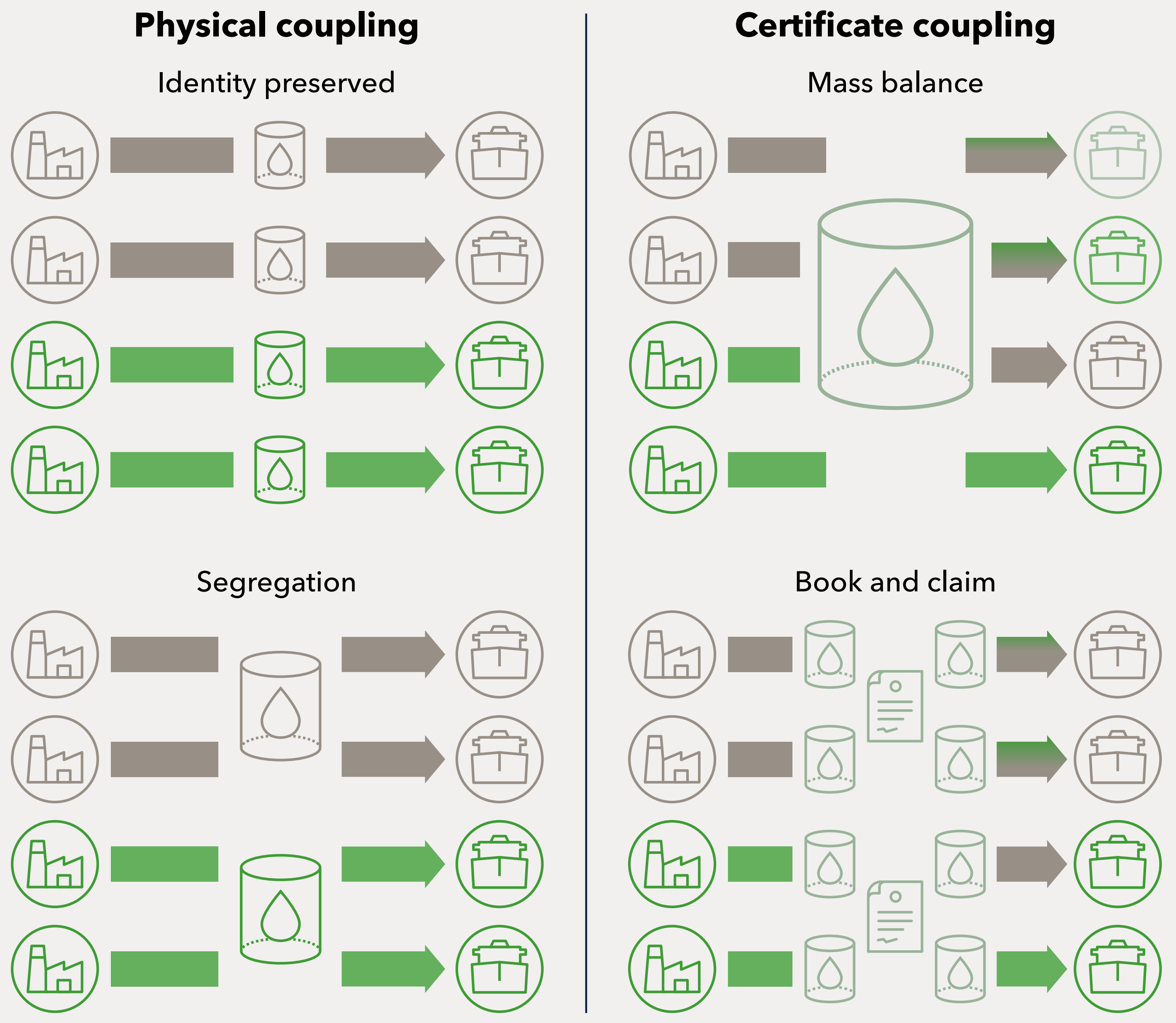
Reducing GHG emissions is in many respects a bookkeeping exercise, counting GHG emissions from different sources and fuel pathways (fossil, renewable or nuclear, or a combination of these). The goal is to ensure that actual reduction in GHG footprint in a global system perspective is achieved as it is reported. The way low GHG fuels are produced and delivered to the ship affects both the cost and the well-to-wake GHG emissions for the corresponding fuel. There are different frameworks for bookkeeping systems for either physical or virtual accounting, moving carbon-neutral or low GHG fuels from a production facility to a consumer, and with different market mechanisms that are covered by different Chain of Custody rules. Some market mechanisms (Figure 5-6) can utilize existing infrastructure and therefore reduce the need and cost for a separate infrastructure for low-carbon fuels. In addition, some market mechanisms can reduce the transport need for carbon-neutral fuels around the globe.

Last year's Maritime Forecast (DNV, Maritime Forecast to 2050, 2023b) outlined two specific products and services where Chain of Custody is relevant:

- Verifying the well-to-tank GHG emissions of fuel sold to ships, mainly for regulatory compliance, but also for ESG reporting (scope 1 and scope 3).

FIGURE 5-6

Different models for Chain of Custody for emissions related to marine fuels. Inspired by https://www.circularise.com/blogs/four-chain-of-custody-models-explained



- Verifying the GHG emission intensity of a zero-emission shipping transport service, mainly for ESG reporting (scope 1 and scope 3 emissions).

Chain of Custody is an important concept in decarbonization efforts. It is used to ensure the validity of emission-reduction claims in a supply chain. International standard ISO 22095:2020[70] has defined Chain of Custody as a process by which inputs and outputs and associated information are transferred, monitored, and controlled as they move through each step in the relevant supply chain. In the context of decarbonization, it is used to define a set of Chain of Custody models that can keep track of GHG emissions for a product or service along a supply chain from origin to final user.

The ISO standard has further defined a set of models for Chain of Custody that can be applied (see Figure 5-6):

- Identity preserved model: The fuel originates from a single source and its specified characteristics are maintained throughout the supply chain.

- Segregation model: Specified characteristics of a fuel are maintained from the initial input to the final output. Addition of material with different characteristics and/or grade to the input is not allowed.

– Mass balance model: Fuels with a set of specified characteristics are mixed according to defined criteria with fuels without that set of characteristics. The proportion of the input with specified characteristics might only match the initial proportions on average and will typically vary across different outputs.

– Book and claim model: The administrative record flow is not necessarily connected to the physical flow of fuels throughout the supply chain. This Chain of Custody model is also referred to as 'certificate trading model' or 'credit trading'. Book and claim can have different boundaries; in-sector, out-of-sector, fuel for fuel, across fuel types.

In addition, ISO 22095:2020 has defined a Controlled blending model, which is a variation of the Segregated model. In the Controlled blending model, materials or products with a set of specified characteristics are mixed according to certain criteria with materials or products without that set of characteristics, resulting in a known proportion of the specified characteristics in the final output. The adhered claim may refer to a certain percentage, at batch level and/or site level.

All these models can in theory co-exist and run in parallel and thereby serve different needs in the market. However, it can be debated whether this might lead to a lack of trust in the governance of these models. Maintaining several different models might create confusion for stakeholders in the supply chain and could therefore reduce trust in the certification framework.

Chain of Custody is used to ensure the validity of emission-reduction claims in a supply chain.

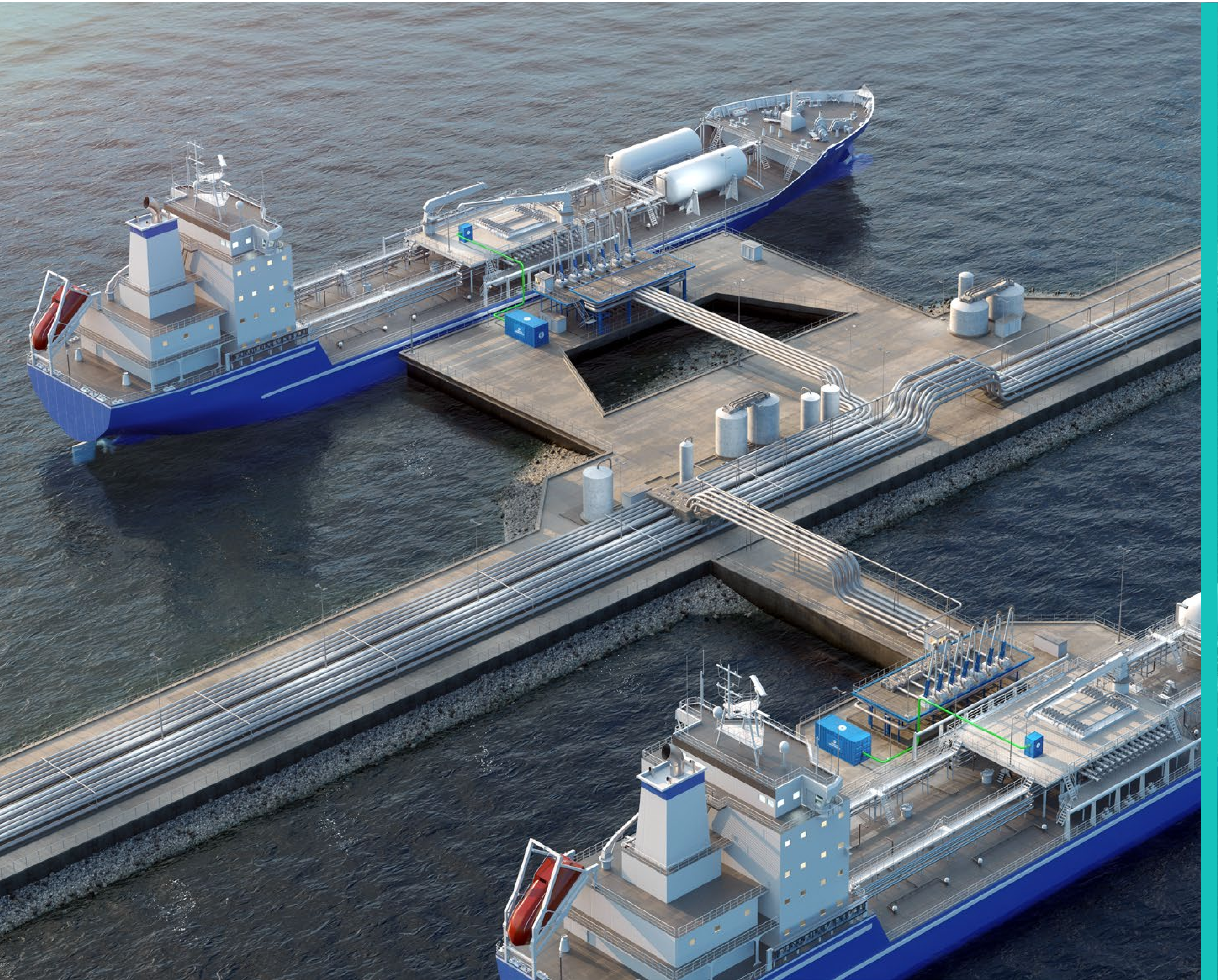
Several existing fuel certification frameworks apply to one or more of these Chains of Custody frameworks. The EU Renewable Energy Directive (EU RED) mandates the use of a Mass Balance Chain of Custody (ref EU RED Article 30(1)) which allows for grid balancing, in-tank balancing, and site-level balancing throughout the fuel supply chain.

A book and claim system can potentially reduce total system emissions. Take, for example, a ship wanting to use bio-LNG as fuel from a system of natural gas pipelines connected to biomethane producers onshore and an LNG terminal with both regasification and liquefaction capability on shore. Biomethane produced onshore and fed into a natural gas pipeline could be sold as 'bio-LNG' to a ship through a certificate in a book and claim system. This would avoid the transport work of the biomethane and the energy cost of regasifying the LNG to enter the pipeline and liquefying the biomethane to bio-LNG. This model can support large production facilities and is useful when local demand exceeds local supply.[71]

This topic is also examined by the Global Industry Alliance to Support Low Carbon Shipping (Low Carbon GIA), which published a paper (ISWG-GHG 16/INF.7) where the segregation, mass balance, and book and claim models are further discussed as alternatives for the shipping industry.

Nevertheless, a robust certification scheme and registry need to be established, similar to what the certification bodies RSB and ISCC have already developed. It builds the necessary safeguards against fraud or double claiming, and will ensure credibility, transparency, and traceability, either as a central registry or a registry ecosystem with interconnected registries.

A book and claim system can potentially reduce total system emissions.



6 EMERGING TECHNOLOGIES TO REDUCE DEMAND FOR CARBON-NEUTRAL FUELS

Highlights

We investigate emerging technologies that can reduce demand for limited carbon-neutral fuels, concluding that:

- Shore power usually emits less GHGs than ship generators and should be promoted by incentives and regulations across regions.
- Up to 7% of the total energy consumption of ships can be covered by use of shore power while ships are in port.
- Existing ships' share of energy used on short voyages shows the potential for electrification with batteries (plug-in hybridization).
- Development of a logistics system for battery swapping in different ports can reduce shipowner investment needs and risk.
- The estimated carbon dioxide storage demand from shipping to achieve emission-reduction goals in 2030 is 6% to 160% of the estimated total global CO_2 storage capacity.

To reduce greenhouse gas emissions from economic and societal activities, renewable power generation is growing strongly and efforts are being made to boost nuclear power production. Many projects are underway or planned to make blue hydrogen from fossil energy with carbon capture and storage, and green hydrogen by electrolysis. The collection of waste biomass for sustainable biofuel feedstock is increasing. However, technologies like electrification, carbon capture and storage, and nuclear propulsion are independent of the future availability of electrofuels and biofuels. How can these trends and technologies play into maritime's decarbonization pathways?

In this chapter, we highlight the efficient energy use and emission reductions of ships that can use electricity directly through shore power and battery storage and compare this to the significantly more energy-intensive alternative of using electrofuels, exemplified by e-ammonia. We also describe shore power developments and emerging battery-charging solutions, presenting an outlook for the direct use of electricity.

We present an outlook for global CO_2 storage plans for the carbon capture and storage (CCS) industry, which needs to be developed for onboard carbon capture to play an important role in shipping, potentially allowing ships to continue using fossil fuels while decarbonizing.

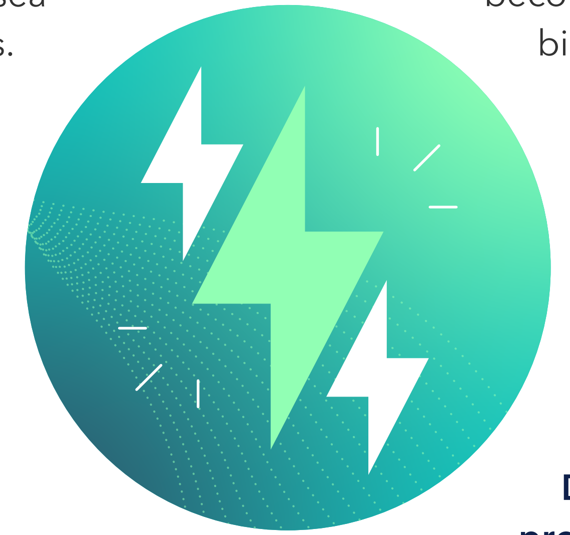
Nuclear propulsion is mainly used today by naval ships, and industry stakeholders are investigating its use for merchant ships. We discuss opportunities for marine nuclear power and the significant regulatory challenges ahead before it can play a more significant role in shipping's fuel mix.

6.1 Electrification

Direct use of electricity from shore is the most efficient way to power ships in terms of the ratio of primary energy used per energy output for propulsion and onboard consumers. Using shore power (also referred to as 'cold ironing') can avoid running ship generators in port. Charging batteries can enable electricity use at sea for propulsion and other energy needs.

Electrification of vessels can range from batteries covering the full power demand ('full electrification') to varying degrees of hybridization where batteries are combined with generators or fuel cells. Ferries are currently the leading segment applying electrification due to their short voyage distances, frequent port visits, and dedicated shore-power connection systems. However, almost all electric ferries are plug-in hybrid solutions with internal combustion engines in backup and for extension of sailing range.

The battery hybridization technology can improve the energy efficiency of combustion engine-based power systems by peak shaving, load optimization, and providing the availability of immediate power and spinning reserve (DNV GL, 2020). This efficiency gain may improve the case for investing in batteries for plug-in hybridization, to enable electric operation of ships.



Shore power installations and battery storage in hybrid and plug-in hybrid solutions use relatively mature technologies. With more energy-efficient ships, improved battery and charging technology, and a decrease in battery costs, the economics of plug-in hybridization will improve and possibly become interesting for longer routes and bigger vessels.[72] However, the electrification of shipping also depends on the development of infrastructure for electric power delivery from shore and on access to electric energy; in other words, the production and distribution of electric energy to ships.

Direct use of electricity versus production of electrofuels – resource intensity and emissions

In Figure 6-1, we illustrate the energy losses associated with the direct use of electricity from shore and compare them with energy losses when producing electricity from onboard generator sets fuelled by e-ammonia. We have mapped the potential energy losses associated with the production and use of electrofuels, drawing on relevant industry literature sources.[73]

Based on this energy loss, we have calculated the total GHG intensity per usable energy unit on the vessel, considering power-grid GHG intensity for different countries and regions[74] as well as from coal power.[75]

Figure 6-1 illustrates two points for reflection:

- The well-to-wake (WtW) emissions from onboard power production in an oil-fuelled generator set are higher than many countries' average GHG intensity from the power grid. Consequently, using shore power can lead to efficient WtW emission reductions.
- To positively affect GHG emissions, electrofuels must be produced from very-low GHG intensity electricity.

