



WHEN TRUST MATTERS

Energy Transition Outlook 2026

MARITIME FORECAST TO 2050

A deep dive into shipping's
decarbonization journey



FOREWORD

Critical choices still lie ahead in shipping’s energy transition

As we publish the 10th edition of the Maritime Forecast to 2050 report, we are reminded how much the industry has evolved in a relatively short time. When the first edition was released, many of today’s discussions around alternative fuels, carbon pricing, and large-scale decarbonization pathways were still emerging. Since then, new regulations have been introduced, technologies have evolved and matured, and industry ambitions have been established.

Yet perhaps the most important lesson from the past decade is that transitions rarely follow a straight line. Progress continues, but the route taken and the pace of change remain difficult to predict.

Continued uncertainty around the International Maritime Organization’s (IMO) Net-Zero Framework (NZF) has created a more complex decision-making environment for the global industry. Regional measures such as FuelEU Maritime and the EU ETS are already influencing fuel choices, operational decisions, and investment priorities. However, much needed global alignment remains elusive, and several future pathways remain possible. For an industry built around assets that often operate for decades, this presents a significant challenge. Many shipowners are making decisions today that will shape fleets well beyond 2050, requiring them to balance today’s compliance requirements with the need to remain adaptable to an evolving regulatory landscape.

This places a premium on flexibility. This year’s report outlines four regulatory scenarios, ranging from full adoption of the initially approved NZF to its rejection and prolonged political gridlock. Together, they offer insight into how evolving policy signals may shape investments, accelerate or delay fuel transitions, and influence the deployment of energy-efficiency measures across global shipping.

Against this backdrop, energy efficiency stands out as the most immediate and practical lever available to shipowners, delivering value regardless of how the future develops. As this report shows, stronger global regulatory signals could accelerate the uptake of energy-efficiency measures, enabling the global fleet to consume up to 25% less energy by 2050 than under a transition driven primarily by regional regulations.

Reducing energy consumption lowers emissions, saves costs, and improves the economics of operating on more expensive low-GHG fuels. It is one of the rare areas where decisions taken today create benefits under almost any future scenario. Just as importantly, it creates resilience in a world where energy markets, fuel costs, and geopolitical conditions can change rapidly.

The development of low-GHG fuel markets remains another key challenge. Significant progress has been made in expanding alternative-fuel capabilities of

vessels and developing new fuel pathways. But scaling future fuel production will hinge on confidence that demand will indeed emerge, while shipowners need confidence that fuels will be available when needed. Creating those conditions will require continued investment, supportive policy frameworks, and sustained progress across energy supply chains.

The scale of this challenge reinforces an important lesson: no single stakeholder can deliver the transition alone. Shipowners may invest in vessels, but fuel suppliers, ports, charterers, cargo owners, financial institutions, technology providers, and regulators all play equally important roles in shaping the conditions for success. Progress in one part of the value chain depends on progress across many others. Only through aligned action can supply chains, infrastructure, and production capacity develop at the pace required to support industry ambitions. Initiatives such as the EU’s Sustainable Transport Investment Plan, alongside public funding, risksharing, and long-term policy commitments in other regions, are critical to enabling large-scale low-GHG fuel production.

The strongest message of this year’s report is clearly that dealing with uncertainty and preparing for multiple possible futures remains one of the most important strategic capabilities. Different regulatory outcomes,

market conditions, and technology developments may lead to different transition pathways. Rather than relying on a single view of the future, the industry should focus on building strategies capable of adapting as conditions evolve. By stress-testing strategies across scenarios, shipowners can identify pathways that balance cost, risk, and flexibility, avoiding decisions that may perform well under one outcome but expose the fleet under others.

There is much to be encouraged by. The industry’s willingness to invest, innovate, and collaborate remains strong. New solutions continue to emerge, experience is accumulating, and valuable lessons are being learned. While the path ahead may not always be straightforward, shipping has repeatedly demonstrated its ability to respond to complex challenges when stakeholders work together towards a common goal.

As we look back on a decade of Maritime Forecast to 2050, we can see how far our industry has come. The next decade will be about turning that progress into scale, resilience, and lasting transformation. This cannot be achieved without a well-balanced, pragmatic, and global regulatory framework. Let’s hope that IMO member states face this challenge in a spirit of collaboration.



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EXECUTIVE SUMMARY

Shipping is undergoing an unprecedented technology and fuel transition to set the industry on a path towards net-zero greenhouse gas (GHG) emissions. International and regional regulatory requirements are critical in determining the scale and pace of maritime decarbonization, driving shifts in uptake of fuels and technologies. Given

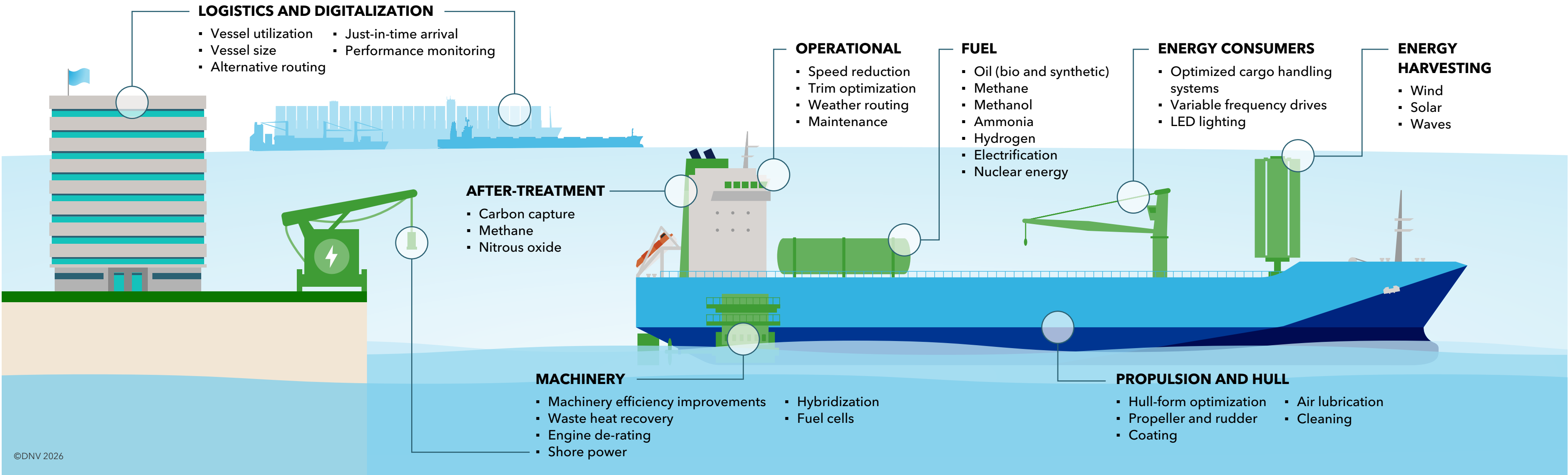
the lifespan of newbuilds today, often beyond 2050, ships must be designed to meet future regulations, reducing risks and costs across fleets. This increases the importance of combining near-term actions, such as energy-efficiency improvements, with long-term flexibility to use low-GHG-emission fuels.

The state of the transition

This report provides an update on the state of this transition, starting with the regulatory landscape. The delayed decision by the International Maritime Organization (IMO) on the Net-Zero Framework (NZF) targeting net-zero GHG emissions by or around 2050 is prolonging uncertainty. However, EU regulations and commercial pressures are already influencing

investment decisions and operational choices. Given uncertainty at the international level, we present four scenarios for possible future regulatory development. The key implication is not only that several regulatory pathways remain possible, but also that prolonged uncertainty at the IMO can increase the likelihood of additional regional regulations targeting international shipping.

FIGURE 1
Decarbonization solutions that can reduce the energy consumption and emissions from ships and fleets



Further, this report assesses the status of the available portfolio of decarbonization measures, focusing on energy-efficiency measures and alternative fuels (see Figure 1 for an overview of measures). Energy efficiency is becoming increasingly important: it reduces fuel use and emissions immediately, while also lowering the cost of operating on more expensive low-GHG fuels. For the world fleet, energy-efficiency measures and speed reductions can reduce energy use by up to 16% in 2030 compared to business-as-usual, and the potential towards 2050 is larger still. However, full maritime decarbonization will require a shift from fossil fuels to low-GHG fuels, complemented by other solutions such as onboard carbon capture and storage (OCCS) and potentially nuclear power.

We find that alternative-fuel capabilities are expanding across the world fleet. The share of alternative fuel-capable ships (measured in gross tonnes) has increased more than 10-fold from 0.4% in 2020 to 5.2% by August 2026 (excluding LNG carriers). The corresponding number of vessels capable of using alternative fuels has grown more than six-fold from 213 to 1,329 (excluding LNG carriers), with significant variations across ship segments. LNG (dual-fuel) remains the dominant fuel technology across segments, but methanol capability is gaining a substantial foothold, particularly in the container-ship segment. Other options, such as ammonia, are also emerging. Bunkering activity is expanding, with low-GHG fuel bunkering operations recorded at nearly 90 ports worldwide.

Next, this report provides an updated perspective on the emerging low-GHG fuel market in shipping. Today, the marine fuel market is dominated by fossil fuels, with energy price being the prime market determinant. Moving forward, GHG regulations will reshape this by penalizing fuels that fail to meet GHG intensity targets. Thus, the abatement cost (USD/

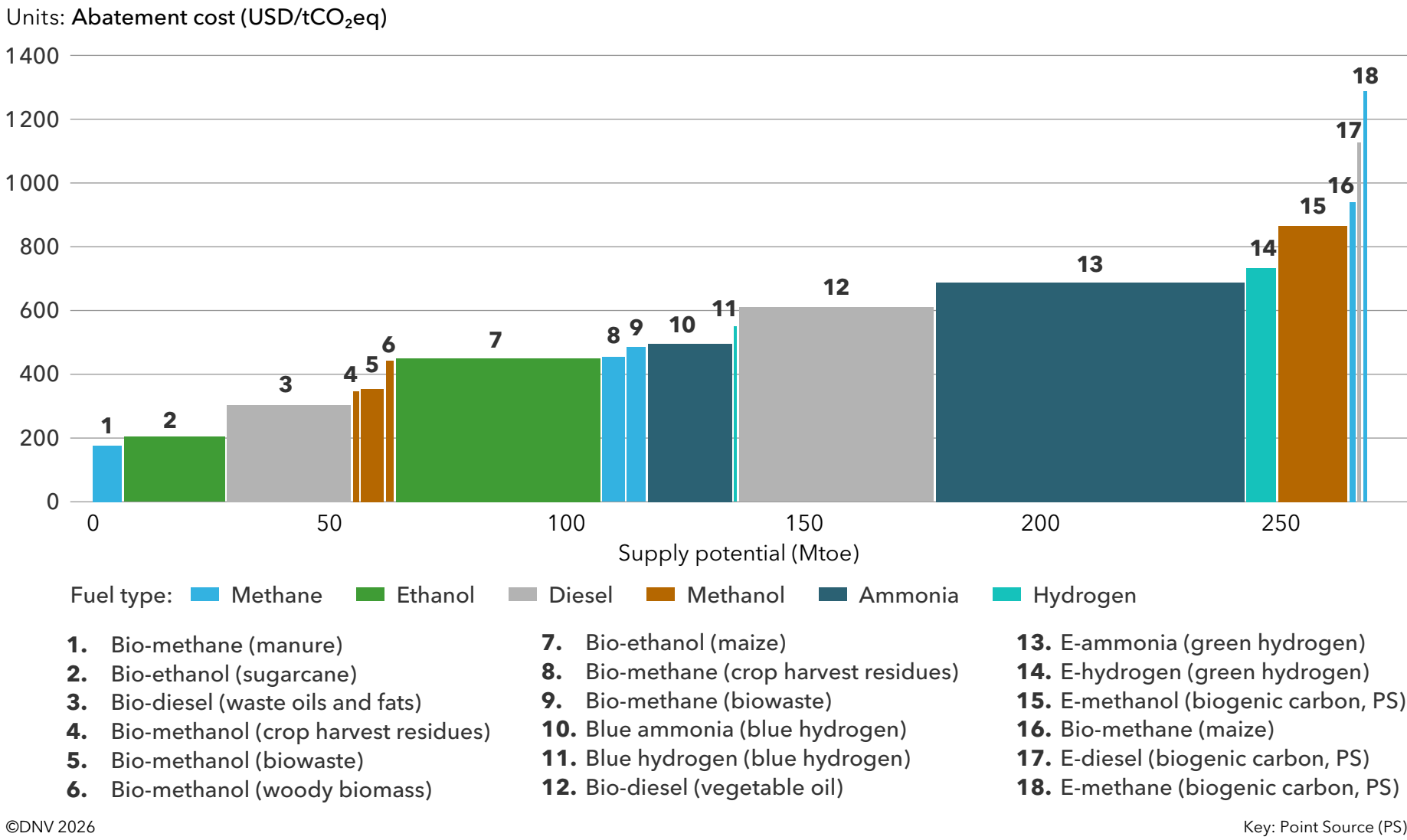
tCO₂eq averted) of each fuel will also determine its competitiveness, capturing not only price but also the extent to which a fuel reduces GHG emissions. We find that global low-GHG fuel supply could reach a maximum of 270 Mtoe by 2030 (see Figure 2), but actual supply in the market is likely to be less because many planned projects still depend on final

investment decisions. About 62 Mtoe of low-GHG fuel supply in 2030 is estimated to be cost-competitive with the initially agreed IMO NZF Tier 2 remedial unit price of 380 USD/tCO₂eq. The corresponding cost threshold under FuelEU Maritime is higher. Demand for low-GHG fuels in shipping is projected to range from 4 to 22 Mtoe in 2030. In 2050, demand could reach 33-185 Mtoe. The lower bound reflects uptake driven by EU regulations, while the upper bound aligns with the initially approved but now delayed IMO NZF.

Importantly, the market for low-GHG fuels is shaped not only by developments within the shipping sector, but also by developments in other sectors that use these fuels directly or compete for the same feedstocks. We find that while many biofuels offer the lowest abatement costs in the near term, their scalability is constrained by the availability of biomass feedstocks, which are also required across competing sectors and applications. As demand for low-GHG fuels grows across shipping and other sectors, the lowest-cost biofuel pathways are likely to be utilized first, with additional demand increasingly met by higher-cost pathways such as e-fuels and blue fuels, including methanol and ammonia.

Even in a maturing market, a single global fuel price is unlikely to emerge, as each fuel type is produced through distinct pathways with different conversion efficiencies, costs, GHG emissions and infrastructure needs. These differences mean fuel prices will likely stay differentiated, and often decoupled, across different fuel molecules and regions.

FIGURE 2
Potential maximum global low-GHG fuel supply in 2030 (x-axis) and abatement cost (y-axis) for each fuel pathway. Pathways are ordered by increasing abatement cost; supply is based mainly on production capacity data, while abatement costs combine DNV-estimated fuel cost with assumed GHG intensity values.



Navigating the transition

In an uncertain regulatory, technology, and fuel-market context, identifying robust technology and fuel strategies for fleets is becoming increasingly important for shipowners. The report introduces a stepwise framework for managing transition risk and cost (Figure 3), guiding shipowners to define potential strategies, test them across multiple scenarios, and identify resilient choices that safeguard fleet net-earnings capacity:

- 1. Define a set of potential fuel and technology strategies for a fleet
- 2. Define a set of possible scenarios describing the development of key parameters including regulations and fuel market
- 3. Robustness check for each strategy against each scenario

The framework is designed to capture both quantifiable costs and broader transition risks, bringing together the key factors shaping fleet decarbonization: GHG regulations, the portfolio of decarbonization measures available, and the market for low-GHG fuels.

In the following, we briefly walk through each step of the framework, using an illustrative very large crude carrier (VLCC) fleet case study to demonstrate how different fleet strategies perform under contrasting scenarios, highlighting their strong sensitivity to regulatory developments. We consider a timeline towards 2050.

Step 1: Strategies

Feasible fuel and technology strategies vary across ship segments and across areas of oper-

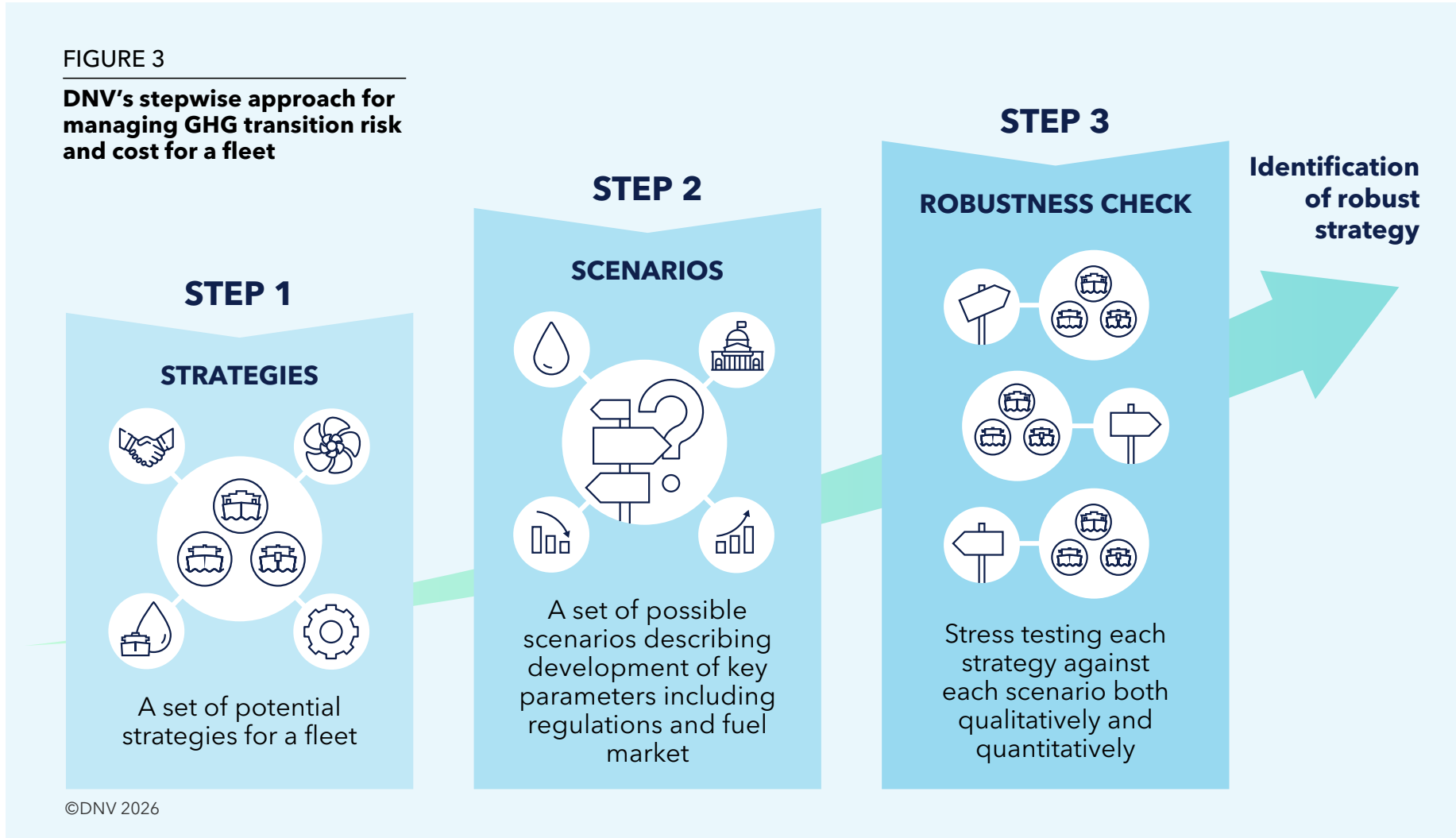
ation, and are also influenced by factors such as investment horizons, financial capacities, and risk acceptance levels. To illustrate how strategy choices can differ in practice, two such strategies can be defined for a fleet of five VLCCs.

One strategy is to continue operating vessels fuelled conventionally with high sulphur heavy fuel oil (HSHFO) and equipped with exhaust gas cleaning systems (scrubbers), combined with standard

energy-efficiency measures (Strategy A: HSHFO + scrubber). Another is to phase in LNG dual-fuel tonnage and combine this with more ambitious efficiency improvements (Strategy B: Phase-in of dual-fuel LNG ships). Many more strategies could be considered, incorporating a wide array of solutions.

Step 2: Scenarios

Scenarios describe alternative but plausible futures towards, for example, 2050 and help shipowners



prepare for uncertainty in the external environment. The aim is not to capture every possible outcome, but to define a set of internally consistent futures that can be used to test strategy performance. For example, for a VLCC fleet, broader developments can be translated into contrasting cases such as slow- and rapid-transition scenarios:

- In a slow-transition scenario, the delay at the IMO turns into a prolonged regulatory standstill. Regional and national regulations continue to advance, but progress in the global marine low-GHG fuel market remains sluggish. Biofuels remain the most economically competitive low-GHG fuel option for shipping. Charterers and financial institutions place limited value on greening their value chains and portfolios.
- In a rapid-transition scenario, the IMO NZF is back on track from 2029 and further strengthened in the following years. Biofuel demand rises sharply in the maritime sector, alongside growing demand in other sectors, placing upward pressure on prices and limiting availability for shipping. From 2040, e-fuels emerge as the main price setters for low-GHG methane and low-GHG diesel. Charterers and financial institutions place increasing value on green transportation.

Step 3: Robustness check

A robustness check is an evaluation of how each strategy performs under different scenarios, consisting of two parts:

- A cost assessment focused on how each strategy performs economically assuming all inputs hold, including fuel availability, technology reliability, regulatory clarity, and stable market conditions.
- A risk assessment providing a systematic approach identifying and qualitatively assessing potential risks impacting each strategy within each scenario (similar to a Hazard Identification (HAZID) process used in safety analyses).

In sum, the comparative robustness check for our exemplary case with five VLCCs shows that no single strategy is clearly preferable across all the scenarios considered (see Figure 4). Here, the results are expressed on a common 1-5 scale, where 1 indicates strong performance and 5 weak performance, allowing cost and risk to be compared directly.

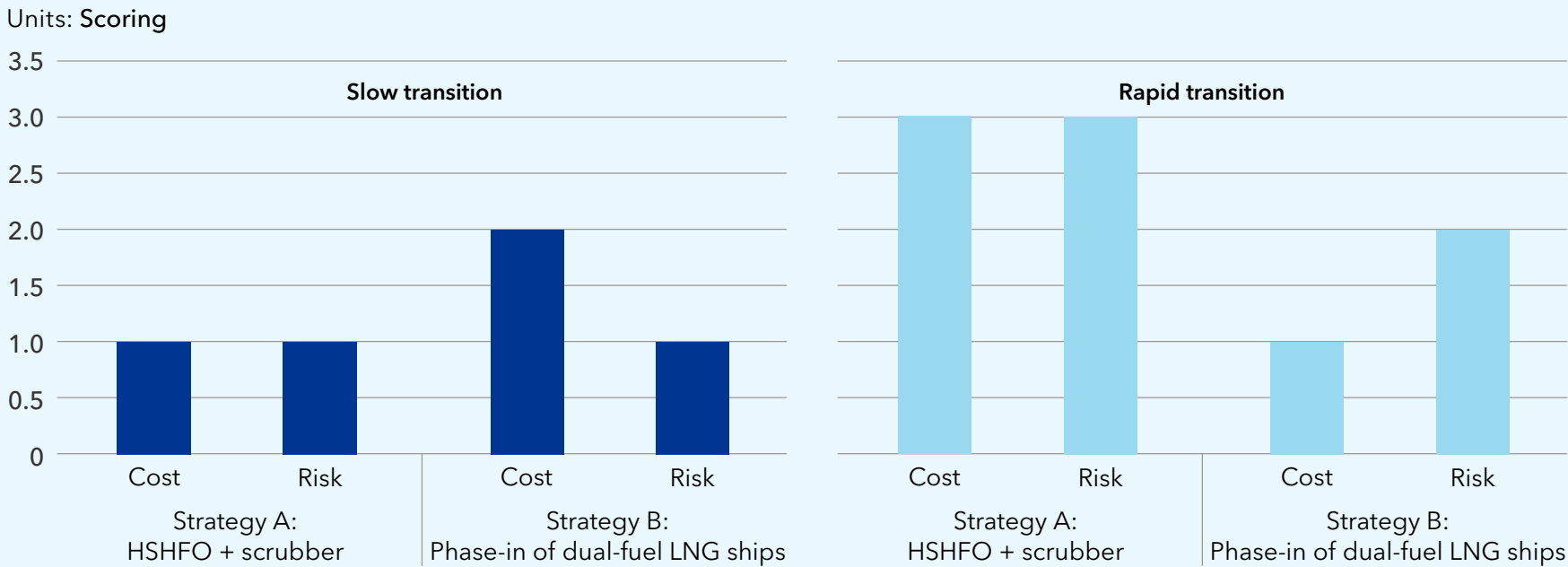
In a slow-transition case, the conventional HSHFO + scrubber strategy performs better on cost, mainly because of lower capital costs, modest compliance benefits from dual-fuel LNG, and continued access to lower-cost HSHFO. Under those conditions, the added capital cost of dual-fuel LNG ships is

not sufficiently offset by fuel and compliance savings. Risk, meanwhile, is assessed to be similar, and low, for both strategies.

In a rapid-transition case, the result reverses. Stronger GHG regulation sharply increases the exposure of the scrubber strategy to high compliance costs, expensive low-GHG diesel, or penalties, while a dual-fuel LNG pathway benefits from lower fuel consumption and access to lower-cost low-GHG methane. Under such conditions, the cost gap can widen materially over time, and the LNG strategy delivers the stronger overall cost performance. In such conditions, the strategy involving HSHFO and scrubber is assessed to have a higher risk.

The conclusion to such an analysis – that is, the decision on which strategy to pursue – will depend on how the likelihood of the varying scenarios is judged and how risk is handled. This risk management framework supports ship-owners with a structured comparison of strategies and enables assessment of the trade-offs between cost efficiency and exposure to transition risks. It should be noted that results presented here for the VLCC case are for illustrative purposes; a full analysis should include additional strategies (e.g. more fuel technologies and scenarios).

FIGURE 4
Assessed cost and risk score for Slow transition (left) and Rapid transition (right)



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Recommendations to shipowners

Based on the findings of this report, we recommend that shipowners focus on three priorities:

First, accelerate the uptake of energy-efficiency measures as near-term no-regret actions, as these reduce fuel use and emissions immediately while also improving the case for use of low-GHG fuels. This applies to both newbuilds and existing ships, as retrofit opportunities remain significant and can be

economically attractive even for older vessels. For ships with exposure to EU/EEA trade, the business case can be even stronger, as FuelEU Maritime and the EU ETS add further value to fuel savings and emissions reductions.

Second, maintain flexibility in fuel and technology choices. Fuel decisions should consider abatement cost rather than energy cost alone, as fuel competitiveness depends on both price and GHG intensity

under emerging regulations. Shipowners should also consider pooling as an effective compliance tool under FuelEU Maritime, providing both a business case for ships using low-GHG fuels and supporting compliance for remaining vessels. Where exposure to regulatory or commercial pressure is high, early action to secure access to low-GHG fuels through partnerships and offtake agreements should also be considered.

Third, develop a fleet strategy guided by scenario-based planning. This study presents one way of doing so. Regulatory and fuel market uncertainties mean that robust strategic choices cannot be identified from a single forecast alone. Fleet strategies should therefore be tested against multiple plausible futures, including different levels of regulatory ambition, fuel availability, and fuel-price development. Both cost and risk should be assessed in each scenario, as cost alone will not capture important transition risks related to fuel availability, charter markets, operations, and financing. In a fast-evolving landscape, it is important to continuously monitor regulatory and technology developments, and to reassess fuel and technology strategy.

In an uncertain regulatory and fuel-market environment, robust fleet strategies must be tested across multiple plausible futures, reflecting different levels of regulatory ambition, fuel availability, and fuel-price development.





1 | INTRODUCTION

This tenth edition of the Maritime Forecast to 2050 is part of DNV's 2026 suite of Energy Transition Outlook (ETO) reports. With this latest edition we aim to support shipowners in identifying robust technology and fuel strategies for their fleets under uncertain future regulatory and fuel-market conditions, as well as an evolving technological landscape.

Shipping is undergoing both a technology transition and a fuel transition. Unlike earlier shifts, which were largely market-driven, today's transition is primarily shaped by regulation, which will determine both the pace and scale of maritime decarbonization.

Although delayed decisions on the IMO Net-Zero Framework (NZF) – which targets net-zero GHG emissions by or around 2050 – are prolonging uncertainty, EU regulation and commercial pressure are already affecting investment decisions and operational choices. Moreover, recent supply-chain disruptions, including the blockade of the Strait of Hormuz, have underscored the link between energy security and the green transition, as reduced reliance on fossil fuels may lower geopolitical risk while supporting investment in alternative fuels and more resilient maritime systems.

Meeting regulatory requirements will require a broad portfolio of decarbonization measures across ship design, operations, and fuels. Energy efficiency is a key part of this

portfolio, as it reduces fuel use and emissions immediately while also improving the economics of operating on more expensive low-GHG fuels. However, full maritime decarbonization will require a shift from fossil fuels to low-GHG fuels, complemented by other solutions such as onboard carbon capture and storage (OCCS) and potentially nuclear power.

As the transition accelerates, identifying robust technology and fuel strategies for fleets is becoming increasingly important for shipowners. To support this, the report brings together three core elements shaping maritime decarbonization: regulatory developments (Chapter 2), the uptake of decarbonization solutions and bunker infrastructure (Chapter 3), and the emerging market for low-GHG marine fuels (Chapter 4). These insights are then applied in a stepwise framework for managing transition cost and risk, guiding shipowners to define potential strategies, test them across multiple scenarios, and identify resilient choices that safeguard fleet net-earning capacity (Chapter 5). The structure of the report is illustrated in Figure 1-1.

FIGURE 1-1

Structure of the report: contents progress from regulations and key drivers, through decarbonization solutions and the low-GHG marine fuel market, to their integration in practical decision-making for shipowners



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Clarifying low-GHG vs. alternative fuels

This report uses the term low-GHG fuels when referring to fuels with a significant improvement in well-to-wake (WtW) GHG emissions from conventional fossil fuel oils. Alternative fuels are fuels that require a different energy converter technology, such as LNG, LPG, methanol, ammonia and hydrogen, regardless of WtW GHG intensity.

2

OUTLOOK ON REGULATIONS AND OTHER DRIVERS

Highlights

With international shipping in an uncertain regulatory landscape on GHG emissions, our analysis finds:

- Several regulatory pathways remain possible as the IMO continues negotiations on the Net-Zero Framework.
- Prolonged uncertainty at the IMO can increase the likelihood of further regional regulations.
- FuelEU Maritime and the EU ETS remain the strongest regulatory drivers of shipping decarbonization, covering an estimated 10% to 15% of global fleet fuel consumption.
- Charterers remain important drivers for the uptake of alternative fuel technologies, low-GHG fuels, and energy-efficiency measures.

The regulatory landscape on GHG emissions is uncertain after the October 2025 postponement of a decision to adopt the IMO Net-Zero Framework (NZF). This chapter reviews recent regulatory developments and presents scenarios to explore possible futures. The scenarios sketch out potential outcomes for the NZF and consequential developments in regional regulations.



2.1 IMO developments

Net-Zero Framework

2025 was a turbulent year for the IMO. In April 2025, the IMO's Marine Environment Protection Committee (MEPC) approved the Net-Zero Framework (NZF), a compromise carefully crafted between member states to set shipping on course to reach the 2023 IMO GHG Strategy ambition of net-zero GHG emissions by or around 2050. This groundbreaking regulatory framework sets requirements on a ship's GHG fuel intensity, in combination with a pricing and reward mechanism, the first of its kind to cover a global industry. The NZF was considered for adoption at an extraordinary MEPC session in October 2025, but the positions of key member states had shifted since April, with revenue collection and disbursement highlighted among the major concerns. On the last day of an unprecedented week at the IMO in October, a vote was finally held to adjourn the session for one year due to considerable disagreement among member states on the way forward.

Despite the adjournment, the IMO continued work on developing guidelines to provide clarity on the NZF and support its implementation through intersessional working groups and informal meetings. This includes guidelines related to 1) GHG fuel intensity (GFI) calculation and verification, including work in progress on how to account for wind propulsion systems, shore power, and onboard carbon capture and storage, 2) fuel certification, and 3) zero or near-zero GHG emissions technologies and fuels

(ZNZs).¹ This continuing work included constructive technical discussions among member states.

The NZF was revisited at MEPC 84 in April 2026, which held extensive discussions on the possible way forward. Although there were still divergent positions on key elements such as establishing an IMO Net-Zero Fund, the MEPC agreed to continue discussions to ensure consensus. No decisions on NZF design features were expected or forthcoming at the meeting, but it was agreed that two additional intersessional working group meetings are to be held before MEPC 85 in the first week of December 2026 to continue negotiations.

If concerns over the NZF are handled through the development of implementation guidelines and with no major changes to the draft MARPOL Annex VI text, the NZF could be adopted in December 2026. However, it is likely that substantive changes are required, in which new legal text must be negotiated, approved, and circulated before adoption can take place at least six months later. This means that the earliest time the regulations could take effect is 2029. However, negotiations could also continue beyond 2026, further extending the time to entry into force.