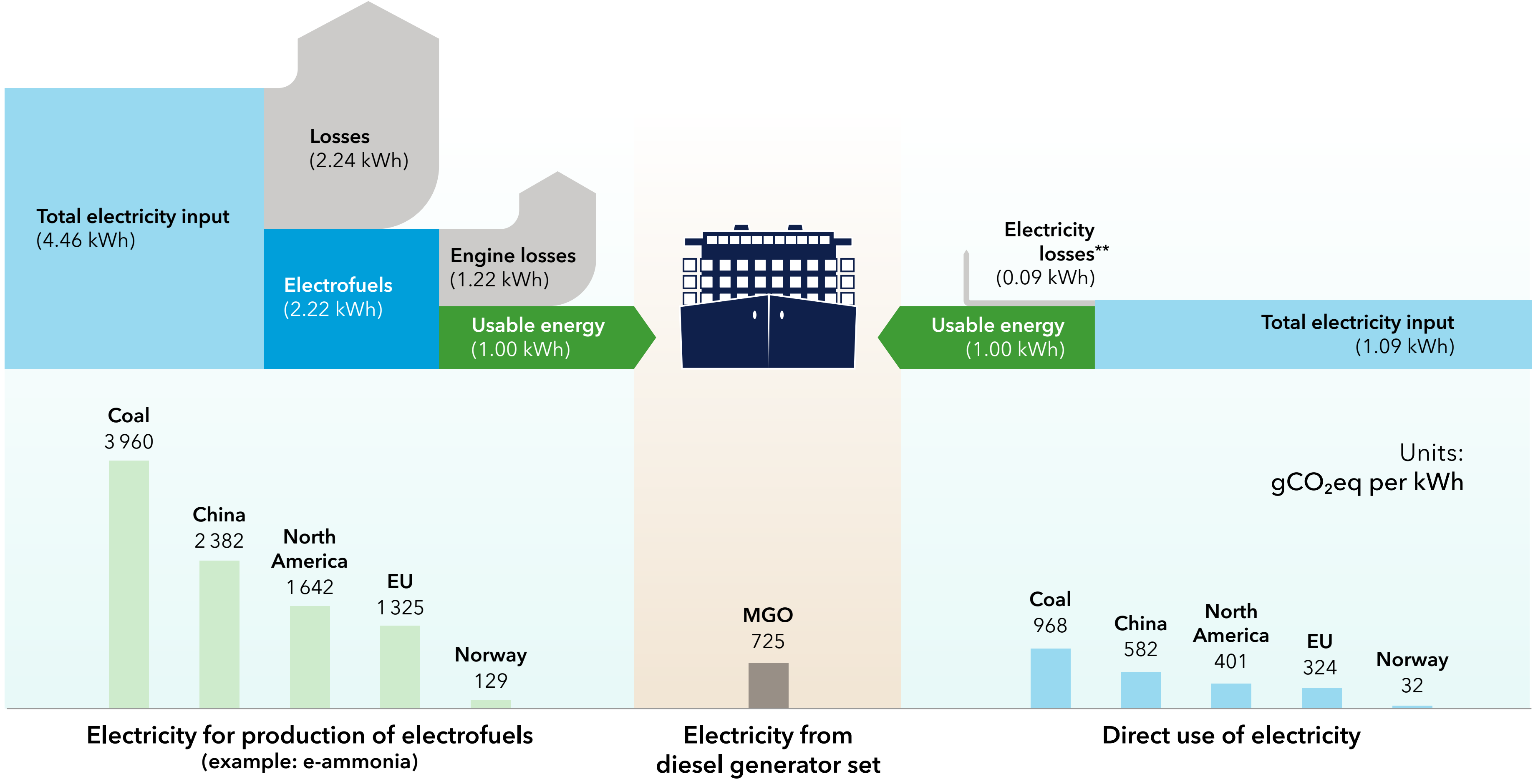
Providing electric power to ships in port

The California Air Resources Board At Berth Regulation[76] requires container, reefer, and cruise vessels to connect to shore power (or employ another approved emission control strategy) during visits to all regulated terminals in California as of 1 January 2023. The requirements will extend to RoRo and tanker vessels in 2025 and 2027.

In the EU there are upcoming regulatory requirements for the supply and use of shoreside electricity. The Alternative Fuels Infrastructure Regulation mandates core and comprehensive ports in the Trans-European Transport Network to install enough onshore power-supply facilities to provide shoreside electricity for at least 90% of the port calls by seagoing passenger and containerships above 5,000 GT every year from 2030.[77]

FIGURE 6-1

Energy use and emissions associated with direct use of electricity versus electrofuels, compared to electricity from the onboard diesel generator set fuelled by marine gas oil (MGO)



Key assumptions
Energy efficiencies: electric grid (92%); electrolysis (68%); H-B synthesis (69%*); onboard generator (45%)
Electric grid GHG intensity in gCO_2eq per kWh: North America (368); EU (297); China (534); Norway (29); coal power (888)
MGO WtW GHG intensity in gCO_2eq per kWh: WtT GHG (52); TtW GHG (274), based on FuelEU Maritime default emission factors
*includes loss of hydrogen and electrical energy; **excludes any losses related to battery charging

The FuelEU Maritime Regulation complements this requirement by mandating zero-emission while at berth.[78] This means that seagoing passenger and containerships above 5,000 GT must use onshore power supply or alternative zero-emission technologies[79] from 2030 onwards to meet their electrical power needs when berthed for more than two hours in a Trans-European Transport Network port. From 2035, this requirement applies to all ports where shore power is available. Support instruments like the Connecting Europe Facility (CEF) provide financing for onshore power supply facilities.

Shore power connector.

Providing electricity to ships may strain the capacity of the onshore grid and compete with power demands from other sectors. In many cases, developing grid infrastructure and increasing power production may be necessary, which could require long lead times and entail high costs. However, ships using shore power can be disconnected from the grid if necessary, as they can generate the required power from onboard ship machinery. This means ships can act as a flexible load, which is advantageous for the grid company and can help decrease grid-connection costs.

In a study for Transport & Environment, DNV has established an overview of the current status and plans for onshore power supply in around 40 major ports in the EU and UK. Only three of these ports have installed or planned enough connection points to meet the FuelEU Maritime and Alternative Fuels Infrastructure regulatory requirements. This demonstrates the need for further development of shore-power infrastructure across Europe.

Using the time ships spend in port and their corresponding energy use allows us to evaluate the potential for shore power to cover their power needs during port stays. The voyage-based analysis uses DNV's MASTER model[80] and combines Automatic Identification System (AIS) data with geometrical data of ports to estimate the duration and fuel consumption of ship voyages and port stays. Port stays have been identified by comparing AIS data with port locations (GPS coordinate shapes) and the registered speed of the ship being zero. We have used activity data from 2023 including all ships larger than 400 GT (around 65,000 ships).

The analysis found that the world fleet used 17 Mtoe of fuel while in port. This corresponds to 7% of the world fleet's energy consumption. It must be regarded as a high estimate of the potential for the use of shore power to reduce the demand for carbon-neutral fuels, because some energy for vessels in port is provided by boilers, which is more difficult to replace with electricity from shore.

The new Buquebus ferry will utilize Corvus Energy's high-density Dolphin NextGen battery.

Potential for electrification with batteries (plug-in hybrid solutions)

According to DNV's Alternative Fuels Insight (AFI) platform, more than 900 ships are operating with batteries. The capacity for electric operation (charged from shore) varies, and the number also includes ships with battery packages installed solely to optimize diesel generators (i.e. no charging from shore). In 2023, around 45% of the global fleet of ships with batteries were operating in Nordic countries, Norway having the largest fleet (DNV, 2023c). Other studies have examined how plug-in hybrids can be used in shipping, such as (Kersey, Popovich & Phadke, 2022) estimating the range at which plug-in hybrids can be economical for a given battery price. Due to operational flexibility and safety, we anticipate that plug-in hybrid will be the chosen solution for practically all electrification of significance, including for ships that cover up to 100% of their energy need from electricity charged from shore. This is true for the Norwegian ferry sector, where practically all battery ferries are plug-in hybrid.

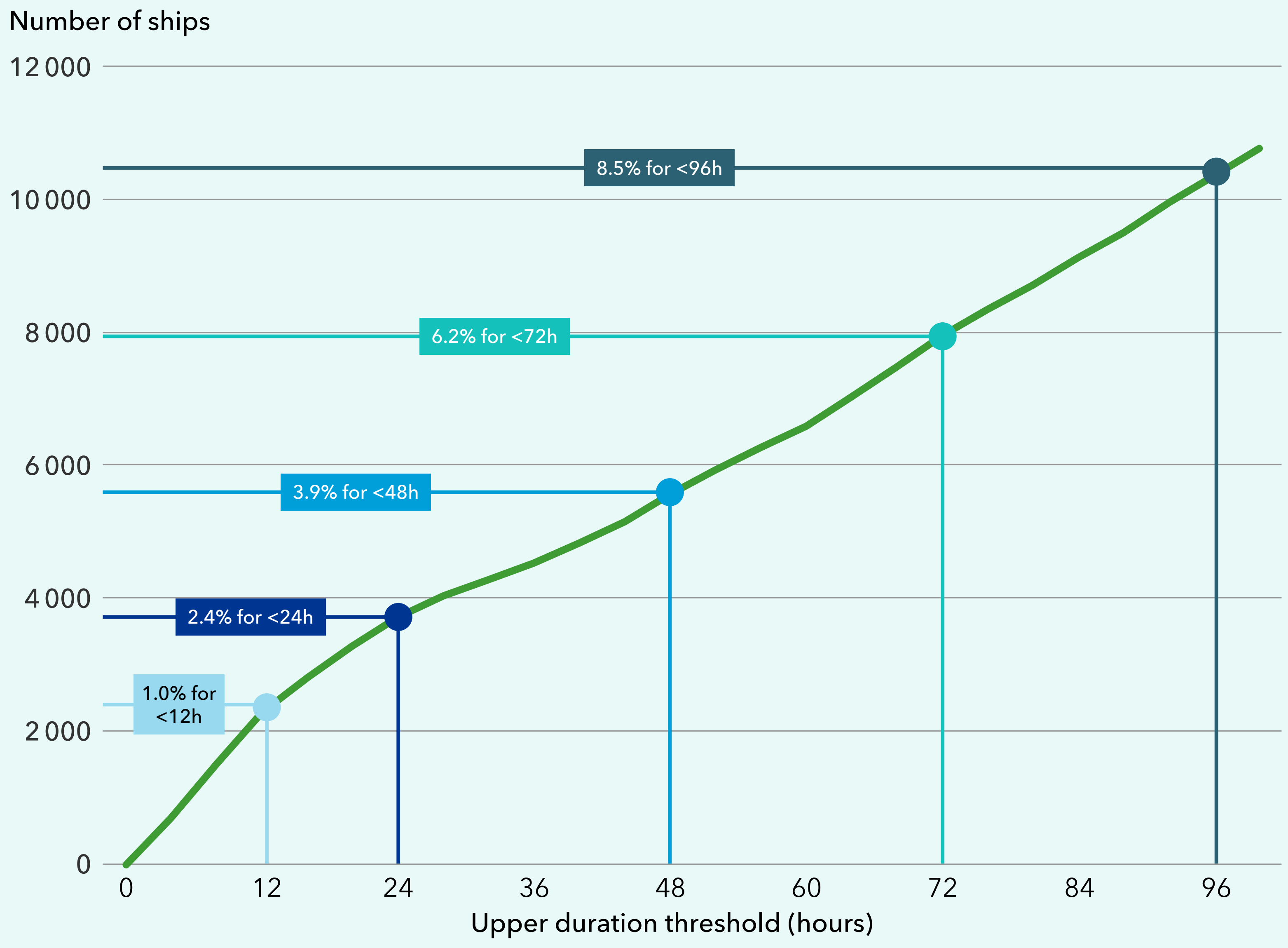
Several factors influence the decision to invest in battery installations on ships to enable use of electricity from shore:

- The degree of electric operation depends on technical constraints/capacities, operational pattern (sailing distances and time in port, etc.), and availability of charging infrastructure.
- Increasingly stricter emission requirements and more widespread charging infrastructure will gradually improve the business case for plug-in hybridization.
- As the lifetime of batteries increases through technological development, the cost per delivered energy from batteries over their lifetime will decrease.
- Reduced CAPEX for a given battery installation will decrease the cost per delivered energy from batteries.
- The more frequently a ship can charge the batteries, the more of a ship's energy need can be covered by the same installed battery, decreasing the cost per delivered energy from batteries.

To evaluate the economic feasibility of investing in batteries and using electricity from shore while sailing – to different degrees in plug-in hybrid solutions – a shipowner will compare the total cost of the energy supplied by the batteries against the total cost of energy supplied by other fuels, similar

FIGURE 6-2

Number of ships using 80% of energy on short voyages and corresponding share of world fleet fuel consumption



to Figure 6-1.[81] Even in cases where the total cost of energy is favourable compared to alternatives, the degree of electrification will depend on several technical, operational, and economic factors.

The overall cost of energy provided by batteries for a plug-in hybrid ship mainly consists of a) CAPEX for the battery and related systems and adaptations onboard, and b) the shoreside costs. The shoreside costs have two distinct cost elements: the CAPEX of infrastructure for battery charging and grid connection, and the cost of purchasing electricity.

The cost of connecting to the grid can be marginal in some cases and prohibitively high in others. This depends on whether there is available power in the grid and, if not, the cost of increasing grid capacity. The shoreside infrastructure can often provide shore power to several ships, and the more the infrastructure is used throughout the year, the lower the cost will be.

The business case for using batteries in a plug-in hybrid ship depends on how often the batteries are charged/discharged. A ship making many voyages of short duration will have more opportunities to charge its batteries while in port than one sailing longer-duration voyages. We have therefore performed an AIS analysis of the length of voyages for all existing ships above 400 GT in 2023, finding ships using 80% of their fuel (out of port) on short voyages, which allows for frequent battery charging and for the batteries to cover a substantial amount of the ship's annual energy needs, see Figure 6-2.

We then evaluated the amount of fuel consumed on these short voyages to investigate each ship's potential for plug-in hybridization, which when summed up illustrates the existing fleet's potential for plug-in hybridization.

Around 4,000 ships use 80% of their voyage energy consumption on voyages shorter than 24 hours. They consume 6 Mtoe in energy on these voyages, which is 2.4% of the world fleet energy use. Increasing the voyage duration to 72 hours, we find the corresponding number of ships using 80% or more of their voyage energy on short voyages to be 8,000, accounting for 6.2% of the world fleet energy use.

The potential for plug-in hybridization can be increased by modifying operational patterns of existing ships or by building vessels specifically for shorter voyages.

Emerging battery-charging solutions

Although existing shore-power facilities can be used for charging onboard batteries, dedicated charging facilities have also been built out; for example, for electric ferries. There are currently no international standards for battery charging of vessels, but such standards are under development. Utilizing charging technologies developed for land transport, such as the Megawatt Charging Standard[82], can reduce costs, due to mass production. Alternatives to conventional plug-based charging methods include automated connection, battery swapping, and offshore charging solutions.

Plug-in hybrid vessels with limited time in port, such as ferries, require fast automated connection and disconnection to maximize the time available for charging. This can increase the amount of energy that the vessel receives (charging with the same power input but for longer), or it can decrease the power output of the charging infrastructure by increasing the time to deliver the same energy and thereby reducing the load on the grid. Several different concepts have been adopted depending on the requirements for individual vessels[83], including pantographs and open sliding contacts, gravity-assisted plugs, and wireless charging. Wireless charging systems[84] reduce the maintenance requirements and safety issues associated with harsh environments and salt water, but also pose challenges related, for instance, to cost, onboard weight, and efficiency.

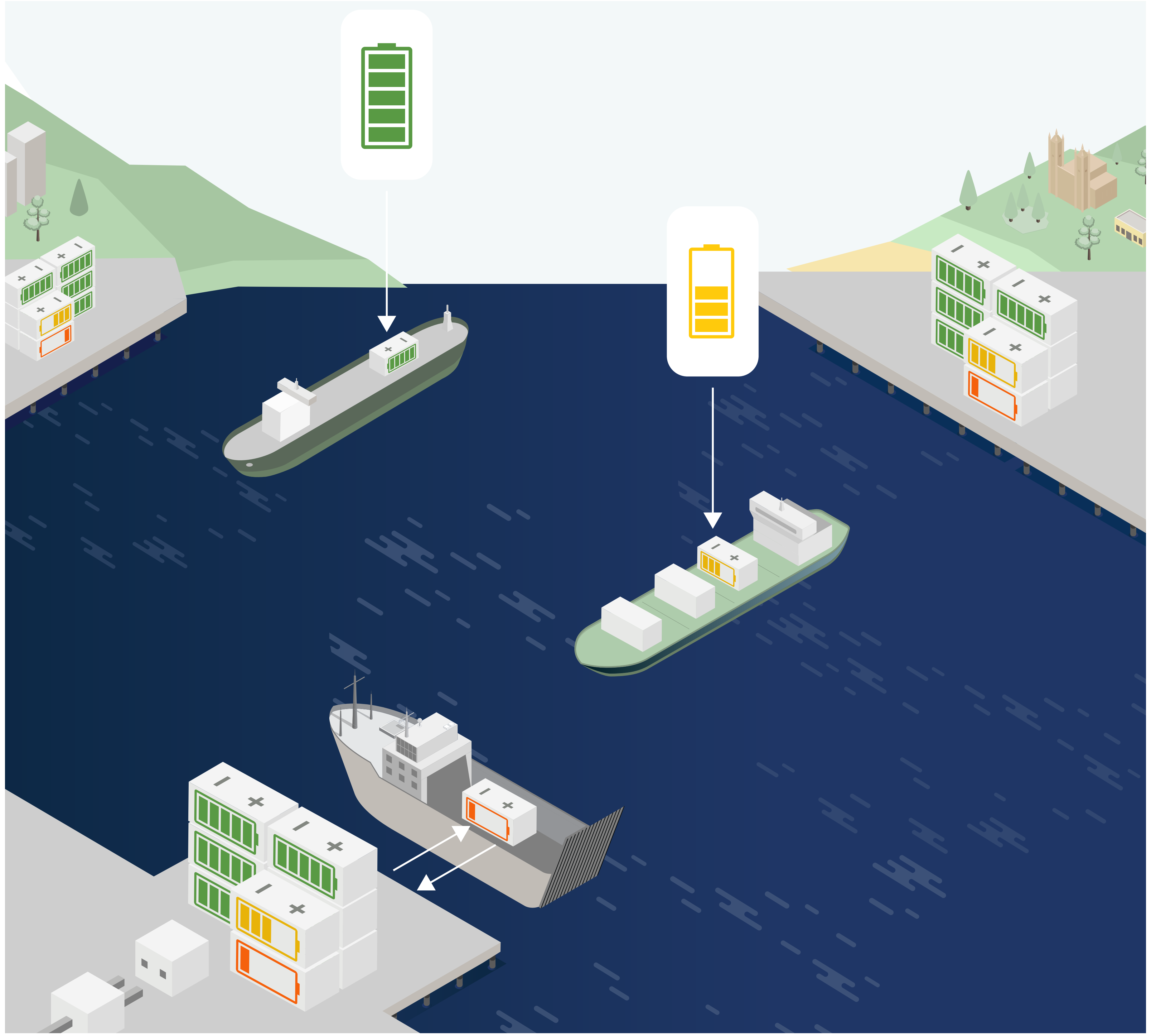
Battery swapping is a method where discharged onboard batteries are exchanged with fully-charged batteries while at berth.[85] For vessels that have a critical docking time, robotic equipment can be used to automate the exchange process. For containerships, some container capacity can be taken up with batteries as swappable units. For RoPax and RoRo vessels, battery trailers could be used to reduce the fuel consumption when there is available onboard space. A main advantage of battery swapping is that onshore battery packs do not have to be charged in a short time, thereby reducing the charging power required from the grid per unit energy delivered to a ship. Furthermore, the need for high-power onboard converters for fast charging is eliminated. However, battery swapping requires investment in extra battery packs on shore, and there is a need for standardization to establish such services to cover shipowners' needs.

Development of a logistics system for battery swapping in different ports, illustrated in Figure 6-3, can reduce shipowners' investment and risk since the extra battery packs and the associated charging infrastructure can be shared among several ships for increased utilization. The utilization is the most important cost factor, both for batteries and for charging infrastructure. Such a logistics system can also facilitate the provision of grid-balancing services from the batteries to the electricity market, which can further improve the business case. The batteries can be offered as a service instead of being owned by the ports or the shipowners.

Offshore charging solutions are also emerging[86], and offshore charging points can be connected to offshore renewable power plants such as wind parks and/or to the onshore grid through subsea cables. The development of offshore grids and energy islands could enable offshore charging of vessels at strategic locations and hence enable electrification of longer routes. Battery charging along the route will increase the charging frequency and battery utilization, and thereby reduce the cost of plug-in hybridization. For decarbonization of anchorage zones, offshore charging solutions can also be used by vessels idling outside busy ports.

FIGURE 6-3

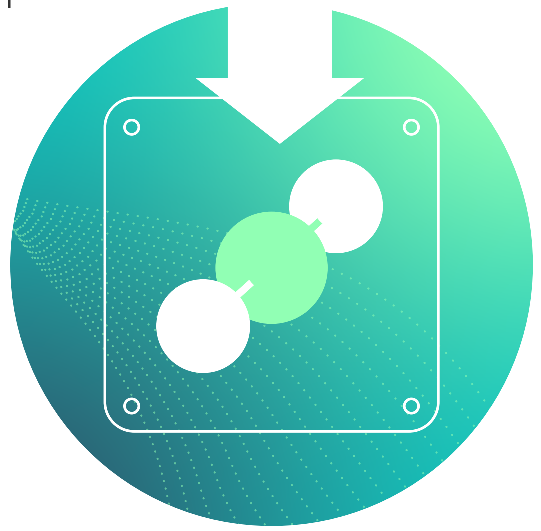
Logistics system for battery swapping



6.2 Carbon capture and storage

While many efforts to reduce GHG emissions from shipping focus on switching to carbon-neutral fuels (Chapter 5), another option is to capture the CO_2 produced by carbon-based fuels – whether fossil or carbon-neutral – and store it away from the atmosphere.[87] A case study was performed in last year's Maritime Forecast to 2050 (DNV, Maritime Forecast to 2050, 2023), with more details on capturing and storing CO_2 on a ship. In this section we describe the value chain needed for onboard carbon capture and present the status of and outlook for the development of the carbon storage industry.

Ongoing demonstration projects[88] aim to demonstrate parts or the complete process of onboard carbon capture and storage. Work is also underway in the IMO and the EU to integrate onboard carbon capture technologies into the regulatory framework to reduce GHG emissions. Regulatory clarity is important for the commercial viability of onboard carbon capture for shipowners. The decision for shipowners to adopt onboard carbon capture technology also depends, for example, on the extra fuel consumption needed, the impact on cargo space, and the need for frequent port stops due to space limitations on onboard fuel and CO_2 storage. However, the presently limited availability and high prices of carbon-neutral fuels can help



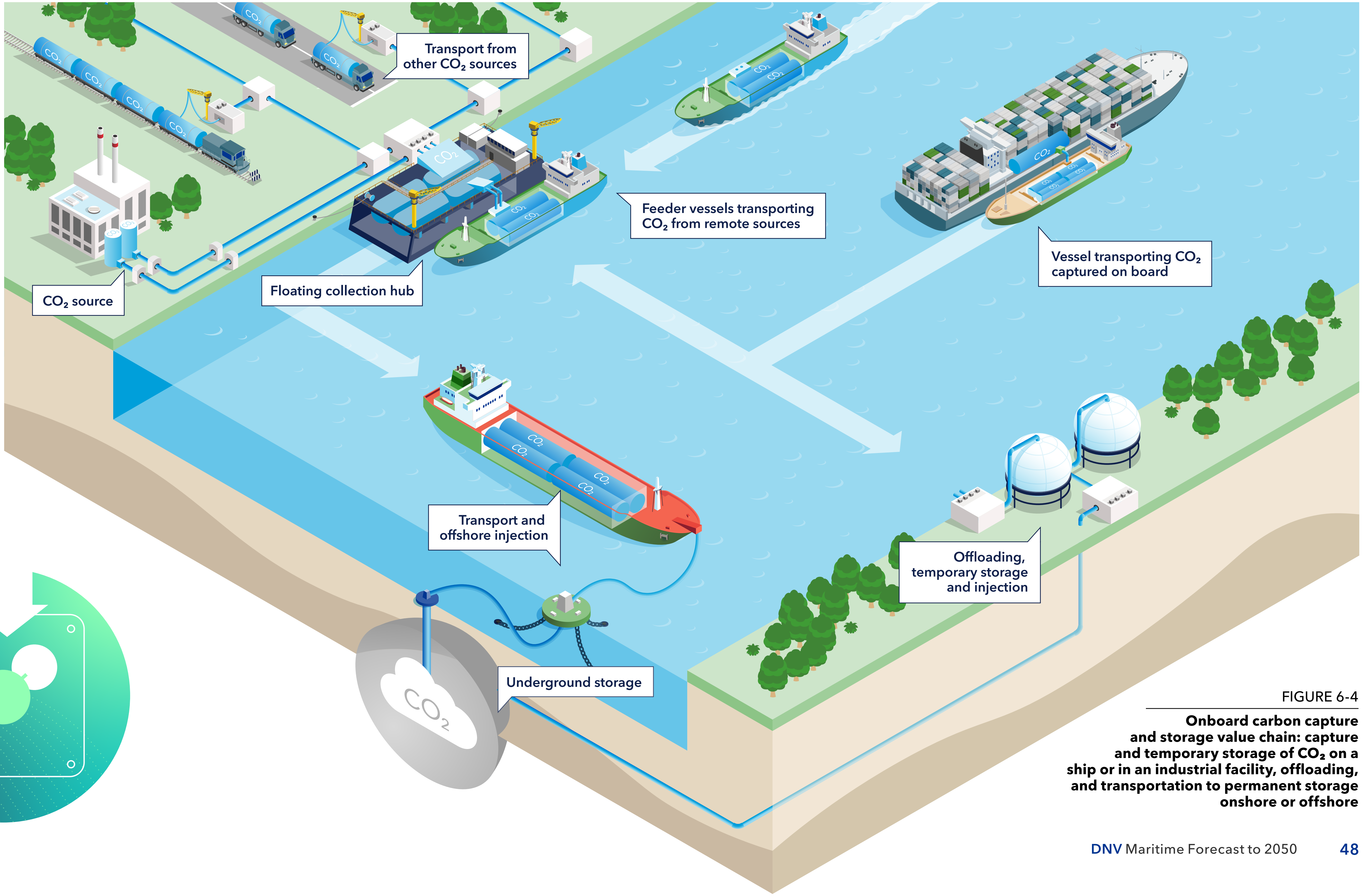


FIGURE 6-4

Onboard carbon capture and storage value chain: capture and temporary storage of CO_2 on a ship or in an industrial facility, offloading, and transportation to permanent storage onshore or offshore

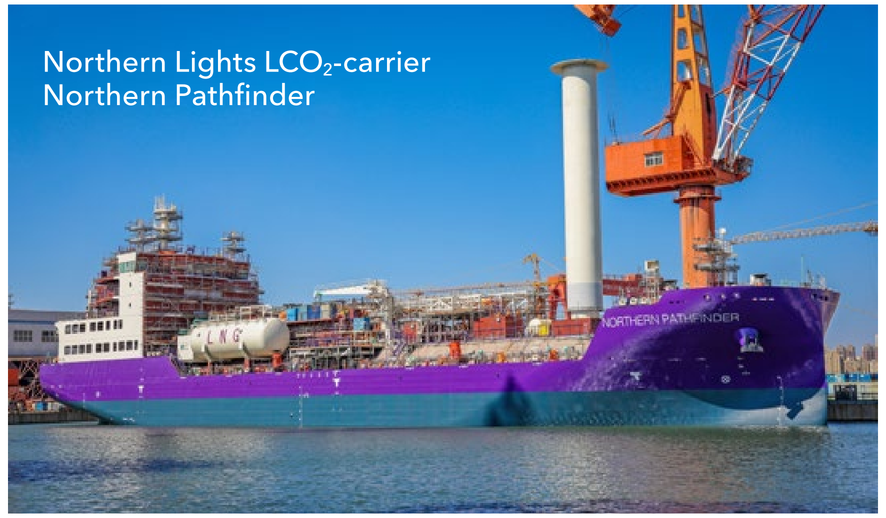
the business case of onboard carbon capture and storage.

The maritime carbon capture and storage value chain

In general, captured carbon can be handled in two ways. The first is carbon capture and storage (CCS) – the process of capturing CO_2 and permanently storing it in deep underground geological formations. The second is carbon capture and utilization (CCU) – the process of capturing CO_2 to be recycled for further use. Both pathways would typically involve transporting CO_2 from one site to another.

Onboard carbon capture is the starting point of a long value chain that can also serve other industries, as illustrated in Figure 6-4, with permanent storage as the endpoint. For geological storage of CO_2, it is fundamental to create confidence that the geological formations selected for CO_2 storage are suitable for the purpose, will deliver long-term CO_2 emission reductions, and do not involve unacceptable risk.

Figure 6-5 shows the stepwise process of the value chain connected to onboard carbon capture. The ship will require a capture system to remove CO_2 from the exhaust; a process unit for after-treatment of the captured CO_2 to a state (such as liquefaction) suitable for storage; onboard storage systems; and offloading facilities enabling discharge to shore or transport ship. Once captured and ready for discharge, the ship offloading facilities must be



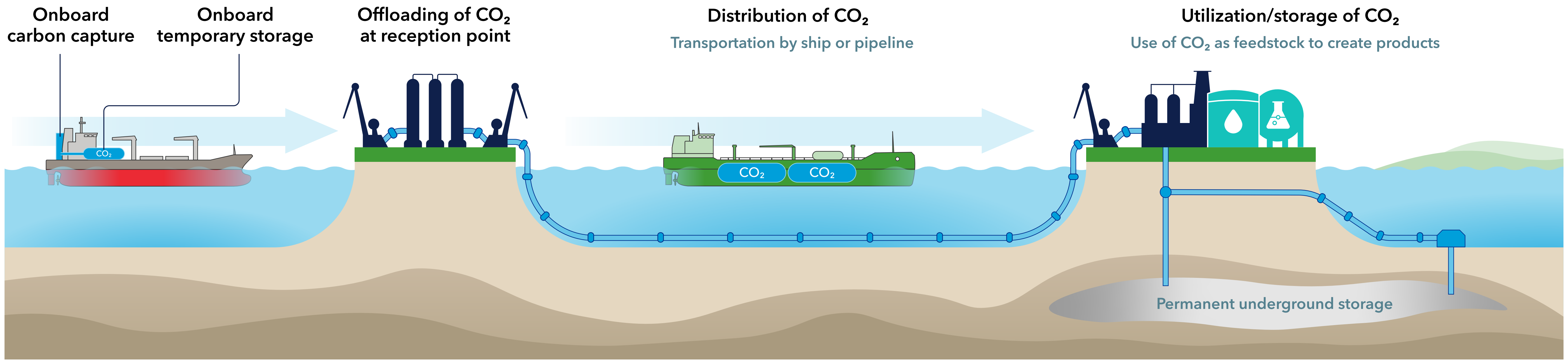
connected to a transport network of pipelines or ships to get the CO_2 to sites of permanent storage. The offloaded CO_2 product must also meet product specifications for the dictated end-use (storage or utilization). Differences in purity standards limit the interoperability of carbon utilization facilities to handle captured CO_2, or can lead to increased costs if the CO_2 must be conditioned to the highest purity standard.

In general, CO_2 transportation by pipeline is the most cost-effective option when sufficient volumes are available, but shipping offers greater flexibility for transporting CO_2 over long distances and in smaller volumes, particularly when the sources and destinations are geographically dispersed. Shipping of CO_2 can enable a flexible and scalable CCS infrastructure that can adapt to future capture projects and storage sites. Ships are also preferable for small or short lifetime CO_2 sources that cannot economically justify a dedicated pipeline. Existing experience with CO_2 shipping is limited and relates to ships used in the European trade of CO_2 for industrial uses. Four ships for the Northern Lights CCS project are under construction.[89]

Today, there is a lack of infrastructure ready to receive and handle the CO_2 captured on ships. Ongoing CO_2 infrastructure projects are typically located near or connected to industrial clusters that emit CO_2. However, there are initiatives to advance CCS value chains; for example, the Northern Lights project[90] aiming to develop and operate CO_2 capture, transport, and storage facilities. There are also ongoing developments of CO_2 reception facilities near port terminals, for example the ports of Rotterdam[91], Antwerp[92], Gothenburg[93], Gdansk[94], Dunkirk[95], and Wilhelmshaven.[96] The proximity

FIGURE 6-5

Stepwise process of the onboard carbon capture value chain



of shipping trades to the available disposal or collection nodes, or to available services for receival of captured by-products, is an essential decision-making factor to invest in onboard carbon capture.

A future scaling of the CO_2 infrastructure could involve many different operators, and transportation both onshore and offshore. This requires a CO_2 network across geographies and nations, as well as large-scale CCS clusters. A co-location of CCS and CCU hubs could potentially be an attractive commercial future option (e.g. global e-fuel production hubs could be co-located with CO_2 capture hubs). The acceptance of simultaneous operations, like fuel bunkering and CO_2 disposal, will favour the timing and the overall business case of onboard carbon capture projects.

Status and outlook on carbon storage industry

Successful downstream integration of onboard carbon capture in the carbon value chain depends on the ability to offload the CO_2 at convenient locations, thereby connecting to the carbon-storage network ashore. It is reasonable to assume that the shore-based CO_2 capture industry will drive the development of this logistic chain, as the volumes that will be captured ashore are estimated to be much larger than for shipping. Shipping emits around 880 $MtCO_2$/year, tank-to-wake.[97] Forecasted global CCS capacity in net-zero policies' 2050 scenarios ranges from 4,000 to 8,400 $MtCO_2$/year, part of which could be made available for CO_2 captured from shipping (Ricardo; DNV, 2023).[98]

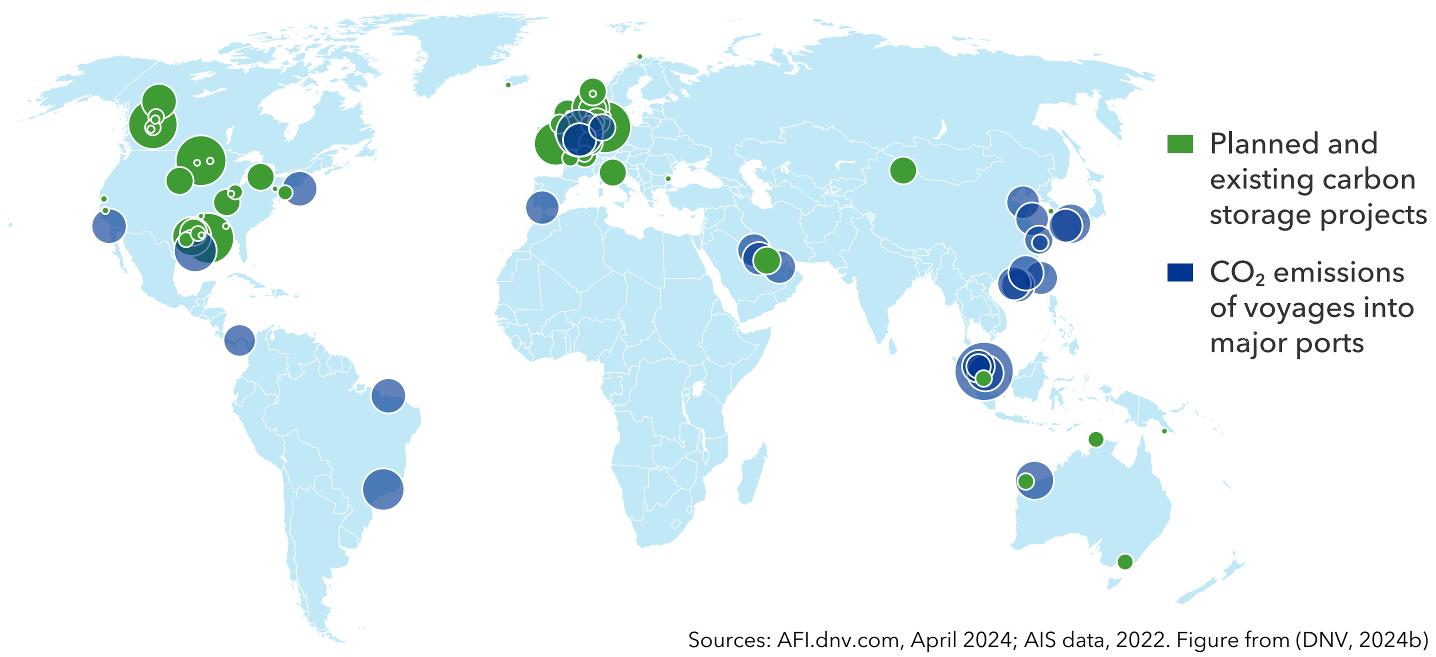
In DNV's white paper on onboard carbon capture (DNV, 2024b), the accumulated volumes of CO_2 emissions in the busiest shipping locations are shown to be large even when compared with single onshore emitters. On their last voyage, vessels entering the ports of Singapore and Rotterdam collectively emitted 24 and 13 $MtCO_2$, respectively. In comparison, the 10 largest announced projects for dedicated CO_2 storage have a planned capacity of 7.5 to 20 Mtpa, see Figure 6-6. With ports having the potential to transmit large amounts of CO_2 emissions, incentives to build out CCS infrastructure and dedicated CO_2 storage for shipping in the most travelled shipping hubs should be considered.