Other work streams on GHG topics have continued at the IMO in the past year. They include further development of the IMO 2024 Guidelines on life cycle GHG intensity of marine fuels (LCA guide-

lines) and the start of the second phase of review of the Carbon Intensity Indicator (CII) rating and Ship Energy Efficiency Management Plan (SEEMP) mechanisms. Below, we highlight some key developments within these work streams and why shipping stakeholders should keep an eye on upcoming work.

LCA guidelines

The emission reduction ambitions in the 2023 IMO GHG Strategy, and the requirements for individual ships in the NZF, are both based on well-to-wake (WtW) GHG emissions, with the aim to prevent a shift of emissions from shipping to other sectors.² The 2024 LCA guidelines thus form a critical part of the IMO GHG regulatory framework, stipulating how to calculate the well-to-tank (WtT) and tank-to-wake (TtW) GHG emissions of marine fuels and electricity delivered to the ship.

Over the past year, the IMO has continued developing these guidelines, focusing particularly on refining calculation methods, including discussion on how to set default emission factors and account for land-use change and onboard carbon capture. This work has also included discussion on how to further develop and operationalize sustainability criteria for marine fuels, and on Chain of Custody models for traceability of fuel supply chains.

Further work is also needed to populate the list of more than 100 fuel pathways with placeholders for default emission factors. Currently, the LCA guidelines provide default WtT emission factors for the fossil heavy fuel oil (HFO) and marine gas oil (MGO) fuel



pathways, as well as TtW factors for the main types of fossil fuel. To address these gaps, a scientific working group has been established to assess proposals for new default emission factors and provide recommendations to the MEPC, including for fossil liquefied natural gas (LNG) and several biofuel pathways.

Work on the LCA guidelines is expected to continue in the coming years, and they will be updated regularly. Decisions relating to default emission factors, land-use change, sustainability criteria, and Chain of Custody models will be particularly consequential, as they will influence the eligibility and relative competitiveness of different fuel pathways.

MEPC 84 also adopted guidelines related to measurement of methane (CH₄) and nitrous oxide (N₂O) emissions from marine engines. These guidelines create a toolkit that can be used to determine actual tank-to-wake methane and nitrous oxide emission values. They are currently not connected to any mandatory reporting framework but are anticipated to support the use of actual emission factors under the LCA framework, as well as for calculation of the attained GFI under the NZF. The guidelines can also be used for determining actual methane and nitrous oxide under the EU ETS and FuelEU Maritime.³

Despite the adjournment, the IMO continued work on developing guidelines to provide clarity on the NZF and support its implementation through intersessional working groups and informal meetings.

Review of the short-term GHG measures (CII and SEEMP)

The CII and SEEMP are key instruments for delivering the carbon intensity ambitions set out in the 2023 IMO GHG Strategy. MEPC 84 initiated Phase 2 of the review of these short-term measures, planned for completion in 2028, and discussed the potential development of alternative CII metrics, enhancement of the SEEMP framework, and how to ensure synergies between the IMO short-term measures and the NZF. The review is linked to progress on the NZF, as synergies between NZF and CII/SEEMP can only be considered when clarity emerges on the design of the NZF.

2.2 Regional and national developments

EU

While there is turbulence at the IMO, the EU continues its efforts to regulate shipping within the EU and European Economic Area (EEA), as well as parts of international shipping to and from the EU/EEA. Since 1 January 2025, the FuelEU Maritime Regulation (EU 2023/1805) has been setting GHG emission intensity ($\text{gCO}_2\text{eq/MJ}$) requirements for ships over 5,000 GT transporting cargo or passengers for commercial purposes in the EU or EEA, and also applies to 50% of energy used on voyages into or out of the EU/EEA (DNV, 2024c). Increasingly stringent GHG intensity targets and shore power requirements, combined with substantial penalties for non-compliance, will incentivize ships sailing into EU/EEA ports to shift to low-GHG fuels and shore power. The FuelEU Maritime Regulation will be reviewed by 31 December 2027. Among other issues, the review will consider including new ship types and sizes, potentially extending the scope to offshore vessels and ships below 5,000 GT; more stringent GHG intensity targets in light of strengthened EU climate ambitions; and the inclusion of onboard carbon capture as a compliance method.

The EU Emissions Trading System (EU ETS) has now also finished its phase-in period. Since 1 January 2026, the maritime sector has to surrender allowances for 100% of its emissions within the scope of the EU ETS, which now also covers



methane (CH_4) and nitrous oxide (N_2O) emissions. The EU ETS is currently under review following the European Commission's proposal published in July 2026, with political agreement expected in Q1 2027. The proposal includes the expansion of the EU Monitoring, Reporting and Verification (MRV) and ETS scopes to additional ship types, sizes, and activities, as well as the streamlining of reporting requirements by making the MRV system the common framework for data collection and reporting under both the EU ETS and FuelEU Maritime. In addition, the proposal introduces a new allowance-based support mechanism to

accelerate the uptake of sustainable maritime fuels and the deployment of zero-emission propulsion technologies. The EU ETS and FuelEU Maritime include provisions that the regulations will be reviewed if the IMO adopts similar measures, and the European Commission highlights in its Industrial Maritime Strategy that it “will revise relevant EU legislation taking into consideration global measures at IMO in order to avoid double payment” (EUC, 2026).

Reported data from ships indicates that FuelEU Maritime, in combination with emissions pricing

through the EU ETS, is a driver for uptake of bio-methane and liquid biofuel.⁴ FuelEU Maritime pooling has opened for new business models, with ships over-complying using low-GHG fuels and selling surplus units in the market. For the compliance year 2025, around 91% of ships joined a pool, while 1.6% borrowed compliance and 3.5% ended with a deficit after applying flexibility mechanisms.⁵ Hecla, a maritime emissions trading and compliance platform, reports a market price of surplus units starting above 200 euros per tonne (EUR/t) in January 2026 and ending at 118 EUR/t in May 2026.⁶ The market price in general followed the alternative cost of switching to biofuels. Market participants have also reported FuelEU Maritime as the main reason for signing long-term offtake agreements on low-GHG fuels, including e-fuels.⁷ Chapter 4 discusses prospects for the marine fuel market in further detail.

Other regional and national schemes

There are also other regional and national regulatory schemes that include international shipping in their scope. Individually, these schemes have limited impact on the global fuel and technology transition, but collectively they increase regulatory pressure and compliance complexity.

This includes the UK Emissions Trading Scheme (UK ETS), covering cargo and passenger vessels of 5,000 GT and above from 1 July 2026. As with the

EU ETS, offshore vessels of 5,000 GT and above will be included in the UK scheme from 1 January 2027. The UK ETS applies to domestic voyages, meaning those that begin and end at UK ports, and to port calls within the UK by all vessels including those making international voyages. The UK is also considering including 50% of UK/EEA voyages at a later stage (Department for Energy Security & Net Zero, 2025). While actors engaging solely in international voyages may not face very high UK ETS costs, they will still need to engage in all required administrative activities if sailing to a port in the UK. Emissions within scope (CO₂, CH₄, N₂O) are the same as for the EU ETS and all are being considered in a TtW perspective, with a potential shift to WtW at a later stage. The EU and UK are considering linking their ETS systems, though the timeline and implications remain unclear (EUC, 2025).

Norway has also introduced specific requirements for certain ship segments and operating areas. This includes zero-emission requirements for operation in the World Heritage fjords, effective from 1 January 2026 for passenger ships of less than 10,000 GT, and from 1 January 2032 for passenger ships of 10,000 GT and more.⁸ Further, from 1 January 2025, public procurement of ferries and ferry services must, as a main rule, specify zero-emission solutions, with defined exceptions where this is not technically or economically feasible, or where necessary infrastructure is lacking.⁹ Finally, from 2029, offshore operators on the Norwegian Continental Shelf are required to reduce the GHG intensity of vessels used in petroleum activities. These requirements

apply at the level of the operator’s fleet over defined compliance periods, rather than at the level of individual ships.¹⁰

Through the African Sovereign Carbon Registry initiative, Djibouti and Gabon have also introduced a carbon tax of 17 USD/tCO₂eq on half of the emissions on voyages in and out of their ports. More African countries are considering joining this carbon tax scheme (Africa Sovereign Carbon Registry Foundation, 2026).

Other countries are also developing national ETS and MRV schemes, with either an unclear scope so far or focusing only on domestic shipping. Türkiye has approved a scheme to include shipping in its ETS (TR ETS), which is expected to launch as a pilot scheme in 2026. The scope of the TR ETS, including ship types, size threshold, and reporting procedures, is yet to be developed.¹¹ In addition, a series of national ETS schemes include domestic maritime transport but have no clear plans to expand their scope to international shipping. Examples include the Shanghai Pilot ETS¹² and the Korea Emissions Trading System (K-ETS)¹³. Brazil is developing a national ETS, which lists maritime as a covered sector. This system is under phased implementation, currently focusing on reporting, and is not yet operational.¹⁴ China developed its MRV system in 2022¹⁵, and in April 2026, a high-level policy on the green and low-carbon transition of shipping reiterated the intention to further develop the system.¹⁶ However, the policy does not specify whether an ETS system will be introduced, nor

Share of global CO₂ emissions from shipping related to different countries

Through the EU ETS and FuelEU, the EU has introduced requirements targeting emissions from port calls and voyages within the EU/EEA, and voyages into and out of the region. Other countries are considering adding regulations based on a similar scope, or only on domestic voyages (e.g. the UK).

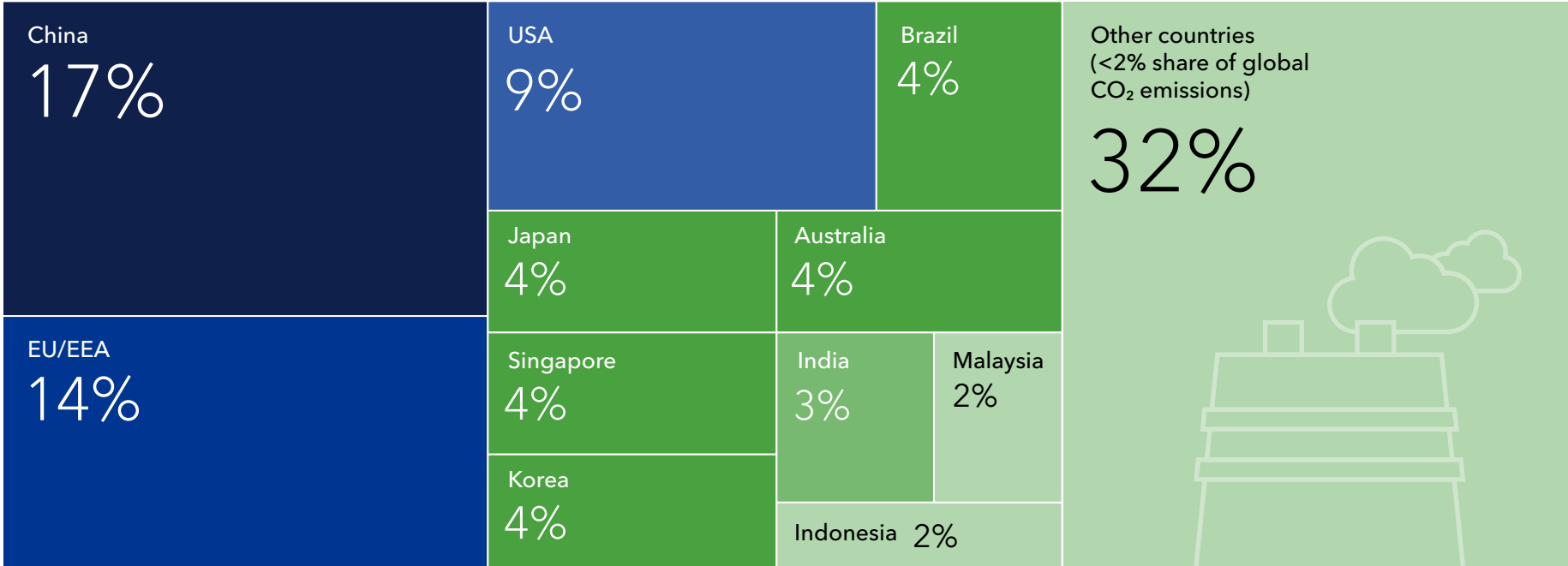
To illustrate how much emissions such schemes would cover, Figure 4-1 provides an overview of the share of global tank-to-wake CO₂ emissions

from ships above 5,000 GT attributed to different countries and the EU/EEA as a region, including 100% of emissions from domestic/within EU/EEA voyages and 50% of emissions from incoming/outgoing voyages.

The figure shows that China (17%), the EU/EEA (14%), and the US (9%) dominate, while the 10 leading countries and EU/EEA collectively account for three-quarters (68%).

FIGURE 2-1

Overview of the share of global tank-to-wake CO₂ emissions from shipping related to different countries and EU/EEA. The results are estimated based on global AIS data for 2025 and DNV’s MASTER (Mapping of Ship Tracks, Emissions and Reduction potentials) and Voyage models. Only ships above 5,000 GT are included.



Due to rounding, percentages may not add up to exactly 100%; Source: Global AIS data for 2025 and DNV’s MASTER (Mapping of Ship Tracks, Emissions and Reduction potentials) and Voyage models

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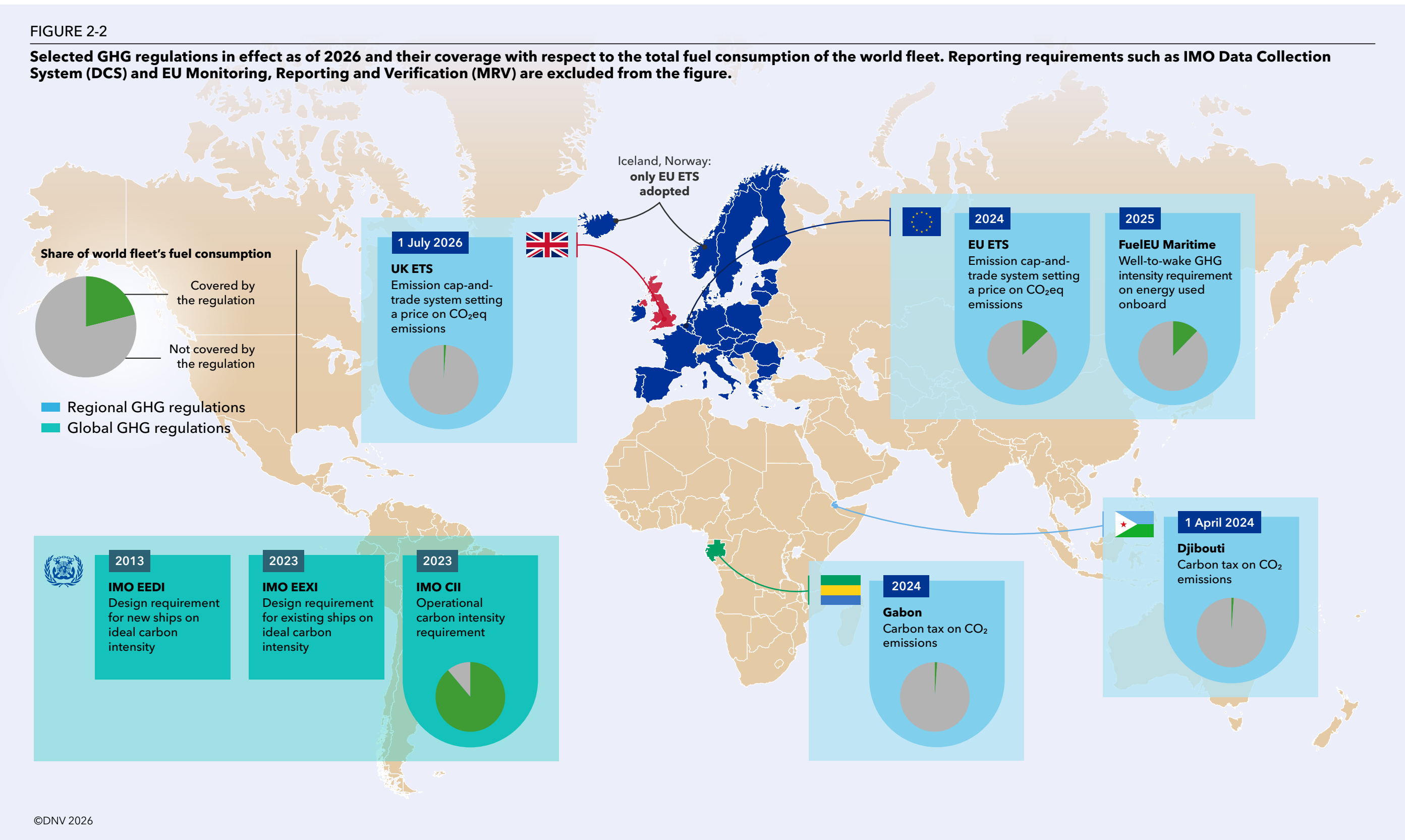
whether it would apply to foreign-flagged vessels. We highlight that, in general, the timeline for developing an ETS is relatively long. The timeline for the possible inclusion of international shipping depends on whether there is an existing system that can be thus expanded, or whether a new one must be developed from scratch.

Figure 2-2 summarizes and maps GHG regulations in effect as of 2026, with international shipping in scope. As discussed further in Chapter 3, existing IMO regulations on energy efficiency have so far been a considerable driver for energy-efficiency improvements in the global fleet.

Supply-side policies for low-GHG fuels and infrastructure

While regulations incentivizing reduced GHG emissions remain the main driver of shipping decarbonization, supply-side policies can help by lowering the cost and improving availability of low-GHG fuels while enabling roll-out of supporting infrastructure, including shore power.

For example, the EU’s Sustainable Transport Investment Plan (STIP) aims to unlock more than 20 million tonnes (Mt) of sustainable low-GHG fuels to cover the demand arising from ReFuelEU and FuelEU Maritime.¹⁷ This is to be achieved through reducing producer risk, mobilizing capital, and increasing long-term market certainty. The EU’s Alternative Fuels Infrastructure Regulation (AFIR)¹⁸ sets binding targets for deploying interoperable alternative-fuel infrastructure as well as shore power infrastructure in



ports. Under AFIR, relevant TEN-T (Trans-European Transport Network) core and comprehensive ports will need to provide shore power to cover at least 90% of relevant annual port calls from container and passenger ships of 5,000 GT and above by 2030.

China emphasizes long-term planning and pilots to scale low-GHG fuels, and provides policies through multiple frameworks rather than a single unified programme. For example, in 2025, the country's National Development and Reform Commission (NDRC) introduced a national investment scheme that provides up to 20% public co-funding for low-carbon demonstration projects, explicitly covering sustainable aviation fuel (SAF), green methanol, and fuels produced from captured CO₂ as an example of carbon capture, utilization and storage (CCUS).¹⁹

In the US, tax credits and clean hydrogen incentives provided through the Inflation Reduction Act (IRA) to support low-GHG fuel production have been significantly reduced or cancelled. However, certain elements remain active, such as the EPA Clean Ports Program directly enabling uptake of alternative marine fuels and related infrastructure.²⁰

These policies can be expected to reduce production costs over time, particularly for the targeted fuels, enabling large-scale capacity expansion. Chapter 4 discusses in detail the future low-GHG fuel market. See also Chapter 3 in DNV's Hydrogen to 2060 outlook for a more detailed analysis of policies and regulatory frameworks related to hydrogen (DNV, 2026a).

Other regulations shaping technology and fuel choices

Alongside regulations aimed directly at reducing GHG emissions, other measures also affect fuel and technology choices for the global fleet. Key examples include shore power requirements and regulations targeting emissions of nitrogen oxides (NO_x) and sulphur oxides (SO_x).

Shore power requirements are increasingly mandated to reduce emissions at berth (DNV, 2026d). For example, California's At-Berth Regulation requires certain ship types to use shore power or equivalent measures, and China mandates shore power use for capable vessels when staying more than two hours in river ports or three hours in coastal ports, with limited exemptions. Under FuelEU Maritime, container and passenger ships will be required to connect to shore power at major EU ports from 2030, with limited exemptions and high penalties for non-compliance.

Emissions of NO_x and SO_x are regulated under IMO MARPOL Annex VI through global fuel sulphur limits and tiered NO_x engine standards. Ships can comply with SO_x limits either by using compliant fuel or by using scrubbers as an equivalent measure, with open-loop systems discharging wash water to sea and closed-loop systems recirculating it.



Since 2020, a 0.50% global sulphur cap applies, reduced to 0.10% in Sulphur Emission Control Areas (SECAs). NO_x Tier III standards, around 80% stricter than earlier tiers, apply to new ships operating in NO_x Emission Control Areas (NECAs). The IMO has designated eight SECAs and seven NECAs, including the North-East Atlantic ECA entering into force in 2027.

Beyond the IMO, some jurisdictions enforce local controls. For example, China's domestic ECAs limit fuel sulphur to 0.5% in general coastal waters and to 0.1% in specific areas; California's 24-nm zone permits only distillate fuel with less than 0.10% sulphur (thus banning heavy fuel

oil); and the Panama Canal mandates a switch to marine distillates for transiting ships. Similarly, the EU's Sulphur Directive requires ships at berth in EU ports to burn fuel with less than 0.10% sulphur, mirroring ECA-level standards in European waters.

A growing number of ports and coastal jurisdictions are restricting or prohibiting scrubber discharges, particularly from open-loop systems. For example, under the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), several countries in northwest Europe will ban open-loop discharges in inland waters and port areas from 1 July 2027.

2.3 Commercial actions driving decarbonization

Regulatory requirements at international and regional levels are critical in determining the scale and pace of maritime decarbonization. Demand-side action by charterers and cargo owners also plays an important role in accelerating uptake of energy-efficiency measures, alternative fuel technologies, and the use of low-GHG fuels.

Some charterers and cargo owners support implementation of alternative fuels and energy-efficiency measures. They do this by issuing tenders that specify fuel or design requirements for newbuilds; initiating pilot projects on chartered vessels to test emerging technologies; and by sharing investment costs and fuel-saving benefits with shipowners through added charter party clauses. Such arrangements are predominantly limited to long-term time-charter contracts.

Charterer willingness to support the uptake of low-GHG fuels and pay a premium for lower emissions is driven by regulatory exposure, internal company GHG reduction targets, customer pressure, and scope 3 emissions disclosure requirements at company and/or product level, and varies significantly by

shipping segment.²¹ In general, customer-facing charterers, especially within container shipping and the car carrier trade, face higher reputational risk and scope 3 disclosure requirements, making them both more willing and able to absorb higher freight rates for lower-emission transport. In contrast, bulk and tanker charterers operate in cost-driven markets with limited differentiation, thin margins, and low end-customer visibility, which constrains their ability and incentive to pay for emission reduction unless it is mandated by regulations, making such action less common. These differences may also have led to an

uneven uptake in alternative fuels across ship types in the global fleet, as shown in Chapter 3.

Cargo owner action can also take the form of collective initiatives. A notable example is the Zero Emission Maritime Buyers Alliance (ZEMBA), which aggregates freight demand from cargo owners and has supported the uptake of low-GHG fuels in first-mover initiatives. The second tender from ZEMBA focused on e-fuels, and concluded with two winners in December 2025: Hapag-Lloyd will use e-methanol on large methanol dual-fuel containerships on a trans-oceanic route, and North Sea Container Line (NCL) will use e-ammonia on the world's first ammonia-capable containership – Yara Eyde – on a northern European route (ZEMBA, 2026). For Yara Eyde, the contract with ZEMBA will contribute to closing the fuel cost gap.

While the finance industry continues to support maritime decarbonization with capital through sustainable as well as conventional financing, there is little evidence that private financing has been a decisive driver for the decarbonization achieved to date. Public funding and financing schemes remain critical to supporting both the production and uptake of low-GHG fuels, and to de-risking private finance.

Charterer willingness to pay a premium for lower emissions is driven by regulatory exposure, internal company GHG reduction targets, customer pressure, and scope 3 emissions disclosure requirements at company and/or product level, and varies significantly by shipping segment.

Going forward, especially given regulatory uncertainty, we highlight in Section 4.1 that strategic and coordinated action among all maritime stakeholders will be important to address barriers such as fuel-technology adoption depending on fuel availability (production, distribution, bunkering infrastructure) and vice versa. Solving the demand side of this 'chicken-and-egg' challenge can, for example, be assisted by buyer alliances like ZEMBA, green shipping corridor partnerships, and industry collaborative forums like the Global Industry Alliance and Global Maritime Forum.



Yara Eyde, the world's first ammonia-capable containership.

2.4 Four scenarios for GHG regulatory development for international shipping

As international shipping has entered a period of regulatory uncertainty, we have drawn up four regulatory scenarios as a ‘thinking tool’ to explore possible outcomes and support decision-making. For each scenario, we sketch developments at the IMO, and given this, what could be potential developments in EU and other regional regulations. Figure 2-3 provides an overview, including regulatory timelines, followed by a short description of each scenario.

The scenarios span from adoption of the NZF ‘as is’ when the MEPC meets again in December 2026, to the rejection of the NZF and a period of political gridlock in the IMO. We focus on changes in regulations, on top of already adopted regulations.

In the following chapters, we dive further into how these scenarios could shape the emerging marine market for low-GHG fuels (Chapter 4), as well as transition risk for shipowners (Chapter 5).

Scenario 1: Current NZF is adopted

In scenario 1, the current NZF is adopted as is at the resumed extraordinary session in December 2026. This means that the broad agreement from MEPC 83 has been re-established, with a strong majority of IMO member states supporting the NZF. Concerns from member states on the NZF have been addressed through the NZF implementation guidelines, rather than through adjustments to the legal text in MARPOL Annex VI. Adoption in

December 2026 entails entry into force of the NZF in April 2028, with the first implementation year likely to be 2029.

Given these developments at the IMO, this scenario assumes that the EU revises FuelEU Maritime and the EU ETS to avoid double payment, which is in line with the EU’s Industrial Maritime Strategy. The scenario also assumes that the UK aligns with the EU ETS, and that there are no further regional regulations

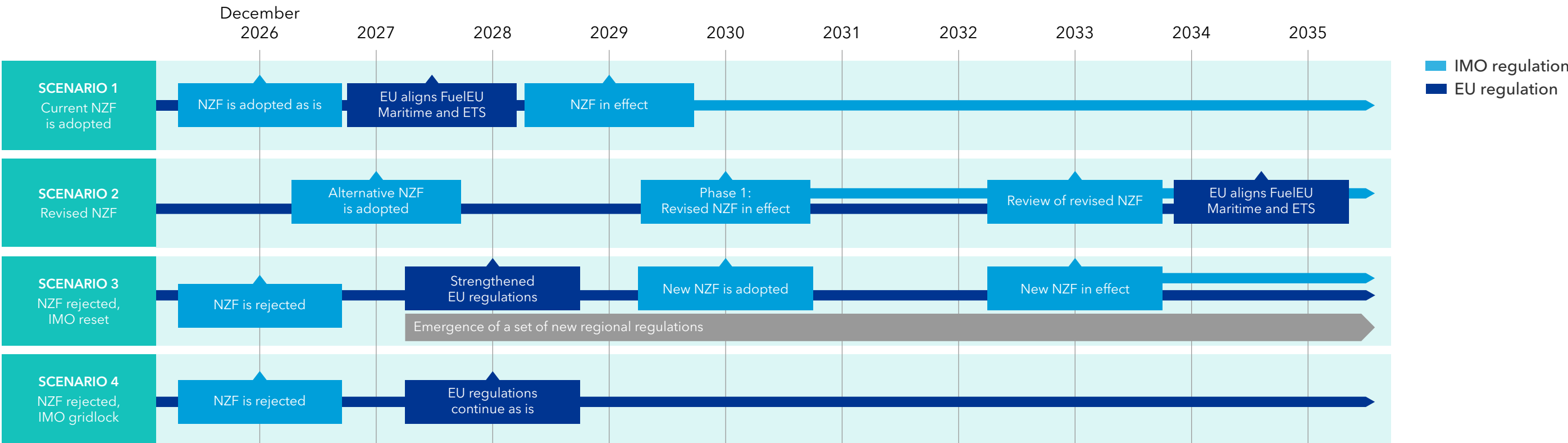
targeting international shipping. In this scenario, the NZF will be the main driver for maritime decarbonization.

The IMO will review the NZF five years after entry into force (2033) to consider, among other things, amending the GFI reduction factors, Remedial Unit (RU) prices, and the inclusion of ships of 400 GT and above.

Scenario 2: Revised NZF

In scenario 2, IMO member states negotiate a compromise on the NZF which is approved at MEPC 85 in December 2026 and adopted at MEPC 86 in 2027. This timeline implies that the NZF takes effect in 2030 at the earliest. Concerns over the NZF are addressed by removing or adjusting elements in the regulations, possibly including a staged introduction starting with the technical elements, and with a review after a few years.

FIGURE 2-3
Four scenarios for GHG regulatory development for international shipping



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Given these developments at the IMO, the scenario assumes that the EU continues with FuelEU Maritime and the EU ETS until at least two years after full NZF implementation in the second phase – in other words, well into the 2030s. This is in line with the EU's plans to review these regulations in light of developments at the IMO to consider possible alignments. The scenario also assumes that the UK will follow the same timeline as the EU, and that there will be no further regional regulations elsewhere that will regulate international shipping.

Scenario 3: NZF rejected, IMO reset

In scenario 3, the NZF is rejected in December 2026, and the IMO restarts the process of negotiating a new framework with an unknown regulatory design and timeline. This could, for example, involve the negotiation of a regulatory measure with only technical requirements, leaving out economic elements with revenue collection and disbursement. This scenario assumes that a new regulatory measure is negotiated in 2029 and adopted in 2030, with entry into force in 2032. This timeline could easily be extended depending on the global geopolitical situation and how it spills into the IMO negotiations.

If the current NZF is rejected, and with an unknown timeline for a new negotiation process, this scenario assumes that the EU strengthens FuelEU Maritime and the EU ETS to compensate for the lack of global action, with more stringent reduction targets and stricter cap on emission allowances. This scenario also assumes the emergence of a range of regional

regulations inspired by FuelEU Maritime and the EU ETS, leading to a patchwork of regulations that shipowners will have to navigate.

In this scenario, we could also see an increased focus on the IMO short-term measures – for example, an EEDI phase 4, a new EEXI phase 2, a further strengthening of the SEEMP, and the CII being revamped as a WtW technical GHG regulation with more robust enforcement.

Scenario 4: NZF rejected, IMO gridlock

In scenario 4, the NZF is rejected in December 2026, and the IMO enters an indefinite period of gridlock in the GHG negotiations. This means there are no negotiations of substance under the agenda item on GHG emissions from ships, and the IMO will continue to tinker with existing regulations, but with no major changes.

With this standstill at the IMO, this scenario assumes that the EU continues with FuelEU Maritime and the EU ETS as is, with no further strengthening to compensate for the lack of a global regime. It also assumes that there is no appetite for implementing other regional or national regulations that include international shipping in their scopes.

We highlight that there may be other possible outcomes at the IMO not captured here. Importantly, the regulatory timelines sketched here could be extended depending on how the negotiations unfold. See the box 'Global regulations take time' for more details on the IMO regulatory process.

Global regulations take time

The IMO is a UN specialized agency where member states with diverging interests strive to find consensus-based solutions to ensure that adopted regulations are widely implemented and enforced.

As with previous IMO GHG emission regulations, the NZF has been included as amendments to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL Convention).

The regulatory process follows a particular rhythm, with a set meeting schedule and procedures and steps for regulatory development. It progresses from submission of proposals, through drafting, approval, circulation, adoption, acceptance, to eventual entry into force. Negotiations are dynamic and marked by other developments in international politics which spill into the IMO.

Considering proposals and drafting can take years before a text with amendments to MARPOL Annex VI reaches the approval stage. Even if a decision is eventually passed through voting at the IMO (which is an exception), the negotiation process leading up to the final vote



involves a series of large and small compromises. For the NZF, it took around two years from the adoption of the revised 2023 IMO GHG strategy, marking the start of negotiations, until the text was approved at MEPC 83 in 2025. However, ideas and general proposals had been circulating for several years already before the negotiations started.



3

DECARBONIZATION SOLUTIONS AND THEIR UPTAKE FOR SHIPPING

Highlights

With shipowners under growing pressure to improve efficiency and prepare for low-GHG fuels, our analysis finds:

- Vessels delivered under successive EEDI phases show consistently enhanced CO₂ emission efficiency.
- Even a 15-year-old vessel can present a compelling business case for retrofitting energy-saving measures.
- Alternative fuel-capable gross tonnage surged from 0.4% of the global fleet in 2020 to 5.2% by 2026.
- LNG and methanol dominate alternative fuel technologies; their installed capacity is not fully used but growth in their use is driving demand for bunkering infrastructure.
- Ports with low-GHG fuel bunkering activity are concentrated along major trade routes in Europe and East Asia.

Newbuild decisions today will have long-term impacts on compliance, costs, operational flexibility, and long-term competitiveness. Emphasizing an integrated system approach, this chapter reviews energy-efficiency adoption, presents a business case and retrofit timeline over a 15-year dry-docking, and highlights the importance of quantifying efficiency impacts. We examine uptake of alternative fuels, covering technology status, actual usage, growth in bunkering capacity, and the availability of low-GHG fuels in ports.