DNV has undertaken a comprehensive mapping of ongoing and announced global projects dedicated for CO_2 storage. Out of 96 planned projects for dedicated storage, less than 10 have reached a final investment decision, with most of the projects still in the conceptual phase. To estimate the potential storage capacity in each of the upcoming years, each mapped CCS project is assigned a probability based on its current development stage, in the same way as for the carbon-neutral fuel production in Section 5.3. The projects are categorized in development stages and a delay factor is added to the originally planned completion date of the project. This allows us to define two distinct scenarios, the first with high probability and one-year delay, and the second with low probability and two-year delay. The storage capacity in both scenarios is calculated as the sum of planned storage capacity by a given year, weighted by the assigned probability of completion.

Figure 6-7 shows our high and low estimates for global carbon-storage capacities – for all industries and purposes excluding enhanced oil recovery. For 2030, the estimated global carbon-storage capacity is between 47 and 67 Mt, compared with the estimated storage demand (see Section 5.2) of 4 to 76 Mt.

FIGURE 6-6

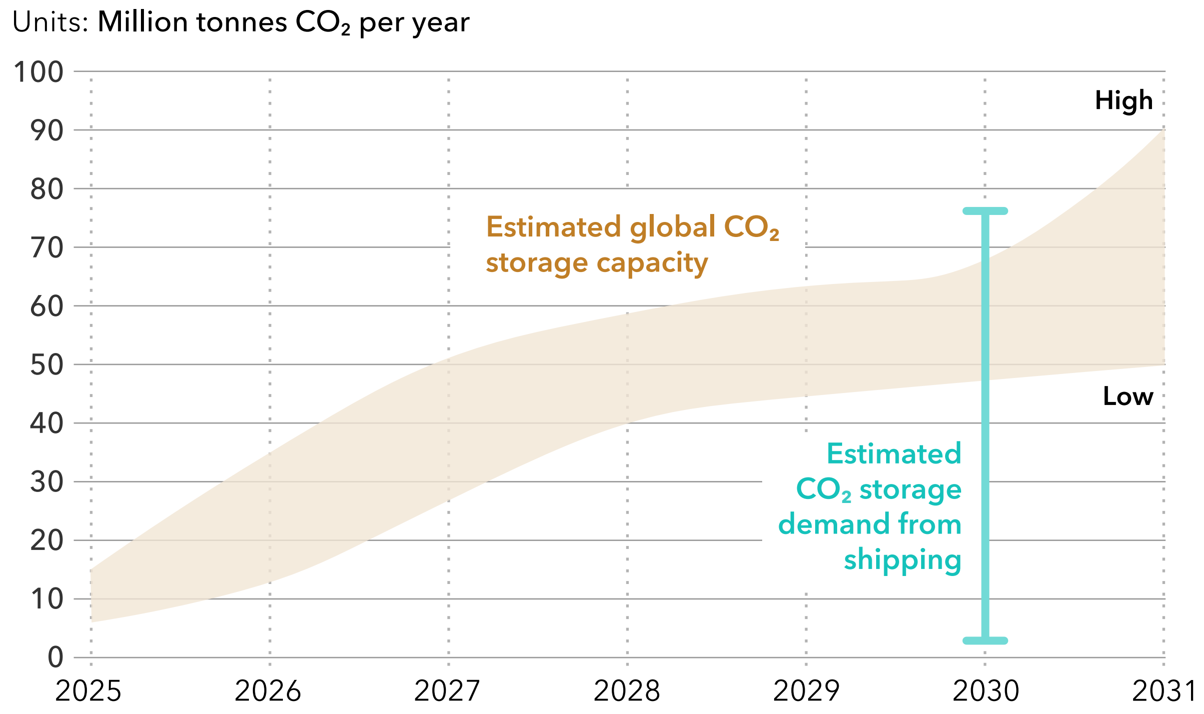
Planned and existing carbon storage projects, excluding enhanced oil recovery, by capacity (size of bubble) and location as well as voyage-based estimates of CO_2 emissions from direct voyages into major shipping ports, by annual tonnes of CO_2 emissions and location



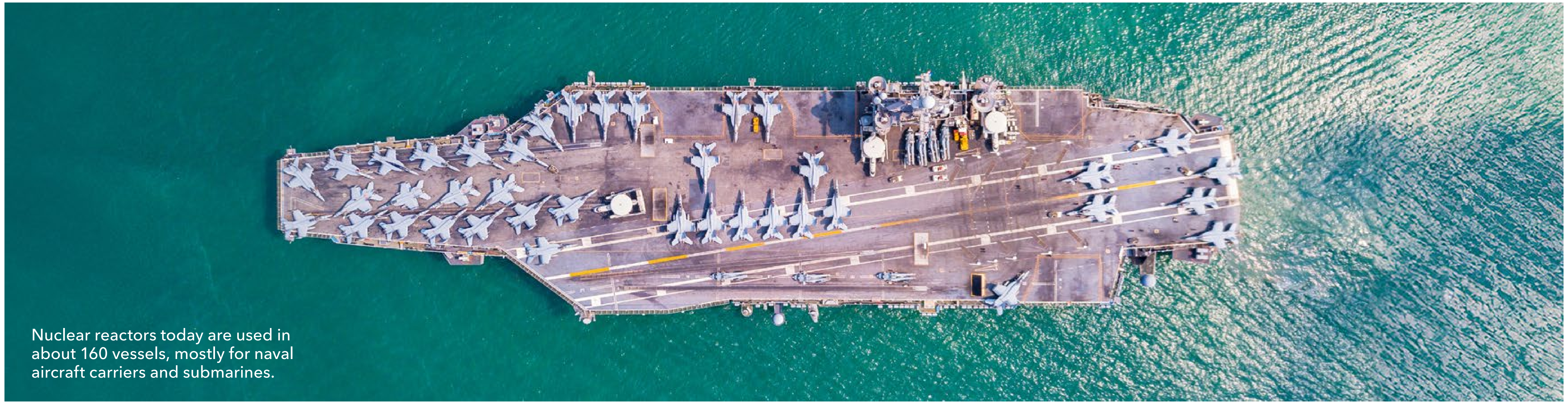
Sources: AFI.dnv.com, April 2024; AIS data, 2022. Figure from (DNV, 2024b)

FIGURE 6-7

Estimated global CO_2 storage capacity (excluding enhanced oil recovery)



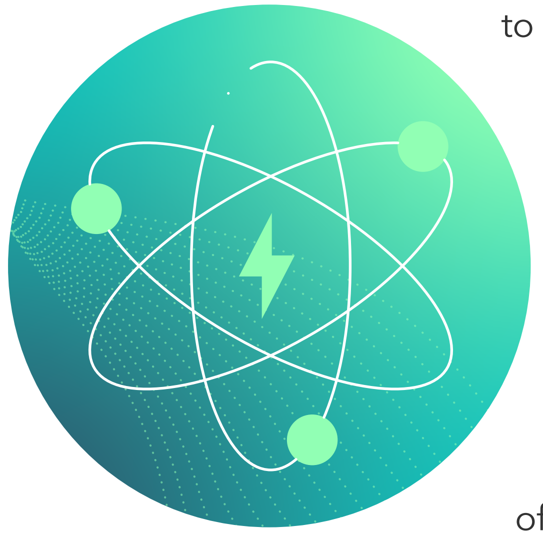
6.3 Nuclear propulsion



Nuclear reactors today are used in about 160 vessels, mostly for naval aircraft carriers and submarines.

In the preceding sections, we have looked at technologies for ships and the connection to shoreside industry for the necessary production of carbon-neutral fuels, electrification, and onboard carbon capture. Nuclear propulsion is again being investigated, where the advantages of no emissions, no bunkering, low weight, and high design speeds are being weighed against the disadvantages of security concerns, complicated monitoring, non-proliferation issues, social/political risks and high CAPEX.

Nuclear reactors today are used in about 160 vessels, mostly for naval aircraft carriers and submarines, but also in Russian icebreakers, one merchant ship, and a floating nuclear power plant (Maritime Nuclear Application Group, 2022). Nuclear propulsion is today used for strategic reasons, with supreme range allowing for autonomous operations for naval vessels and icebreakers, while the first nuclear merchant vessels – Savannah, Otto Hahn, Mutzu (Schøyen & Steger-Jensen, 2017) – did not lead to a large uptake of the technology in shipping. The onboard ship technology of nuclear propulsion has the potential to decarbonize ships without being dependent on the other carbon-neutral alternatives based on renewable electricity (Eide et al., 2013) (DNV, 2010), sustainable biomass, or fossil energy with CCS. However, nuclear propulsion faces unique regulatory and public perception challenges as well as challenges to conventional business models for building, operating, and decommissioning ships.



Naval nuclear propulsion

The relevance of US military ship propulsion technology for nuclear merchant shipping today is limited. The technological basis for US naval reactors is different from that of other navies and commercial nuclear power. It has been developed over 70 years and is one of the country's best-kept and best-guarded secrets with its lifetime cores, enrichment levels of over 90%, and advanced fuel geometries with high reliability characteristics.[99] For other naval programmes, still emerging and improving technologically, there has been a spillover effect from the military programmes to the civilian sphere. This has been extensively documented for the Russian naval programme; the Akademik Lomonosov floating reactor vessel is based on the KLT-40 reactor, which emerged from the icebreaker programme that matured in parallel with the Russian submarine reactor programme. Today, the US company Lightbridge[100] promotes a commercial fuel design for civilian power reactors that utilizes the Russian ship fuel design used in the Sevmorput[101] metallic uranium-zirconium alloy fuel core, with the fuel co-extruded and metallurgically bonded to a zirconium alloy cladding.

Reactor technologies being investigated

In last year's version of this report (DNV, 2023b), a case study was presented using a 15,000 TEU container vessel with a 42 MW(e)[102] reactor, along with the listing of other concepts, including the eVinci 5 MW(e) microreactor and other, larger reactors installed on icebreakers and military vessels. Limiting space-usage for purposes other than for cargo (Houtkoop, Visser, & Sietsma, 2022) is essential for cargo vessels, and the lower range of available planned small modular reactor (SMR) power outputs is suitable for shipping. Smaller reactors can potentially also make it less strenuous to gain regulatory approval and public acceptance. As an example, the KEPCO BANDI-60 model under consideration in South Korea has a rated power of 60 MW(e) and is based on light water reactor (LWR) technology.[103]

Conventional nuclear technology, based on light water[104] or heavy water, stands in contrast to the new technologies under development using other types of nuclear fuel and coolant. For conventional nuclear technology, the basis is a proven and qualified technology, with less technical and licensing risks at this stage. For the non-conventional technologies – for example, those using lead, molten salt, or other components to cool the process or enable efficient fission – the associated risk for all subsequent development stages is less familiar.[105] As far as the KEPCO BANDI-60 model is concerned, no initiative has yet been taken by the South Korean safety authorities to initiate a licensing procedure, as a first mover has yet to come forward. Nevertheless, the concept is an example of a project that falls within a known regulatory framework and could be realized within a decade if an experienced industrial player acts in cooperation with a mature regulatory authority prepared for such a task.

Licensing for nuclear reactor operation

Unlike other ship propulsion technologies, nuclear propulsion will require approval from national nuclear regulatory bodies in addition to following IMO rules, flag state rules, port/coast state rules, and class rules. Before a nuclear reactor can be used on ships, it will require a licence to operate from at least one nuclear regulatory body. A licence must be issued both for the reactor and for the fuel to be used in it.

For light water-based options, fuel qualification is a fundamental step to demonstrate that the fuel produced to a specification will perform as described in the safety case that forms the basis for the licence application. This can be a challenge, especially if the aim is to use higher fuel enrichment than the commonly used 3% to 5% of Uranium-235 in commercial power units. This may prove worthwhile, however, as it allows for smaller reactor cores and potentially fewer fuel changes over the life of the vessel. Major factors are costs and guarantees of supply, as the nuclear fuel supply lines are already limited and shrinking with the growing need voiced by several countries for strategic autonomy within the nuclear fuel industry.

Unlike other ship propulsion technologies, nuclear propulsion will require approval from national nuclear regulatory bodies in addition to following IMO rules, flag state rules, port/coast state rules, and class rules.

For non-light water-based options, the path is more complicated, as all materials used with the reactor, as well as the fuel itself, must be qualified for the entire fuel cycle (before, during, and after operation). Together with fuel qualification, a master design must be established that describes the necessary manufacturing, construction, testing and performance of the safety-related structures, systems, and components. A proposed non-light water design must be accompanied by a recognized methodological basis (e.g. event-specific analysis methods, reactor coolant analysis methods, core design methods, and reactivity control methods). Everything should also be well established in the context of a national regulatory system before being applied in a nuclear merchant shipping project.[106]

NS Savannah was the first nuclear-powered merchant ship.

International development of nuclear power

The most striking feature of the nuclear power industry of recent years is that China and South Korea represent – through standardization and the ability to deliver export initiatives on time and on budget – two countries with a long-awaited success for the nuclear industry.[107]

An important part of the efforts in land-based nuclear energy is the development of SMRs, which also gives hope to efforts on sea-based nuclear propulsion, which aim for flexibility and compactness in addition to standardization of the reactor fleet. The preliminary conclusion among regulators is that changes in the way of working are needed to implement SMR projects quickly and efficiently worldwide.[108] Regulators may need to engage earlier with the supply chain and associated accreditation initiatives to enable vendors to progress the design and manufacturing of safety-related components prior to the establishment of a licensee, an organization that holds a licence to operate a nuclear reactor.

The development of small modular reactors and merchant nuclear propulsion

A question that arises is whether the nuclearization of merchant shipping can become a driving force for the development of SMRs and not vice versa. China has been able to demonstrate the power of standardization in its commercial programme, and standardization is needed for nuclear propulsion to be widely used in the global merchant fleet. As for power reactors, where national programmes are often essentially just that – a national endeavour – the question is whether the development of nuclear merchant ship reactors may provide an opportunity for standardization and joint development in technology choice, regulation, and safety follow-up. If overcome, the specific challenges for the international maritime industry in using nuclear power across port and coast states could potentially lead to an opportunity for a nuclear reactor programme dedicated to the shipping industry to accelerate the development of nuclear power.

7 FUELEU MARITIME COMPLIANCE POOLING CASE STUDY

Highlights

We investigate if the pooling mechanism in FuelEU Maritime, effective 2025[109], could trigger a sustainable business case for methanol-capable vessels utilizing full green-methanol capacity over a 10-year period, showing that:

- In a pool, an over-compliant vessel (i.e. with compliance surplus) can cover several vessels with compliance deficits and could, under some circumstances, help to justify the extra costs associated with investing and running an over-compliant vessel on costly low GHG intensity fuels.
- With time, due to stricter GHG intensity targets in FuelEU Maritime, the window of opportunity to use compliance pooling as a business opportunity for a green vessel will close.

The FuelEU Maritime Regulation taking effect from 2025 will allow ships to pool their compliance balance to meet their annual GHG intensity targets. In this chapter, we focus on pooling as a compliance option for FuelEU Maritime and investigate how this flexibility mechanism can lead to increased uptake of alternative fuel technologies. Our study focuses on how a case study methanol vessel on a low GHG intensity fuel can sell its compliance surplus to several other vessels with deficits in a compliance pool.

Figure 7-1 illustrates the pooling potential of one over-compliant vessel operating on e-methanol in a pool with other vessels fuelled by fossil marine gas oil (MGO). For simplicity, and to illustrate the effect of pooling, the e-methanol vessel and the MGO vessels are equal – in other words, they have the same annual energy requirement, share of time in the EU, and so on. The only difference between the vessels is the fuel molecules used for power generation. As shown in Figure 7-1, depending on the GHG intensity of the e-methanol[110] used, one e-methanol vessel can offset deficits for a maximum of 55 to 64 fossil MGO vessels annually in the years 2025 to 2029, and 13 to 16 fossil MGO vessels in the years 2030 to 2034. The number of MGO vessels that benefit decreases continuously over time.

As shown in Figure 7-1, one vessel running on e-methanol can cover deficits for several fossil MGO-fuelled vessels in a compliance pool. Hence, having an over-compliant vessel in the period 2025 to 2039 could give a business advantage as several owners may want to pool with green vessels to offset their compliance deficits. With time, the FuelEU Maritime targets become more stringent. This results in a diminishing effect on compliance surplus for the over-compliant vessel, and as such, one green vessel on low GHG intensity fuel may no longer be able to cover the fossil vessels' compliance deficits.

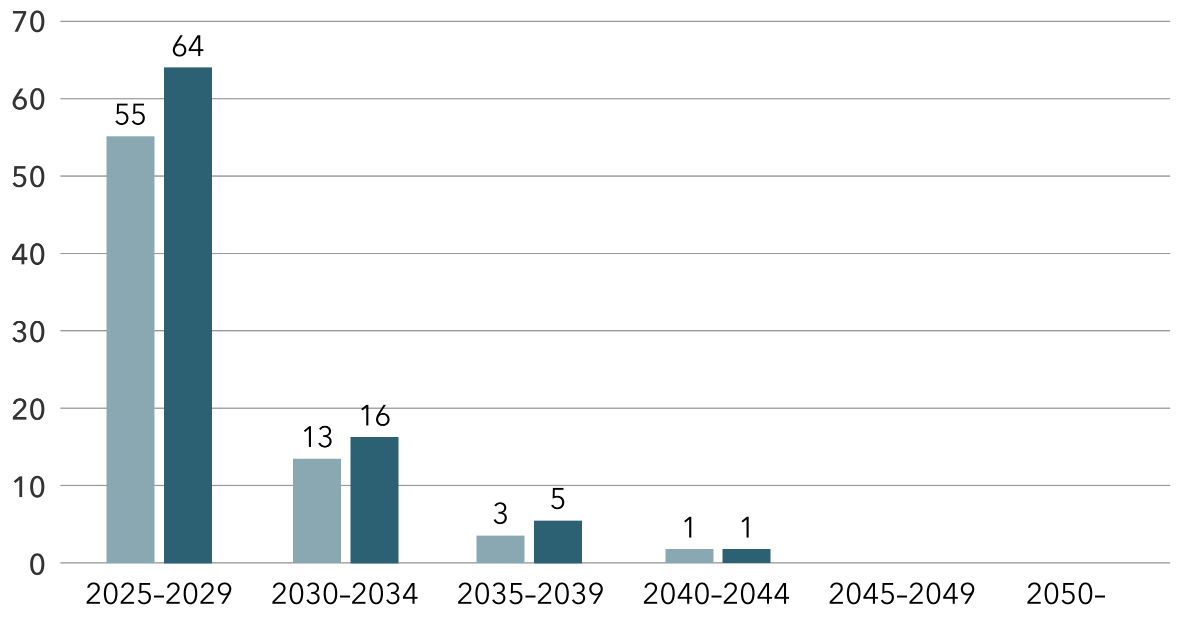
As discussed in Chapter 3, beyond FuelEU Maritime there are several other policy measures and initiatives with potential to drive maritime decarbonization. These other regulatory drivers include the EU ETS, the IMO's basket of measures, commercial drivers (e.g. the Zero Emissions Maritime Buyers Alliance (ZEMBA)[111] and offering green transportation services to customers) and incentive schemes (e.g. the EU's Innovation Fund). However, for illustrating the effect of compliance pooling, this chapter focuses solely on the FuelEU Maritime Regulation, see Section 3.2.