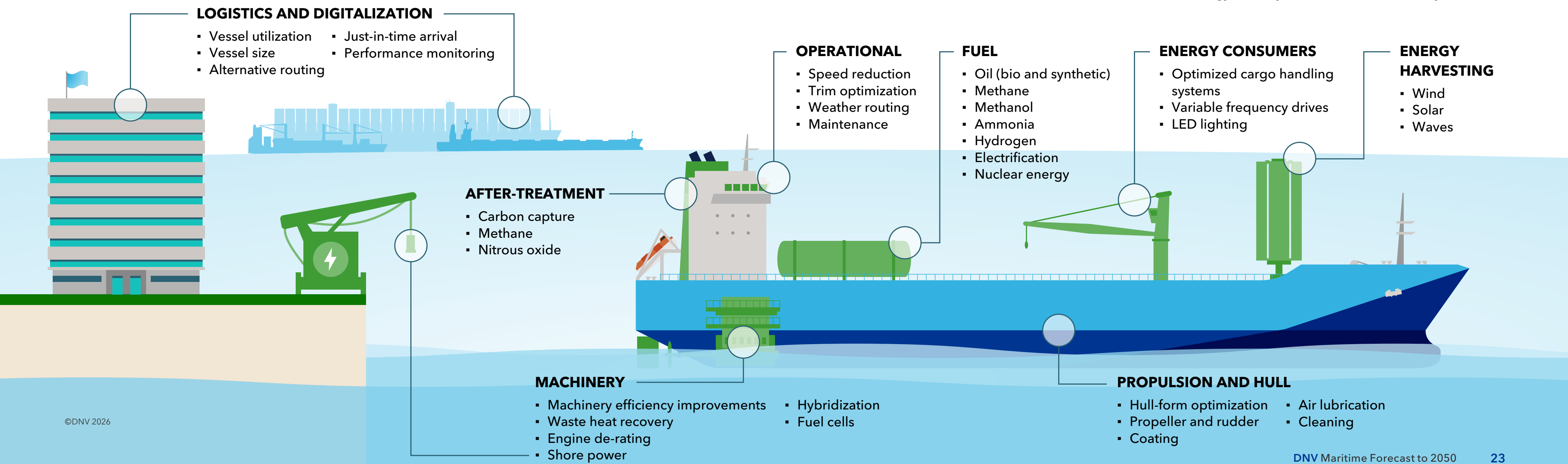
3.1 A snapshot of the maritime decarbonization landscape

As shown in Figure 3-1, decarbonization solutions span a broad spectrum of measures. These range from operational and technical energy-efficiency measures to increased fuel flexibility and the adoption of low-GHG alternative fuels (DNV,

2026c; DNV, 2025b; DNV, 2025d; DNV, 2025e; DNV, 2025f; DNV, 2025i). They also include the deployment of advanced energy-conversion technologies with internal combustion engines, fuel cells and batteries in hybrid machinery configurations,

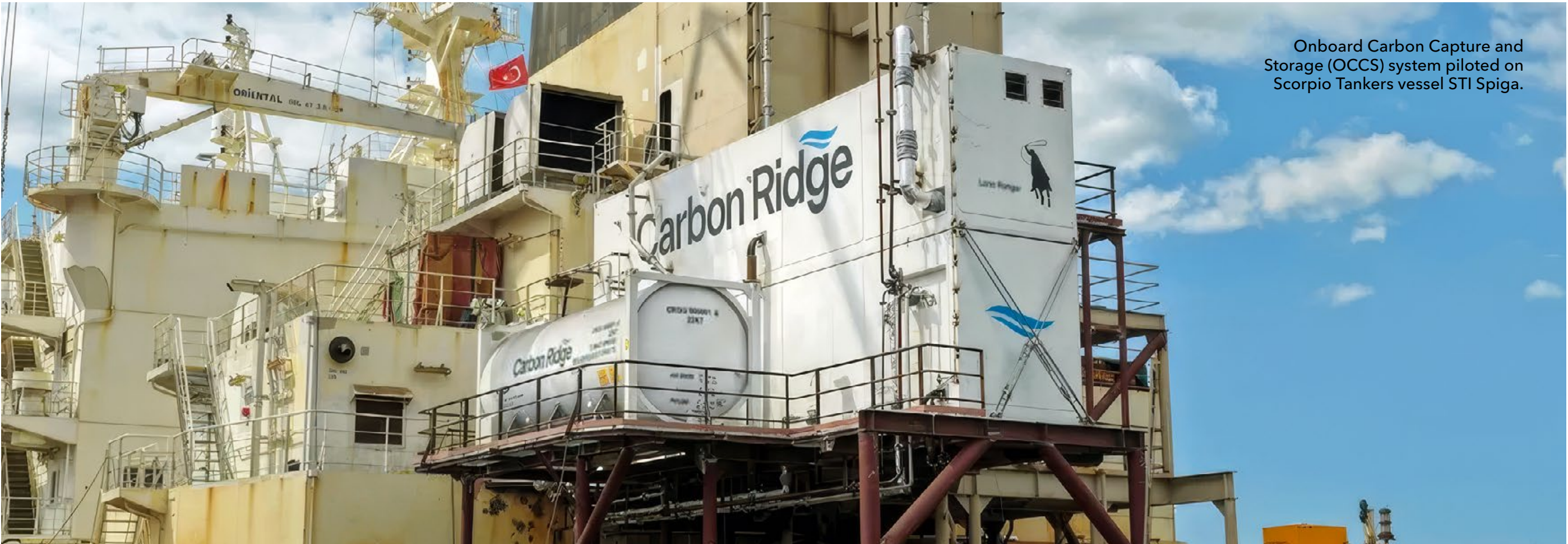
FIGURE 3-1

Decarbonization solutions that can reduce the energy consumption and emissions from ships and fleets



enabling connection to onshore power for charging when available during port calls, and wind-assisted propulsion systems (WAPS) (DNV, 2026d; DNV, 2025c). Emerging options include onboard carbon capture and storage (OCCS) and, over a longer time horizon, the potential incorporation of nuclear propulsion into the commercial fleet (DNV, 2025h; DNV, 2024c). In addition, direct use of shore power while at berth is a well-known practice and has the potential to provide notable GHG reductions, although availability today is scattered (DNV, 2026d).

Implementing operational energy-efficiency measures may reduce fuel consumption by adjusting speed and operational decisions based on prevailing conditions. These measures may require low investment and moderate operating costs but often need changes in ship management and training. Investments in shore-side infrastructure may also be necessary as part of logistics optimization that



Onboard Carbon Capture and Storage (OCCS) system piloted on Scorpio Tankers vessel STI Spiga.

Together, more than 50 operational and technical efficiency measures provide the foundation for reducing energy use and emissions across the fleet.

enables speed reduction and/or better vessel utilization, which will typically require involvement from other stakeholders such as cargo owners and ports. Using high-quality data and real-time insights enables digitalization and AI-driven optimization of maritime logistics, supporting just-in-time (JIT) operations that reduce waiting times, improve cruising efficiency, and lower fuel consumption and emissions (IMO, 2022a; UCL & UMAS, 2024). This is particularly relevant, as AIS-based studies show ships spend a substantial share of time stationary or at low

speeds due to coordination inefficiencies across the transport chain (DNV, 2018; UCL & UMAS, 2024). Technical energy-efficiency measures reduce engine power demand or improve fuel-conversion efficiency. Although these measures generally require higher investment, they can deliver significant reductions in fuel consumption and emissions and are expected to become more attractive as fuel prices and emission-related costs increase. Together, more than 50 operational and technical efficiency measures

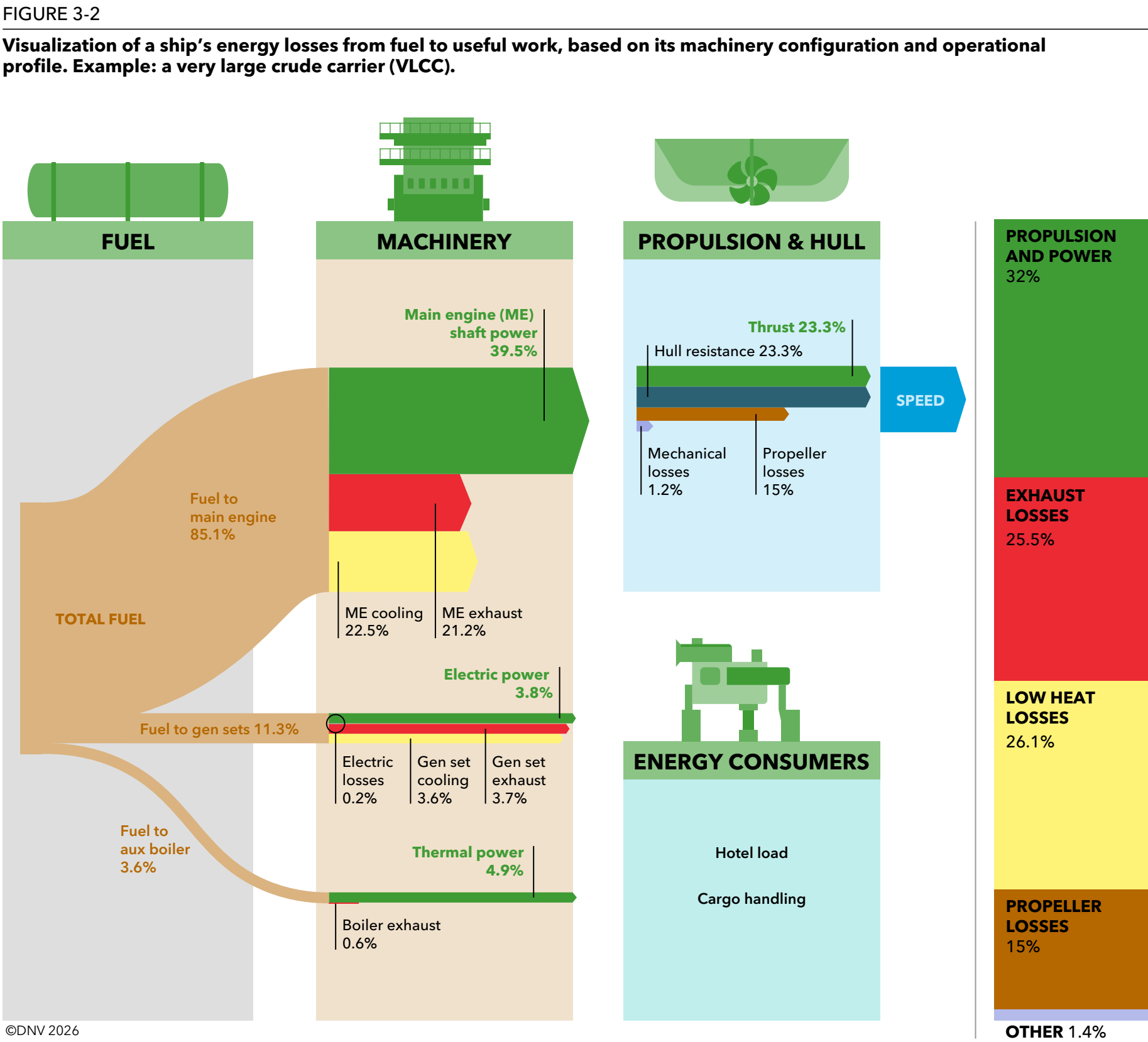
provide the foundation for reducing energy use and emissions across the fleet (DNV, 2025b). The fuel savings, GHG reduction potential, cost and applicability of measures depend on whether the vessel is a newbuild or an existing ship, on its type and age, on its operational characteristics, and on the available infrastructure in its area of operation for shore power, low-GHG fuels and reception of CO₂ captured from OCCS (DNV, 2025a; DNV, 2026e). To ensure that decarbonization solutions

deliver the expected GHG-reduction potential, lower compliance costs, and a satisfactory return on investment, it is important to adopt a systematic approach based on comprehensive analysis. An integrated system approach to ship decarbonization entails analysing the ship and its systems as an interconnected energy system that depends on external infrastructure beyond the ship and is part of a fleet. In this way, we can evaluate how energy is supplied, stored, transformed and consumed throughout the vessel's operation. Using information about the machinery configuration (main engine, auxiliary engines, and boilers), propulsion and hull performance, as well as the vessel's operational profile (including transit, manoeuvring and in-port



cargo handling operations), we can map the ship's energy flows and losses and identify opportunities for improved energy efficiency as illustrated by the energy-efficiency mapping in Figure 3-2. Tools such as DNV's COSSMOS can be applied for modelling, simulation, and optimization of ship-energy systems.

The mapping can be used in the newbuild phase and through the vessel's lifetime to evaluate potential energy-efficiency measures. For existing ships, standard maintenance (hull cleaning, recoating, machinery overhaul) yields energy-efficiency gains, while retrofitting during these periods can unlock additional savings. Dry-dock windows are pivotal. When a ship operates as part of a larger fleet, the decarbonization strategy should also consider fleet-level mechanisms such as pooling, shared compliance schemes, and collective emissions accounting. Fleet pooling can allow emissions reductions achieved by one vessel to offset those of others, creating flexibility in how and when individual ships adopt new technologies or fuels. It also enables more efficient allocation of low-GHG fuels, shore-power capable berths, or energy-saving technologies across the fleet. Digitalization and intelligent fleet management systems are increasingly becoming critical enablers, improving operational efficiency, enhancing fleet utilization, and enabling the collection, verification, and reporting of reliable emissions data. DNV's Emissions Connect platform addresses this need by providing an integrated digital solution that enables continuous monitoring and management of emissions performance, from raw data to operational control.



3.2 Energy-efficiency adoption in the world fleet

For the world fleet, simulations with sufficient regulations and pricing of GHG emissions showed that energy-efficiency measures and speed reductions can lower energy use by up to 16% in 2030 compared with a business-as-usual scenario, rising to as much as 25% to 28% by 2050 (DNV, 2024a); see also Section 4.3.1. A 16% reduction potential in 2030 corresponds to savings of roughly 40 Mt of fuel and 120 MtCO₂eq, equivalent to operating the 2,500 largest vessels (or the 55,000 smallest vessels above 400 GT) (DNV, 2025b). This, in turn, translates into a potential fuel cost saving of about USD 23 billion annually with a fuel price of 580 USD/tonne²² and even greater cost savings if considering use of more expensive low-GHG fuels.

A recent DNV study modelling the CO₂ emission abatement potentials and costs towards 2050 for all ships above 400 GT indicates that a large share of the reduction potential from energy-efficiency measures is cost-effective by 2030, with a growing share towards 2050, driven mainly by the uptake of more costly low-GHG fuels (Longva, et al., 2024). This highlights substantial untapped potential across both the sailing fleet and the order book, although significant economic, technical, and operational barriers remain. These findings are supported by World Bank estimates (World Bank, 2025). Retrofits are essential to unlocking the sector's full energy-efficiency potential. As shown in the text box on page 27, even a 15-year-old vessel can offer a compelling business

case for retrofitting energy-saving devices. The box also outlines a practical, step-by-step approach to taking such a retrofit from concept to implementation.

Increasing the adoption of energy-efficiency technologies requires overcoming several key barriers. Studies identify obstacles such as financial limitations, technical challenges, managerial and organizational practices, and legal constraints (e.g. Rehmatulla & Smith, 2015; DNV, 2025b). These can include conflicting organizational priorities and split incentives in charter parties. The disconnect between those who fund efficiency upgrades and those who pay for fuel, along with standard contracts that favour speed over efficiency, hampers investment in energy-saving solutions and sustains dependence on inefficient operational methods. Another barrier is uncertainty about real fuel saving in realistic operating conditions and limited trust in vendors' fuel-saving claims. The importance of strategic alignment within organizations, as well as collaboration within organizations and across the maritime value chain to unlock efficiency at scale is highlighted in a recent Global Maritime Forum study (GMF, 2026). The use of technical performance indices such as the Vessel Technical Index (VTI) can also help reduce barriers to uptake by making the impact of energy-efficiency measures easier to quantify and verify. Introduced by DNV Recommended Practice DNV-RP-0675, VTI showcases a ship's technical performance relative to its initial state, excluding external operational factors (see page 28).



General cargo vessel, Heinz, equipped with an enhanced bow design and suction sails to reduce fuel consumption.

Retrofit business case and timeline for energy-saving devices on a 5,000 TEU containership

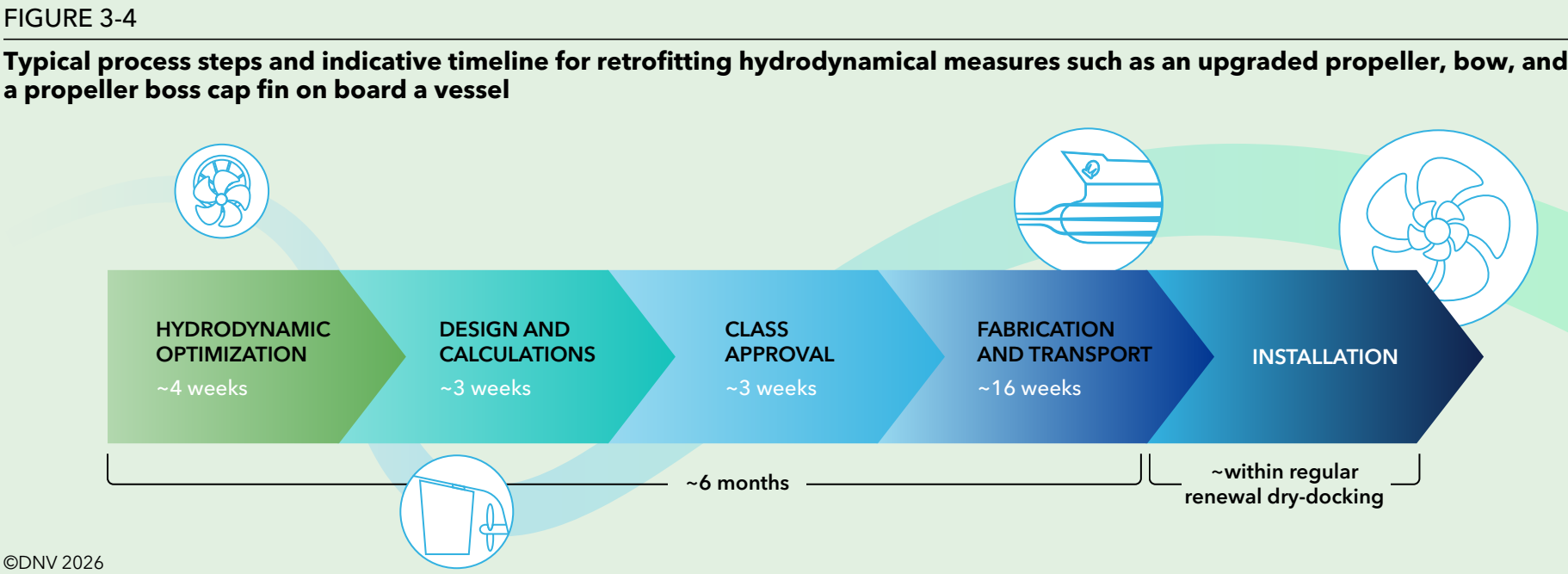
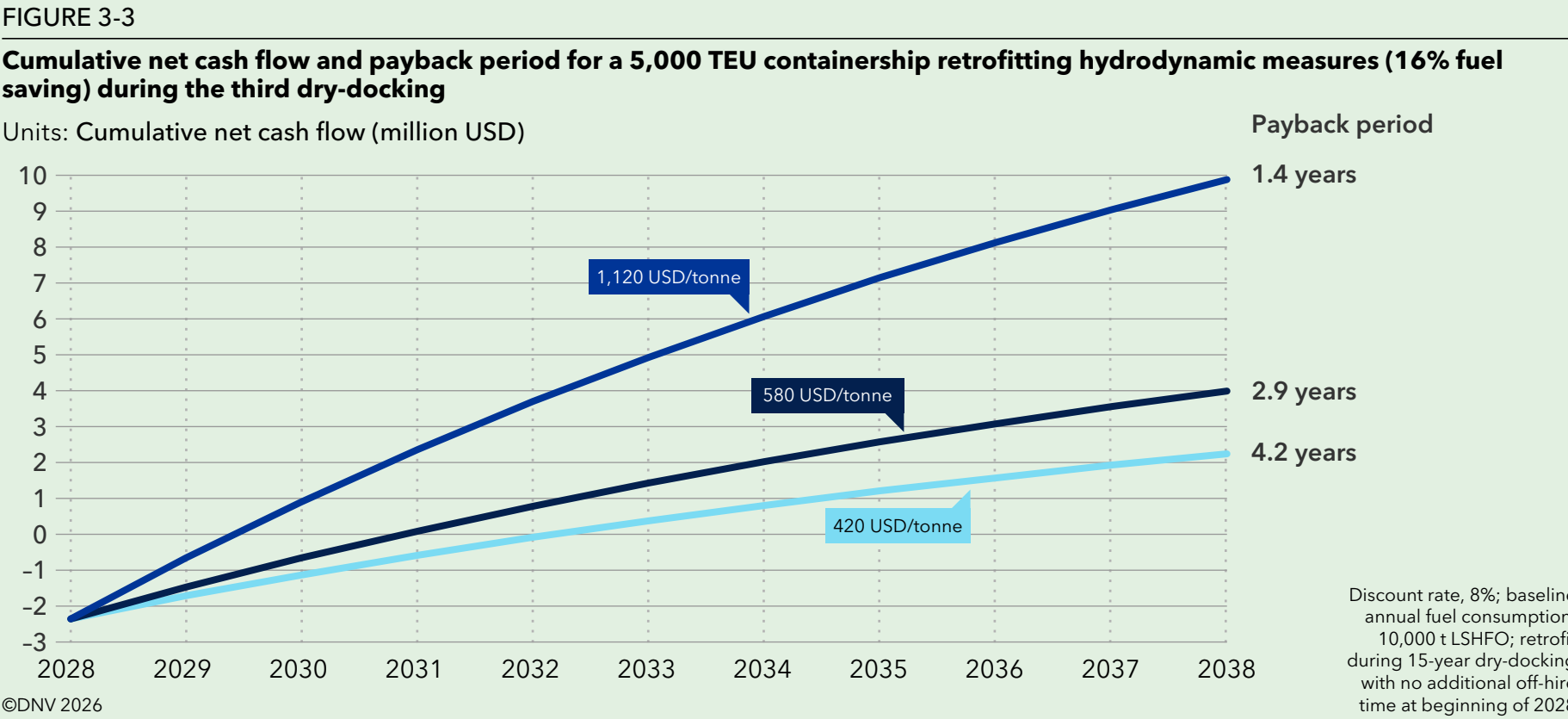
Based on a hydrodynamic optimization study, a 5,000 TEU containership built in 2013 was estimated to achieve fuel savings of around 16% through a combination of a bow retrofit, propeller retrofit, and installation of a propeller boss cap fin, at a total investment cost of approximately USD 2.35 million. We assume that the vessel complies with EEXI requirements after the retrofit.

To assess the business case for the retrofit, we applied two financial metrics: payback period and cumulative net cash flow (both discounted at a rate of 8%). These were evaluated across three fuel-price scenarios based on historical low sulphur

heavy fuel oil (LSHFO) prices in Singapore from 1 January 2024 to 30 April 2026: USD 420 per tonne (minimum), USD 580 per tonne (average), and USD 1,120 per tonne (maximum). The high-price scenario reflects the potential for fuel-price volatility driven by geopolitical events. Exposure to the IMO Net-Zero Framework and/or EU ETS, as well as FuelEU Maritime, was not included in the assessment, but would further strengthen the business case.

The results in Figure 3-3 show that implementing the 16% saving measures during the vessel’s 15-year dry-docking at the beginning of 2028, without any extra off-hire time, results in a payback period of roughly 1 to 4 years, depending on assumed fuel price. By 2038, the total net present value of fuel savings is projected to be between USD 2 million and USD 10 million, depending on fuel prices.

Retrofits of hydrodynamic measures should typically be initiated at least six months ahead of the scheduled dry-docking. The main process steps and indicative timelines are shown in Figure 3-4. Provided the retrofit is well planned, installation can normally be completed within the scope of a standard renewal dry-docking. Adequate schedule buffers should nevertheless be included to account for resource availability, project coordination, and yard planning constraints.



Verifying the impact of energy-efficiency measures – hull and propeller cleaning

Verifying real-world fuel savings from energy-efficiency measures is essential to assess business cases with confidence, but is challenging because savings depend on operating and environmental conditions. Establishing robust estimates requires reliable sensors, high-quality and high-resolution data, and thorough analysis of verified operational data to build sufficient trust in the results.

DNV's Recommended Practice DNV-RP-0675 Technical Ship Performance introduces a Vessel Technical Index (VTI) showcasing a ship's technical performance relative to its initial state, separating the impacts of operational factors (speed and loading condition), weather, and hull or propeller fouling. VTI has no unit – it is a normalized, dimensionless propulsion power index; a lower VTI means the ship requires less propulsive power to maintain the same speed at a given loading condition, directly indicating reduced fuel consumption.

In Figure 3-5, verified VTI values (meeting all procedural requirements of the Recommended Practice) were used to demonstrate realized performance improvements from hull and propeller cleaning on a Cargill-chartered ship. Voyage 1 was performed before the cleaning, while voyage 2 was performed after, each one lasting 33 days. VTI estimates show a statistically significant reduction in VTI from voyage 1 to voyage 2; from a mean (μ) of 1.32 to 1.14, relative

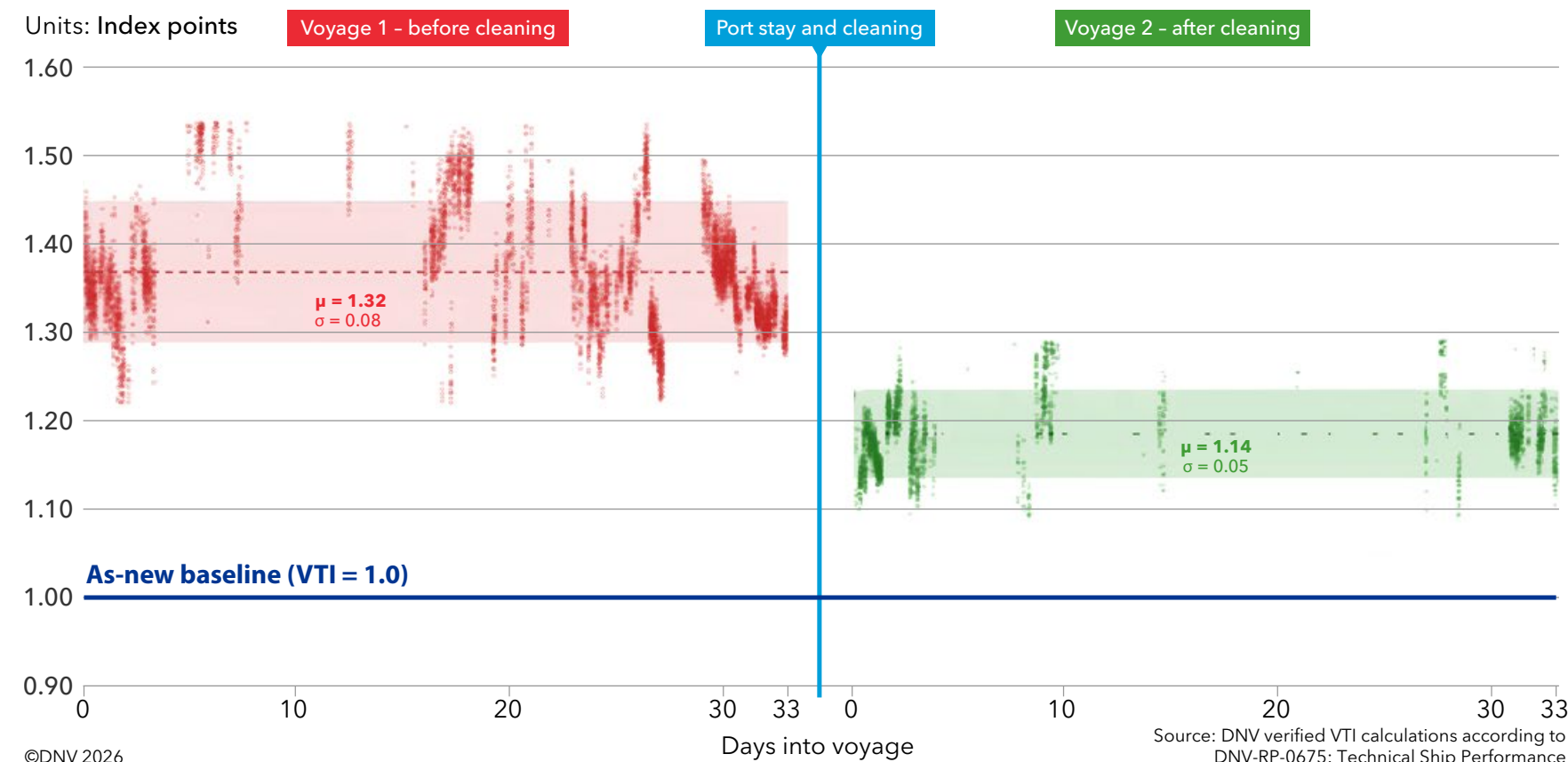
to an 'as-new' baseline (1.00). This improvement corresponded to approximately 120 tonnes of fuel saved over a 33-day voyage, with fuel cost savings amounting to about USD 56,000, assuming a fuel price of 470 USD/tonne, far exceeding the cleaning expenses of about USD 14,000.

More generally, gaining a reliable understanding of the fouling condition requires more than just installing sensors. In addition to ensuring correct calculation of the VTI, the measurement data can be incomplete, biased, or inaccurate, potentially leading to misguided decisions. A robust programme for

data quality assessment and verification is therefore essential, combining technical insight with cross-checks against other data sources. With confidence in the quality of the input data, shipowners can make better-informed decisions on hull and propeller cleaning, ultimately reducing operating costs.

FIGURE 3-5

Sensor data used to calculate the Vessel Technical Index (VTI) shows that cleaning reduced actual fuel consumption. Results before (left) and after (right) indicate an improvement in VTI following the cleaning. VTI values are excluded when data does not meet procedural requirements of the Recommended Practice (DNV-RP-0675 Technical Ship Performance). μ denotes the mean and σ the standard deviation.





Wallenius Wilhelmsen's Shaper Class ships incorporate air lubrication systems.

3.2.1 Energy-efficiency adoption by segment

The industry lacks comprehensive data on the universal adoption of energy-efficiency technologies (World Bank, 2025). However, data from Clarksons Research indicates that ships on order are adopting energy-efficiency technologies to a greater extent than the current fleet.²³ The adoption differs by deep-sea segment: containerships, car carriers, LNG carriers and cruise vessels lead adoption of energy efficiency with advanced, capital-intensive technologies due to predictable operations and strong commercial or regulatory pressure. Bulk

carriers and tankers favour low-cost operational measures and selective retrofits, and as with other segments, a higher uptake on larger vessels. Operational measures such as regular hull and propeller cleaning and weather routing are commonly applied throughout the fleet. Below is an indicative status update on common energy-efficiency measures for different ship segments based on Clarksons and other public data:

- **Containerships:** Major carriers are undertaking significant upgrades to several hundred ships in their fleets.^{24, 25, 26} A primary focus is improving hydrodynamic efficiency at lower service speeds by modifying bulbous bows, enhancing propellers,

and installing pre-swirl devices. Aerodynamic efficiency is also enhanced through the application of windshields and deflectors. They also increase cargo capacity through various structural and technical enhancements, such as raising lashing bridges and deckhouses, strengthening dead-weight for deeper drafts, and upgrading lashing systems and loading computer functions.²⁷

- **LNG carriers:** LNG carriers are rapidly integrating high-efficiency technologies centred on reducing fuel consumption and managing boil-off gas (BOG). Newbuilds commonly feature dual-fuel 2-stroke engines, shaft generators, fuel containment systems with lower boil-off rates and BOG reliquefaction systems. Hydrodynamic enhancements such as twin skegs, propulsion-improving devices (PIDs), and air lubrication systems (ALS) are commonly implemented. Digital optimization tools, speed management, and trim adjustments further enhance voyage efficiency.^{28, 29}
- **Car carriers:** The segment has become one of the most proactive adopters of energy-efficiency technologies. Newbuilds frequently incorporate ALS, which pair well with the design operation of car carriers. Enhanced hull forms, aerodynamic design, and improved hydrodynamic appendages contribute to efficiency.^{30, 31}
- **Cruise:** Here, advanced waste-heat recovery systems, shore-power capability and air lubrication systems are frequently implemented on newbuilds, while batteries and hybrid arrangements support

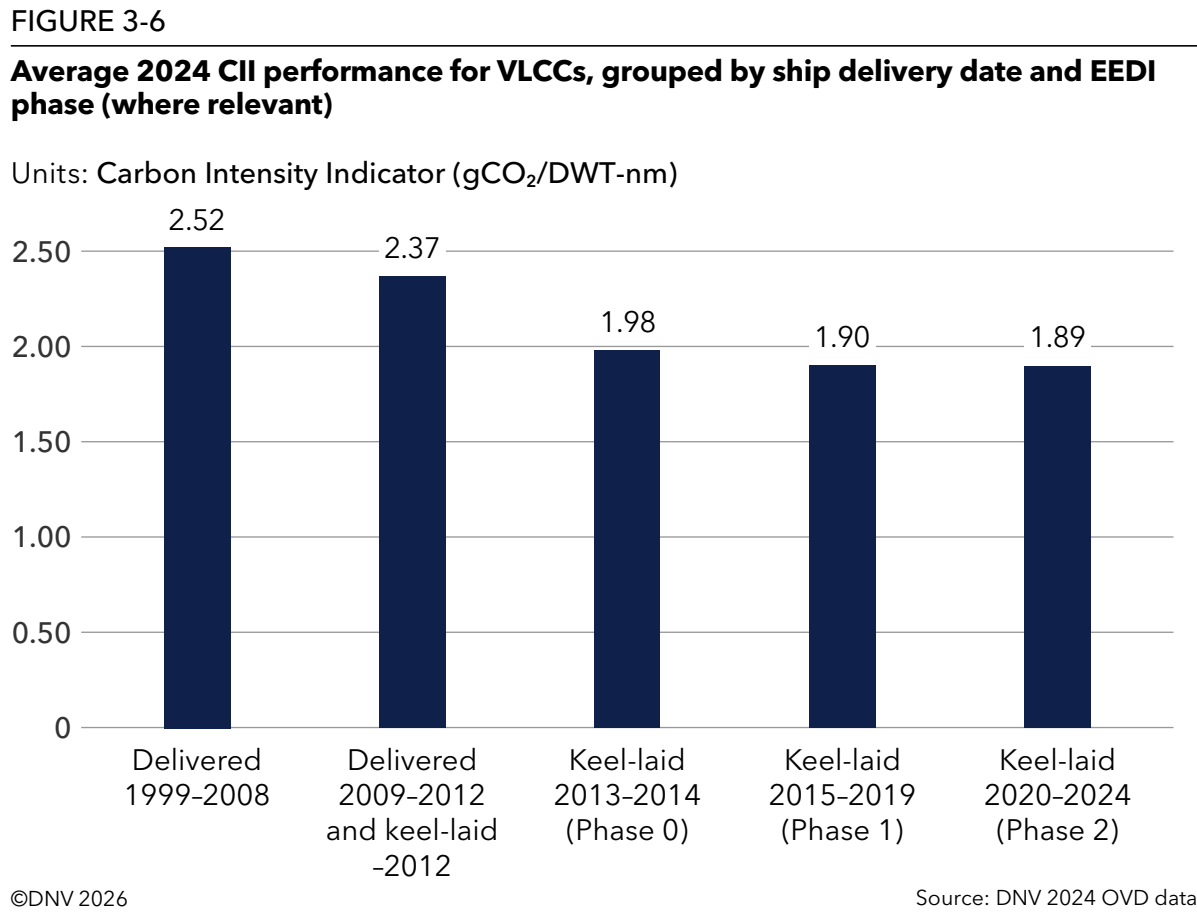
zero-emission port stays and low-speed manoeuvring. In addition, cruise vessels focus heavily on reducing hotel-load energy consumption. Key measures to reduce energy demand include optimized heating, ventilation and air conditioning (HVAC) and lighting systems.³²

- **Bulk carriers:** In the bulk segment, hydrodynamic retrofits like propeller boss cap fins (PBCF) and pre-swirl ducts are common during dry-dockings, alongside low-friction coatings and upgraded rudders. Engine power limitation is a near-universal compliance tool for EEXI. Bulk carriers with alternative-fuel capabilities are more often implementing comprehensive energy-efficiency measures such as rotor sails, pre-swirl stator fins, post-propeller vortex-dissipating fins, shaft generators, and variable-frequency motors.³³

Containerships, car carriers, LNG carriers and cruise vessels lead adoption of energy efficiency with advanced, capital-intensive technologies due to predictable operations and strong commercial or regulatory pressure.

– **Tankers:** In this segment, energy-efficiency strategies emphasize hydrodynamic improvements and operational optimization. Propulsion improvement devices – including Mewis ducts, PBCF, and optimized rudder designs – are among the most widely adopted retrofits. Slow steaming and trim/ballast management deliver fast, low-cost efficiency gains, while machinery upgrades such as engine power limitation, waste-heat recovery, and variable frequency drives (VFDs) help further reduce consumption.³⁴

IMO short-term measures play an important role in improving energy efficiency and emission performance. Vessels delivered under successive EEDI phases exhibit systematically improved CO₂ emission efficiency. This structural improvement is reflected in the CII performance, as demonstrated by the 2024 CII values reported for 132 VLCCs across age groups ranging from 1999 to 2024, based on DNV’s Operational Vessel Data (OVD) for 2024 (see Figure 3-6). Newer vessels outperform older ones, with CII improving across all age groups and an overall improvement of nearly 25%, underscoring the impact of design driven efficiency gains.



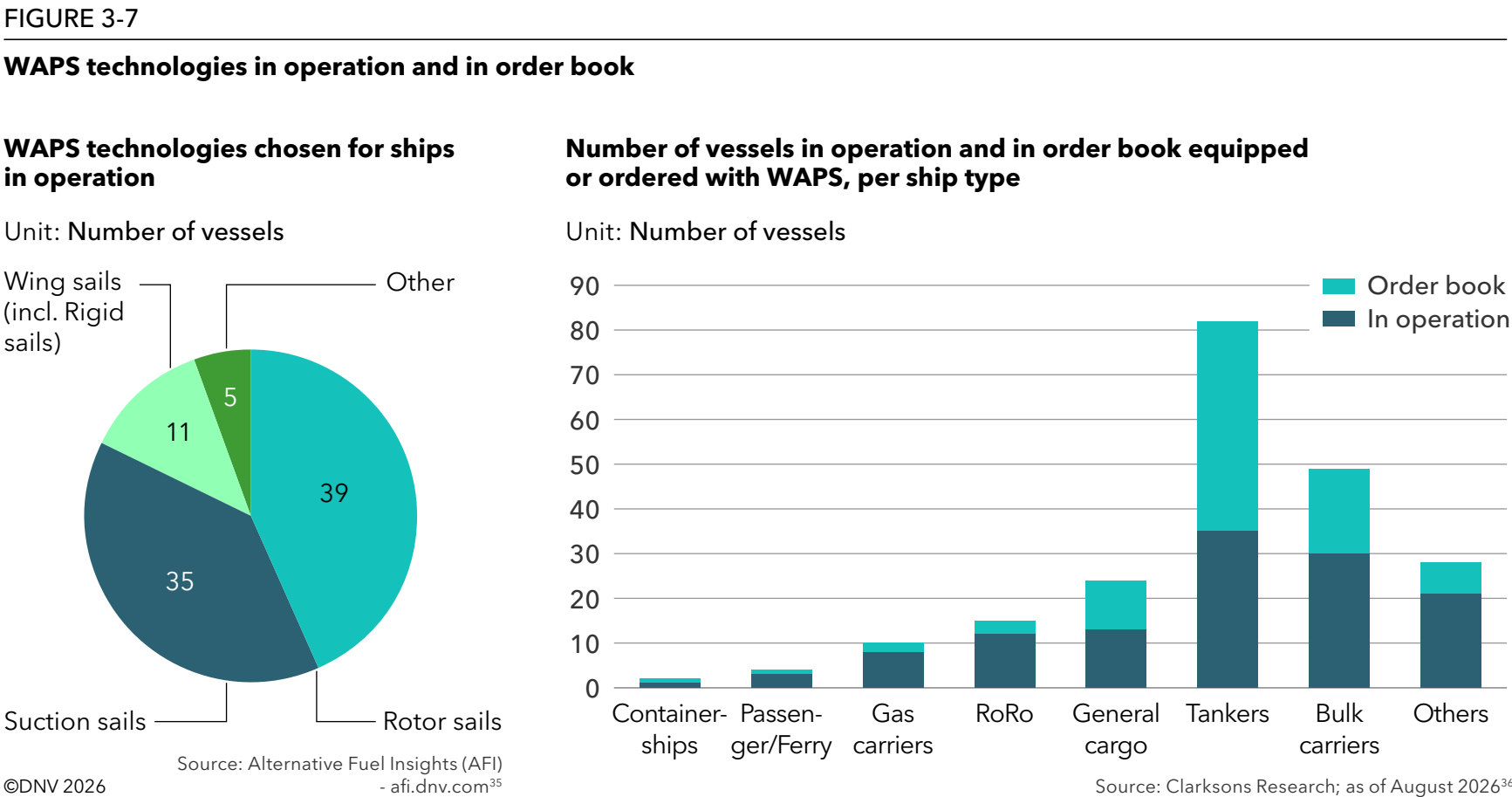
3.2.2 Wind-assisted propulsion systems uptake

Wind-assisted propulsion systems (WAPS) including rotor sails, suction sails, and wing sails give ship-owners another option to reduce fuel costs and GHG related regulatory exposure under EU and IMO frameworks. A recent modelling study indicates that widespread deployment of Flettner rotors across the wind-suitable fleet could reduce annual CO₂-equivalent emissions by around 4% to 5% from international shipping by 2050 (Seas at Risk, 2026). As GHG regulations tighten, uptake of WAPS is expected to

increase significantly in the coming decades (DNV, 2025c).

Beyond pure fuel savings, WAPS provides a compliance benefit under FuelEU Maritime, where installation alone can deliver an improvement in the vessel’s GHG intensity via the Wind Reward Factor.³⁷ This acts as a strong early-stage incentive for adoption and could be further leveraged by regulators to accelerate technology uptake.³⁸

As of August 2026, the WAPS fleet comprises 90 vessels³⁹ in operation and about 91 vessels on



order⁴⁰ (Figure 3-7). Vessels with WAPS operate in global deep-sea trade, with most installations on bulk carriers, tankers, and general cargo vessels. The uptake on container vessels is almost non-existent due to practical constraints such as limited deck space and free airflow to the sails. To date, only one container feeder has been equipped with WAPS.

Current uptake of WAPS reflects a mix of technical maturity and vessel design constraints rather than clear segment preferences. However, rotor sails account for nearly half of WAPS uptake among ships in operation. For tankers, newbuilds on order are predominantly selecting rigid wing sails, while suction sails and rotor sails dominate in the existing fleet. This appears to be driven more by vessel size than ship type, as current rotor sail offerings are better suited to smaller installations, although larger units are under development and may shift this balance. In the bulk segment, rotor sails continue to gain traction, with the recent installation on the 325,000 DWT very large ore carrier (VLOC) Grand Pioneer, equipped with four 35 × 5 m rotor sails, highlighting their applicability at scale.⁴¹ For general cargo vessels, uptake of WAPS depends on vessel-specific design constraints, with available deck space and interaction with existing equipment playing important roles in determining technical feasibility and achievable performance. In the container segment, activity remains in an exploratory stage, with studies by operators such as Hapag Lloyd⁴² and product development efforts focused on wing sail solutions⁴³, which are better suited to higher vessel speeds.



Berge Olympus, a bulk carrier equipped with four retrofitted wing sails.

WAPS have moved decisively from concept to demonstrated performance, but the efficiency range and communication of effects require careful interpretation. Simulation results underscore the variability of WAPS performance. Power gains vary significantly by season, year, and direction of travel, with winter months typi-

cally delivering several times the gains of summer periods. Even across a five-year period on the same route, average power gains can fluctuate meaningfully. This reinforces that WAPS should be evaluated as probabilistic, route dependent energy-efficiency measures, not as fixed-percentage solutions.

While current CAPEX remains relatively high, there is clear potential to reduce costs through industrial scaling and supply-chain maturation as production volumes increase. Retrofitting WAPS is possible for almost any ship with adequate deck space and unobstructed airflow, even if not originally designed for sails, although newbuild integration offers greater potential savings by allowing the design to be optimized from the outset.⁴⁴ Recent installations on vessels up to 19-years old demonstrate that WAPS can be commercially viable beyond newbuilds. In certain markets, performance improvements, such as increased speed or enhanced operational flexibility, can further strengthen the business case. New business models are developing around leasing⁴⁵ and modular installation, allowing vessels to become 'wind ready' and deploy sails selectively on wind-favourable routes. This flexibility reduces commitment risk and enables alignment with changing trade patterns.

Overall, the strongest value lies not in isolated peak savings, but in verifiable long-term performance supported by standardized measurement and verification practices. When applied with realistic expectations and transparent communication, WAPS represents a robust contributor to near-term decarbonization and regulatory compliance pathways.

3.3 Alternative fuel uptake in the world fleet

Alternative fuel capabilities in the global fleet have grown rapidly since 2020. While LNG and methanol dominate the fleet’s alternative fuel technology mix, installed capacity is not fully utilized. The growth is nonetheless driving demand for bunkering infrastructure. Ports with low-GHG fuel bunkering activity are geographically diverse, though clearly concentrated in Europe and East Asia.

3.3.1 Status of alternative fuel technology uptake

Alternative fuel technology refers to onboard machinery and fuel systems that enable operation on fuels other than conventional oil-based fuels or their drop-in low-GHG equivalents (i.e. bio-diesel). Driven by new vessel deliveries, the share of alternative fuel-capable gross tonnage (excluding LNG carriers) has increased from around 0.4% of the world fleet in 2020 to 5.2% by August 2026, as shown in Figure 3-8. The shift towards larger ships is illustrated by the fact that while the number of ships increased six-fold, the gross tonnage increased by a factor of nearly 15. Practically all the alternative fuel-capable vessels have dual-fuel technology, thus also enabling operation on conventional oil-based fuel.

Figure 3-9 breaks this down in more detail for the world fleet including LNG carriers. In 2020, LNG fuel

technology on smaller vessels dominated, with 185 ships, while 538 LNG carriers, 12 methanol tankers, and 14 LPG carriers could use their cargo as fuel. Since then, uptake of other fuel technologies has increased significantly.

As of August 2026, 813 LNG carriers and 929 other ships can use LNG as fuel, most of which are large vessels with high energy-storage needs. More than

While LNG and methanol dominate the fleet’s alternative fuel technology mix, installed capacity is not fully utilized.

42 methanol tankers and 112 other ships capable of using methanol as fuel are currently sailing. With minor modifications, methanol-capable vessels can also burn ethanol – a molecule with similar properties – providing flexibility in the future fuel pathway. 234 LPG carriers can use their LPG cargo as fuel. In addition, 8 vessels can use hydrogen as fuel, while 4 have demonstrated use of ammonia as fuel.

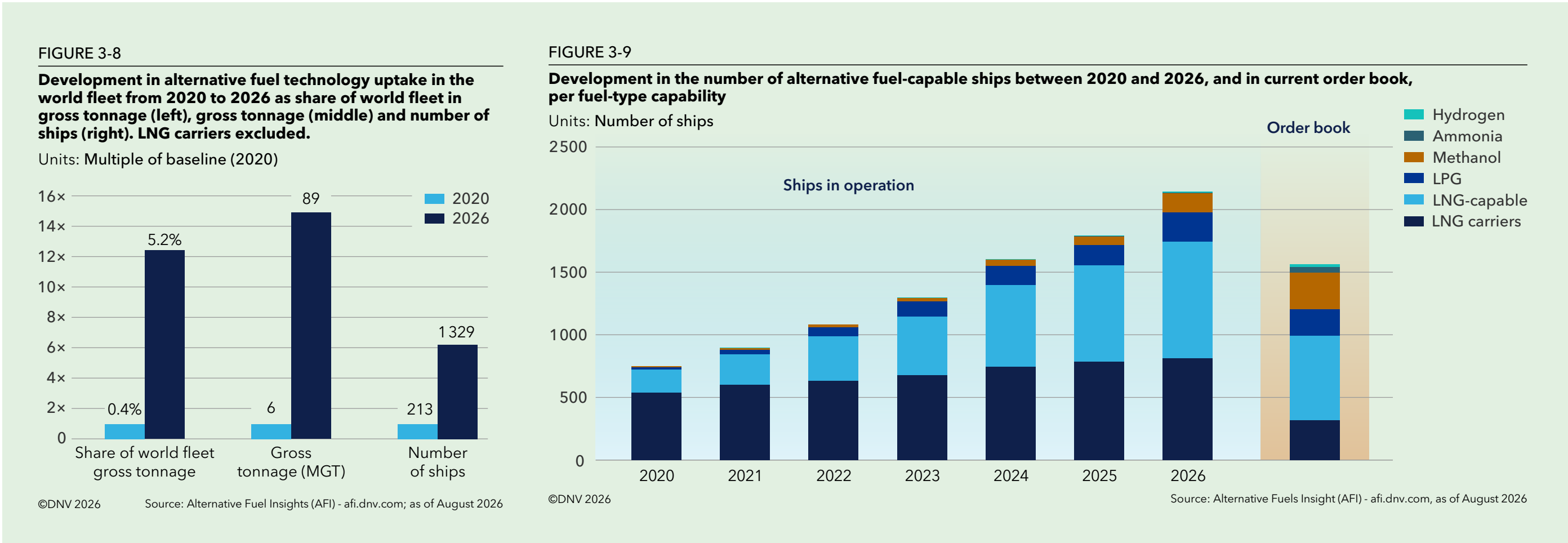


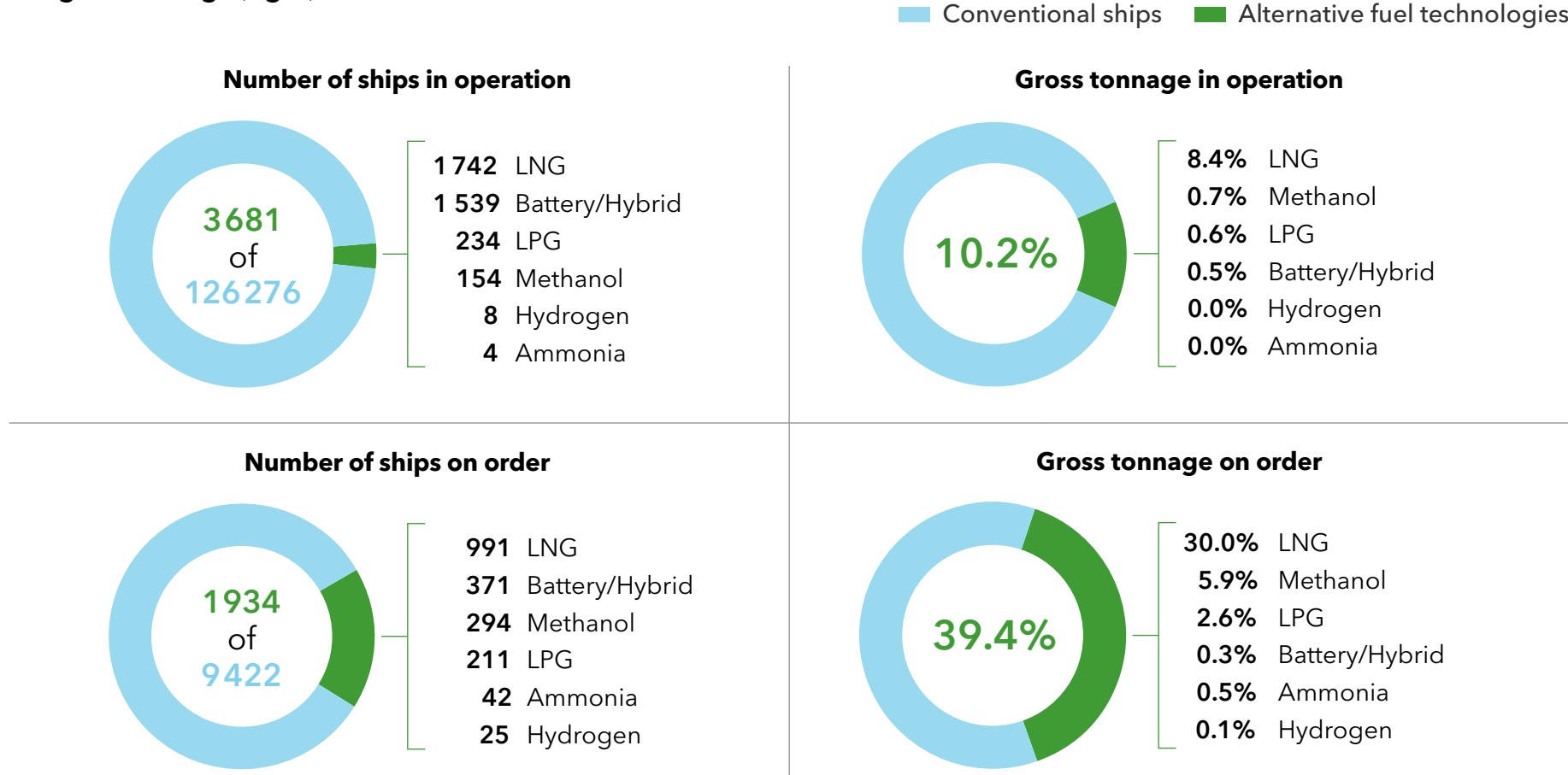
Figure 3-10 presents the status and details of the uptake of alternative fuel technologies in the world fleet⁴⁶ and the order book as of August 2026. LNG-capable is clearly leading the order book, with 672 vessels and 319 gas carriers. The order book for methanol-capable vessels remains strong, with over 294 vessels on order. Ships fitted with ammonia fuel systems total 42, while hydrogen-capable ships number 25. By gross tonnage, 39.4% of vessels on order can use alternative fuels in addition to fuel oil, down from 49.5% last year.

The decrease in ordering could partly be due to regulatory uncertainty, as many owners delayed ordering decisions pending clarity on the IMO’s Net-Zero Framework (NZF). However, the main driver is a shift in order book composition. Alternative fuels have primarily been adopted in segments such as container vessels, cruise ships, and car carriers, while the current order book is increasingly dominated by tankers and bulk carriers, which have lower uptake. As a result, the overall share declines even though progress continues within leading segments.



NCL Vestland, a methanol dual-fuel container feeder vessel.

FIGURE 3-10
Alternative fuel technology uptake in the world fleet (in operation and on order) by number of ships (left) and gross tonnage (right)



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Sources: S&P Global, Alternative Fuel Insights (AFI) - afi.dnv.com, as of August 2026

Alternative fuel capabilities vary significantly across ship segments due to differences in operating profiles, commercial structures, and fuel availability (Figure 3-11). Our analysis shows that the share of vessels with alternative-fuel capabilities – measured by the number of ships in operation and on order – ranges from 1.1% for bulk carriers to 26% for car carriers, and almost all LNG carriers use cargo boil-off as fuel.

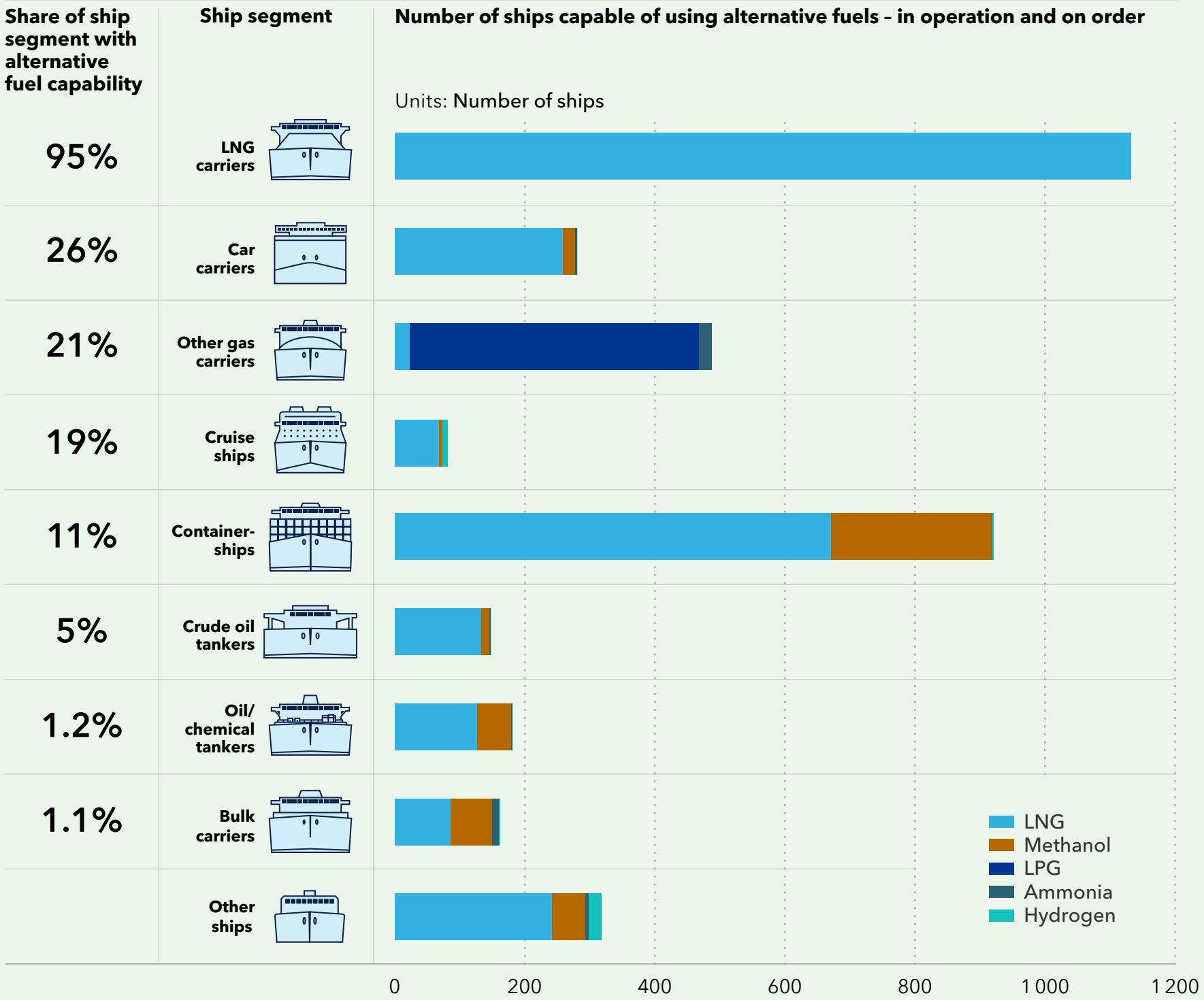
Upon reviewing the preferred fuel technology options for both operational and ordered ships, we find that:

– **In the world fleet, 89.8% of the operational gross tonnage can operate only on oil fuels.** This implies reliance on drop-in fuels such as fatty acid methyl ester (FAME) or hydrotreated vegetable oil (HVO) for decarbonization, unless these vessels are converted to use alternative fuels or equipped with onboard carbon capture and storage. For vessels currently on order, 60.6% of

the tonnage and 79.5% of the ships by number face similar limitations.

- **Almost all LNG carriers are alternative fuel-capable.** LNG carriers account for 813 of the LNG-fuelled ships in operation, with a further 319 on order. LNG carriers use their cargo as fuel, primarily to manage the natural evaporation of liquefied natural gas during transit to prevent pressure build-up in cargo tanks.
- **21% of other gas carriers can use their LPG or ammonia cargo as fuel.** The use of LPG as a marine fuel is currently limited to LPG carriers. Its adoption in other vessel types remains to be seen. Currently, 234 of the approximately 1,800 LPG carriers in operation can use their LPG cargo as fuel. As expected, early adopters are also present in the ammonia carrier segment, with 1 in operation and 19 on the order book capable of using ammonia cargo as fuel.

FIGURE 3-11



- **26% of car carriers are alternative fuel-capable:** The segment is among the leading adopters of alternative fuels in global shipping, with the highest dual-fuel technology uptake. The automotive industry increasingly demands low-carbon logistics pathways, prompting carriers to invest in future-proof propulsion. Of the approximately 940 car carriers in the sailing fleet, 149 can use LNG as fuel, while 3 are methanol-capable. The current order book lists 109 LNG-, 15 methanol-, and 4 ammonia-capable car carriers.
- **11% of containerships are alternative fuel-capable:** Containerships are currently among the most active adopters of alternative fuel technologies. The swift shift towards LNG, methanol, and ammonia capability is driven by regulatory and commercial pressure (scope 3), cargo owner expectations, and strategies to avoid future carbon costs. In terms of technology adoption, LNG technology recently competed with methanol for the lead; it has since regained popularity, with 424 LNG-capable vessels on order. The container segment continues to have the most (158) methanol-capable ships on order. In the smaller regional container segment, 2 hydrogen-capable vessels and 1 ammonia-capable vessel are also on order. In terms of overall segment adoption, there are currently about 6,700 container vessels in operation, of which 335 are equipped with alternative fuel capabilities, primarily on larger ships. The order book is expected to add another 585 alternative fuelled vessels by 2030, bringing the fleet to 11% dual-fuel capable, measured by the number of ships.
- **19% of cruise vessels are alternative fuel-capable:** There are about 350 ocean-going cruise ships in operation, including 35 LNG-capable and 1 methanol-capable. The uptake is increasing rapidly, with more than half of newbuild orders now featuring alternative fuel capabilities. The order book statistics for cruise vessels show that 32 are LNG-capable, 4 can use methanol, and 9 plan to use hydrogen to varying degrees.
- **5% of crude oil tankers are alternative fuel-capable:** For a fleet of around 2,400 crude oil tankers, LNG is the most widely adopted alternative fuel technology; 91 LNG-capable tankers are currently operating and 41 more are on order. There is one methanol-capable crude oil tanker in operation and 11 more on order. No ammonia-capable crude oil carriers are currently sailing, but 3 ammonia-capable tankers are in the order book.
- **1.2% of oil and chemical tankers are alternative fuel-capable:** Out of the almost 13,500 oil and chemical tankers, 98 are LNG-capable, with 28 more on order. 32 methanol tankers can use their cargo as fuel, and 1 is on order. Additionally, 10 other methanol-capable oil and chemical tankers are in operation, with 9 more on order. The first two ammonia-capable oil and chemical tankers are also on order.
- **1.1% of bulk carriers are alternative fuel-capable:** Of the around 13,000 bulk carriers in operation, 72 are LNG-capable and 3 methanol-capable. The order book will add 13 LNG-, 60 methanol- and 11

ammonia-capable vessels to this. LNG technology is primarily used on larger bulk carriers. The order book includes 10 methanol-capable 325,000-DWT ore carriers, and 2 which can use ethanol.

– **Other ship segments:** In other ship segments, LNG technology is the most popular choice, with 241 ships either in operation or on order. The RoPax/RoRo/Ferry segments account for nearly half of

these. The remainder includes 51 ships capable of using methanol, five ammonia-capable, and 21 hydrogen-capable ships. Uptake of hydrogen fuel technologies is limited to smaller ships in short-sea shipping. Three vessels are currently operating with hydrogen-powered proton-exchange membrane (PEM) fuel cells: the Norwegian ferry Hydra, the American ferry Sea Change, and a small Japanese passenger vessel, Hanaria. Additionally,

three crew transfer vessels and two tugs operate with hydrogen-powered internal combustion engines. The ammonia order book for other ship segments includes one general cargo carrier and one offshore supply ship.

In addition to vessels that can use alternative liquid and gaseous fuels, more than 1,500 are currently operating with batteries. Battery applications

vary from energy optimization of engine operation (without charging electricity from shore) to varying degrees of electric operation (charged from shore), typically in plug-in hybrid configurations enabling both battery and combustion engine operation – in other words, a ‘dual-fuel’ solution. Most ships referred to as ‘fully electric’ in operation will also depend on oil-fuelled generator sets as backup. Additionally, 371 ships on order

Onboard carbon capture and storage technology uptake

The concept behind onboard carbon capture and storage (OCCS), an abatement technology, is to capture CO₂ from the ship exhaust during operation and store it on board for delivery at a reception point. While OCCS can lower emissions, it involves an energy penalty and needs additional onboard storage capacity for captured carbon. It also relies on a supply chain capable of receiving and permanently storing the captured carbon away from the environment (Figure 3-12).

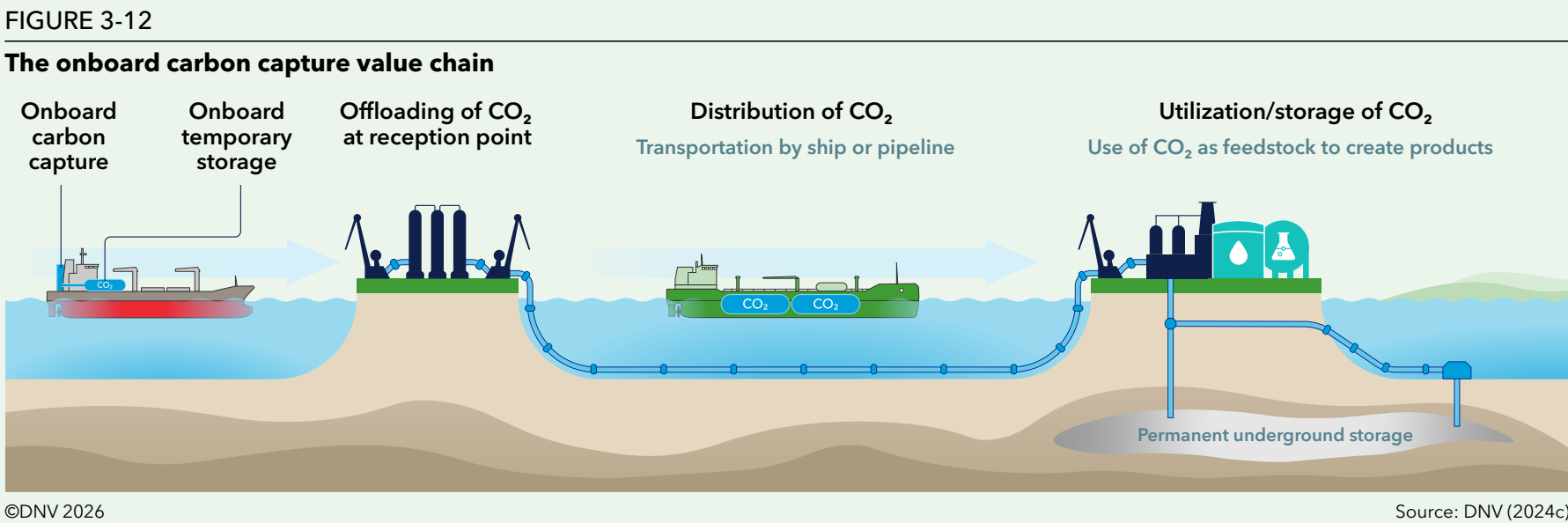
Currently, 32 vessels are sailing with systems in which chemicals (amines) absorb CO₂ from the exhaust. Three of these have systems capable of storing liquefied CO₂ on board for offloading to a reception point. The others store CO₂-rich amines for offloading to onshore processing prior to further distribution of CO₂ for use or permanent storage. For more information, see DNV’s AFI platform.