There will be opportunities and risks for shipowners depending on whether they take on the role of early adopters, early followers, late followers, or laggards in the fuel transition (Tuukka Mäkitie, 2022). Technology adoption starts with early adopters overcoming key barriers in the preparation phase. Early adopters are firms that

FIGURE 7-1

Maximum number of fossil MGO vessels that one e-methanol vessel with 100% of operations subject to FuelEU Maritime can cover annually in a compliance pool in the period 2025-2050

Units: Annual number of fossil MGO vessels



e-methanol produced with 70% GHG saving (28.20 gCO_2eq/MJ)

e-methanol produced with 97%* GHG saving (2.47 gCO_2eq/MJ)

Assumptions

Fuel energy share e-methanol vessel: 10% on fossil MGO (90.63 gCO_2eq/MJ), 90% on e-methanol.

The RFNBO reward factor of 2 is included between 2025 and 2034.**

N_2O and CH_4 emissions are included.

*Note that this GHG saving potentially will be challenging to achieve in practice. **For renewable fuels of non-biological origin (RFNBO), a reward factor of 2 from 1 January 2025 to 31 December 2033 can be applied. For simplification, in the figure the RFNBO factor is also included for the year 2034.

TABLE 7-1

Methanol-capable 1,300 TEU container vessel – main assumptions

1,300 TEU Methanol-capable container feeder vessel	
Capacity	1,300 TEU (DWT 14,000)
First year of operation	2025
Annual fuel consumption	4,000 t VLSFO equivalent[114] (162,400 GJ)
Area of operation	100% in EU/EEA
Fuel options	Fossil/bio-/e-MGO, fossil-/bio-/e-methanol

TABLE 7-2

Individual FuelEU Maritime compliance strategies

Strategy	Name	Description
A	*Take the penalty*	The vessel continues running on fossil MGO and takes the penalty cost.
B	*Use just enough bio-MGO*	The vessel runs on just enough bio-MGO in combination with fossil MGO to comply with the FuelEU Maritime GHG intensity target.
C	*Use just enough e-methanol*	The vessel runs on just enough e-methanol in combination with fossil MGO to comply with the FuelEU Maritime GHG intensity target.
D	*Use full methanol capacity (over-comply)*	The vessel over-complies with the FuelEU Maritime regulation using e-methanol and obtains compliance surplus which can be used for covering other vessels' compliance deficits in a compliance pool. The vessel still must use some MGO for pilot fuel.

seek to exploit the current and foreseen business opportunities related to new technologies and fuels. By doing so, early adopters expose themselves to risks as there is still much uncertainty regarding the performance and often higher costs of the technology. Early adopters are not only important for maturing technologies in the preparation phase, but also for testing and maturing cost-sharing models, for example in a FuelEU Maritime compliance pool.

Several actors have already examined the implications of FuelEU Maritime and pooling: see among others, contributions from Zero Carbon Shipping[112] and Wärtsilä[113]. In this chapter, we aim to provide an explanation of how the pooling mechanism can impact shipowners, while in the next and final chapter we show simulations of how pooling and different technological developments can impact the future fuel mix of the world shipping fleet.

Compliance pooling case study – 1,300 TEU methanol-capable container feeder vessel

Over the last two years many methanol-fuelled vessels have been ordered, in particular containerships. Some are already operating and others will soon follow. All are dual-fuel vessels that can run on both VLSFO/MGO and methanol. In the short to medium term, several will possibly operate on fossil fuels, primarily due to the higher prices and low availability of low GHG intensity fuels.

This picture might change with the forthcoming FuelEU Maritime Regulation, under which one methanol vessel on a low GHG intensity fuel can sell, within a 'compliance pool', its compliance surplus to several other vessels with compliance deficits. As shown in Figure 7-1, the window of opportunity for pooling with one vessel on low GHG intensity fuel is greatest in the period 2025 to 2034.

We investigate if the pooling mechanism in FuelEU Maritime could help trigger a sustainable business case for a methanol-capable vessel utilizing fully its green methanol capacity over a 10-year period from 2025 to 2034. The case study focuses only on the fuel expenses and does not consider CAPEX. Future fuel prices are collected from DNV's Marine Fuel Price Mapper model providing long-term fuel price projections (DNV, Maritime Forecast to 2050, 2023b). For simplicity, EU ETS costs are not included in this case study.

The FuelEU Maritime Regulation rewards vessels for the use of renewable fuels of non-biological origin (RFNBO, such as e-methanol). For the calculation of the GHG intensity of the energy used on board by RFNBO fuels, from 1 January 2025 to 31 December 2033 a reward factor of 2 can be used.[115] In this case study, for simplicity, we extend this time period by one year to cover also 2034. The RFNBO sub-target[116] possibly introduced from 1 January 2034, is not covered in this case study.

Case study vessel's FuelEU Maritime compliance options

There are several options for the case-study vessel to be compliant with the FuelEU Maritime Regulation without pooling with other ships. It can pay the penalty cost[117], use fuels/energy sources with lower well-to-wake (WtW) GHG intensity (i.e. bio/e-methanol, bio/e-MGO, or shore power), or utilize the FuelEU Maritime flexibility mechanisms (e.g. borrowing advance compliance surplus). In the case study, we focus on the four compliance strategies A to D seen in Table 7-2.

Early adopters are not only important for maturing technologies in the preparation phase, but also for testing and maturing cost-sharing models.

TABLE 7-3

Fuel-specific assumptions for case study

Fuel type	Price (USD/GJ)	Price (USD/ tonne)	WtW GHG intensity (gCO_2eq/MJ)
Fossil MGO	15	630	90.63
bio-MGO	35	1,470	34.05
e-methanol	60	1,200	28.20

These strategies are selected to explore the potential competitive advantage of a methanol-capable vessel compared to conventional oil-fuelled vessels. It should not be regarded as a comprehensive list of possible compliance strategies or fuels. For example, running on 100% bio-MGO is another relevant strategy to explore for offsetting other vessels' compliance deficits in a compliance pool. In Figure 7-2, we present the annual fuel cost including FuelEU Maritime penalty cost for these four strategies. For the case study we used the fuel-specific assumptions seen in Table 7-3, using e-methanol produced with 70% GHG emission savings. In addition, we do not consider CAPEX; the e-methanol capable ship has 10% pilot fuel that must be covered by MGO; and we do not include the FuelEU Maritime compliance deficit factor for ships not complying over consecutive years.

Assuming full fuel availability for the selected low GHG intensity fuels, all compliance options presented above are technically feasible for the methanol-capable container feeder vessel. However, each strategy comes with an annual cost. In particular, Figure 7-2 shows that over-complying (strategy D) costs about three times more than the other compliance options. Hence, if using maximum e-methanol is to be economically feasible, this option's net cost needs to be reduced through an additional revenue stream reflecting the reduced GHG emissions due to e-methanol use. The FuelEU Maritime compliance pooling mechanism can potentially facilitate such a revenue stream through a fee paid by pool participants with a compliance deficit to those with a compliance surplus. Such a fee can be regarded as the price paid for a 'pool ticket'.

Pool participants' willingness to pay for pool ticket

To make a pool an attractive compliance option for owners of conventional oil-fuelled vessels, the price for the pool ticket must be designed to be economically advantageous compared to the other compliance alternatives. Several factors can impact the willingness to pay for a pool ticket; for example, the price of drop-in fuels (e.g. bio-MGO). In the present case study we use a pool ticket price for owners of conventional oil-fuelled vessels derived from:

1. the cost of paying FuelEU Maritime penalty for compliance

2. the additional cost of using drop-in fuels (e.g. bio-MGO) to bring the well-to-wake GHG intensity in line with reduction requirements.

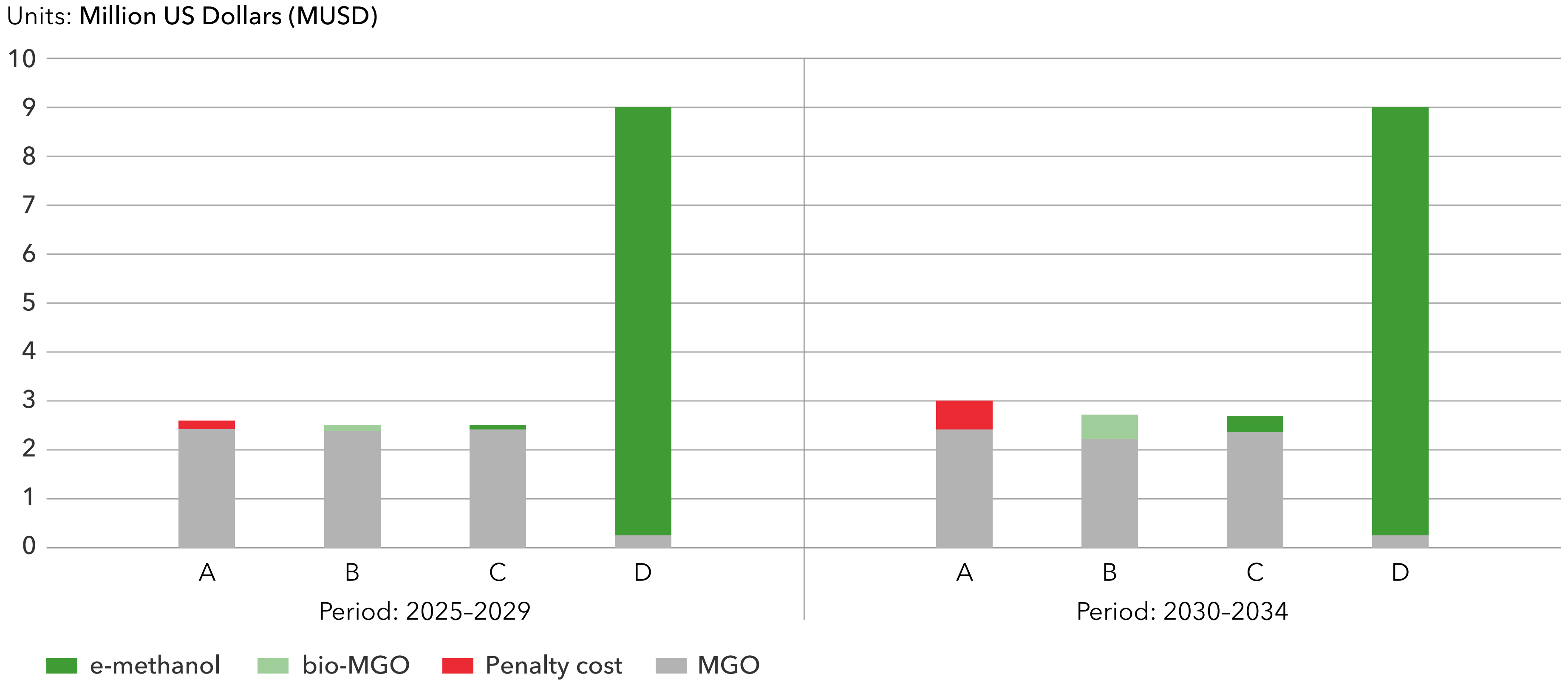
Figure 7-3 illustrates the pool ticket price dynamics with a scenario where the annual cost of blending in a drop-in fuel (e.g. bio-MGO) is seen in the right column and is lower than paying the penalty for the fossil-fuelled vessel, seen in the left column. In this scenario, the pool participant is likely to be willing to pay a pool ticket price which is comparable to the cost of using the drop-in fuel, seen in the middle column. With a higher price on the drop-in fuel, the cost of paying the penalty could be the dimensioning cost, resulting in a higher willingness from the pool participant to pay for the pool ticket.

Methanol-capable vessel in a compliance pool

With the constraints on pool ticket price discussed above, a key question is whether or not the business case still adds up for an owner with methanol-capable tonnage to utilize its full methanol consumption capacity. Here, we assess a compliance pool's impact on the case study vessel's annual fuel expenses in the period 2025 to 2034. As illustrated in Figure 7-1, a methanol vessel running on full e-methanol (90% methanol, produced with 70% GHG saving) capacity can offset the deficits of 55 fossil MGO vessels with the same energy consumption in

FIGURE 7-2

Annual fuel expenses (including penalty cost) for the case-study vessel exploring the selected four FuelEU Maritime compliance strategies described in Table 7-2 - CAPEX not included



EU/EEA[118] for the period 2025 to 2029, and 13 fossil MGO vessels for the period 2030 to 2034. In Figure 7-4, we present the annual fuel expenses for the methanol-capable vessel both in a pool and outside (same individual compliance strategy C as shown in Figure 7-2).

On the basis of the results presented in Figure 7-4, the pooling mechanism appears to have the potential to encourage the use of full green-methanol capacity in the methanol-capable container feeder vessel. The results are highly sensitive to fuel prices and the GHG intensity, however. This simplified analysis shows that FuelEU Maritime has the potential to be a tool for sharing costs and driving the uptake of alternative fuel technologies and their corresponding low GHG intensity fuels.

The analysis presented here focuses on pooling as a tool for decreasing the costs for first movers, but there are also other potential benefits of being a first mover, such as green financing opportunities, premiums for net-zero emission transport services, and support for establishing green shipping corridors.

Pooling can reduce the costs of decarbonization

There are discussions in the IMO (as seen in Chapter 3) on introducing a GHG fuel intensity requirement (measured as gCO_2eq/MJ) for shipping, requiring a gradually increasing use of low GHG emission fuels. Similar to under FuelEU Maritime, the IMO is also considering a flexibility mechanism where the GHG fuel intensity requirement can be met by pools of ships rather than by individual ships. In (DNV, 2024a), we used the GHG Pathway Model to assess the impact of including a pooling mechanism globally as part of the IMO GHG fuel intensity requirements. The impact is greatest in the early phase to 2030 when there are capital-intensive solutions, such as ammonia or methanol engines or onboard carbon capture systems, which enable ships to run on fuels with lower prices than drop-in fuels such as bio- and e-MGO. An additional benefit of the pooling mechanism comes during the early phase with the build-up of production and infrastructure for alternative fuels when low GHG emission fuels have limited global availability. Instead of requiring each ship to find low GHG emission fuel, the mechanism allows for ships that cannot find such fuels to pool with ships trading in areas where these fuels are more readily available. The report indicates that a pooling mechanism can reduce the total cost per tonne of GHG emission reduction by 6% in the period 2023–2050.

FIGURE 7-3

Pool participant's willingness to pay for pool ticket

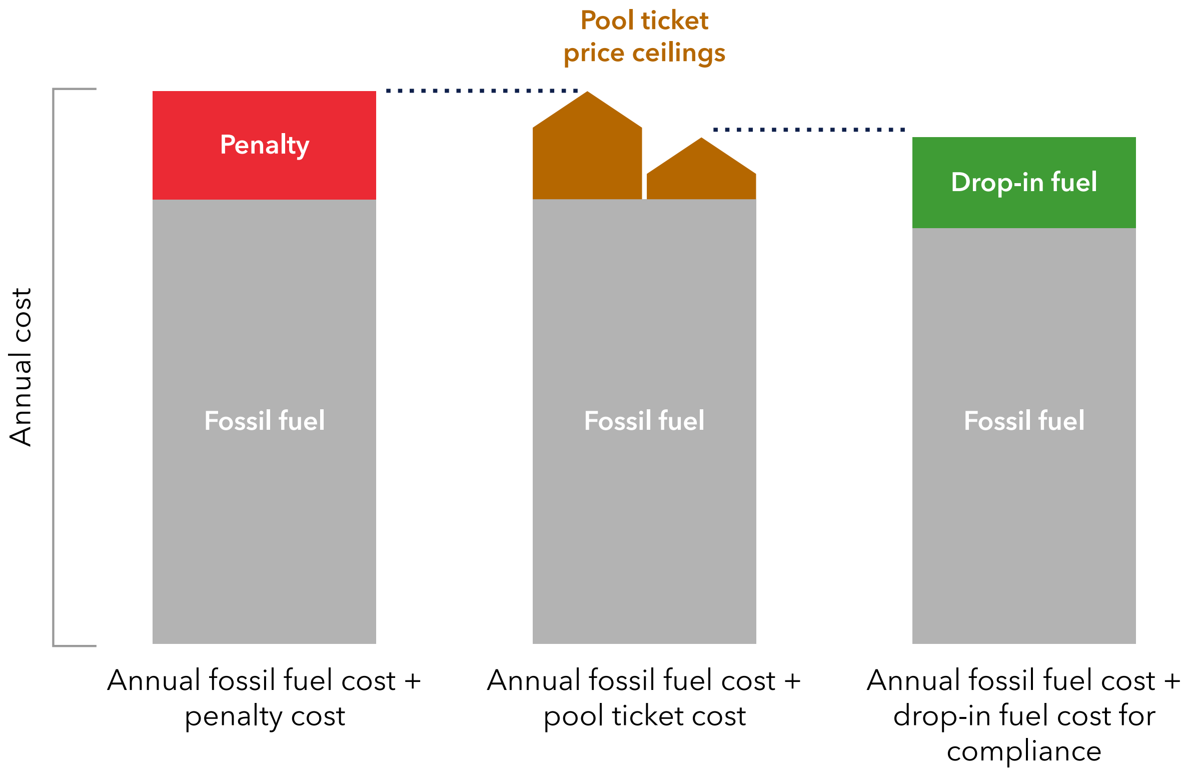
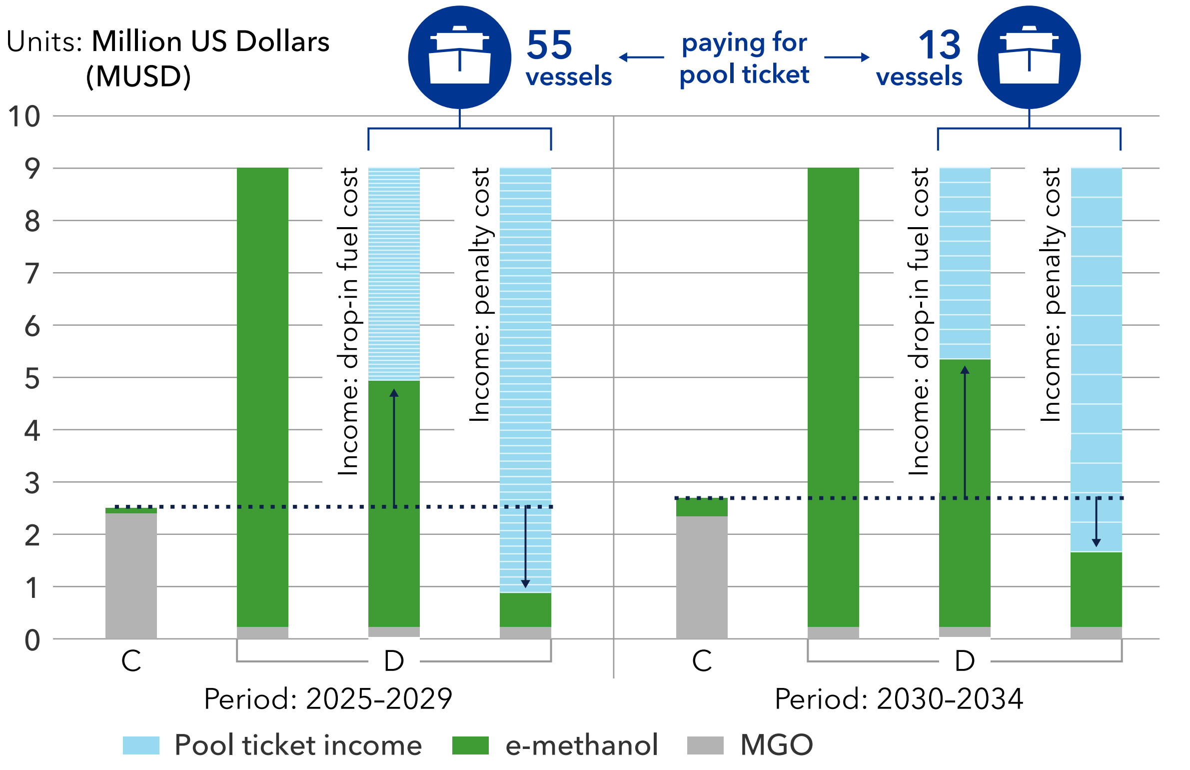


FIGURE 7-4

Annual fuel expenses including pool ticket income for a methanol-capable vessel in a FuelEU Maritime compliance pool



8 PATHWAYS FOR DECARBONIZATION OF SHIPPING

Highlights

Building on our previous modelling, we investigate the conditions under which uptake of certain fuel types will accelerate with decarbonization towards 2050, finding that:

- Small changes in fuel prices lead to significantly different fuel mixes.
- Decarbonizing shipping will double the cost of transporting goods by containers.
- Onboard carbon capture has the potential to become an important technology for reducing greenhouse gas emissions from shipping.
- While biofuel and electrofuel production grows and carbon capture projects boost the output of blue fuels and the use of onboard carbon capture at scale, shipping should mitigate the potential shortfall of carbon-neutral fuels by maximizing the energy efficiency of ships.