Pilot projects – for example, Solvang’s and Wärtsilä’s OCCS installation on Clipper Eris, GCMD’s CAPTURED on Ever Top, and EverLoNG – have demonstrated OCCS feasibility under real-world marine conditions. Chemical absorption systems tested on various vessel types have shown promising capabilities for efficiently capturing CO₂ and maintaining stable operations. Mineralization pilots have validated the process of converting CO₂ into solid carbonates. These initiatives provide useful insights into system performance, integration challenges, and regulatory considerations, supporting OCCS as a practical solution for reducing shipping emissions (EMSA, 2026).

Technology providers are actively developing concepts and pilots to demonstrate the technical feasibility of OCCS alternatives. However, it is important to recognize that their successful imple-

mentation depends on regulatory acceptance and the development of downstream infrastructure for receiving, transporting, and permanently storing or utilizing carbon dioxide. The EU ETS currently offers the only explicit incentive for OCCS

in maritime GHG regulations, while the IMO is developing a dedicated regulatory architecture, including LCA-based crediting of captured CO₂, and classification societies provide interim safety guidelines.



will feature batteries. The growth in the maritime battery fleet has been driven primarily by car and passenger ferries, which still dominate global battery uptake, largely in Northern Europe and China⁴⁷. Australian shipbuilder Incat Tasmania has built the world's largest fully battery electric ship – a lightweight ferry with over 40 MWh of capacity for Buquebus, it is scheduled to enter service in 2026.^{48, 49} Offshore support vessels and tugs are the second largest adopters of batteries. Coastal and short-sea general cargo and feeder container vessels are increasingly adopting

batteries, especially where ports offer incentives and shore power. Some expedition and coastal cruise vessels have large battery packs for silent sailing and zero-emission operation in sensitive areas. German shipbuilder Meyer Werft has recently announced a concept for a fully battery-electric large cruise ship.⁵⁰ For deep-sea shipping, the battery uptake is generally limited to engine optimization and auxiliary loads. From a well-to-wake perspective, GHG emissions associated with electricity generation should, in principle, be accounted for.

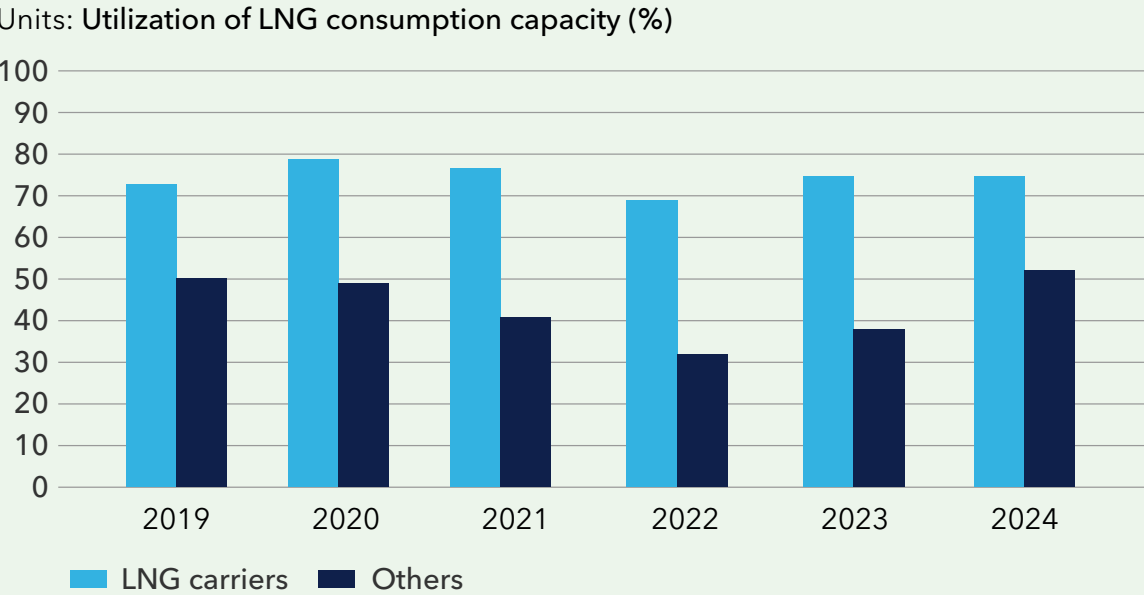


3.3.2 Actual use of alternative fuels

If the fleet's alternative-fuel capacity were fully utilized, alternative fuel consumption could reach almost 60 million tonnes of oil equivalent (Mtoe) by 2030, when the current order book is fulfilled. LNG has the highest potential of around 48 Mtoe (or 42 Mt of LNG), largely due to the LNG carrier fleet, which accounts for approximately 60% of potential LNG consumption in 2030. In the context of alternative low-GHG fuels, it should be noted that LNG carriers cannot easily achieve GHG reductions from liquefied low-GHG methane without a flexible Chain of Custody system in place. This requirement is because the carriers rely on consuming boil-off gas from cargo tanks with fossil LNG to manage tank pressure, which is typically used for propulsion (DNV, 2026c). Excluding LNG carriers, the container segment could consume more LNG than the remainder of the LNG-capable fleet, accounting for about 30% of the total fleet's consumption capacity.

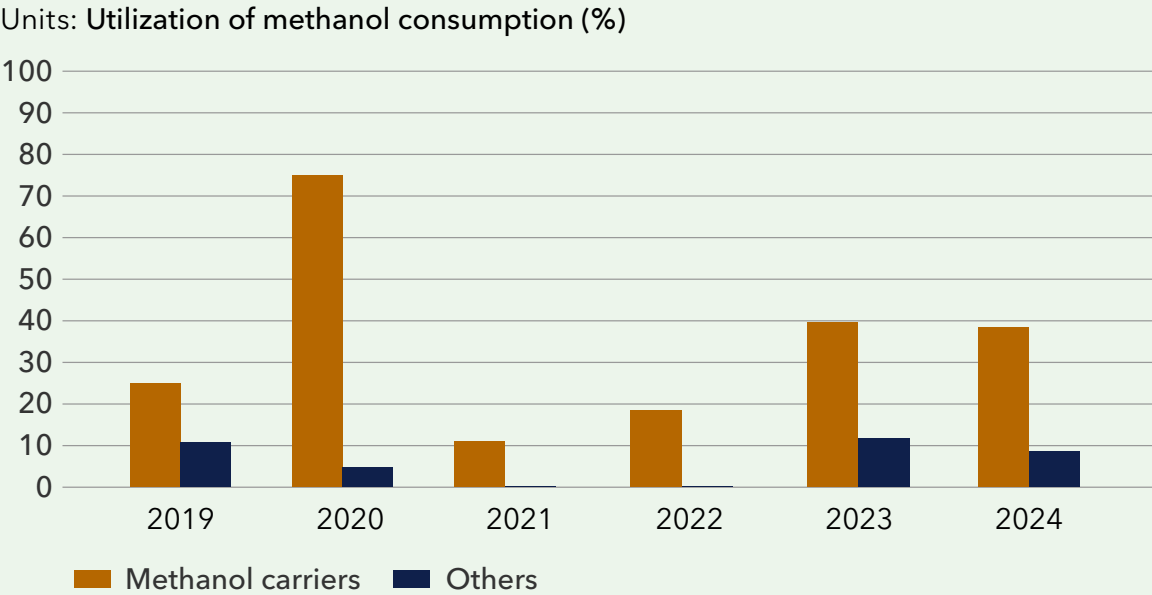
After LNG, methanol is the fuel with the second-highest potential for consumption in 2030, at approximately 7 Mtoe (5 Mt of methanol). Containerships account for 80% of the total methanol fuel capability, followed by bulkers at 5%. A large share of the increase in methanol consumption capacity is in the ultra-large container vessel segment and in new Panamax container vessels, which together represent 60% of the projected total methanol consumption capacity.

FIGURE 3-13
Estimated utilization of LNG consumption capacity for LNG-capable ships, separating between LNG carriers and other ship types.⁵¹ Utilization is measured as reported volumes of LNG consumed as a percentage of estimated maximum potential use of LNG.



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FIGURE 3-14
Estimated utilization of methanol consumption capacity for methanol-capable ships, separating between methanol carriers and other ship types.⁵² Utilization is measured as reported volumes of methanol consumed as a percentage of estimated maximum potential use of methanol.



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However, historical data from the IMO’s Data Collection System (IMO, 2020; IMO, 2021; IMO, 2022b; IMO, 2023; IMO, 2024; IMO, 2025) shows that actual reported consumption of alternative fuels remains significantly below its potential maximum between 2019 and 2024 (see Figure 3-13 and Figure 3-14). This is mainly due to high fuel prices and a current lack of regulatory drivers to limit GHG emissions.

Between 2019 and 2024, the annual utilization of LNG consumption capacity varied between 69% and 79% for LNG carriers and 32% to 52% for other ship types. In both cases, there was low utilization in 2022, with a subsequent rise towards 2024. LNG bunkering prices in 2022 were considerably higher than those for fuel oil in major bunkering hubs such as Singapore and Rotterdam. Depending on the chartering contract, the decision to operate in gas mode or diesel mode typically rests with either the ship-owner or the charterer. When LNG bunkering prices are high, operating in diesel mode can be more cost-effective, leading many owners and charterers to limit LNG use. Some operators also prioritize fuel oil bunkering over LNG to avoid the extended off-hire time associated with LNG bunkering (DNV, 2026c). The vast majority of LNG consumed has been fossil-based so far.

Between 2019 and 2024, the annual utilization of methanol consumption capacity varied between 11% and 75% for methanol carriers and 0% to 12% for other ship types. For methanol carriers, the utilization was high in 2020 and low in 2021 and then rose towards 2023 and 2024. 2020 saw a collapse in

methanol prices, driven primarily by the COVID-19 pandemic’s impact on industrial activity and demand for methanol. The vast majority of all methanol consumed so far has been fossil-based.

3.3.3 Growth of bunker vessel fleet and availability of low-GHG fuels in ports

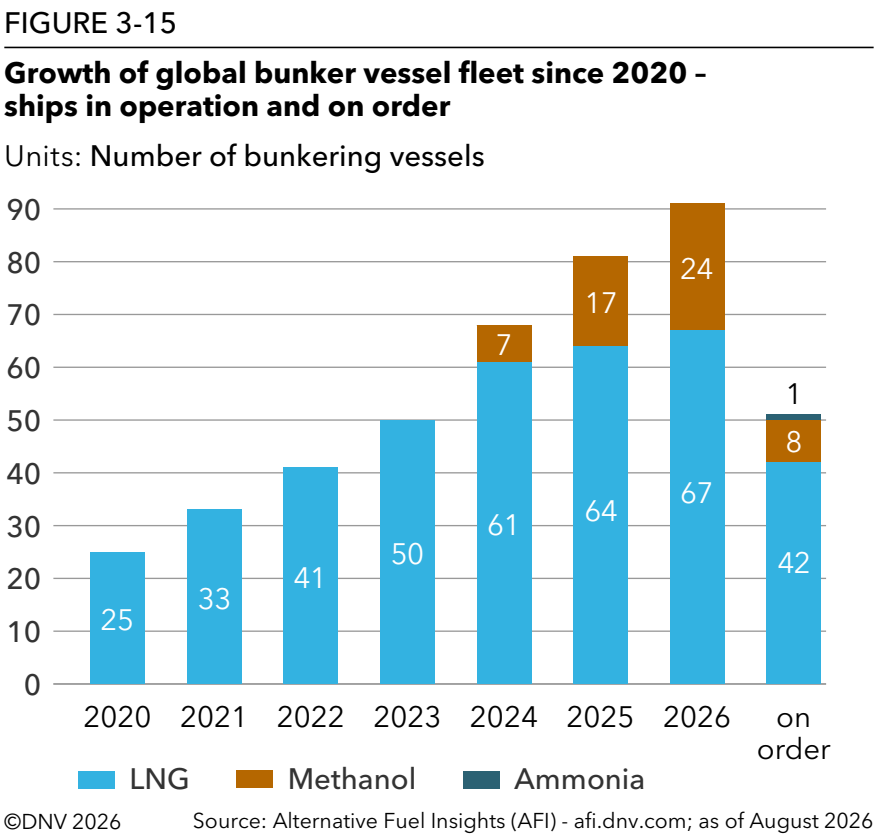
The rapid growth of alternative fuel-capable ships is driving demand for bunkering infrastructure, including dedicated bunker barges and ship-to-ship fuel transfer operations.

The number of LNG bunkering vessels has grown swiftly, rising from 25 in 2020 to 67 today (Figure 3-15). The LNG bunkering vessels are distributed worldwide, largely concentrated around major ports along trade routes for LNG-capable vessels. Over the past five years, the number of bunkering vessels operating in Europe has increased from 15 to 33, in Asia from 6 to 20, and in America from 3 to 13. One is reported to operate globally.

Since 2020, the number and size of LNG-fuelled ships have increased significantly, thereby boosting their potential LNG consumption. To meet this demand, the size of LNG bunkering vessels has increased over the

past five years and continues to rise. Of the 67 LNG bunkering vessels currently in operation, 23 have a capacity above 10,000 cubic metres (m³). Most bunkering vessels on order exceed 18,000 m³ (DNV, 2026c).

In 2020, demand for methanol bunkering services was very low, as most methanol-capable ships in operation were methanol tankers, which were less reliant on traditional bunkering infrastructure. Since then, the demand potential has significantly increased, with larger methanol-fuelled ships having fuel tanks exceeding 16,000 m³. In response, 24 methanol bunker ships of various capacities are



now operational, with 8 more on order (Figure 3-15). Most will operate from Singapore, four from Chinese ports, and five from European ports.

Establishing bunkering infrastructure for ammonia-fuelled ships will require investment in tonnage capable of refuelling large ocean-going vessels. In 2020, there was no such infrastructure for bunkering ammonia-fuelled vessels (DNV, 2025i). Today, we have seen the first order book entry of a 5,000 m³ bunker vessel for ammonia, which will operate from Singapore (Figure 3-15).

Although ammonia bunkering infrastructure has not yet been established and presents new complex-

ities and safety challenges, notable progress has been made since 2020, with major bunkering hubs like Singapore and Rotterdam preparing for safe ammonia bunkering, as well as significant advancements in other ports (DNV, 2025i).

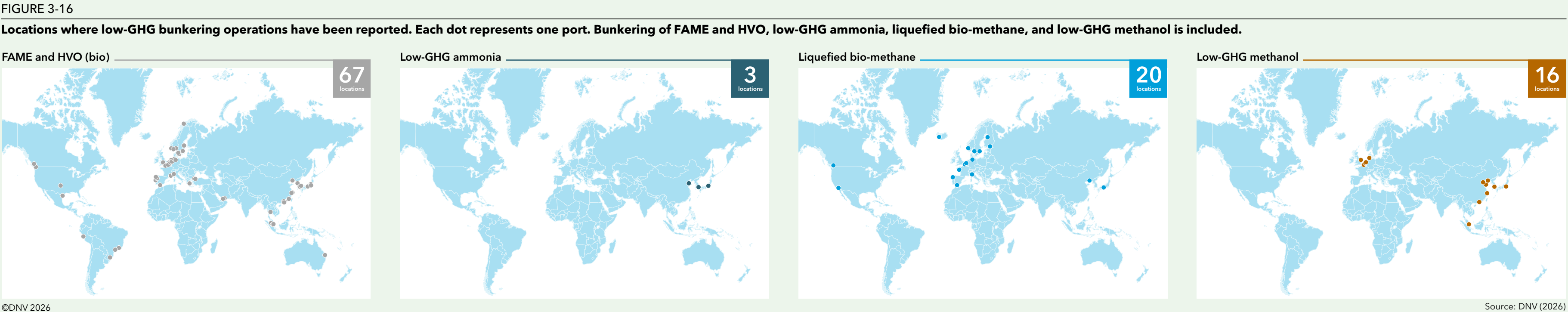
Through a systematic collection of publicly available data on low-GHG fuel bunkering across ports worldwide, DNV has mapped locations where at least one low-GHG bunkering operation – either using a pure low-GHG fuel or a blend – has occurred between 2015 and April 2026. The results, illustrated in Figure 3-16, show that ports with low-GHG fuel bunkering activity are geographically diverse, though with a clear concentration in Europe and East Asia.

In total, various variants of low-GHG fuels have been bunkered at nearly 90 ports worldwide. The biofuels FAME and HVO are the most widely available, having been supplied in almost 70 ports. Liquefied bio-methane has been bunkered at a minimum of 20 ports, primarily in Europe, with additional locations in North America and East Asia. Low-GHG methanol (both e-methanol and bio-methanol) has been supplied in at least 16 ports, mainly in East Asia and parts of Western Europe. Low-GHG ammonia bunkering has been recorded in three ports in East Asia.

It should be noted that several of the bunkering operations included in this dataset were pilot

projects, in some cases involving smaller vessels, and therefore do not necessarily indicate commercial availability for ocean-going ships. Additionally, some operations involve mass-balanced fuels – particularly liquefied bio-methane and low-GHG methanol – which are permitted under the EU ETS and FuelEU Maritime.

Understanding the dynamics of the emerging marine market for low-GHG fuels is critical for all stakeholders in shipping and fuel production. In the next chapter, we characterize this market and the major factors that will shape it.





4

MARINE MARKET FOR LOW-GHG FUELS

Highlights

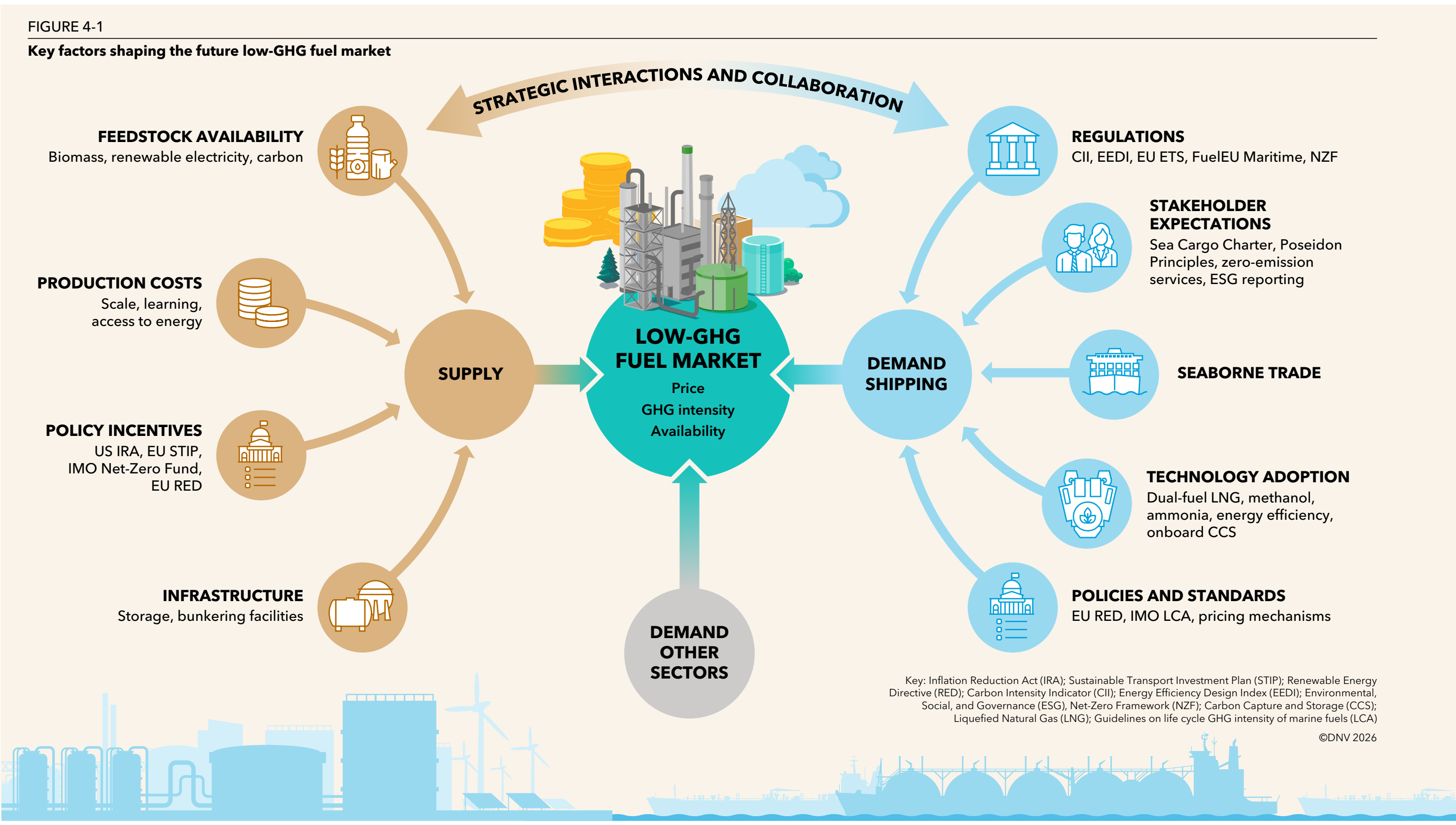
The future market for low-GHG fuels will be shaped by developments in both shipping and other sectors. This chapter reviews key factors influencing this market and offers new data and DNV modelling results, including:

- In a net zero by 2050 future, global cross-sectoral demand for low-GHG fuels could top 2,200 Mtoe, requiring large-scale deployment of biofuels, blue fuels, and e-fuels.
- Low-GHG global fuel supply could reach 270 Mtoe at most by 2030.
- Shipping demand for low-GHG fuel grows from 4-22 Mtoe in 2030 to 33-185 Mtoe in 2050.
- Price differences between low-GHG fuel types will remain and often be decoupled from each other.

Fossil fuels dominate today’s marine fuel market, and energy price is the main factor defining their competitiveness. With growing use of low-GHG fuels in shipping, this chapter considers their future supply and cost, demand, and the willingness of shipping and other industries to pay for them. We combine these insights to examine how the marine low-GHG fuel market may develop and how prices could evolve in the future.

4.1 Key factors shaping the marine low-GHG fuel market

There is limited literature that systematically describes and quantifies key supply and demand factors shaping the marine low-GHG fuel market. Most existing studies tend to focus on individual components of the market such as cost and fuel supply potential, or demand in different sectors, and in some cases only for specific fuel types – see, for example, recent work such as MMMCZCS (2026); BCG (2025); IEA (2025c) and Ricardo & DNV (2023). Others take a broader energy system perspective on maritime decarbonization, modelling use of low-GHG fuels in shipping consistent with scenarios for global decarbonization – see, for example, Kramel et al. (2026); Kanchiralla et al. (2026); DNV (2025g).



No single analytical model can fully characterize the dynamics of the future marine fuel market. Using core economic principles, the marine low-GHG fuel market will be shaped by the supply of fuel products and the demand from shipping and other industries, with a price equilibrium where the supply and demand are in balance. These core dynamics are influenced by multiple factors, as illustrated in Figure 4-1.

The potential global supply and cost of low-GHG fuels mainly depend on feedstock availability, production technologies, and supporting distribution infrastructure. Overall demand is primarily driven by regulations and, to some degree, commercial stakeholder expectations. Market prices will be determined by the balance between supply and demand and the valuation of the low-GHG fuel products in terms of achieving compliance and

fulfilling stakeholder expectations. Significant variability can be expected depending on local and regional market conditions and policies.

Technology development and adoption play an important role both on the supply and demand sides. Technology learning and economies of scales will reduce fuel production costs. Uptake of fuel technologies in the maritime sector, such as dual-fuel LNG, methanol and ammonia engines, enables the world fleet to use alternative fuel types with different production costs and availability. Uptake of energy-efficiency measures and other decarbonization solutions such as shore power, onboard carbon capture and storage (OCCS) and wind-assisted propulsion systems (WAPS) can further reduce the demand for low-GHG fuels.

The marine fuel market will be significantly shaped by policy designs beyond the direct regulatory requirements. Lifecycle emissions assessment (LCA) and certification standards will determine which fuels and feedstocks are eligible for compliance. Financial penalties as an alternative compliance mechanism establish an upper bound on fuel prices that ship-owners are willing to accept. Investment support schemes and risk sharing mechanisms can mobilize capital into fuel production projects with long lead times and high upfront risk as well as distribution infrastructure. The increasing global focus on energy security will shape the green transition by accelerating investment in alternative energy sources, thereby reducing dependence on fossil fuels and mitigating geopolitical risk.

The potential global supply and cost of low-GHG fuels mainly depend on feedstock availability, production technologies, and supporting distribution infrastructure.

In an emerging market, strategic interactions and collaboration among shipowners, fuel suppliers, ports and regulators are essential to address barriers such as the 'chicken-and-egg' challenge between fuel availability, ship fuel technology adoption, and distribution and bunkering infrastructure. These elements all need to be developed in parallel to enable the initial use of low-GHG fuels.

Early deployment is likely to concentrate in trades with predictable routes and cargo flows, typically found in container and car carrier liner trades, and in certain tank and bulk trades, where fuel availability can be coordinated across ports and fleets. Green shipping corridors and similar initiatives can accelerate early scale-up by reducing coordination risk.



4.2 Supply of low-GHG fuels

Understanding the future supply of low-GHG fuels is central to assessing the development of the marine fuel market. This analysis covers key fuel types – diesel-type fuels, methane, methanol, ethanol, hydrogen and ammonia – produced from a range of feedstocks, including biomass and green and blue hydrogen (see box on page 43). In the analysis, we make no distinction between sustainable and non-sustainable biofuels. Nor do

we attempt to apply related categories such as ‘advanced’ or ‘conventional’, as definitions and sustainability criteria vary between regulations and certification standards, and have not yet been determined under the IMO LCA framework.

Global supply of low-GHG fuels amounted to approximately 135 Mtoe in 2025, dominated by ethanol (64 Mtoe), bio-diesel including FAME and

HVO (56 Mtoe), and bio-methane (10 Mtoe), with the remainder of the supply consisting of bio-jet fuel, ammonia, methanol, and hydrogen.⁵³ Only a small fraction was used in the maritime sector, estimated to be in the order of magnitude 1 Mtoe per year.⁵⁴

We estimate the maximum global supply of low-GHG fuels in 2030 using data on production projects already operating or announced, and short-term

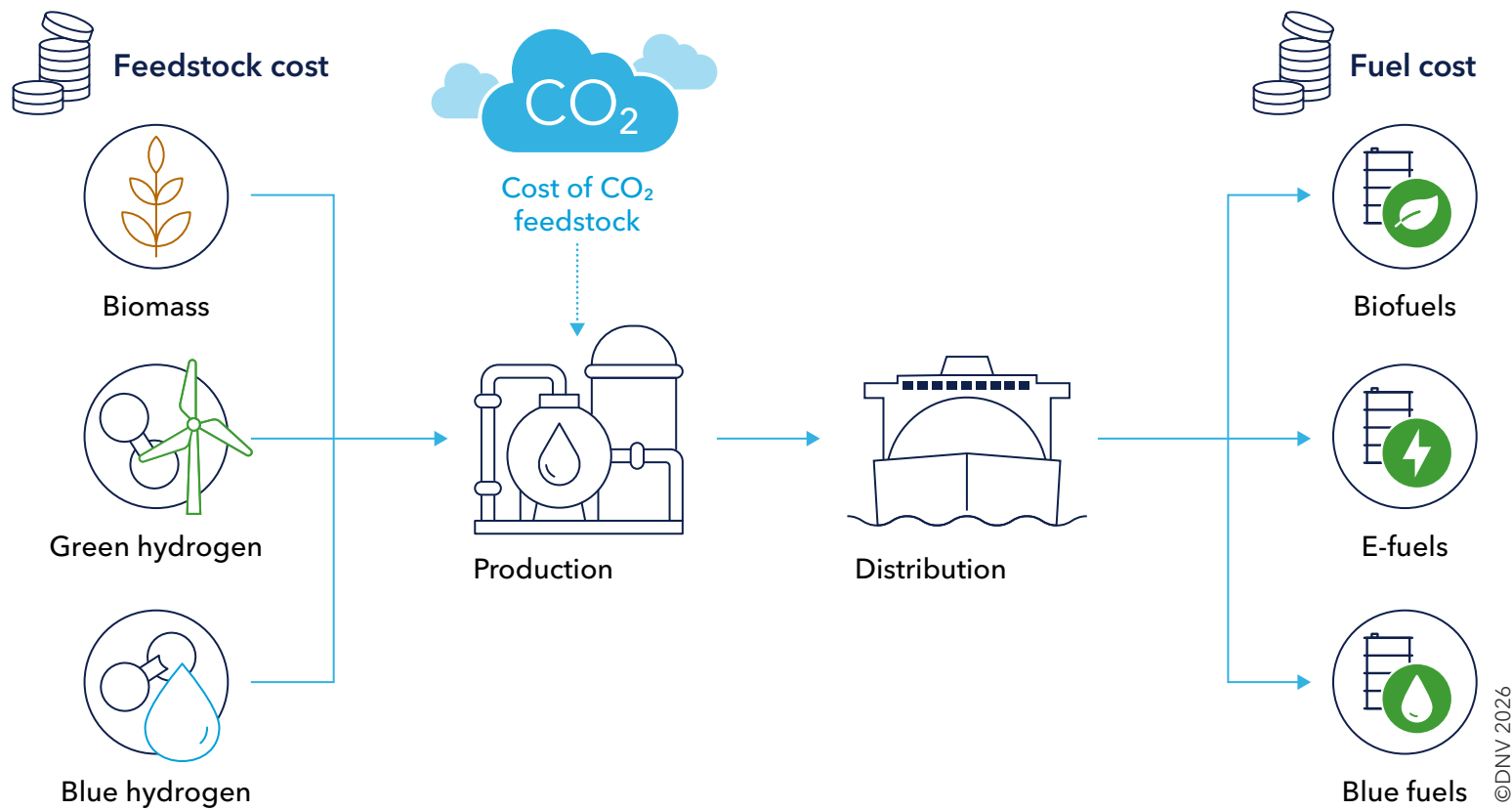
supply forecasts for some fuel types. This estimate draws on a range of sources, including production capacity data from DNV’s Alternative Fuels Insight Platform (AFI), and data from IEA (2025b). Further, we provide long-term estimates of the maximum potential supply of biofuels in 2040 and 2050, based on assessed feedstock availability from DNV (2023a) and other sources.

We calculate fuel supply costs in 2030, 2040, and 2050 using DNV’s Marine Fuel Cost Mapper (see Figure 4-2), which models the full production and delivery chain. Supply costs, in terms of cost per unit of energy, include the investment and operating costs of feedstocks, feedstock-to-fuel conversion, and distribution costs. We focus on production costs and have not taken into account any policies that may impact the cost and availability of low-GHG fuels, such as subsidies and tax credit schemes. See Section 2.2 for a discussion of such policies.

We then combine this with each fuel’s GHG intensity based on the EU Renewable Energy Directive (EUC, 2024) and other sources, to calculate the abatement costs (cost per tonne of GHG reduced) for each fuel pathway in 2030, 2040, and 2050. This indicates how cost-effective each fuel type and feedstock is in reducing GHG emissions relative to a fossil-fuel benchmark – see page 44 for an explanation of abatement costs. Appendix A gives more information about our approach and key modelling assumptions.

FIGURE 4-2

DNV’s Marine Fuel Cost Mapper is used for modelling costs in the production and delivery chain of low-GHG fuels, see DNV (2024b) for more information



Low-GHG fuel pathways included in supply analysis

Low-GHG fuels can be produced from three main feedstock categories: biomass, green hydrogen, and blue hydrogen.

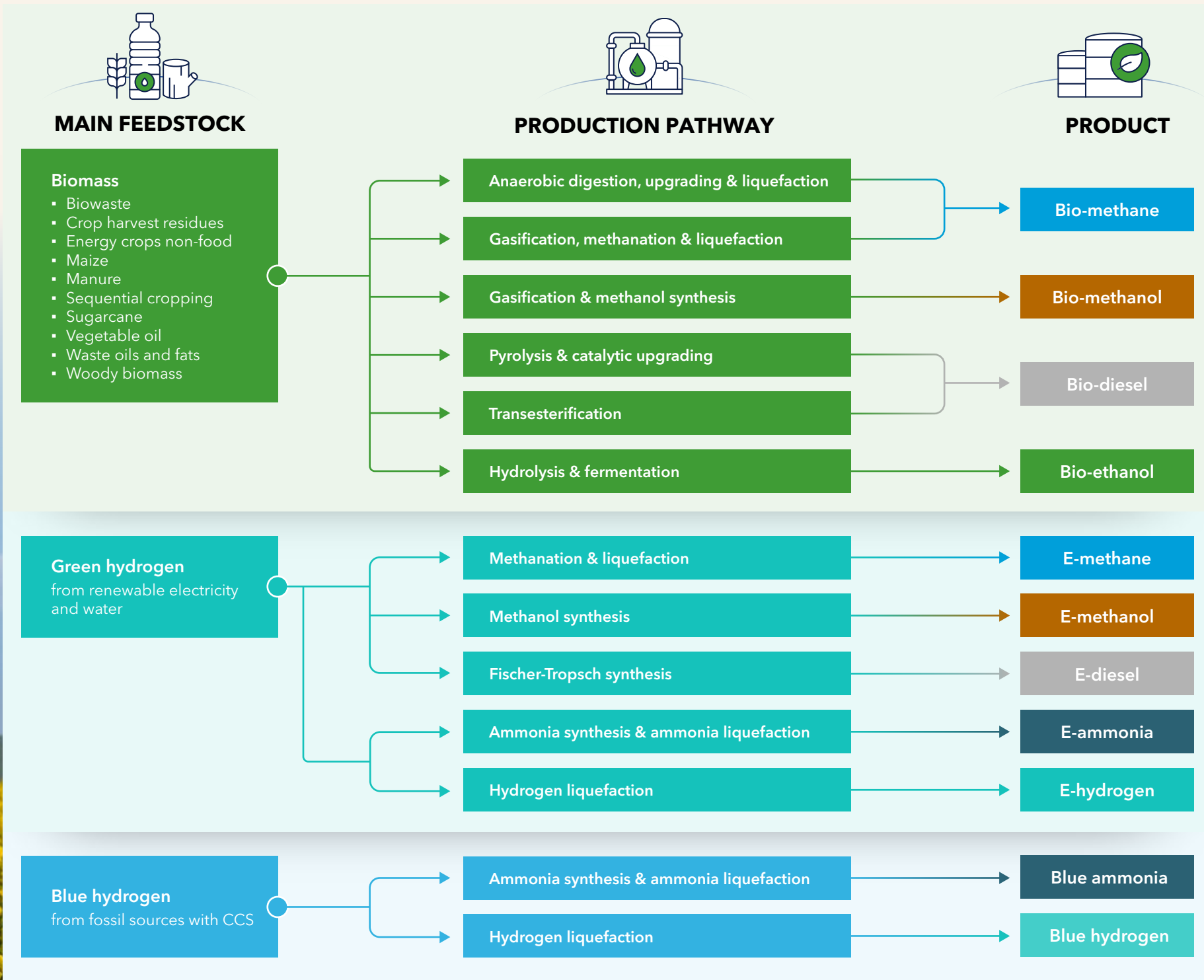
Biomass feedstocks (e.g. biowaste, crop residues, manure, sugarcane, and waste oils) provide the primary energy for biofuels like bio-methane, bio-methanol, bio-diesel, and bio-ethanol. Bio-diesel is used here as an umbrella term. It covers all bio-based fuels with drop-in capability in diesel engines and produced from renewable biomass and waste feedstocks, including fatty acid methyl esters (FAME), hydrotreated vegetable oils (HVO), and other bio-based diesel pathways.

Green hydrogen (from renewable electricity) and blue hydrogen (from fossil sources with carbon

capture and storage (CCS)) act as the key feedstocks for e-fuels and blue fuels, respectively. For synthesizing carbon-containing e-fuels, CO₂ feedstocks, sourced either from biogenic point sources or direct capture from air (DAC), are required to supply the carbon molecule for synthesis to e-methane, e-methanol and e-diesel. For ammonia production, nitrogen is required as the additional synthesis input.

Figure 4-3 shows the low-GHG fuel pathways included in the supply analysis and considered relevant for shipping. It is not exhaustive, and some fuel molecules and production pathways are not shown. For example, compressed hydrogen is excluded from the analysis, although it could contribute to ship decarbonization, particularly in short-sea segments.

FIGURE 4-3
Low-GHG fuel pathways included in the supply analysis. Additional feedstock inputs, such as CO₂ and nitrogen, are considered but not shown in the figure.



Note on units and metrics

The low-GHG fuel market is expected to consist of many different fuel types of various lower heating values, and produced from different feedstock and production pathways resulting in different GHG intensities (GFI), expressed in grammes CO₂eq per MJ of energy content. A tonne of blue ammonia with a lower heating value (LHV) of 18.6 GJ/tonne and a GHG intensity of 50 gCO₂eq/MJ will sell at a different price than FAME bio-diesel from used cooking oil with a LHV of 37 GJ/tonne and a GHG intensity of 16 gCO₂eq/MJ.

In order to compare various fuel types and production pathways we need to use comparable metrics.

For energy we use the metric tonnes of oil equivalents. 1 toe = 41.868 GJ = 1.02 tonnes LFO (light fuel oil) = 0.98 tonnes MGO (marine gas oil)

For GHG intensity we use gCO₂eq/MJ where CO₂eq includes CO₂, CH₄ and N₂O using a 100-year Global Warming Potential (GWP). This is in line with the IMO's life cycle assessment (LCA) guidelines.

Abatement cost is the cost of reducing a tonne of CO₂eq by switching from a benchmark fossil

fuel to a low-GHG fuel. In this study, abatement costs for all fuels except low-GHG methane are calculated relative to fossil low sulphur heavy fuel oil (LSHFO), using assumed LSHFO energy prices of 502, 389, and 394 USD/toe in 2030, 2040, and 2050, respectively, and a GHG intensity of 95.48 gCO₂eq/MJ. For low-GHG methane, we assume that it replaces fossil LNG at a cost of 410, 440 and 473 USD/toe in 2030, 2040 and 2050, respectively, and with a GHG intensity of 77.19 gCO₂eq/MJ. The abatement cost is calculated as the cost difference divided by the GHG intensity difference between the benchmark fossil fuel and the low-GHG fuel (see formula below).

For example, a FAME bio-diesel with a GFI of 16 gCO₂eq/MJ and priced at 1,800 USD/toe would have an abatement cost of about 390 USD/tCO₂eq in 2030. The abatement cost is directly comparable with the IMO NZF Remedial Unit (RU) price and the FuelEU penalty. If the abatement cost of a low-GHG fuel falls below the price of



RUs or penalty, switching to the low-GHG fuel is the most cost-effective compliance option. The abatement cost varies slightly if using IMO LCA default emissions factors and EU RED and FuelEU emission factors. However, for simplification we use only one set of abatement costs based on IMO LCA factors.

Abatement cost =
$$\frac{\text{Cost}_{\text{LowGHG}} - \text{Cost}_{\text{Fossil}}}{(\text{GFI}_{\text{Fossil}} - \text{GFI}_{\text{LowGHG}}) \times 0.0419}$$

Formula for calculating the abatement cost of a low-GHG fuel relative to a benchmark fossil fuel. Costs are in USD/toe and GFI in gCO₂eq/MJ. The factor 0.0419 converts the GFI difference to tCO₂eq/toe, giving abatement cost in USD/tCO₂eq.

4.2.1 Short-term potential supply in 2030

Our estimates show that if all announced fuel production projects are realized and commissioned as scheduled, the global supply of low-GHG fuels could reach up to 270 Mtoe by 2030, more than doubling compared to 2025. This potential is shown on the horizontal axis of Figure 4-4. Of the total, diesel-type fuels would account for 69 Mtoe and methane for 19 Mtoe, both representing substantial growth from current levels. Methanol and ammonia could reach 24 and 84 Mtoe, respectively, despite starting from very low current levels. Ethanol is projected to grow more moderately to 65 Mtoe, while hydrogen could reach 8 Mtoe. The above estimates represent maximum, upper-bound potentials, and actual supply is likely to be significantly lower due to project delays, cancellations, and other uncertainties.

In Figure 4-4, we also show the abatement cost plotted against the potential supply of each fuel production pathway considered in this study. The pathways are ordered from low to high abatement cost. Unlike supply cost, abatement cost also takes into account the GHG intensity of the specific fuel pathway (see box on units for more details). It is important to highlight that the aggregated results mask significant variations for each fuel type, regionally and from project to project, when it comes to cost and GHG intensity.

Overall, biofuels are estimated to have the lowest abatement costs in 2030, with liquefied bio-methane from manure, ethanol from sugarcane, and bio-diesel

from waste oils and fats having the lowest estimated abatement costs, ranging roughly between 180 and 300 USD/tCO₂eq. However, these represent less than 20% of the total potential. About 62 Mtoe of low-GHG fuel supply in 2030 is estimated to be cost-competitive with the IMO NZF Tier 2 RU price of 380 USD/tCO₂eq, meaning these fuels could

be cheaper than paying for non-compliance in a scenario where the NZF is adopted. No fuels have an estimated abatement cost below the Tier 1 RU price of 100 USD/tCO₂eq. 18 Mtoe of blue ammonia can be produced with an abatement cost of about 490 USD/tCO₂eq, while 66 Mtoe of e-ammonia can be produced at an estimated cost of 680 USD/tCO₂eq.

Our projected fuel supply and abatement cost estimates are subject to several uncertainties that can materially affect the results. These include, for example, feedstock prices, capital costs for production plants, grid electricity and other energy costs, distribution distances, and type of bunkering infrastructure (e.g. tank-to-ship, bunkering vessel, or truck-to-ship). Certain feedstocks and processing residuals not considered here could provide marine fuels not suitable for other sectors, such as cashew nutshell liquids (CNSL) and fatty acid methyl ester (FAME) residuals.

In addition to fuel supply costs, the estimated abatement costs depend on the assumed GHG intensity of each modelled fuel pathway, which can vary substantially across supply chains. We use global-average assumptions for fuel supply costs and GHG intensities; however, there will be regional and project-specific differences. The supply costs are based on a net-present value (NPV) assessment including cost of capital and should be interpreted as a minimum supply cost, excluding any additional allowances for project specific or market risks. Further, no subsidies or other project-specific financial support have been taken into account.

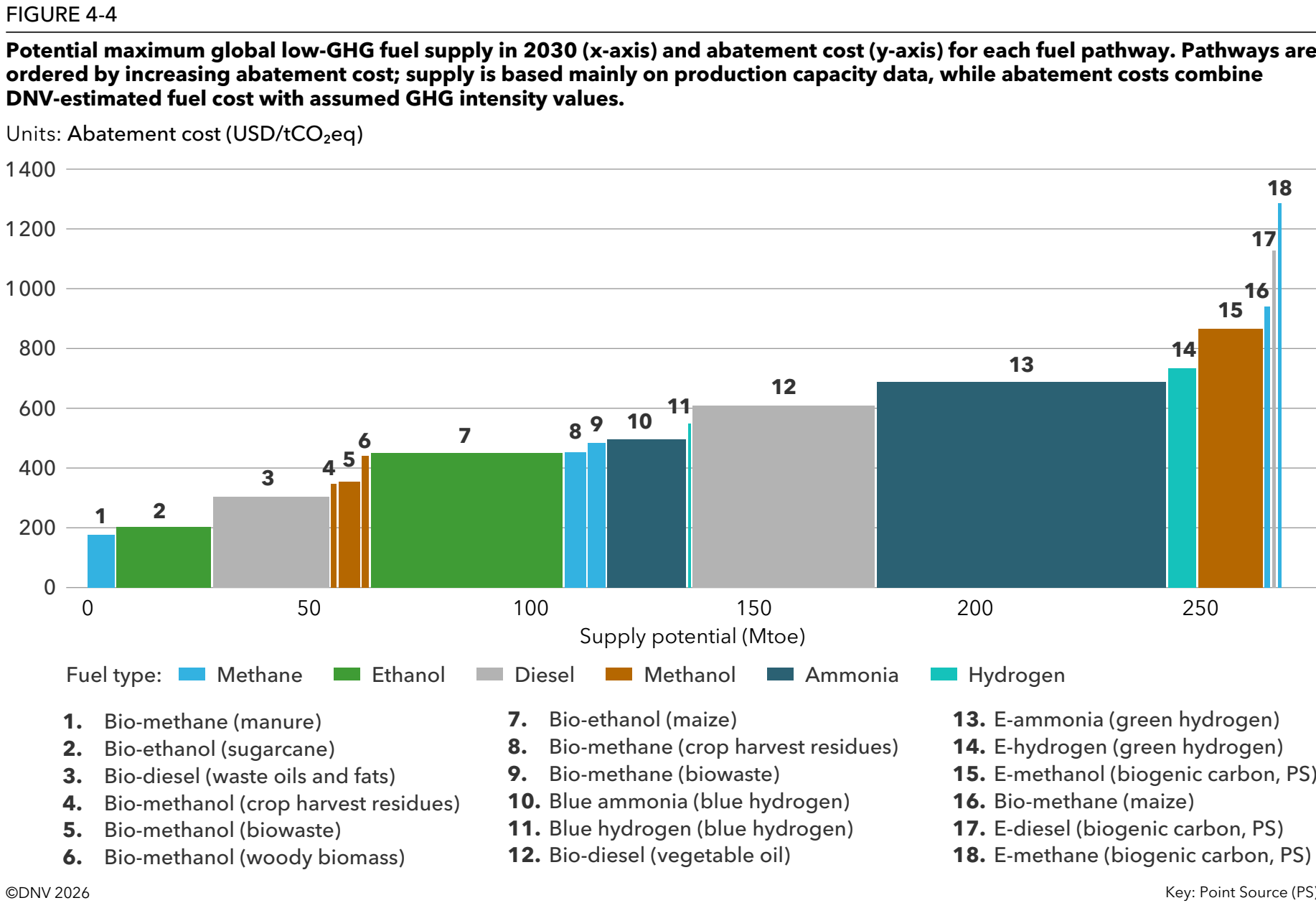
Importantly, many projects included in the presented estimate have not yet reached an investment decision, introducing uncertainty regarding how much supply will materialize. The financing and commissioning of projects are dependent on clear demand signals, including clarity that alternative compliance options such as penalties are higher than

About 62 Mtoe of low-GHG fuel supply in 2030 is estimated to be cost-competitive with the IMO NZF Tier 2 RU price.

the abatement costs. New facilities may require more than five years to become operational. Interviews with low-GHG fuel suppliers suggest that the postponement of a decision on adopting the IMO NZF has increased regulatory uncertainty and weakened near-term demand signals for marine low-GHG fuels, potentially slowing investment and project momentum. See Sections 4.3 and 4.4 for further discussions on demand signals from shipping and other sectors.

4.2.2 Long-term potential supply in 2040 and 2050

For the long-term horizons to 2040 and 2050, supply is not constrained by today's project pipeline but by factors such as the availability of sustainable feedstocks and the pace at which infrastructure can be developed. Based on feedstock availability, production potentials can be estimated, however, as the same feedstocks (e.g. woody biomass) can be converted into multiple fuels (e.g. diesel, methanol, ethanol, methane) this is not straightforward.



Thus, we do not attempt to quantify the maximum potential for low-GHG fuel production in 2040 and 2050. Rather, we provide a maximum production potential for biofuels as a group.

We estimate that the maximum global biofuel potential could reach up to about 1,000 Mtoe in 2040, increasing to 1,300 Mtoe in 2050. These estimates are based on physical constraints on the availability of suitable feedstocks such as agricultural residues and municipal waste, and include both conventional and waste-based feedstocks (see Appendix A for more information). The values represent the biofuel production pathway with the highest conversion efficiency for each feedstock. If the least efficient conversion process is used instead, the volume could be around 20% lower.

The supply potential for blue fuels and e-fuels does not have a clear upper limit. However, blue fuels do depend on access to carbon capture and storage, which could be a key constraint. E-fuels depend on renewable electricity, which also could become a key constraint. For the e-fuel production pathways using biogenic carbon, biomass supply can be an important constraint. More broadly, growth in production is limited by the ability to obtain permits and develop the necessary production, distribution and infrastructure.

In Table 4-1 we indicate the range in abatement cost estimated for different fuel types within each feedstock group, namely biofuels, blue fuels, and e-fuels. Abatement costs are projected to decline

towards 2040 and 2050 for blue fuels and e-fuels, with the steepest reductions expected for e-fuels. This is driven mainly by technological improvements and the scale-up of production plants, which lowers capital costs per unit of output. As such, these e-fuel cost reductions are contingent on large-scale deployment that enables learning and scaling effects to materialize (DNV, 2026a). In 2040, abatement costs for the majority of biofuel pathways are projected to remain lower than those of e-fuels and blue fuels, with up to around 870 Mtoe potentially produced at an abatement cost below 500 USD/tCO₂eq. Among e-fuels, the lowest-cost option is e-ammonia at about 550 USD/tCO₂eq, while the cost of e-methanol, liquefied e-methane, and e-diesel produced using biogenic CO₂ feedstock, ranges roughly from 710 to 1,000 USD/tCO₂eq. Blue ammonia has an abatement cost of around 520 USD/tCO₂eq in 2040. By 2050, a further decline in e-fuel costs narrows these differences, with e-ammonia falling to about 380 USD/tCO₂eq.

TABLE 4-1
Estimated range in abatement costs per fuel feedstock group in 2040 and 2050

Fuel feedstock group	Abatement cost (USD/tCO ₂ eq)	
	2040	2050
Biofuels	160-880	130-810
Blue fuels	520-580	420-490
E-fuels	550-1 440	380-890



4.3 Low-GHG fuel demand from shipping

The main driver for low-GHG fuel demand in the maritime sector will be regulations such as FuelEU and EU ETS for ships trading to the EU, and potentially the IMO’s Net-Zero Framework (NZF), which is being renegotiated and could add GHG intensity requirements with a global scope (see Sections 2.1 and 2.2). Commercially driven demand remains limited, primarily linked to stakeholder decarbonization goals and environmental, social, and governance (ESG) reporting (see Section 2.3). Beyond direct regulations, demand will be further shaped by the additional cost of operating on low-GHG fuels compared to fossil fuels, as well as world fleet capacity to operate on different fuel types. Implementation of policies and standards can provide incentives and disadvantages for certain fuel types and feedstocks; for example, FuelEU providing a reward factor for e-fuels (renewable fuels of non-biological origin) and considering biofuels based on food and feed crops as fossil fuels. Such issues are also under discussion in the work on the IMO LCA guidelines (see Section 2.1).

In the following subsection, we start by investigating the total potential demand for low-GHG fuels in shipping using two of the regulatory scenarios defined in Chapter 2. We then assess the capability of using alternative fuel types such as LNG, methanol, and ammonia by looking at the potential fuel technology uptake in the fleet. Finally, we analyse the willingness to pay for, and the value of,

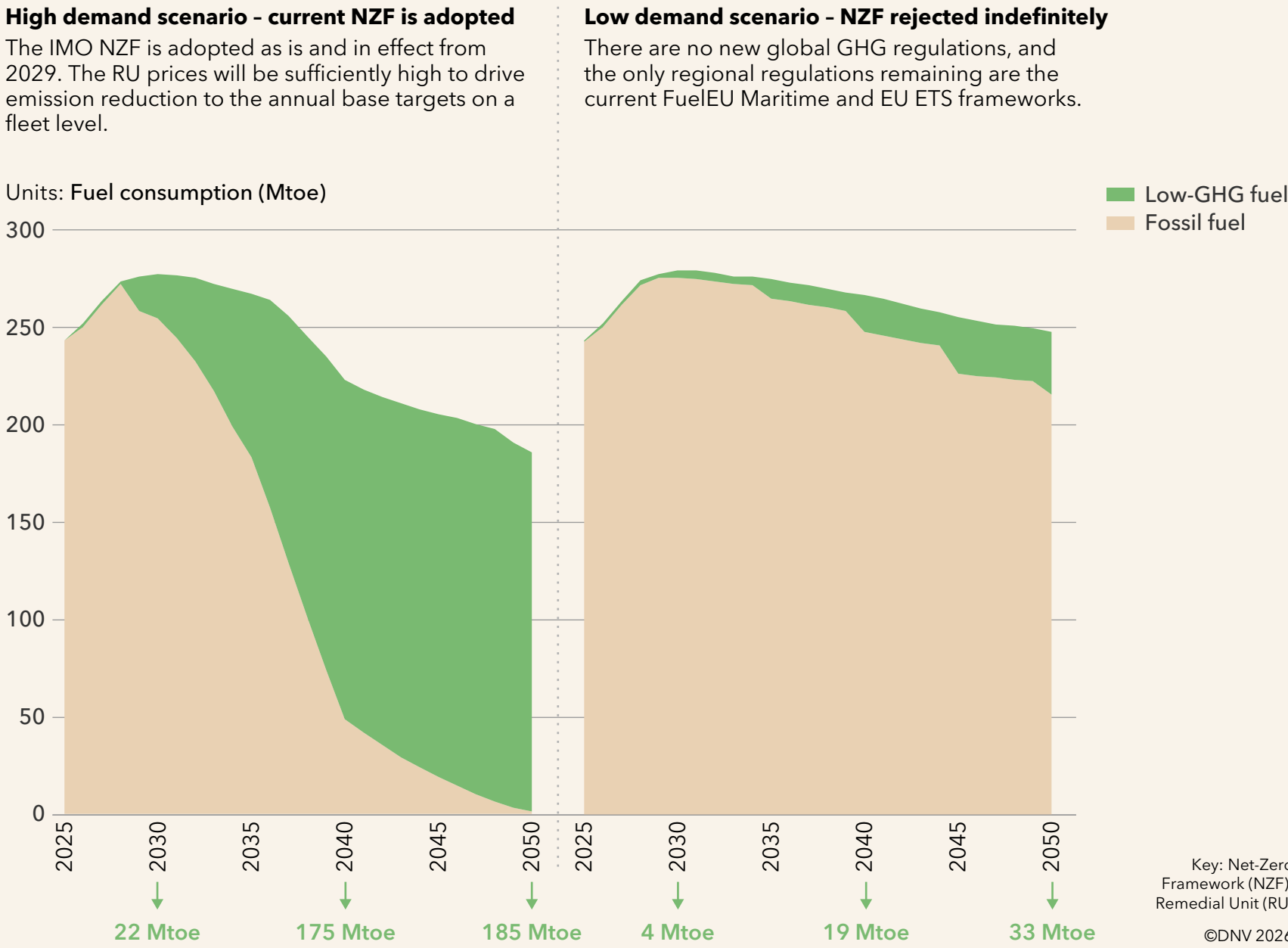
low-GHG fuels of different types and GHG intensities, and how this is affected by regulatory mechanisms and the cost of alternative fuel technologies.

4.3.1 Demand scenarios towards 2050

The total low-GHG fuel demand in shipping depends mainly on regulations setting the emission trajectory, growth in seaborne trade determining the total volume of shipping, and the uptake of energy-efficiency and other measures impacting energy use – for example, wind-assisted propulsion systems, and shore power and shore-side charging for plug-in hybrid vessels. To assess the interaction of these factors, we use DNV’s GHG Pathway Model (DNV, 2024a; DNV, 2024b) to simulate the fleet to 2050 and derive the total demand for low-GHG fuels. Our aim is not to assess the uptake of individual fuel types, but to estimate the overall demand for low-GHG fuels. The model is populated with today’s fleet of ships above 400 GT that operate internationally, and takes as input relevant GHG regulations, seaborne trade growth, energy-efficiency and fuel technology options, and fuel emission factors. It then models the required volume of low-GHG fuels needed to fulfill the relevant regulations. For more details, see Appendix A.

Due to the uncertainty on future regulations, we establish a range for the low-GHG fuel demand from

FIGURE 4-5
High (left pane) and low (right pane) demand scenarios for low-GHG fuels and fossil fuels towards 2050



shipping using the two scenarios from Chapter 2 resulting in the highest and lowest demand. Figure 4-5 describes the two scenarios briefly and shows the resulting demand for low-GHG fuels and fossil fuels.

Total uptake of low-GHG fuels varies significantly across the two scenarios, being about six to nine times greater in the case of high demand. Uptake of fossil LNG using engines with low methane slip reduces the demand for low-GHG fuels. Higher fuel and regulatory GHG costs push additional uptake of energy-efficiency measures and speed reduction, which have a significant impact on the total energy use and consequently the demand for low-GHG fuels. In the high-demand scenario, total energy use in 2050 is 25% less than in the low-demand scenario, corresponding to 62 Mtoe of fuel energy. The uptake will depend on the cost and impact on energy use of implementing energy-efficiency measures, compared to the price of low-GHG fuels.

Beyond energy-efficiency improvements, technologies that can reduce demand for low-GHG fuels include, among others, shore power, plug-in hybridization, nuclear power, and onboard carbon capture systems. These solutions have not been considered in the simulations.

In the high fuel demand scenario, total energy use in 2050 is 25% less than in the low-demand scenario, corresponding to 62 Mtoe of fuel energy.

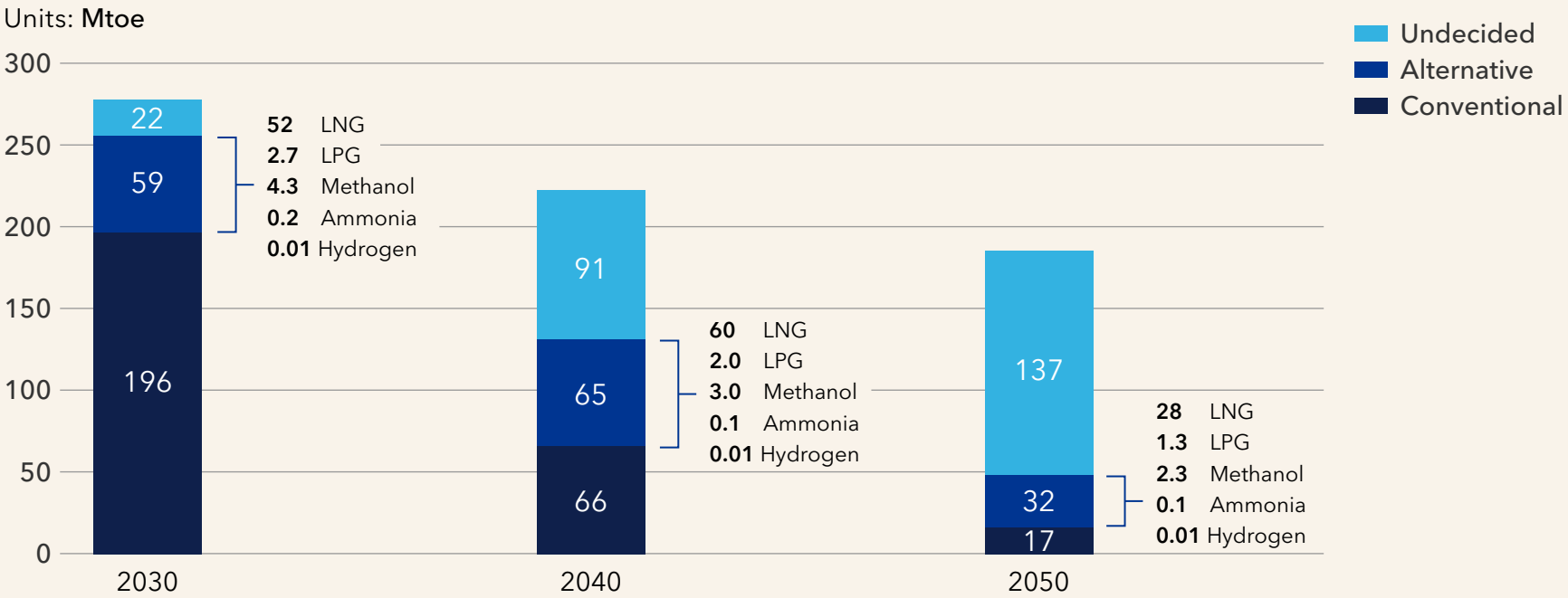
4.3.2 Capability to run on alternative fuel types

Existing ship fuel technologies and distribution networks create a strong lock-in effect for incumbent fuel types such as fuel oils and, to some degree, LNG. As described in Section 4.2, future low-GHG fuels and fuel types, such as methane, ethanol, methanol, ammonia and hydrogen, will have different supply and abatement costs. A significant difference in market price between different fuel types would drive investments in alternative

fuel technologies on the ship side. The future capacity to use alternative fuel types will depend on building or retrofitting ships with the relevant fuel technologies.

Section 3.3 presented the current status on the alternative fuel uptake in the world fleet. Based on the fleet development and energy use in the high-demand scenario in the previous section, Figure 4-6 shows the distribution of potential fuel consumption per fuel technology in 2030, 2040, and 2050. The share of alternative fuel consumption is based on

FIGURE 4-6
Simulated world fleet capability of running on conventional and alternative fuel types in 2030, 2040, and 2050, using the high-demand scenario and assuming no retrofitting



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existing ships and the order book. An increasing share of the consumption capacity is labelled undecided – meaning ships which are assumed to enter the fleet but have not yet been ordered and therefore have unknown fuel technology. We assume that the ships run fully on the alternative fuel type except for the necessary pilot fuel. We assume no retrofitting of existing ships in this scenario. The low-demand scenario would show a similar trend, but due to less speed reduction, the need for additional newbuilds to replace the lost capacity is less, leading to a lower share of undecided fuel type.

By 2030, the capacity to adopt specific fuel types will be largely determined by the technologies of the existing fleet and order book, as little time remains to place new vessel orders for delivery before then. The total alternative fuel capacity is 59 Mtoe, of which most is LNG and some LPG and methanol. Based on the expected fleet growth, we estimate that about 22 Mtoe fuel capacity is still undecided.

Looking further ahead to 2040 and 2050, there is potential for more substantial shifts in fuel technology across the fleet, contingent on the tech-

nologies chosen by shipowners. The share of undecided fuel technology increases to 91 Mtoe of capacity in 2040 and 137 Mtoe in 2050. Even in 2050, 17 Mtoe capacity remains from existing ships sailing today, and that is based on conventional fuel-oil technology. Given current fuel-selection preferences in shipbuilding (Figure 3-10), we expect a significant share of the undecided capacity in 2040 and 2050 to be taken up by conventional fuel-oil- and LNG-capable vessels. This would further lock the fleet into using low-GHG diesel and methane to decarbonize.

For alternative low-GHG fuels and fuel technologies to succeed, there must be clear financial or structural benefits to overcome the added investment cost and other potential switching costs. The fleet technology will evolve depending on whether alternative fuel types can be produced and distributed at lower cost than conventional fuels. Investment costs and other switching costs can decline, and adoption accelerate, through infrastructure development, standardization, learning effects, or subsidies and reward schemes. In the following subsection, we discuss the required difference in fuel costs to incentivize a switch in onboard fuel technology, and will later combine this with the expected production cost of different fuel types.

Comparing the potential global low-GHG fuel supply in 2030 (Section 4.2) and the maximum capacity of the fleet to apply these fuels (Figure 4-6) indicates that shipping capacity for low-GHG methane (52 Mtoe) is greater than potential supply (19 Mtoe).

By 2030, the capacity to adopt specific fuel types will be largely determined by the technologies of the existing fleet and order book, as little time remains to place new vessel orders for delivery before then.

On the other side, the fleet’s capacity to consume ammonia and methanol (0.2 Mtoe and 4.3 Mtoe, respectively) is below their potential supply (84 and 24 Mtoe). However, these supply estimates assume that all announced production projects are realized and commissioned as planned, even though some may be delayed or cancelled, may not be backed by firm offtake agreements with shipping, and may ultimately supply other sectors competing for the same fuels and feedstocks.

Besides added capacity through newbuilds, retrofitting existing ships remains an option. However, it is more expensive and strongly influenced by whether the ship has been prepared for a retrofit (so-called ‘ready’ designs). Shipowners may prefer to reduce the risk by ordering ready designs and deciding later if a retrofit would be economically viable, when the availability and cost of alternative low-GHG fuel types are clearer.



CM Hong Kong, the world's first methanol-capable car carrier.

4.3.3 Willingness to pay for low-GHG fuel

Shipowner or charterer willingness to pay (WTP) for low-GHG fuels of certain types and GHG intensities (GFI) reflects the value of the fuel product on the market. Financial, technological, and regulatory factors will influence WTP in shipping. A ship obliged to reduce GHGs will, depending on regulatory mechanisms, have various compliance options, one of which is to use low-GHG fuels. Both FuelEU and IMO NZF (as approved but not yet adopted) introduce pricing mechanisms: ships continuing to use fossil fuels and exceeding the GHG intensity limits must pay penalties (under FuelEU) or purchase remedial units (under IMO NZF). The price is 380 USD/tCO₂eq under IMO NZF and around 740 USD/tCO₂eq under FuelEU if operating on fossil fuel oils. These mechanisms effectively set a ceiling on the WTP for low-GHG fuels, and consequently on the demand.

Figure 4-7 shows an example of how to estimate the WTP for two low-GHG fuels, representing the maximum price acceptable to the shipowner. We start by calculating the total cost of ownership (TCO)⁵⁵ baseline covering the period 2029 to 2048 for a vessel using low sulphur heavy fuel oil (LSHFO) and buying both Tier 1 and 2 remedial units (RU) for compliance, applying an LSHFO price of 500 USD/toe. Next, we use this TCO baseline to calculate what the price (including distribution cost) of low-GHG diesel and ammonia needs to be to achieve the same TCO, considering two compliance options:

- 1. Use just enough low-GHG diesel to meet the Base target under the NZF and buy Tier 1 RUs for compliance.
- 2. Maximize use of low-GHG ammonia and the necessary pilot fuel oil, and sell surplus units (SUs) (assumed to have a price of 380 USD/tCO₂eq) accrued due to going below the Direct compliance target.

For these calculations, both low-GHG diesel and ammonia are assumed to have a GFI of 15 gCO₂eq/MJ. We include an added capital cost for the ammonia-fuelled ship (option 2).