Shipping's fuel transition is heading forward on divergent courses towards LNG, methanol, and ammonia, while production of carbon-neutral fuels is commencing. There is uncertainty over several factors influencing the transition, and we shed light on these in presenting explorative scenarios for decarbonization. We use an updated version of our GHG Pathway Model that we applied previously to generating a library of scenarios spanning uncertainties over regulation, fleet growth and energy cost. We now investigate conditions under which uptake of specified fuel types will accelerate with decarbonization towards 2050. We estimate the increased transport costs of decarbonization for the container, tank, and bulk segments.

This year's work builds on our scenario-based framework presented in previous editions of our Maritime Forecast to 2050.[119] There have been significant updates to the GHG Pathway Model since (DNV, 2022), aiming to reflect changes to the technological and regulatory landscape. The inputs in terms of technology costs and fuel prices have been updated, and major changes to the model are the inclusion of GHG fuel intensity regulation requirements with or without ship pooling, well-to-wake (WtW) emission factors, the FuelEU Maritime Regulation, onboard carbon capture and storage, liquid organic hydrogen carriers (LOHC) and nuclear propulsion. Details on the GHG Pathway Model and on input used in the modelling can be found in the Appendix section A.2.

8.1 Exploratory scenarios where different fuels gain a significant market share

Today, shipping is at a point where several fuel technologies are being tested or rolled out. The uptake of LNG is continuing, a large number of methanol and LPG-fuelled ships are in the order book, ammonia is emerging as a ship fuel, hydrogen is being used, ferries are being electrified, and onboard carbon capture is being tested (see Chapters 4 and 6). Use of biodiesels is increasing, and there are large-scale plans for methanol, ammonia, and hydrogen production, as well as plans for carbon storage (see Chapters 5 and 6).

In this preparation phase of a fuel and technology transition in shipping, there are fundamental uncertainties associated with cost, efficiency, and availability, for a range of fuels and technologies. Given the range of uncertainty in input parameters, it is currently challenging to make projections that consistently predict approximately the same fuel mix.

The scenarios presented in this chapter should be understood as an exploration of decarbonization for shipping without too strong constraints on key inputs (e.g. feedstock supply, carbon storage capacity) and opportunities for new and novel technologies (e.g. fuel cells, onboard carbon capture, nuclear propulsion). We investigate how changing a certain subset of inputs – fuel prices, CAPEX, CCS deposit cost, nuclear availability – in the GHG Pathway Model can result in future fuel mixes with a high uptake of different fuels. The other inputs are fixed (e.g. GHG regulations, seaborne trade, cost and emission reduction from energy-efficiency measures). One should be careful in drawing conclusions from analysing a single scenario, as any given scenario has several input assumptions that must be true for the results of the scenario to come true.

The scenarios we simulate achieve decarbonization by 2050 as well as the IMO's indicative checkpoints of a 70% reduction of GHG emissions by 2040, and 20% by 2030, both relative to 2008 and achieved through a WtW GHG intensity requirement without any pooling or IMO GHG pricing mechanisms. Note that our scenarios do not include variations on policy measures which also could impact the future fuel mix

– for example, a pooling mechanism, or rewards for using e-fuels (DNV, 2024a). The scenarios presented here have higher required amounts of carbon-neutral fuels in 2030 than estimated in (DNV, Maritime Forecast to 2050, 2023), due to higher growth in trade from 2021 to 2023 than expected in previous studies, less time in the model to implement energy-efficiency measures, and use of non-zero WtW emission factors for carbon-neutral fuels.

The fuel prices used in the modelling are based on estimated costs of producing fuels, which we have obtained by using the Marine Fuel Price Mapper (see Appendix section A.1). From DNV's Energy Transition Outlook model (DNV, 2023a) we use modelled prices for blue and green hydrogen and electricity in the grid, together with CAPEX and operational expenditure (OPEX) for production plants and efficiency of production processes found in literature to estimate a reference cost of the different carbon-neutral fuels. Our projected reference costs of fuels are within the ranges presented in other studies. These fuel-cost projections are both uncertain and greatly impact the simulation results for the world fleet fuel mix. For example, biofuels are projected at low costs today, but their availability and competition from other sectors for them are uncertain and biofuel prices could increase from our reference projections. While electrofuels are projected to decline in price, it is uncertain how far.

Exploratory scenarios

We present four exploratory scenarios (see Table 8-1) developed with the goal of achieving a significant uptake of a specific fuel or technology (biofuels and onboard carbon capture, methanol, ammonia and hydrogen). The exploratory scenarios are as follows:

- **Bio and fossil with CCS** – There is a high availability of sustainable biomass as feedstock for making bio-MGO, bio-LNG, and bio-methanol for shipping, though with a moderate increase in price over time. At the same time, the CCS industry and infrastructure develops onshore, making onboard carbon capture available for ships from 2030. We assume that nuclear propulsion is available from 2040 onwards.
- **Methanol** – Successful first movers further increase the methanol technology share in the order book, driving the development of methanol production and bunkering infrastructure. Due to the attainment of economies of scale in production and transport, bio-methanol achieves lower production cost than both bio-MGO and bio-LNG, for which capacity is highly sought-after in each case by other sectors, leading to higher prices. Due to both limited availability of sustainable biomass feedstock and competition for biofuels from other sectors, e-methanol eventually becomes the lowest-cost production pathway for carbon-neutral methanol.
- **Ammonia** – There is biofuel scarcity due to heavy competition from other industries for biofuels and a limited supply of sustainable biomass, driving up the price of biofuels. There is a limited supply of sustainable carbon from point sources, resulting in CO_2 from direct air capture being used as feedstock in carbon-based electrofuels, driving up the price of carbon-based electrofuels relative to ammonia. Ammonia is used as a long-distance energy carrier for different industries, and there is a high level of seaborne transport of ammonia. Ships using ammonia cargo as fuel drive technological improvements in engines, ammonia tanks, and fuel cells, as well as development in infrastructure. A rapid decarbonization of electric power production on land leads to a surplus of low-cost renewable or nuclear electric energy, with ammonia used as an energy carrier over long distances.

TABLE 8-1

Overview of each exploratory scenario

Scenario differentiators	Exploratory scenario			
	1. Bio and fossil with CCS (Fig. 8-1)	**2. Methanol** (Fig. 8-2)	**3. Ammonia** (Fig. 8-3)	**4. Hydrogen** (Fig. 8-4)
Biomass availability	High	Low		
Supply of sustainable carbon	Moderate		Low	
Availability of low GHG electricity	Moderate		High	
CCS deposit cost	60–80 USD/tCO_2	130 USD/tCO_2		
Nuclear propulsion availability	From 2040	From 2050		
Liquid hydrogen fuel tanks and fuel-cell CAPEX	Moderate			Low

– **Hydrogen** – There is biofuel scarcity due to heavy competition from other industries for biofuels and a limited supply of sustainable biomass, driving up the price of biofuels. There is a limited supply of sustainable carbon, resulting in CO_2 from direct air capture being used as feedstock in carbon-based electrofuels, driving up their price relative to hydrogen. A rapid decarbonization of electric power production on land leads to a surplus of low-cost renewable or nuclear electric energy, with hydrogen used as an energy carrier over long distances. There is a high level of seaborne transport of molecular liquefied hydrogen due to industries using hydrogen directly at large scale. Ships using hydrogen cargo as fuel drive technological improvements in fuel cells and hydrogen tanks. The technological improvements and increase in uptake of fuel cell technology and liquefied hydrogen tanks leads to both lower CAPEX for ships and lower costs of hydrogen as fuel, due to lower transport costs for the fuel itself.

Table 8-1 provides an overview of the key differences between scenarios, and Figures 8-1 through 8-4 provide simulation results.

Takeaways
Key differentiators for each scenario include the significant uptake of nuclear and bio-LNG (scenario 1), bio-methanol, e-methanol, and e-LNG (scenario 2), blue ammonia and e-ammonia (scenario 3), and finally, blue liquid hydrogen (LH_2) and e-LH_2 combined with fuel-cell technology (scenario 4).

FIGURE 8-1
Bio and fossil fuels with CCS scenario - fuel use in shipping by energy
Units: Million tonnes of oil equivalent (Mtoe)

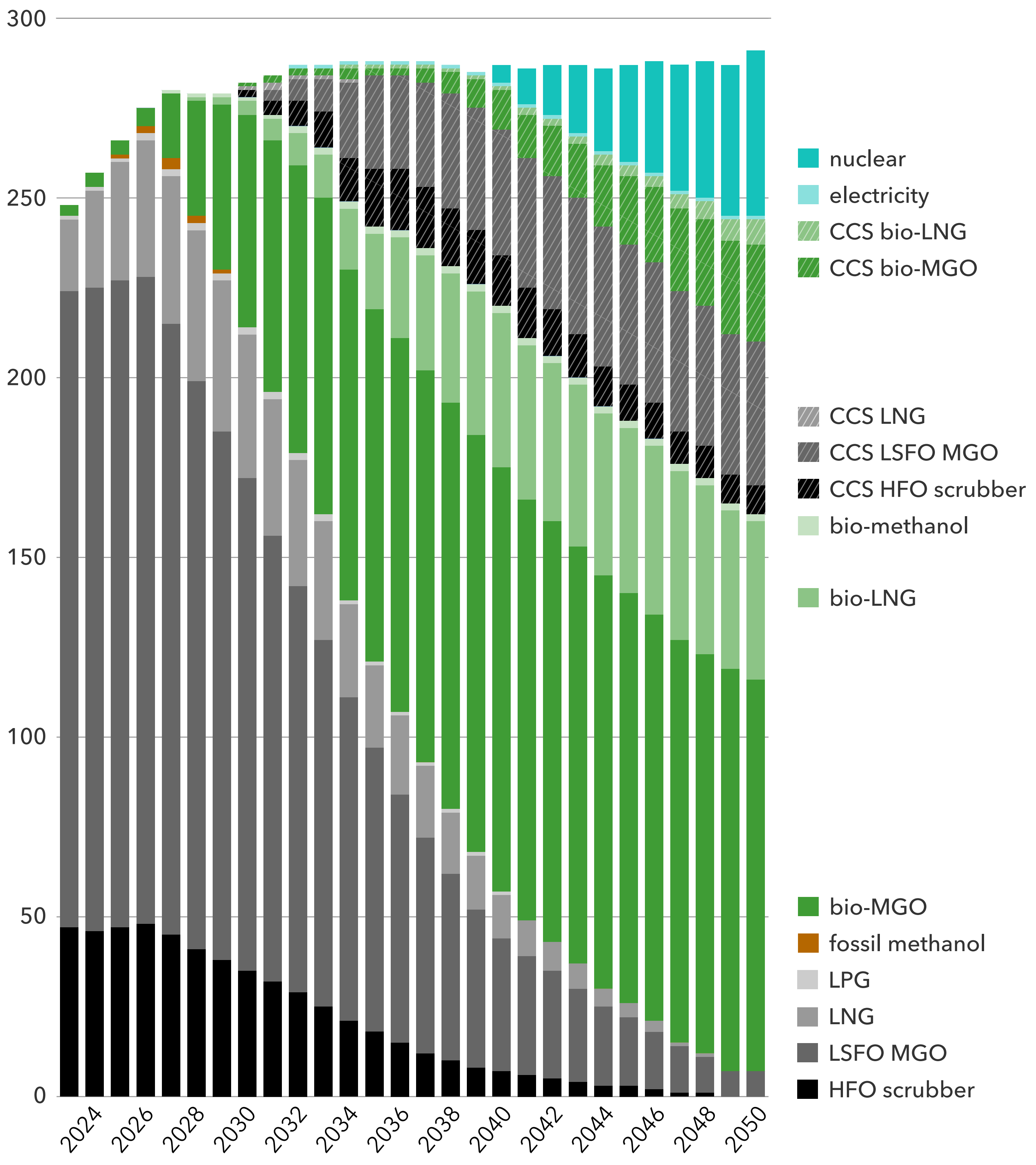
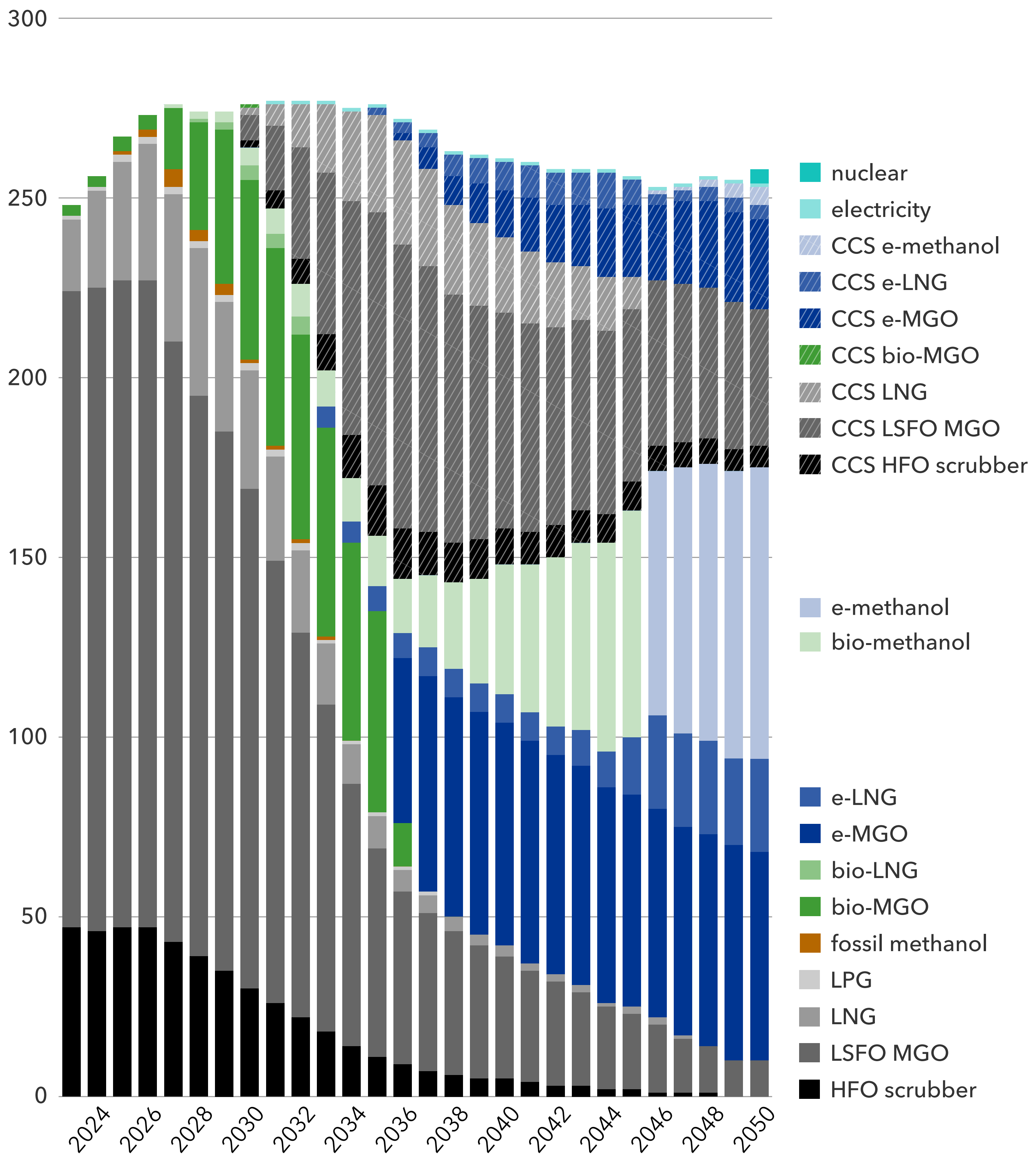


FIGURE 8-2
Methanol scenario - fuel use in shipping by energy
Units: Million tonnes of oil equivalent (Mtoe)



While each scenario results in a unique fuel mix, there are several commonalities. For example, we see a gradual phasing out by 2050 of fossil fuels unabated by carbon capture. In all scenarios, onboard carbon capture emerges as an important technology for GHG reduction after 2030, effectively reducing the volume of carbon-neutral fuels required. However, the need for carbon-neutral fuels is still high, and as we have seen in Chapters 5 and 6 of this report and in (Ricardo; DNV, 2023), it is challenging to attain sufficiently high levels of production of carbon-neutral fuels and carbon storage in the short term towards 2030. While the production of biofuels (bio-MGO, bio-LNG, bio-methanol) and electrofuels is increasing, and while carbon capture projects come online allowing for both increased production of blue fuels and the use of onboard carbon capture at scale, shipping should mitigate the potential shortfall by improving the energy efficiency of ships as far as possible.

Carbon-neutral MGO (i.e. bio-MGO and e-MGO) sees significant uptake in the fuel mix leading up to 2050, in the 2030s and 2040s in each case, as many ships in the model still use mono-fuel engines. No single fuel or technology dominates in any of the scenarios; instead, the energy and technology mix consists of a diverse set of fuels and technologies.

FIGURE 8-3

Ammonia scenario – fuel use in shipping by energy

Units: Million tonnes of oil equivalent (Mtoe)

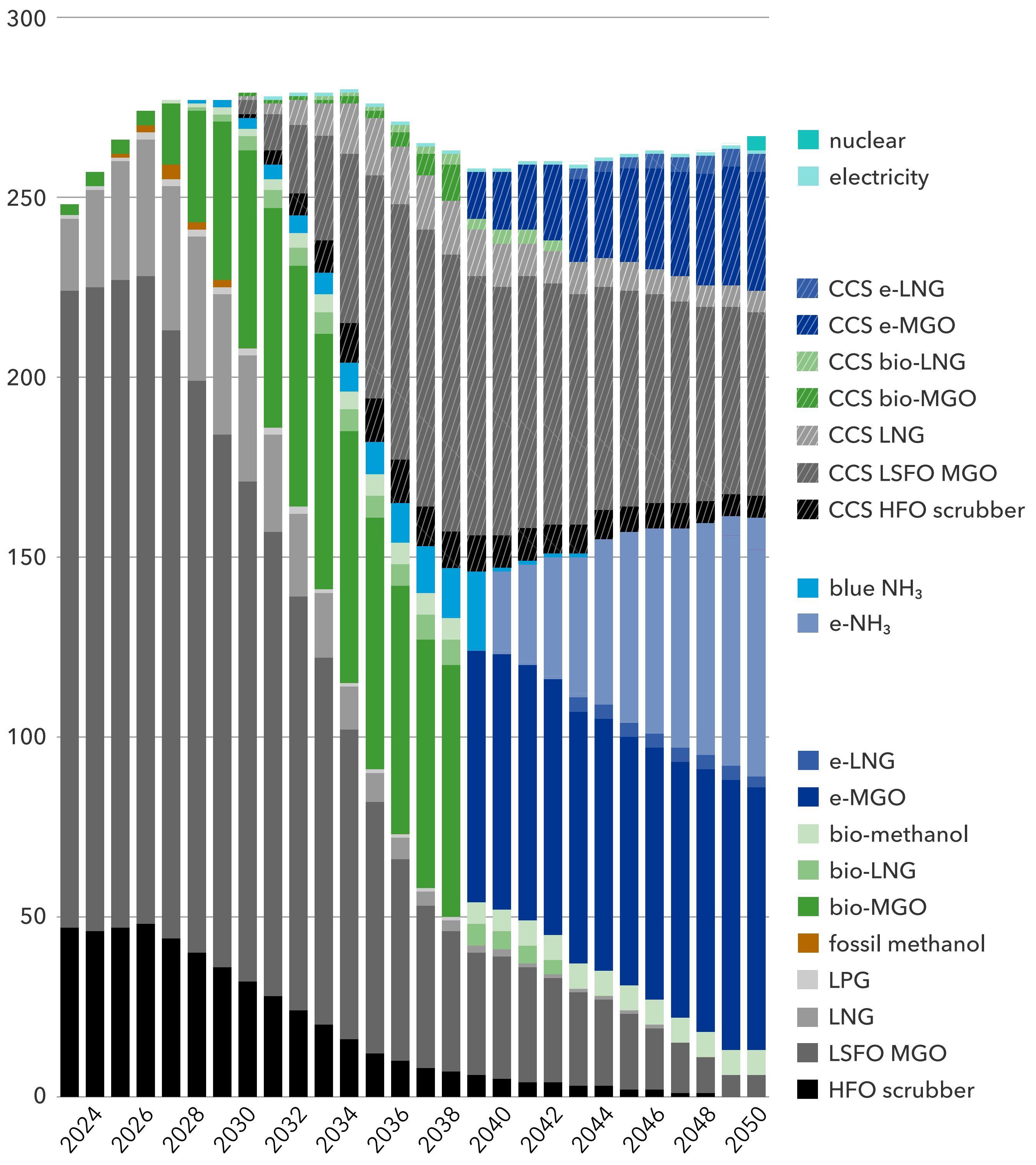
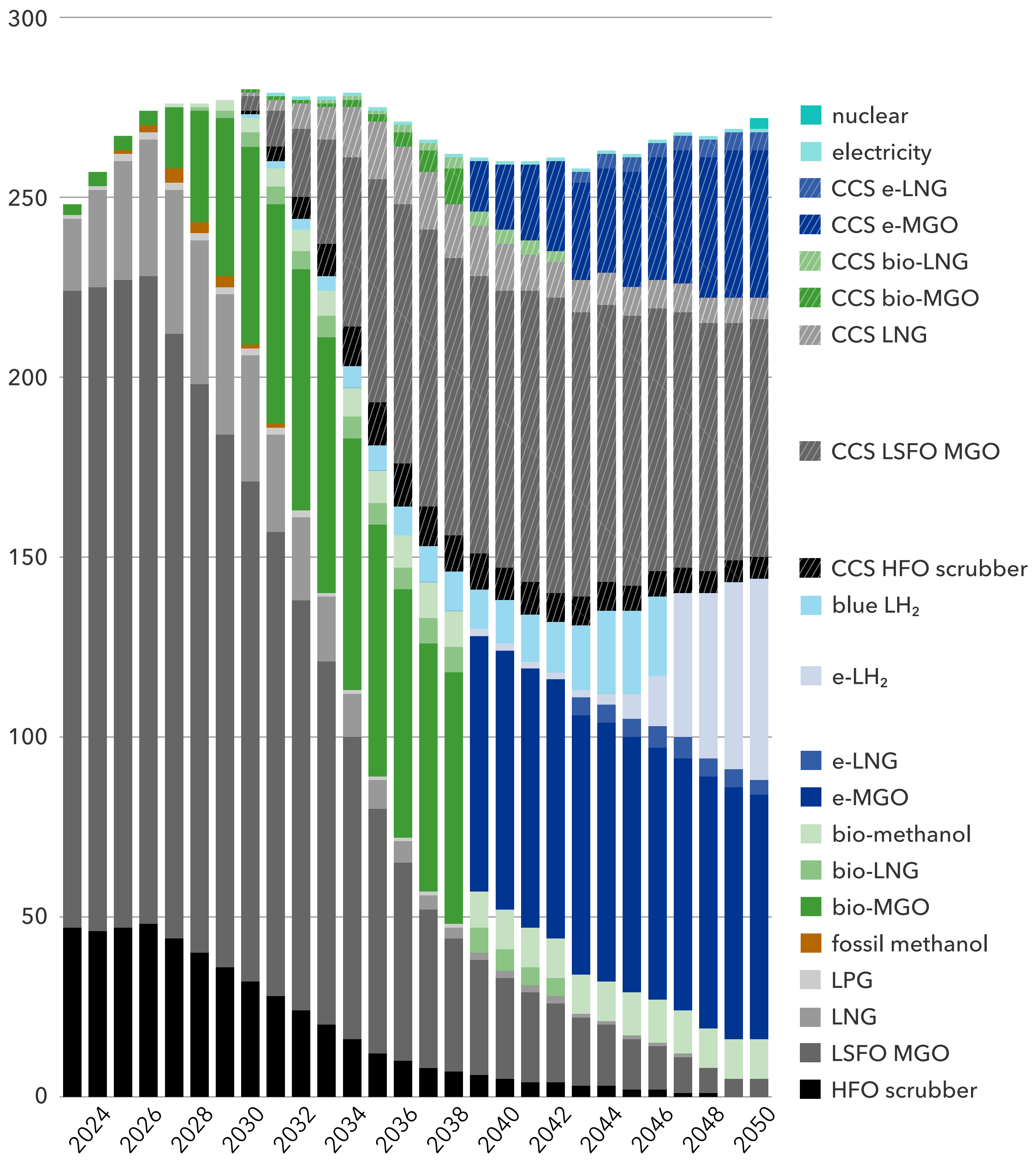


FIGURE 8-4

Hydrogen scenario – fuel use in shipping by energy

Units: Million tonnes of oil equivalent (Mtoe)



8.2 Increased transport costs from decarbonization

In (DNV, 2022) we showed total CAPEX needed for the decarbonization of shipping, as investments in both ships and onshore carbon-neutral fuel production. This year, we instead show the relative increase in total costs of decarbonization for operating ships in a given shipping segment for a given year – total costs including CAPEX of ships and onboard technologies, OPEX, CO_2 price, fuel costs and CCS deposit cost – using the three largest shipping segments: container vessels, bulkers, and tankers. Using the GHG Pathway Model, we obtain estimates for the cost of decarbonization for these shipping segments in 2030, 2040, and 2050. The cost increase per transport work[120] for the four scenarios presented in Section 8.1, has been found by comparing with a business-as-usual scenario, and is seen in Figure 8-5.

Our projected increases in costs are dependent upon the scenario inputs, and in particular our fuel price projections have a strong impact. The increase in cost intensity in 2050 for our four scenarios was 69% to 75% for bulk carriers, 70% to 86% for tankers, and 91% to 112% for container vessels. Scenario 1 with high availability of biofuels and lower-cost CCS requires the least CAPEX and has lower total cost of decarbonization than for scenarios 2, 3, or 4.

Investigating the shipping of containers between Shanghai and Los Angeles, (Perico, Bonello,

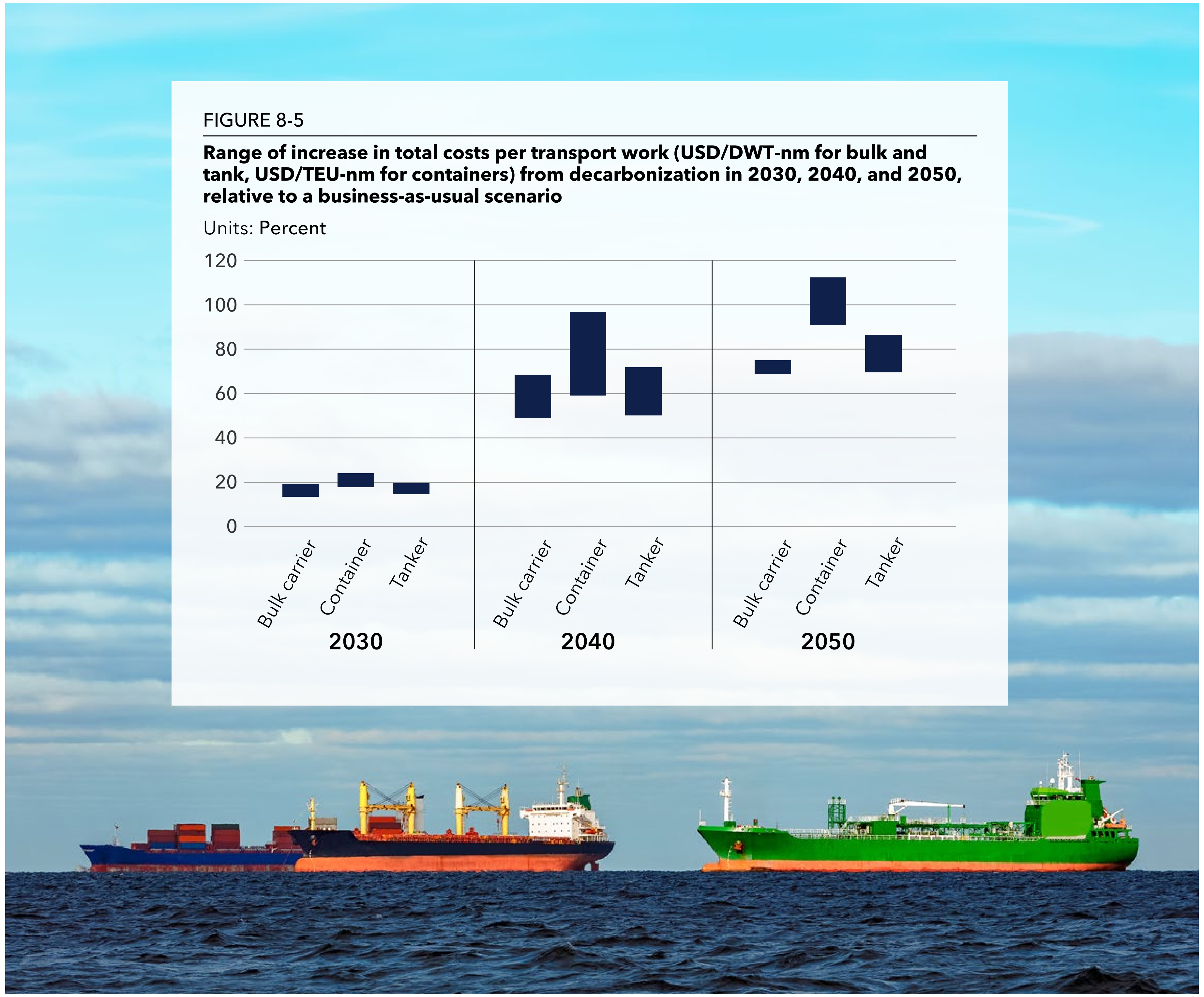


FIGURE 8-5

Range of increase in total costs per transport work (USD/DWT-nm for bulk and tank, USD/TEU-nm for containers) from decarbonization in 2030, 2040, and 2050, relative to a business-as-usual scenario

Rehmatulla, & O'Keefe, 2023) estimated an increased cost of 90–450 USD/TEU in 2030 from running on carbon-neutral fuels, while (IEA, 2024) estimated an increase in freight rates in 2030 of 250 USD/TEU.

In (DNV, 2024a), when investigating scenarios achieving the IMO's base ambitions of 20% and 70% reduction of WtW emissions in 2030 and 2040, respectively, and net-zero by 2050, the ranges of percentage increases in cost per tonne-mile relative to a business-as-usual scenario were estimated to be 16% to 40% in 2030, 56% to 71% by 2040, and 71% to 85% by 2050. The study shows similar differences between the ship segments with higher cost increases for container vessels compared to tankers and bulkers.

Decarbonizing shipping will come at a significant cost, and with increasing costs for owning and operating ships there will have to be an increase in freight rates to compensate. To maintain the same average return on capital invested and used in a shipping segment, the freight rates will have to increase, on average, by the same ratio as the average costs for operating a ship in that segment increase.[121] Ultimately, the increased costs of seaborne transport will have to be moved through the value chain to the consumer as an increase in the price of goods, and there are already movements in the market to move costs to consumers.[122]

APPENDIX

A.1 Projection on fuel prices

Future fuel prices are challenging to predict. We have updated DNV's Marine Fuel Price Mapper tool, see (DNV, 2022) and (DNV, Maritime Forecast to 2050, 2023), that allows us to estimate ranges in production and distribution costs per fuel. We model the production steps for different processes and include the regional costs for different kinds of biomass, electricity, fossil energy, and carbon capture and storage, aligned with DNV's ETO model of the global energy system until 2050 (DNV, 2023a).

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

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

- production and processing steps
- distribution
- cost of CO_2 feedstock (as applicable).

Fossil fuels – Historical relationships between fossil-fuel price and the price of crude oil or natural gas are used to estimate future fuel prices.

Figure A-2 shows our estimated high and low prices for fuels in the period 2030 to 2050. Due to the significant uncertainty in estimating future fuel prices, we have developed scenarios with increased and decreased prices from our baseline price esti-mates. For each year, we calculated the global mean average of all 10 ETO global energy system model regions, and then found the minimum and maximum price per fuel over the given period.