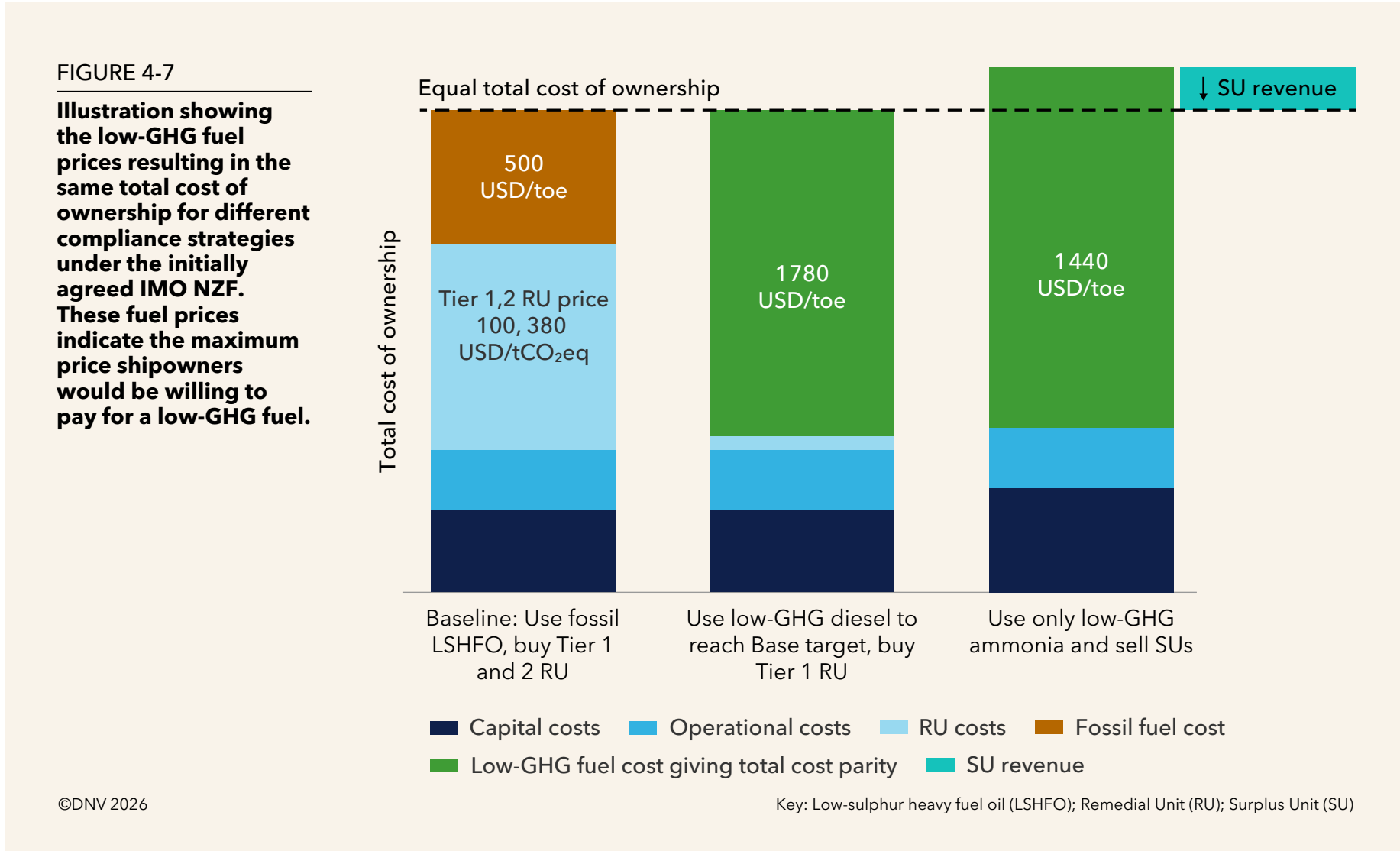
As fuel prices will be given per tonne of fuel or energy unit, and not in per tonne of CO₂eq abated, the example uses fuel prices in USD per tonne of oil equivalent. The differences in price and GFI are directly related to the abatement cost and RU prices in the NZF – see separate box (page 44) on units.

We calculate a WTP of 1,780 USD/toe for low-GHG diesel, which is 1,280 USD/toe higher than the LSHFO price. For low-GHG ammonia the WTP is 340 USD/toe lower due to the additional capital cost. These fuel prices indicate the maximum price shipowners would be willing to pay for a low-GHG fuel.

When in operation, the ship would opt for the lowest-price fuel available for its use. However, in the long-term, the price difference would be a key

determinant of whether to invest in alternative fuel technologies. The relative differences between fuel prices determine how competitive the fuel will be in the long term. If the price is low enough compared to the other fuel types, shipowners are likely to consider building new ships with this fuel technology. Initially, the price difference would also need to cover the additional risk of low availability and missing bunkering infrastructure.

For fuels of lower GFI, less would be needed to reach the same annual GFI requirement for a ship. This implies that such fuels would command a price premium compared to fuels with higher GFI. The premium will depend on the alternative cost for compliance for a ship, namely the cost of penalties/ remedial units, and on pooling or buying surplus units (SU) from other ships. A higher alternative cost implies a higher value and premium for a fuel with a low GFI.



4.4 Low-GHG fuel demand from other sectors

Demand from other end-use sectors plays a critical role in shaping the availability and pricing of low-GHG fuels, as these sectors compete with maritime for limited volumes of fuels and feedstocks. This section first outlines the main decarbonization alternatives across sectors. We then quantify the future low-GHG fuel demand from relevant non-maritime sectors. The analysis is mainly based on the Energy Transition Outlook global model and projections for energy supply and use, as well as technology developments across all sectors (DNV, 2025g; 2023b; 2026a; 2026b), complemented by other outlook studies (e.g. IEA, 2025a; IRENA, 2024). We close with a discussion on the willingness to pay for low-GHG fuels across sectors.

4.4.1 Cross-sector decarbonization alternatives and low-GHG fuel needs

Across all end-use sectors, direct electrification is usually the most economically viable decarbonization route, as electricity can typically be used more efficiently than other alternatives to decarbonize. Low-GHG fuels become more important where direct electrification is difficult; for example, because of energy-density needs, high-temperature heat requirements, long asset lifetimes, or dependence on existing liquid and gas infrastructure. This means

that competition for low-GHG fuels will come mainly from the hard-to-electrify parts of aviation, road transport, manufacturing, power production, and buildings. The key question is therefore which sectors will still need low-GHG fuels or their feedstocks after applying other, more economically viable, abatement options (e.g. electrification, energy efficiency, carbon capture and storage). Long asset lifetimes can lock sectors into specific solutions for a period, meaning that the most viable decarbonization pathways may vary over time as assets and infrastructure are gradually renewed. Below, we briefly outline the main potential decarbonization pathways for each sector towards 2050, with a focus on low-GHG fuels.

Aviation stands out as the clearest case where low-GHG liquid fuels are indispensable. Aircraft require energy-dense kerosene-type fuels compatible with existing engines and airport infrastructure, making sustainable aviation fuel (SAF) the dominant pathway, with bio-SAF leading initially and synthetic e-SAF potentially becoming more important later. Electrification is limited to short-haul flights due to battery weight challenges, with hydrogen considered a longer-term option that may enable some short- to medium-haul applications.

Road transport, covering everything from passenger cars and two-wheelers to buses and heavy-duty trucks, is predicted to decarbonize primarily through



electrification, particularly in light-duty vehicles, but also increasingly in heavy-duty vehicles due to battery development. As replacement of the existing diesel- and petrol-fuelled fleet will take time, biofuels such as bio-ethanol and bio-diesel can play a moderate role in the short to medium term. Range constraints mean that bioenergy and hydrogen-based fuels will have a potential but minor role in long-distance transport. Bio-methane can also support decarbonization in heavy-duty trucks already running on natural gas, and methanol is already used as a road transport fuel.

The manufacturing sector spans many industries, from lighter manufacturing to highly energy-intensive subsectors such as steel, cement, and chemicals, which are all hard to decarbonize. Demand for low-GHG fuels is concentrated in subsectors requiring high-temperature heat where hydrogen and methane may be applied. Steelmaking will likely be the leading user of pure hydrogen in the coming decades. Hydrogen and its derivatives, including methanol and ammonia, can also serve as feedstocks in the chemical and fertilizer industries, which today account for most of the demand for these molecules.

In addition to its use in beverages, ethanol can serve as an industrial and chemical feedstock, though such applications currently account for only a limited share of total demand.

Power generation is increasingly based on renewables such as wind and solar, while also using waste, biomass, and biofuels. Bioenergy can remain important for on-demand power generation and, when combined with carbon capture, can deliver negative emissions. Bio-methane can be blended into natural gas infrastructure and used in existing gas plants. Hydrogen and ammonia may contribute

to peaking capacity and system balancing, but their overall roles are expected to remain minor. Other fuel types, such as diesel and methanol, may be used to generate emergency power or provide power in areas with grid restrictions.

Buildings, including residential and commercial properties, rely on a combination of heating, cooling, hot water and cooking services. This demand sector already consumes large volumes of electricity and biomass, but natural gas is the dominant energy carrier for heating. Energy efficiency and electrification are the main decarbonization options, with the

use of low-GHG fuels such as bio-methane blends in areas where electrification remains challenging. Hydrogen is believed to be a negligible player in buildings.

Figure 4-8 summarizes the relevance of low-GHG fuels for direct use in non-maritime sectors and illustrates the relative extent of current fuel use in each sector to provide a sense of scale. The end-uses shown are illustrative rather than exhaustive, reflecting both current and potential future applications. Some fuels may also be used in sectors not included in the figure. The indicated end-uses are

not exhaustive; only the main direct applications are shown, and additional uses (e.g. ammonia for power generation or methanol in cooking stoves) are not included. The results show that the low-GHG fuels relevant to shipping can also be used across many other sectors, which will create competition for fuel supply. For example, diesel remains relevant in road transport, particularly for the existing vehicle fleet. Methane can be used in manufacturing, power generation, and buildings. Ammonia is a major feedstock for fertilizer production (part of the manufacturing sector).

Beyond direct competition for low-GHG fuels, there is also strong competition for the feedstocks required to produce them. This is particularly relevant for biomass feedstocks, which can generally be converted into low-GHG fuels at lower abatement cost than e-fuel and blue fuel pathways in 2030 (see Figure 4-4). Relevant feedstocks include biowaste, crop residues, woody biomass, manure, maize, sugarcane, and waste oils. As described in the box on low-GHG fuel feedstocks and production pathways (page 43), these biomass resources provide the primary energy input for biofuels such as bio-methane, bio-methanol, bio-diesel (including FAME and HVO) and bio-ethanol, all of which are relevant for shipping.

These feedstocks also serve a wide range of other applications (see Figure 4-9), including the production of bio-SAF. While aviation and shipping are not in direct competition for the same fuel molecules, they draw on many of the same biomass

FIGURE 4-8
Relevance of low-GHG fuels for direct use in non-maritime sectors. The end-uses shown are not exhaustive. They reflect both current and potential future applications, and some fuels may also be used in sectors not included in the figure.

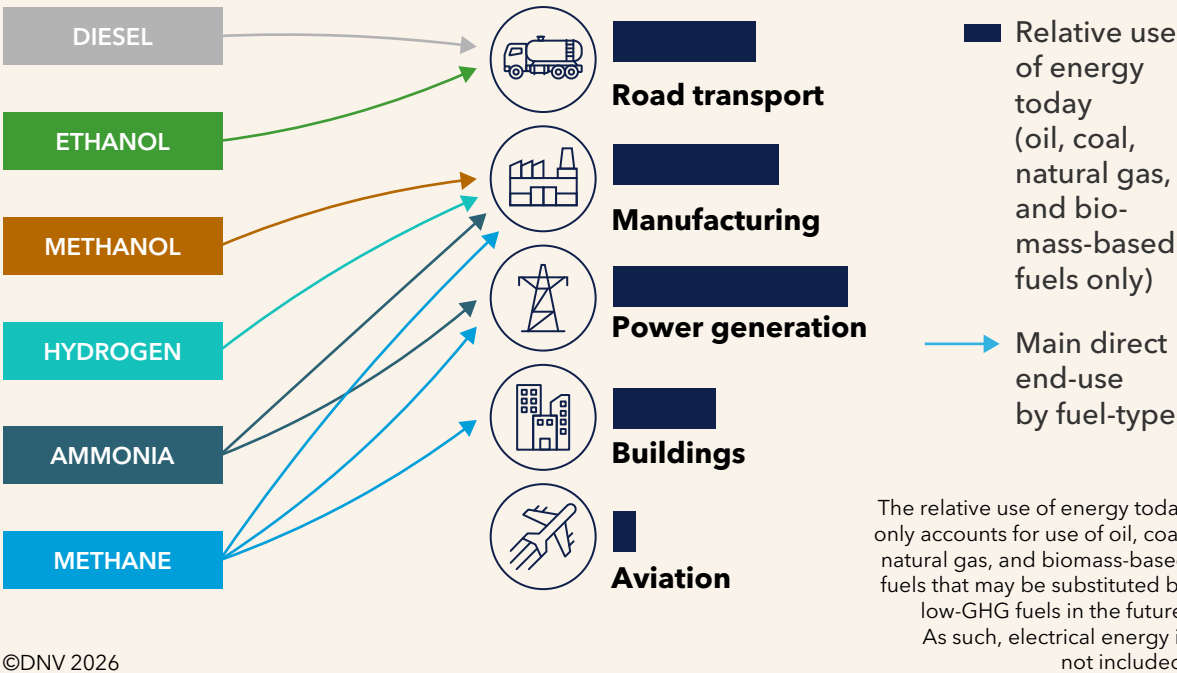
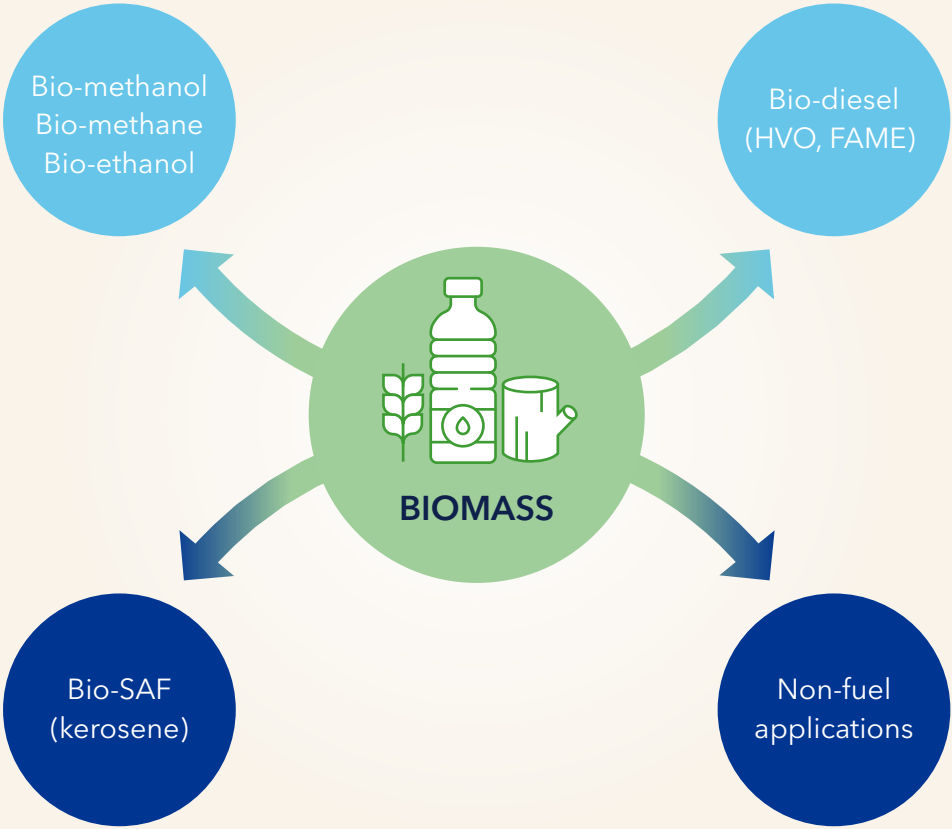


FIGURE 4-9
Competition for biomass feedstocks. Shipping has significant potential to use a range of biofuels, including bio-diesel, bio-methanol, bio-ethanol, and bio-methane (light blue). In addition to direct competition for these fuels, there is also competition for the feedstocks used to produce them (dark blue).



resources, and in some cases the same production capacity, which can shift between outputs such as bio-SAF and bio-diesel. Moreover, these feedstocks face broad competing demand from other applications beyond fuel production. Biomass feedstocks are used in food and feed, chemicals and bioplastics, lubricants and coatings, heat and power generation, and paper and pulp, among other applications.

Feedstock availability for bio-diesel is particularly important, as it is the primary near-term solution for most ships and is likely to remain so in the short to medium term due to technology lock-in (see Section 4.3.2). At the same time, bio-SAF relies on many of the same feedstocks as bio-diesel, including waste oils and fats, residues, woody biomass and other waste streams.

4.4.2 Demand scenarios towards 2050

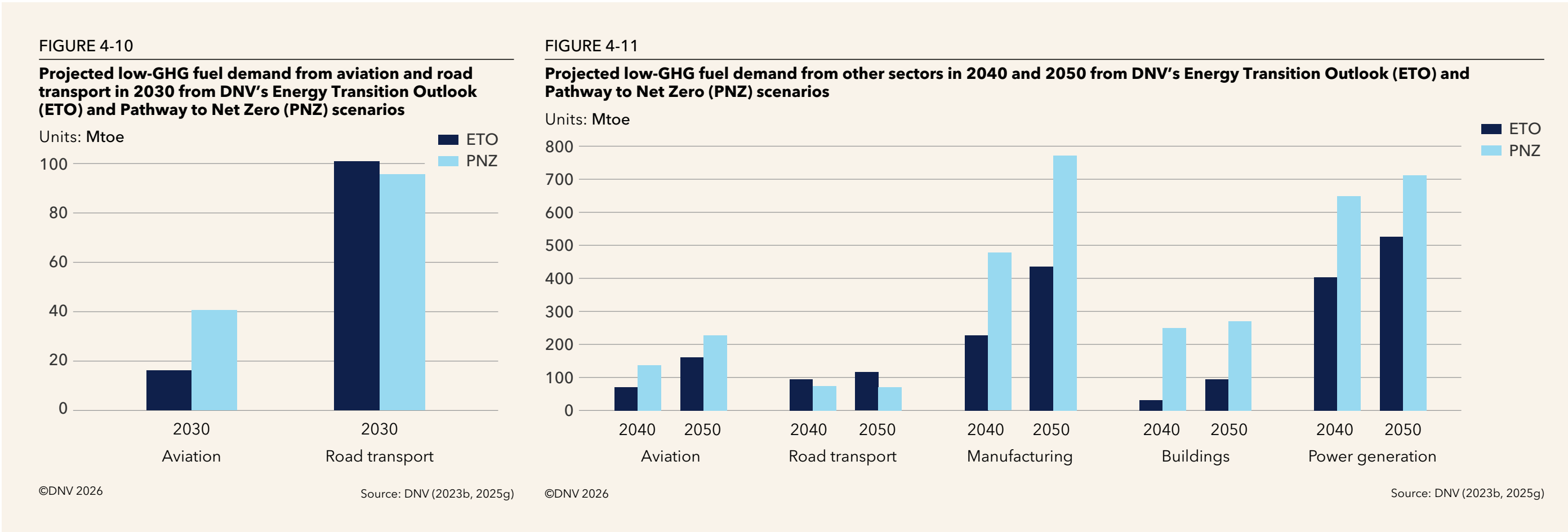
To quantify the future low-GHG fuel demand from the relevant non-maritime sectors towards 2050, we apply two scenarios based on DNV’s energy transition research. First, we use the main Energy Transition Outlook (ETO) 2025 (DNV, 2025g), referred to as a ‘most likely’ scenario. This is a scenario grounded in observed and expected regulatory trends, technology deployment rates, and market behaviour across regions and sectors, leading to an approximately 43% reduction in global GHG emissions by 2050 relative to today. Second, to provide a high-demand projection, we use the Pathway to Net

Zero (PNZ) scenario (DNV, 2023b), which is a back-casting exercise designed to explore what would be required globally to achieve net-zero emissions by 2050. In this scenario, policies, mandates, and carbon prices are assumed to be introduced at sufficient scale and speed to reduce GHG emissions by an amount consistent with a 1.5°C pathway. Compared to the main ETO scenario, PNZ implies earlier and stronger phase-out of fossil fuels, higher effective carbon costs, and faster deployment (in all sectors) of electrification, low-GHG fuels, and enabling infrastructure.

Today, most low-GHG fuels are consumed in the transport sector, although some fuel types, particularly bio-methane, are also used in other sectors such as power generation. To simplify the comparison, Figure 4-10 shows low-GHG fuel demand in 2030 only for the aviation and road transport sectors. Under the ETO scenario, combined demand in these two sectors reaches almost 120 Mtoe in 2030, of which road transport represents the larger share. Aviation demand is smaller in absolute terms but growing rapidly, reaching 16 Mtoe in 2030. Under the PNZ scenario, the combined aviation and road

transport demand increases to almost 140 Mtoe in 2030. Notably, the demand in the road sector is lower than in the ETO scenario due to increased electrification, while for aviation demand is significantly higher.

The 120–140 Mtoe demand range for aviation and road corresponds to roughly half of the potential low-GHG fuel supply in 2030 (Subsection 4.2.1). However, excluding methanol and ammonia (108 Mtoe combined), aviation and road would account for around 80% of the remaining supply.



From another perspective, the combined supply of low-GHG ethanol and diesel (134 Mtoe) would be just sufficient to meet their demand.

For the long-term demand in 2040 and 2050, we look at the low-GHG fuel demand for all relevant non-maritime sectors, as shown in Figure 4-11.

In the ETO scenario, total low-GHG fuel demand from non-maritime sectors is about 830 Mtoe in 2040, increasing to 1,300 Mtoe in 2050, with the largest volumes required by manufacturing and power stations. Demand from aviation and road transport combined reaches about 160 Mtoe in 2040 and 280 Mtoe in 2050, with aviation accounting for a growing share due to increasing electrification in road transport.

In the PNZ scenario, the demand rises more sharply, to around 1,600 Mtoe in 2040 and 2,100 Mtoe in 2050 for all non-maritime sectors. Aviation demand alone reaches almost 230 Mtoe by 2050, while for road transport it stays stable at around 70 Mtoe.

Several limitations and uncertainties should be kept in mind when interpreting these results. We do not include direct use of renewable electricity or unprocessed traditional biomass in the analysis. Traditional biomass is typically used for cooking and heating in low-income regions and is not considered a feedstock for fuel production. We also apply some assumptions to isolate what we define as modern bioenergy, including biofuels for transport and manufacturing, bio-methane blended with natural

gas for use in buildings and manufacturing, and bioenergy for electricity production.

The PNZ scenario was developed in 2023 and, as noted in the 2025 ETO, is no longer fully achievable. The demand ranges presented here should therefore be interpreted as indicative of requirements under a most-likely trajectory and a net-zero trajectory, rather than as precise forecasts.

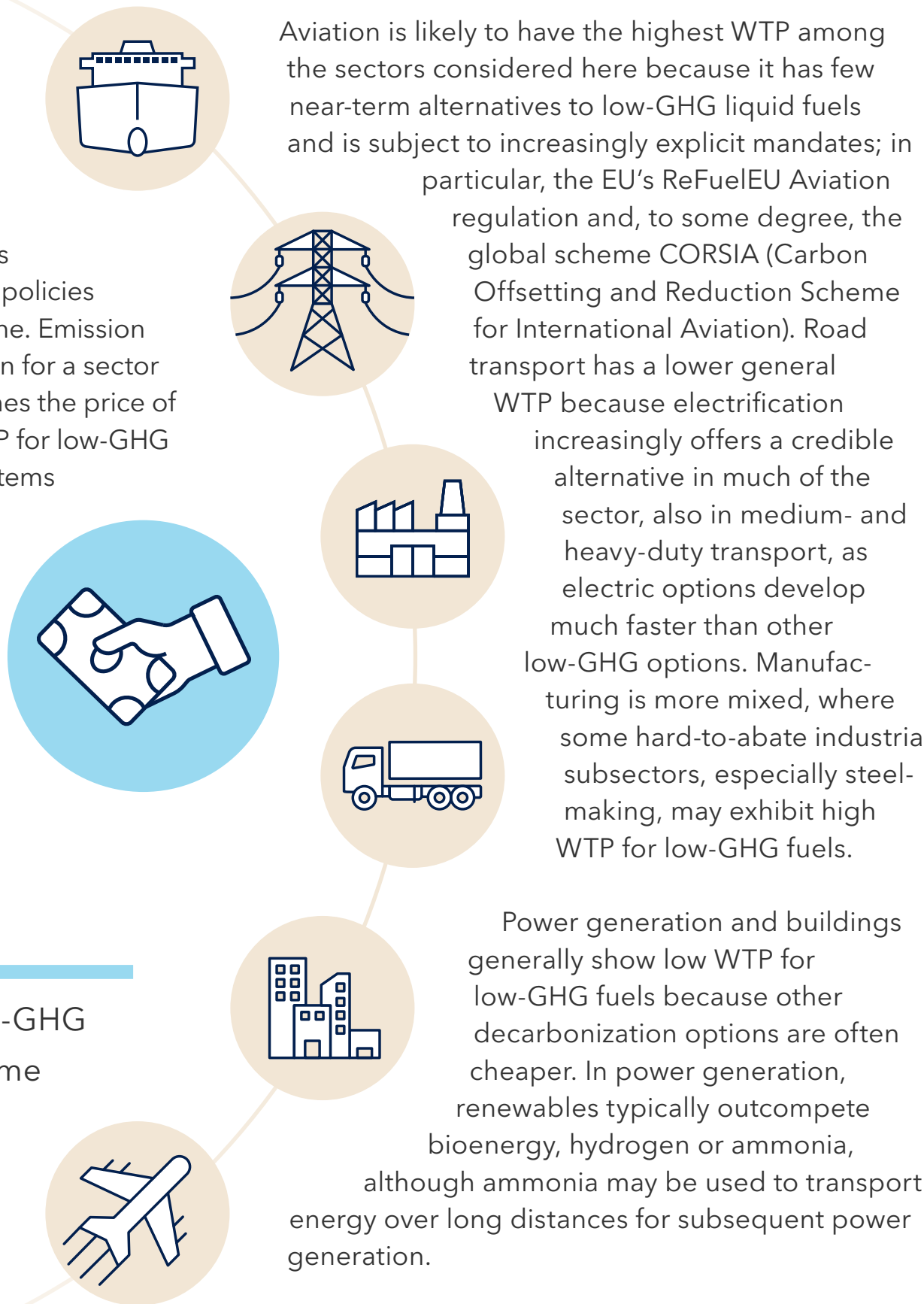
4.4.3 Willingness to pay across sectors

The demand presented in the previous section is primarily driven by regulations and policies, such as mandates, fuel standards, and carbon prices, but also commercial drivers through voluntary reductions and carbon markets. Each driver provides different incentives and impacts the willingness to pay (WTP) for low-GHG fuels. The WTP will differ across sectors, regions, and countries, depending on the drivers and the availability of lower-cost decarbonization alternatives as discussed in Subsection 4.4.1. If the prices of low-GHG fuels are higher than the WTP, demand will reduce.

Sectors will exhibit a larger WTP when low-GHG fuels are necessary to meet binding rules, preserve market access, or as part of policies to promote energy security. Lower WTP will be seen where electrification, efficiency or other abatement options can deliver similar emissions reductions at lower cost, or where regulations offer alternative compliance

options in the form of penalties. Blend-in mandates, such as those imposed by the EU Renewable Energy Directive, impose requirements on use of low-GHG fuels without considering the end-users' WTP. However, where supply remains limited and prices remain high, such policies may prove difficult to sustain over time. Emission trading systems set a cap on emission for a sector or a region, and the market determines the price of emissions and consequently the WTP for low-GHG fuels. Today, 38 emission trading systems are in force globally, with more under development or consideration, covering varying sectors (ICAP, 2025).

In the ETO scenario, total low-GHG fuel demand from non-maritime sectors is about 830 Mtoe in 2040, increasing to 1,300 Mtoe in 2050.



4.5 Developments in the market and pricing of marine low-GHG fuels

Combining the insights from our analysis of supply and demand, here we discuss how the marine low-GHG fuel market may develop and how prices could evolve over time. Provided that sufficient regulatory demand drivers are in place, the marine low-GHG fuel market is generally expected to develop in three stages, with the uptake forming an S-shaped curve (Nordic Roadmap, 2024). We are currently in the first phase, slow initial uptake, in which work is needed to overcome barriers currently preventing rapid upscaling of low-GHG fuel uptake.

This will be followed by a period of more rapid growth once demand for low-GHG fuels is strong enough, and as ship technologies, fuel production, and distribution infrastructure mature. Over time, this growth is expected to slow as the market approaches saturation. In the following, we divide the discussion into an emerging market towards 2030 and a scaling market towards 2050.

The emerging market towards 2030

By 2030, the low-GHG fuel market is likely to remain fragmented across shipping and other sectors. Supply will be limited and unevenly distributed during early scale-up and further constrained by local infrastructure and logistics. Ship fuel technologies will continue to lock vessels into specific fuel types, although fuel oils can be used by all ships with dual-fuel capabilities. Access to fuels such

as methanol and ammonia is likely to depend on long-term offtake agreements between producers and first movers. Early deployment is likely to concentrate in shipping trades with predictable routes and cargo flows – typically found in container and vehicle liner trades and certain tank and bulk trades – where fuel availability can be coordinated across ports and fleets. Green shipping corridors and similar initiatives can accelerate early scale-up by reducing coordination risk.

Until recently, shipping's demand and WTP for low-GHG fuels have been driven by the voluntary carbon credit market and fulfilling cargo owners' decarbonization targets. The recent introduction of the EU ETS and FuelEU Maritime will drive the demand to an estimated 4 Mtoe in 2030. The adoption of a global framework could drive this further, up to a total of 22 Mtoe if the initially approved IMO NZF is adopted.

Regulatory frameworks and embedded pricing mechanisms are required to scale up the low-GHG fuel market, sending strong demand and price signals that define shipowner WTP and fuel producers' investment incentives. With the current regulatory designs, the WTP for marine low-GHG fuels will be defined by regulatory pricing mechanisms, most notably FuelEU's penalty of about 740 USD/tCO₂eq and the Tier 2 RU price of 380 USD/tCO₂eq under the initially approved IMO NZF, should



this be adopted. These prices act as ceilings on the price of low-GHG fuels in shipping.

Due to the fragmentation and limited demand, and unlike what we see for today's fuel oils, there will not be a global spot market price for marine low-GHG fuels. Most prices will be negotiated as part of long-term offtake agreements, but there may be local and regional spot markets for drop-in bio-diesel and liquefied bio-methane, as a significant number of ships can use these fuels. Our supply analysis shows that in the short-term to 2030, some pathways (e.g. bio-methane from manure, sugarcane ethanol, bio-diesel from waste oils) could achieve abatement

costs of roughly 180 to 300 USD/tCO₂eq, though sustainability criteria may limit conventional food and feed-crop based biofuels. Blue fuels sit in an intermediate cost band, with early projects around 490 USD/tCO₂eq. E-fuels are in the short term the most expensive category at roughly USD 680 USD/tCO₂eq or more. These cost levels, together with the price ceiling introduced by the regulatory penalty mechanisms, indicate a possible future market price range.

The scaling market towards 2050

Beyond 2030, the marine low-GHG fuel market could enter rapid growth and possibly reach saturation closer to 2050. Relevant fuel types for shipping

could be in sufficient demand to allow for a liquid spot market and general availability globally, though availability of some niche fuel types may be limited. Which fuel types stay relevant, and which remain niche, depends on many factors including, among others, feedstock availability, production costs, distribution infrastructure, ship fuel technology development, and competition from other demand sectors.

Many biofuel pathways can supply fuels at well below 500 USD/tCO₂eq in 2050. However, the lowest-cost biofuel pathways have finite potential to scale, with our analysis indicating a maximum global biofuel production potential of 1,300 Mtoe in mid-century. In a decarbonization scenario consistent with reaching net zero, global demand for low-GHG fuels across all sectors, including shipping, reaches more than 2,200 Mtoe by 2050. A scenario achieving around 43% GHG emission reduction requires at least 1,300 Mtoe. This indicates that biofuel demand may outpace supply, placing upward pressure on biofuel prices.