FIGURE A-1

DNV's Marine Fuel Price Mapper

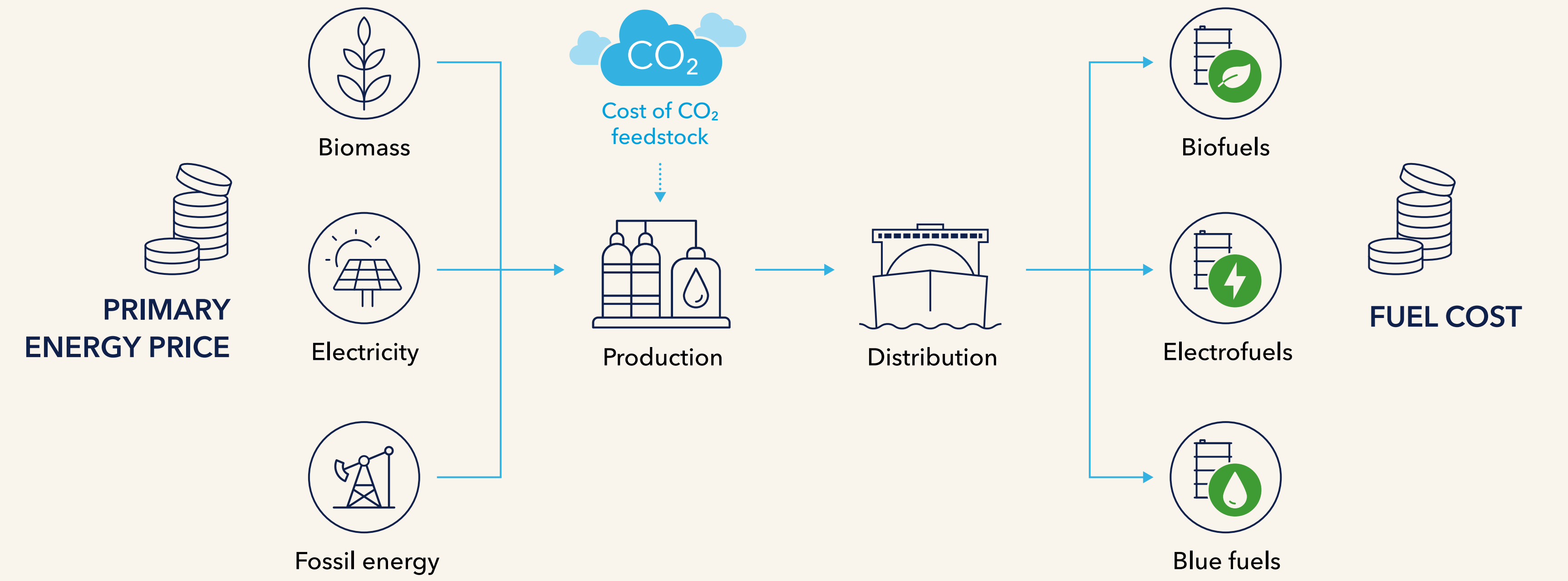
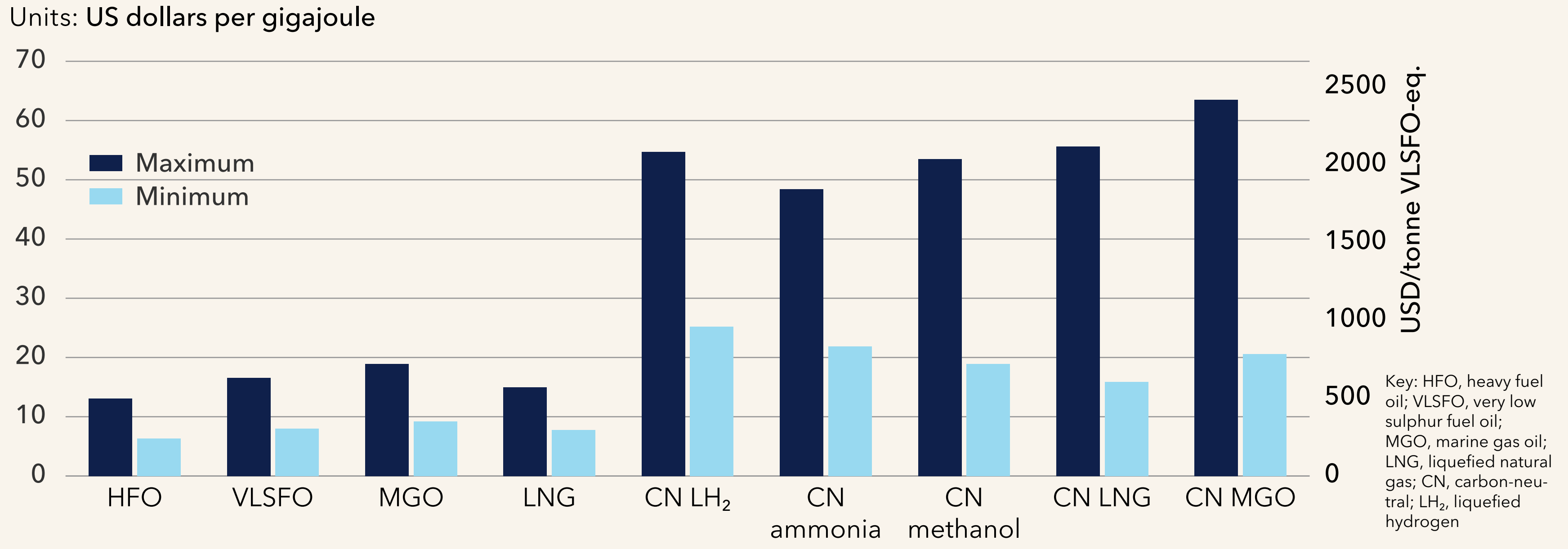


FIGURE A-2

Estimated high and low prices for fuels in 2030–2050 include production and distribution costs and have been taken as a global mean average of all regions. Fossil-fuel prices do not include carbon price.



A.2 DNV's GHG Pathway Model description

The modelling approach we use is to gather a large set of inputs, such as the cost of equipment on ships and for future fuels (see upper part of Figure A-3), and then to use these in two core evaluation modules (middle part of Figure A-3):

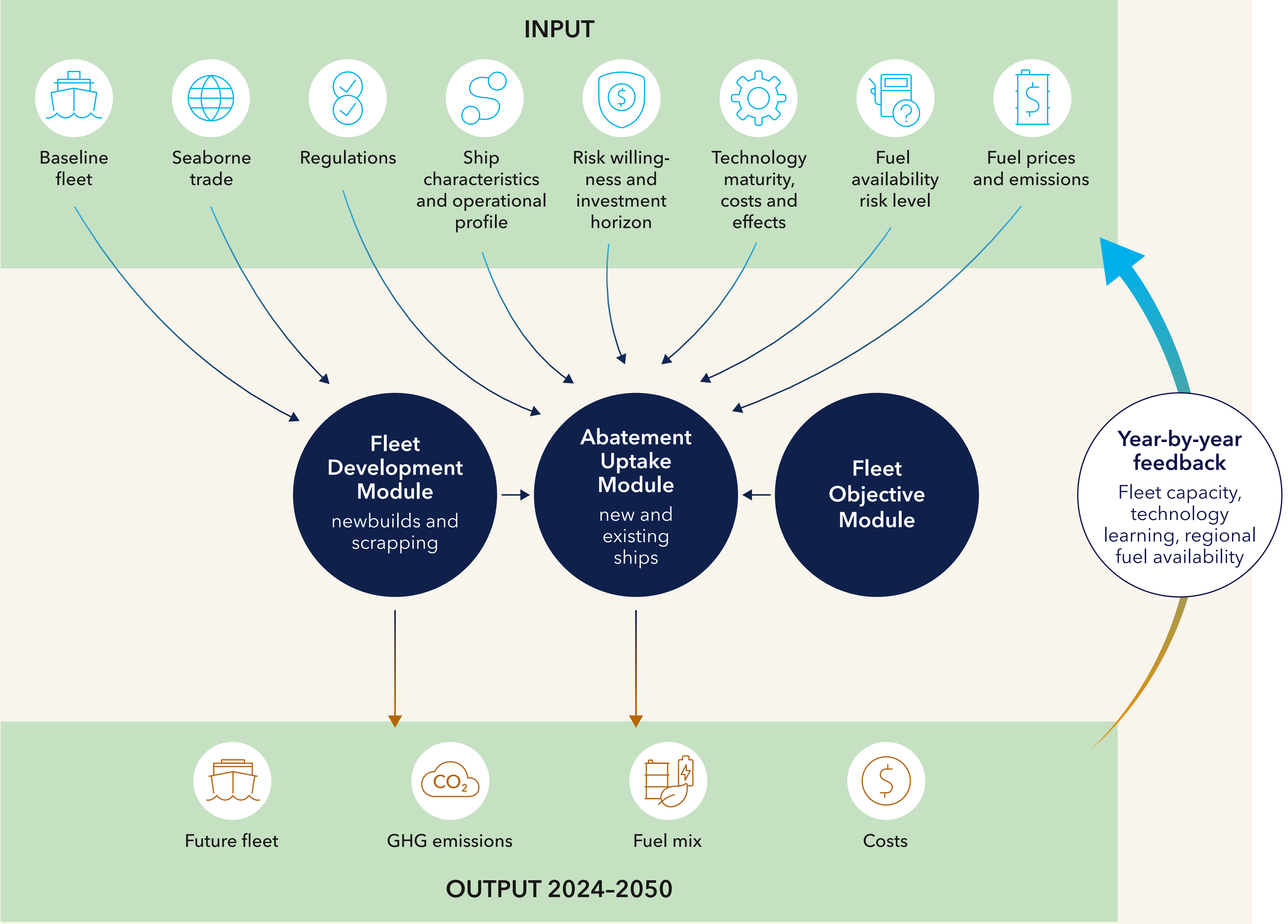
- **the Fleet Development Module**, building and scrapping ships to meet transport demand.
- **the Abatement Uptake Module**, choosing technology and fuels for ships to meet regulations at the lowest cost; the model simulates the world fleet ship-by-ship and year-by-year, providing detailed output (lower part of Figure A-3) on the ships of the future fleet, CO_2 emissions, fuel mix and costs.

DNV's GHG Pathway Model for the future fuel mix of the world fleet is explained in (DNV, 2022) and (DNV, 2024a). This year's enhanced model includes several major upgrades:

- Optional: **Well-to-wake (WtW) emissions from fuels**. Previously, we have used tank-to-wake (TtW) emissions for fossil fuels and zero GHG emissions for carbon-neutral fuels; now we can model different sets of WtW factors and different TtW schemes. The scenarios presented in Chapter 8 use WtW factors.
- Optional: **Fuel Intensity.** We can now include emissions regulations based on Fuel Intensity (gCO_2eq/MJ of fuel heating value), such as is the case for FuelEU Maritime, as opposed to regulations on technical design of ships (e.g. EEDI/EEXI) or on carbon intensity of transport work (e.g. CII). The scenarios presented here use this Fuel Intensity option. The requirements can be set on a regional basis, such that the effect of stricter requirements in the EU through FuelEU Maritime can be simulated.
- Optional: **Pooling.** It is now an option to include regulations for a global or regional pooling mechanism of compliance, where a group of ships can pool together to meet Fuel Intensity requirements. The scenarios presented in Chapter 8 do not use this option.
- **FuelEU Maritime.** The Fuel Intensity regulations of FuelEU Maritime have been included for region Europe in the model, in addition to the global fuel intensity requirement. The pooling regulation can be included as an option but is not used in the scenarios presented in Chapter 8.
- **Order book.** The model incorporates the existing order book as the first ships to be built by the Fleet Development Module.
- **Retrofitting of energy-efficiency technology packages.** The model now evaluates every fifth

FIGURE A-3

The GHG Pathway model



year from its newbuild if retrofitting of energy-efficiency technologies contributes to the most cost-optimal abatement solution to meet the future requirements. The retrofit investment is considered to be 50% higher compared to a similar investment at a newbuild.

- **Liquid organic hydrogen carrier (LOHC)** has been included as a fuel and technology option, either for use with internal combustion hydrogen engines or fuel cells.
- **Nuclear** propulsion has been included. When included in scenario results of future fuel mix, the nuclear share of the fuel mix is represented as the amount of tonnes of very low sulphur fuel oil (VLSFO) that conventional ships would have used instead of nuclear. The main modelling features are:
  - nuclear propulsion is allowed from 2040 in scenario 1, from 2050 in scenarios 2, 3 and 4
  - only reactor sizes of 15 MW are available
  - nuclear ships are able to use MGO as fuel for any remaining energy needs
  - reactors are assumed to be leased, with annual leasing cost calculated as an annual down-payment on an annuity loan with 8% interest over 15 years:
    - reactor CAPEX of 8,000 USD/kW
    - with an additional 2.5 MUSD in annual OPEX covering additional crew/remote monitoring, refuelling, and fuel decommissioning
    - for a total annual leasing cost of 16.5 MUSD per 15 MW reactor.
- **Onboard carbon capture (OCC).** Onboard carbon capture has been included, with up to 75% capture rate from produced CO_2 on a ship, using 40% additional fuel in the capture process. CO_2 deposit costs (including offloading, transport, and sequestration) start at 80 USD/tCO_2 in 2030 and decrease linearly to 60 USD/tCO_2 in 2050 in scenario 1. For scenarios 2, 3 and 4, CO_2 deposit cost is 130 USD/tCO_2 every year.

This year's enhanced GHG Pathway Model includes several major upgrades.

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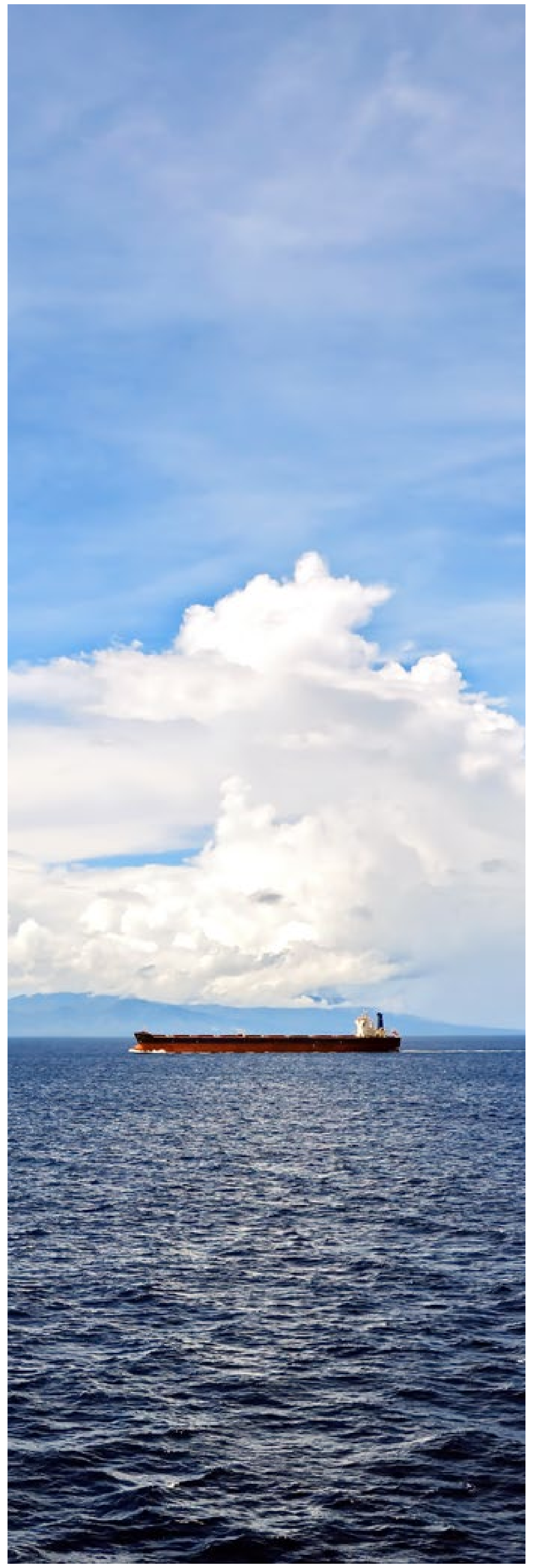

ENDNOTES

Click on an endnote number to navigate to the related page

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98 DNV ETO report (most likely scenario) forecast 1,200 MtCO_2/year in 2050.

99 https://fissilematerials.org/library/doe14.pdf
US Navy cost estimates https://www.everycrsreport.com/files/20070126_RL33360_baec28455c9fb7ccbdc3de-f7605a46f28686ca90.pdf
https://en.wikipedia.org/wiki/United_States_naval_reactors

100 https://seekingalpha.com/arti-cle/4212171-lightbridge-corporation-per-ilous-past-obscures-promising-future

101 A sailing Russian nuclear-powered cargo ship built in 1988 https://en.wikipedia.org/wiki/Sevmorput

102 In nuclear power, MW(e) denotes the electric output of a reactor, while MW(th) is the thermal output. Electrical efficiency is typically 30–35%, i.e. MW(e) is usually 30–35% of MW(th).

103 https://www.iaea.org/sites/default/files/21/07/iaea_webinar_marine-based_smrs_bandi-60_bj_lee_18may2021.pdf

104 https://en.wikipedia.org/wiki/Light-wa-ter_reactor

105 https://www.gen-4.org/gif/jcms/c_207614/travis-boyce-nrc-readi-ness-and-plans-for-non-lwr-licensing

106 https://www.nrc.gov/docs/ML2114/ML21145A106.pdf

107 https://www.world-nuclear-news.org/Articles/Korean-nuclear-suppli-ers-team-up-for-export-drive

108 smr_rf_phase_3_summary_report.pdf (iaea.org)

109 https://eur-lex.europa.eu/eli/reg/2023/1805/oj

110 Using 70% GHG saving as the lower bound as FuelEU Maritime requires 70% GHG saving for e-fuels such as e-metha-nol.

111 The Zero Emissions Maritime Buyers Alliance (ZEMBA) is an initiative aiming to accelerate commercial deployment of zero-emission shipping by pooling cargo owner green transportation demand.

112 https://www.zerocarbonshipping.com/news/explainer-pooling-and-the-busi-ness-case-for-green-shipping

113 https://www.wartsila.com/insights/article/vessel-pooling-what-is-it-and-how-does-it-help-you-avoid-fueleu-maritime-penal-ties?mc_cid=593f4d5b4a&mc_eid=UNI-QID

114 Based on average reported (IMO DCS) annual fuel consumption for container feeders of same size. Reduction by almost 10% to reflect modern vessel and ener-gy-efficiency improvements.

115 Note that this reward factor is only appli-cable for RFNBO fuels in the FuelEU Maritime Regulation.

116 The European Commission shall monitor the annual consumption of RFNBO used on board by ships falling under the scope of FuelEU Maritime. If the share of RFNBO is less than 1% for the reporting period 2031, a sub-target of 2% shall apply for such fuels in the yearly energy used on board by a ship from 1 January 2034.

117 See FuelEU Maritime Regulation (REGU-LATION (EU) 2023/1805 OF THE EURO-PEAN PARLIAMENT AND OF THE COUN-CIL of 13 September 2023) Annex IV.

118 European Economic Area (EEA) includes EU countries and Iceland, Liechtenstein, and Norway.

119 (DNV GL, 2019), (DNV GL, 2020), (DNV, 2021), (DNV, 2022).

120 USD/DWT-nm or USD/TEU-nm, with a modelled utilization of the cargo capacity of the different ship types; DWT-nm; deadweight tonne nautical miles; TEU-nm, twenty-foot equivalent unit nautical miles.

121 Assuming simple formula:
Return = (freight rates – costs) / costs

122 https://www.tradewindsnews.com/containerships/cma-cgm-joins-liner-oper-ator-rivals-in-passing-eu-emissions-trad-ing-costs-to-customers/2-1-1530493

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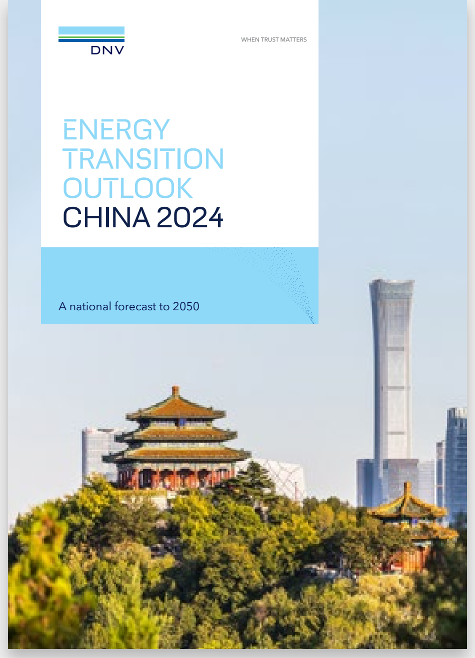

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