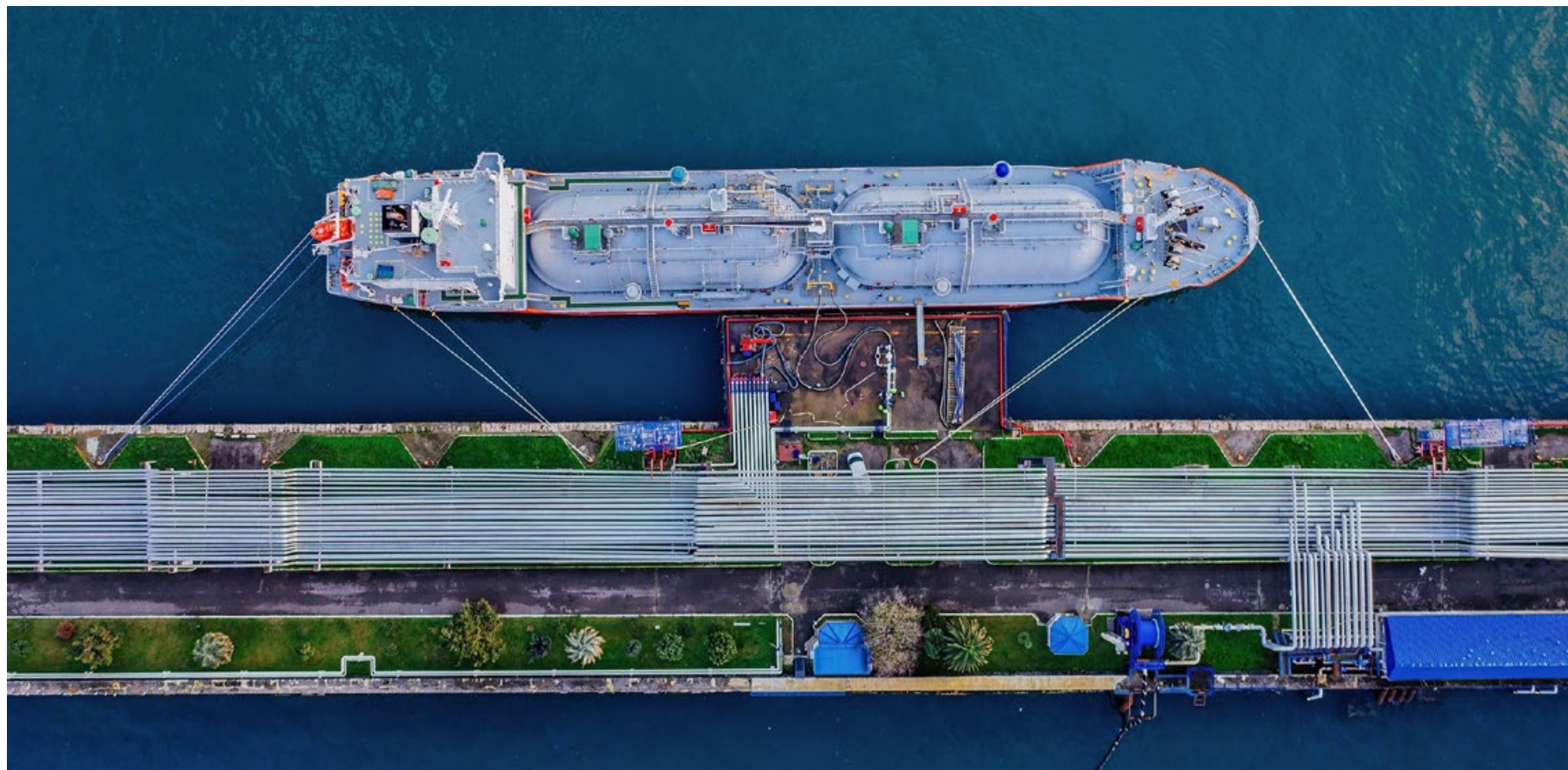
As the demand for marine low-GHG fuels is only a fraction of the total supply (33–185 Mtoe in 2050), it may well be that shipping can secure the biofuel it needs. However, there will also be significant willingness to pay in other sectors. Although aviation will need kerosene-type fuels, the sector will compete for the same feedstocks as for bio-diesel. Road transport can to a larger degree use bio-diesel directly, but the potential for electrification means that the WTP could be lower. Low-GHG methane prices will be shaped

by demand from sectors where fossil LNG is already in widespread use, such as power production, manufacturing, and buildings.

As demand increases in shipping and other sectors, non-biofuel pathways must therefore be deployed, pushing up marginal abatement costs and low-GHG fuel prices towards the cost levels of blue fuels and e-fuels. Blue fuels remain in an intermediate band at about 420 USD/tCO₂eq for blue ammonia in 2050. Scaling and learning effects could lead to substantial cost declines for e-fuels, narrowing the gap to blue fuels and biofuels. For example, in our analysis, the abatement cost for e-ammonia declines from around 550 USD/tCO₂eq in 2040 to 380 USD/tCO₂eq by 2050.

Achieving the projected abatement costs for e-fuels is contingent on the availability and cost of renewable electricity, and on large-scale deployment, which in turn depends on strong and sustained demand signals across sectors. In maritime, this will depend on the ambition and credibility of IMO regulations including any remedial units (RU) pricing signals. In other sectors, different regulatory designs and political dynamics will shape demand. Sustained political commitment to decarbonization is therefore a prerequisite for demand for low-GHG-fuels, and consequently their pricing.

Even in a mature market, we do not expect a single global price to emerge for low-GHG fuels across different fuel types. Prices are instead likely to remain differentiated and at least partly decoupled,



Even in a mature market, we do not expect a single global price to emerge for low-GHG fuels across different fuel types. They are likely to remain differentiated and at least partly decoupled, with regional and local markets.

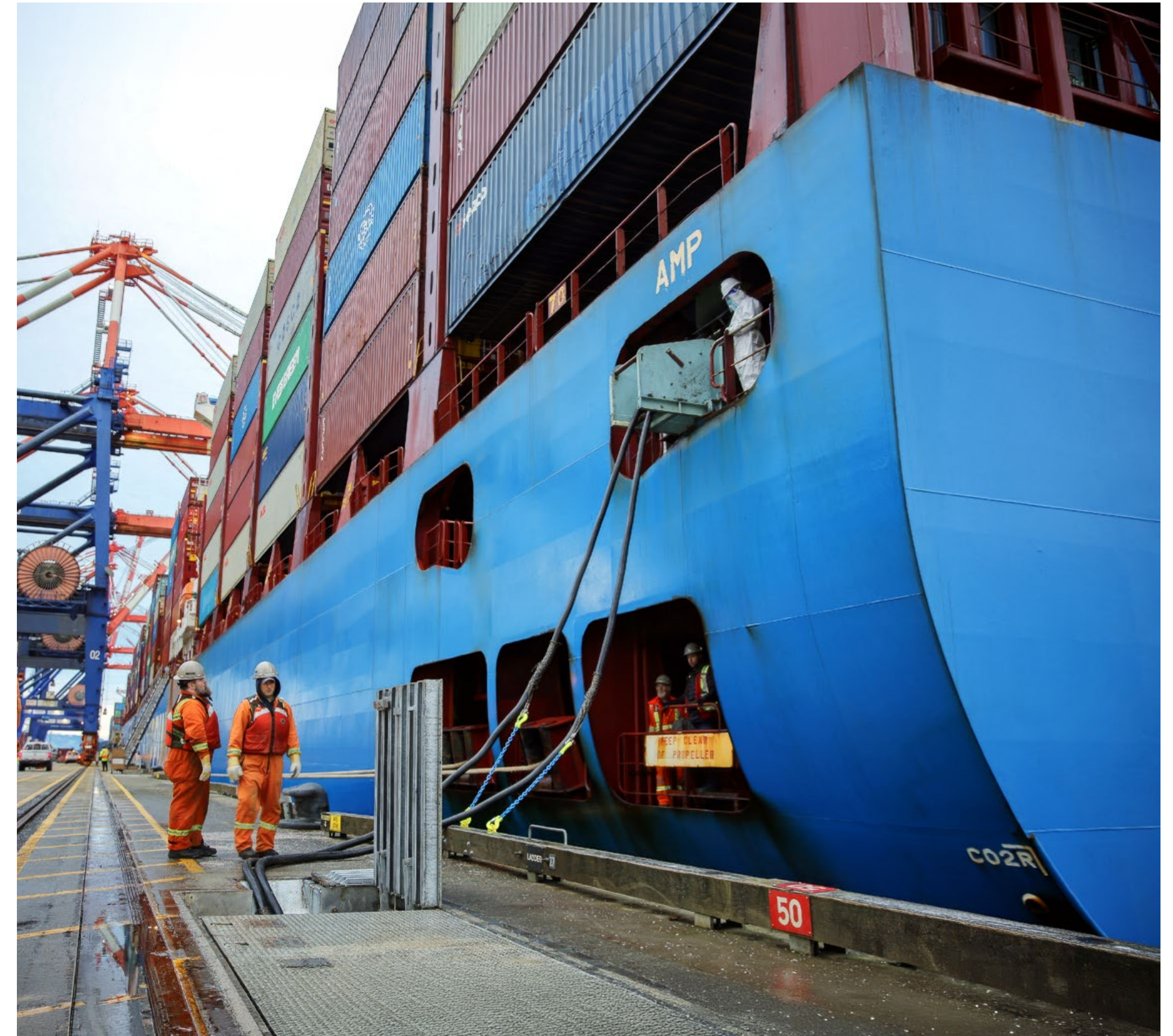
with regional and local markets. Take the relation between low-GHG methane and diesel as an example. These fuels are produced through different pathways, with varying conversion efficiencies, GHG intensities, energy inputs, and infrastructure and storage requirements, resulting in substantial differences in production and distribution costs. This price dynamic mirrors the historical relationship between LNG and crude oil, where prices have alternately coupled and decoupled over time in response to fundamentals such as feedstock availability, production, infrastructure, and regional market conditions (Hupka, et al., 2023). Prices can also be expected to vary across regions as feedstocks and

production are locally sourced and some fuel types are not feasible to transport between regions even if there is a price difference.

Furthermore, they are not interchangeable options for most end-users. This applies to most sectors, including shipping. We have shown that technology lock-in is limiting the near-term potential for ships to use fuels such as ammonia or hydrogen, but that this constraint is relaxed as more alternative-fuel capable ships can be ordered and built.

Finally, the 2050 fuel market will also be shaped by the uptake of technologies that could potentially make a substantial dent in shipping's demand for low-GHG fuels. Examples include shore power, plug-in hybridization and fully electric ships, nuclear power, and onboard carbon capture systems. Further, we see that shipowners' maximum willingness to pay differs by fuel type, reflecting differences in the investment costs required for onboard fuel technologies. These differences may be partially mitigated through compliance pooling and trading of surplus units, which sets a market price on the abatement cost.

In closing, the analysis presented in this chapter represents only a starting point for understanding the future fuel market. Over time, the analysis can be refined, and new data can enable more sophisticated, quantitative analysis. On the next page, we summarize our conceptual framework for low-GHG fuel use and pricing in shipping.



Conceptual framework for low-GHG fuel use and pricing in shipping

In principle, the uptake and pricing of marine low-GHG fuels can be understood considering: production volumes and abatement costs representing the supply curve, and the demand and willingness to pay from shipping and other sectors representing the demand curve. Below, we conceptually outline how this could be done in a simplified framework. While the data needed to apply such a method in full is not available for this study, it provides a useful framework for understanding how cross-sector competition may shape the future marine low-GHG fuel market.

As input, the method requires marginal abatement cost curves for the relevant low-GHG fuels, not only for shipping but also for other sectors expected to compete for the same fuels (see example provided for marine low-GHG fuels in Figure 4-4). In the illustration, shipping and two competing sectors (A and B) are included together with four fuels (1, 2, 3 and 4), each produced through different pathways and therefore available at different abatement costs.

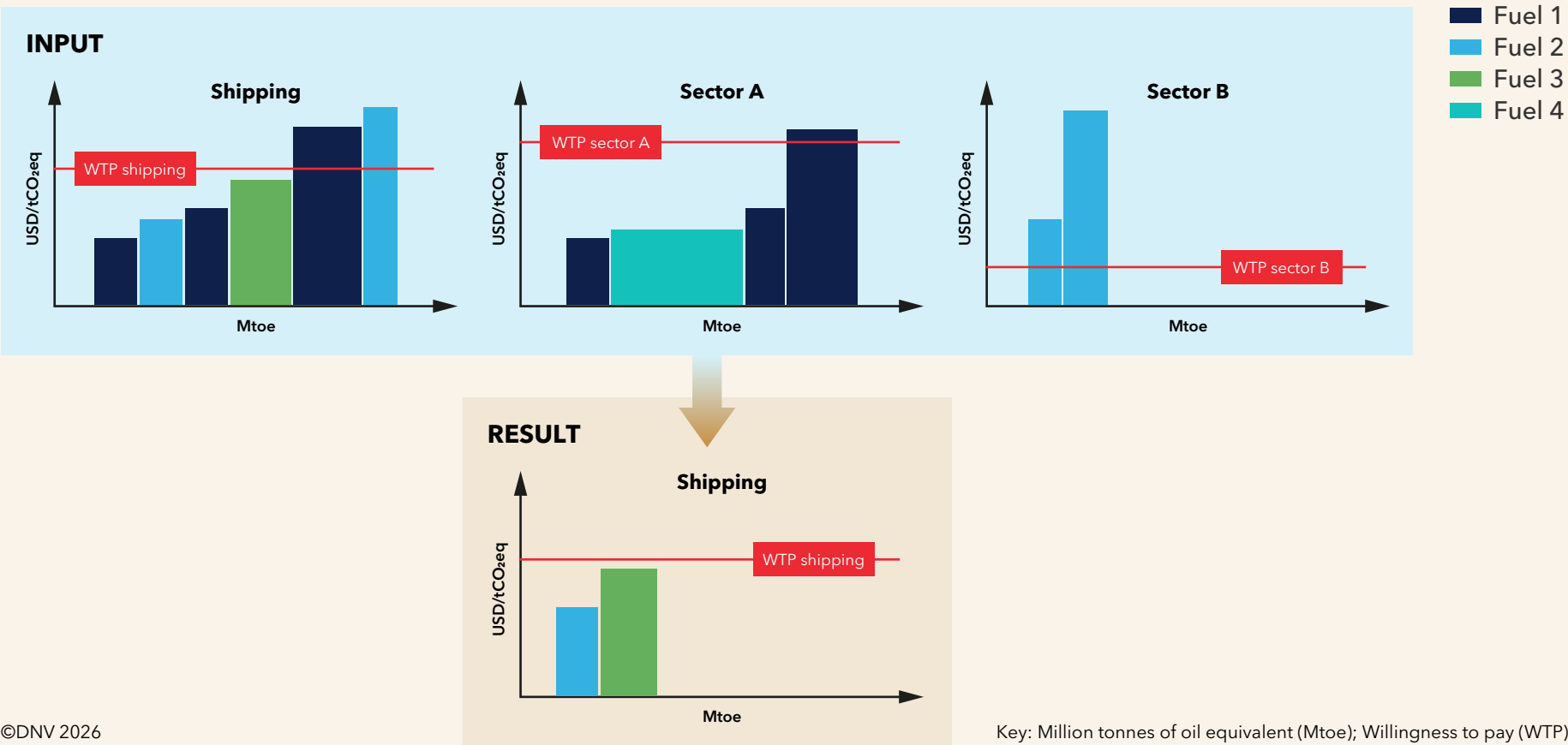
Starting with the fuel that has the lowest cost for shipping (the leftmost fuel in the graph), the first step is to assess whether shipping is willing to pay for it. This requires a measure of shipping's willingness to pay (WTP), such as the IMO NZF Tier 2 remedial unit price of 380 USD/tCO₂eq. If the abatement cost of a fuel is above shipping's WTP, it can be excluded from

further consideration because it will not be used. In the illustration, the cheapest and second-cheapest variants of Fuel 1 fall below shipping's WTP, as do Fuel 3 and the cheapest variant of Fuel 2.

For the fuels that pass this first test, the next step is to assess whether they are also relevant for other sectors, and if so, whether those sectors are willing to pay more than shipping. This depends on two



FIGURE 4-12
Conceptual framework for low-GHG fuel use and pricing in shipping



factors: whether the fuel is physically applicable in the other sector, and the WTP in that sector. In the illustration, Fuel 1 is applicable to Sector A, and Sector A has a higher WTP than shipping with no other alternatives. Sector A will therefore outcompete shipping for this fuel, since the price will rise to converge with Sector A's WTP. Fuel 2 is not applicable to Sector A, but it is relevant for Sector B. However, Sector B has a lower WTP than shipping or has other lower cost options and will therefore not outcompete shipping for this fuel. Fuel 3 has no competing demand beyond shipping.

The result is that Fuel 1 is priced out and will not be used in shipping. In contrast, the cheapest variant of Fuel 2 will be used in shipping, as will Fuel 3. Fuel 4 is not applicable to shipping. While the cost of Fuels 2 and 3 will be below the WTP in shipping, the actual market price may converge closer to shipping's WTP depending on total demand in shipping and other decarbonization options.

Finally, demand in each sector is constrained by the size of the sector, the level of decarbonization ambition, and the availability of other options for reducing GHG emissions and energy use, which together place an upper bound on total fuel uptake. In the illustration, however, these demand constraints are assumed to be sufficiently high that they do not affect the outcome.



5

NAVIGATING THE TRANSITION

Highlights

Using an updated framework for managing GHG transition risk, we run a case study for crude carriers in slow and rapid transition scenarios towards 2050, showing:

- A scenario-based framework can manage transition risk, identifying fuel and technology strategies that minimize cost and risk at fleet level.
- Cost and risk assessment outputs can be combined into an overall strategy score for decision-making.
- Fleet technology and fuel strategies perform differently across slow- and rapid-transition scenarios.

Ambiguity around future GHG regulations, the evolving technology landscape, and marine fuel markets drive uncertainty that translate into material risks affecting competitiveness, revenues, costs, financing, and day-to-day operations. Our framework for managing GHG transition risk aims to identify robust fuel and technology fleet strategies for shipowners by balancing transition risk and cost across both short- and long-term horizons towards 2050. We illustrate its value through a case study, highlighting how cost and risk can be assessed jointly to support more robust strategic decision making.

5.1 An updated framework for managing transition risk

Decarbonization of shipping can impose significant transition risks for a shipowner:

- **Charter risk:** Vessel competitiveness in the charter market is essential for securing stable charter revenues. Depending on the charter contract type, owners must ensure their ships remain attractive to charterers in terms of fuel and compliance costs and operational flexibility, while also minimizing the likelihood of off-hire.
- **Fuel cost and compliance risk:** Owners and operators must manage GHG compliance costs, either by using more expensive low-GHG fuels, or by paying potentially high penalties, influencing both fuel costs and GHG compliance costs.
- **Finance risk:** Capital costs (including cost of financing) typically increase when investing in new fuel technologies or energy-saving appliances.

Access to competitive financing is critical for maintaining a cost-effective fleet.

- **Operational risk:** Introducing new technologies, including digital and data-driven systems, requires competent crew and shore organizations, and effective maintenance practices. Technology shifts may lead to increased technical off-hire due to challenges with new and less mature technological solutions. It can also increase repair and maintenance needs and influence insurance premiums, affecting overall operating expenses.

These risks often arise and evolve because of new regulations (e.g. GHG regulations, shore power mandates), requirements from charterers, or other factors. Furthermore, the fuel and technology that owners select to stay compliant may both mitigate risks and introduce new ones. The risks are also shaped by the solutions selected by a shipowner's competitors, customers, and providers of services, fuel, and technology. It is important to recognize that these risks apply both to conventional tech-



nologies and fuels and to less mature alternatives, though in different ways and to different extents. Behavioural research also suggests that decision-makers may attach greater weight to the risks of new options than to those associated with continuing with current ones (often referred to as 'status-quo bias'). Other than those risks covered in this framework, there are clearly important additional ones related to climate change and cross-sector decarbonization. Perhaps the most important is the risk associated with changes to trade patterns and volumes, in particular for commodities such as oil and coal. We omit these here because they are only marginally influenced by the choice of fuel and technology.

Beyond added costs and new risks, the transition will also create opportunities. For example, first-mover shipowners could capture value by selling green services and using pooling to reduce costs, strengthening their competitive edge and attracting climate-conscious customers.

Our framework for managing GHG transition risk aims to identify robust fleet strategies for shipowners by balancing transition risks and costs across both short- and long-term horizons towards 2050. Using the framework requires multidisciplinary expertise, combining an understanding of a shipowner's specific circumstances and priorities with insights into marine fuel markets (Chapter 4), as well

as relevant technologies (Chapter 3) and regulatory developments that shape risk (Chapter 2). The GHG risk management framework presented here builds on previous DNV work (e.g. DNV, 2021) and draws inspiration from financial climate robustness frameworks such as the TCFD⁵⁶. The main new feature of the updated framework is that it captures risks not easily quantified in monetary terms, and provides a way to jointly assess such risks with cost quantification. It consists of three steps (Figure 5-1):

1. Define a set of potential fuel and technology strategies for a fleet

A ‘strategy’ in this context is a high-level description of the fleet’s primary characteristics in terms of fuel capabilities and performance. It can include the implementation of energy-efficiency measures and/or alternative fuel capabilities (including ‘ready’ options) for both newbuild and existing ships. Furthermore, it can contain elements of fleet renewal, including sale, recycling, purchase of ships, operational area, and charter contract type (i.e. trading on spot or time-charter). The strategy may reflect company-specific decarbonization targets (e.g. reducing fleet carbon intensity by 30% by 2030). A set of strategies should be defined to ensure that the most relevant potential fuels and technologies are covered.

2. Define a set of possible scenarios describing the development of key parameters including regulations and fuel market

A ‘scenario’ in this context is a structured description of a possible future situation (e.g.

‘towards 2050’) used to understand and prepare for uncertainty. It should capture the most relevant external factors influencing net earnings capacity, which are also influenced by the choice of strategy. These factors include fuel supply and prices, bunkering infrastructure, GHG regulations, and competitor behaviour. As the developments in such factors are interdependent, it is important that the developments described are internally consistent. A set of scenarios should be defined, covering a range of potential future situations.

3. Robustness check for each strategy against each scenario, considering risk factors defined above

A robustness check in this context is an evaluation of how each strategy performs under different scenarios and their timeline, revealing vulnerabilities and risks that may not be visible in a single-forecast approach. It consists of two parts: a cost assessment and a risk evaluation. The cost assessment shows how each strategy performs economically assuming all inputs hold – fuel availability, technology reliability, regulatory clarity, and stable market conditions. Key performance indicators (KPIs) can be used, such as break-even daily rate, reflecting the charter income per day and per vessel that an owner must have to make a profit and have a net positive earning. The risk assessment may be structured as a Hazard Identification (HAZID)⁵⁷, systematically identifying and qualitatively assessing potential risks impacting each strategy within each scenario. It identifies where real-world uncertainty may cause deviations from the modelled outcomes in the cost

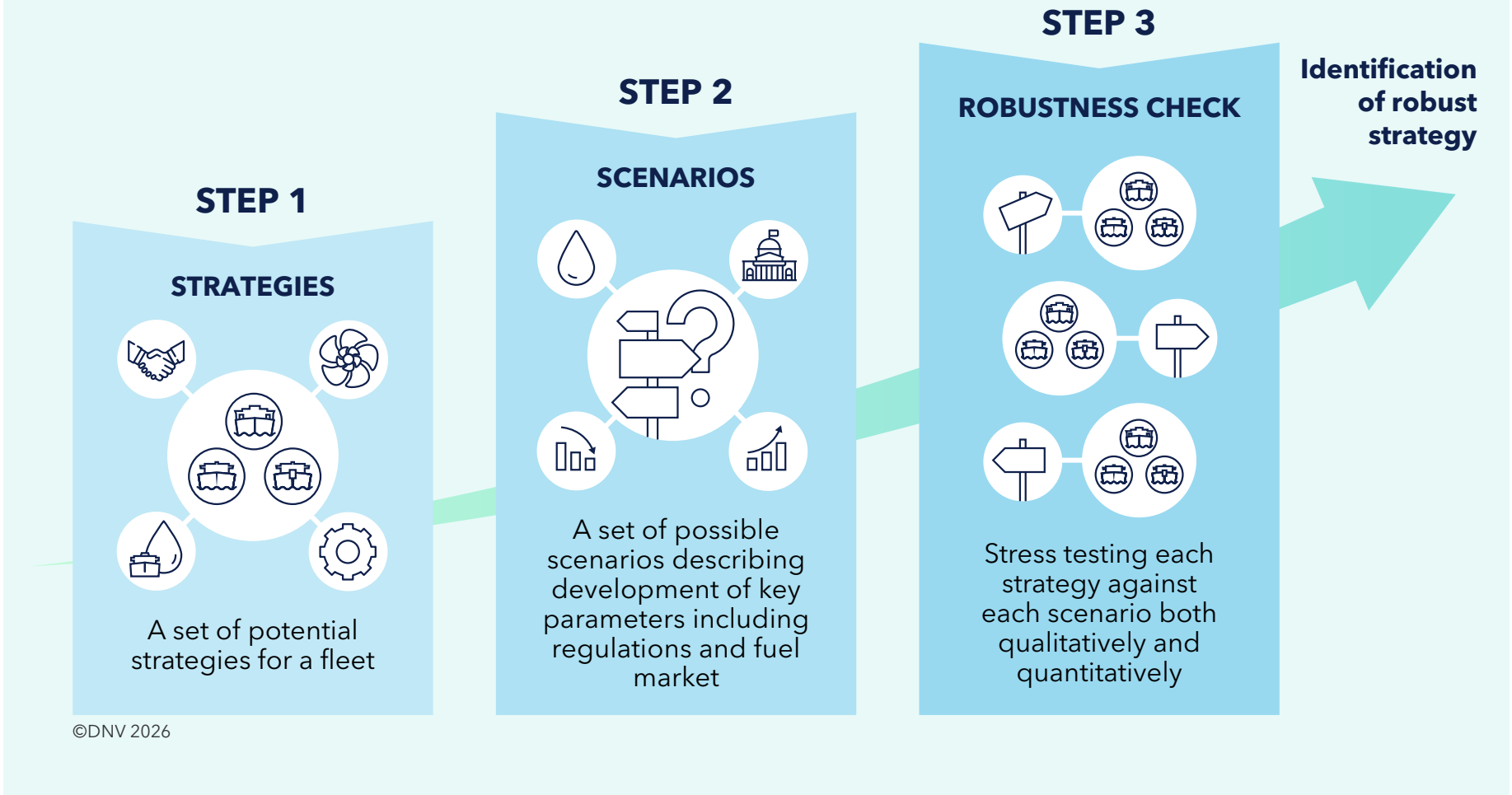
assessment. It also captures a wider range of risks, including those not easily quantified.

The use of the framework is flexible. It can be applied to a wide range of fleet strategies, or to a very limited set; a comprehensive set of futures can be assessed, or a limited few. The tools and methods used to stress test the performance can be

both quantitative and qualitative – detailed or high-level. Results can be updated regularly to reflect the latest developments in regulations, technologies, and fuel markets. A range of possible KPIs can be used as measures of robustness. In practice, an iterative approach can be used, gradually exploring, refining, and detailing the analysis.

FIGURE 5-1

DNV’s stepwise approach for managing GHG transition risk and cost for a fleet



5.2 Illustrative example: a VLCC fleet for renewal

To illustrate the practical application of our framework, we present an illustrative example. We select a shipowner operating a fleet of five Very Large Crude Carriers (VLCCs).

The VLCC trade is characterized by long-haul transportation of crude oil in very large volumes, typically linking major export regions (notably the Middle East and the Atlantic Basin) with large importing centres in Asia and elsewhere (see Figure 5-2). It is a dynamic

market where freight rates can move sharply with changes in tonne-mile demand, fleet availability, repositioning, and disruptions at key chokepoints or loading areas.

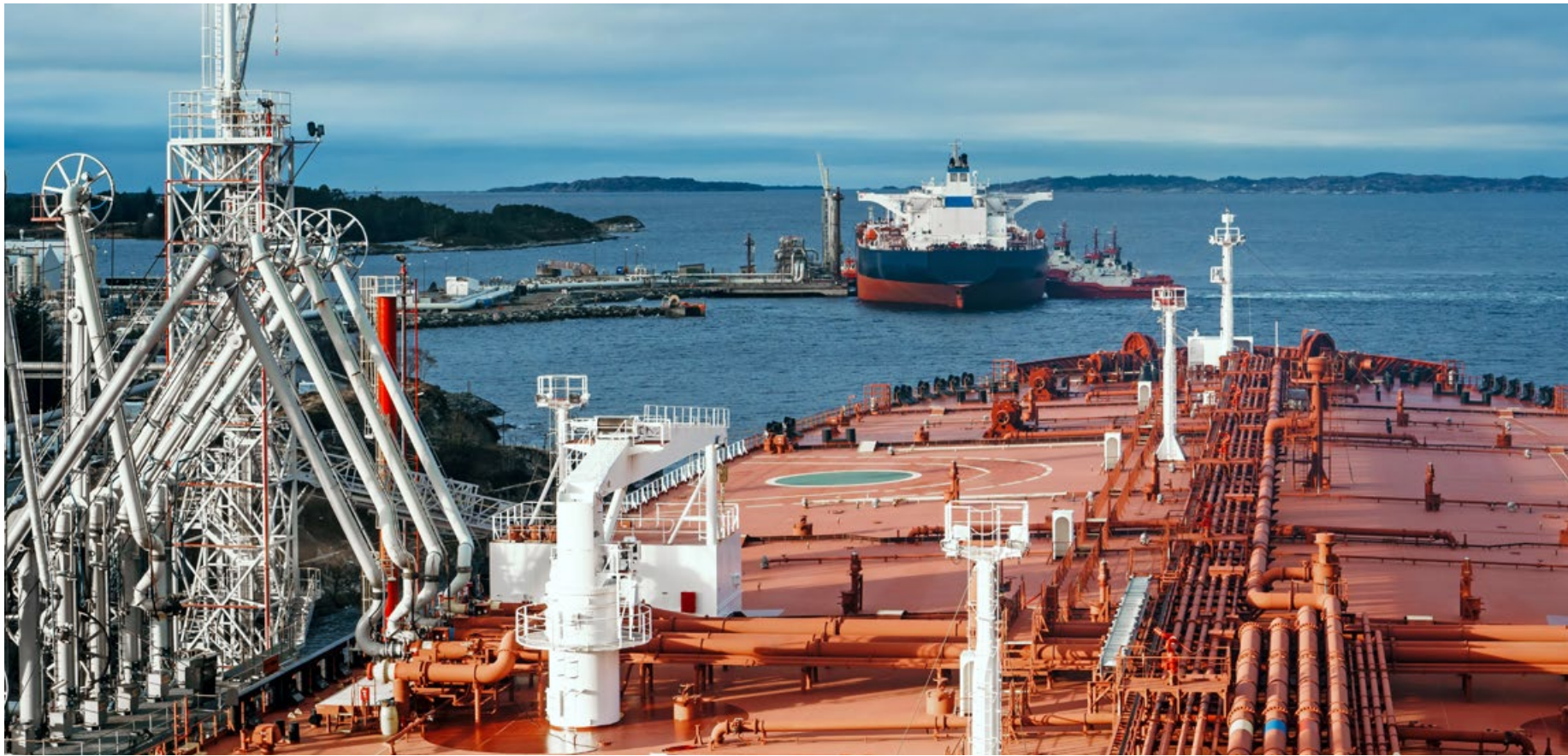
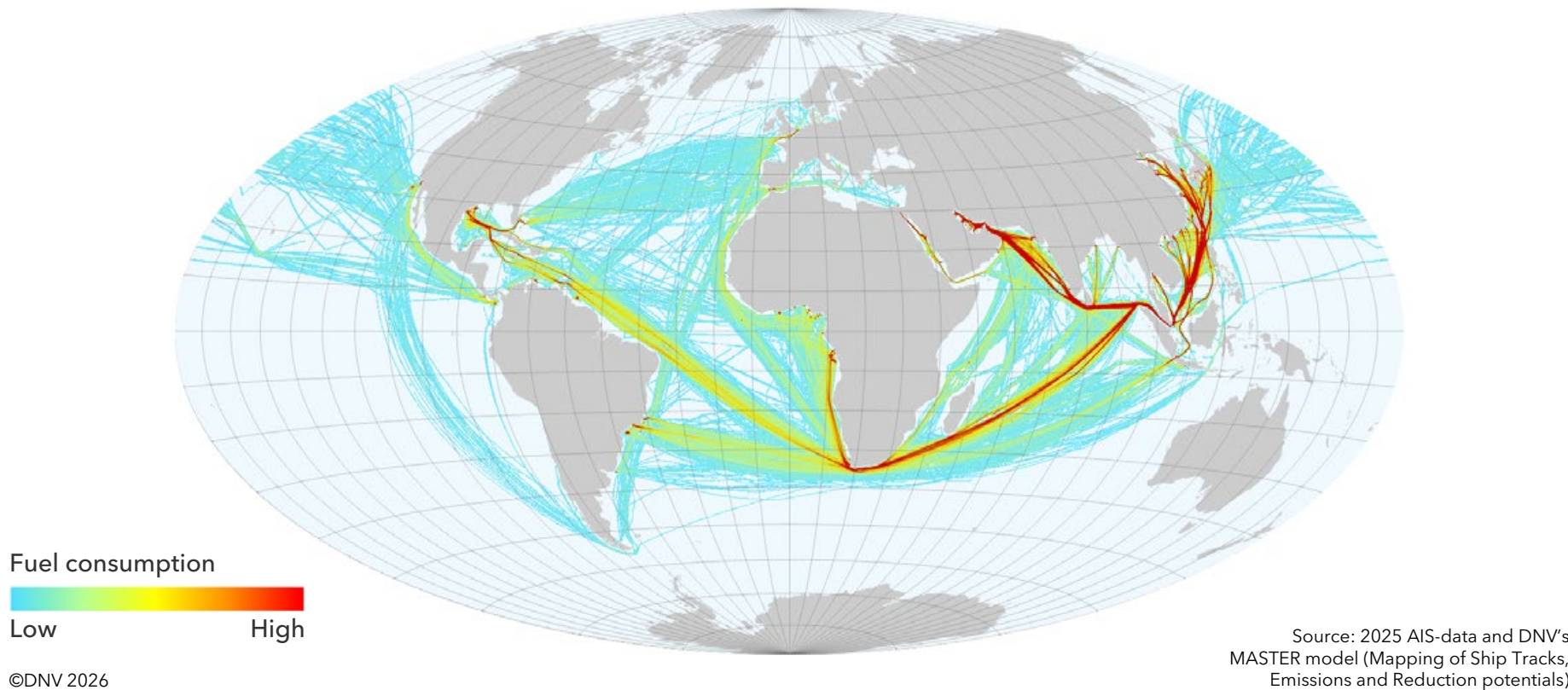
In the following subsections, our three-step framework presented in Figure 5-1 is exemplified for a fully integrated owner of VLCCs⁵⁸, with long-term ownership ambitions. The fleet consists of five ships; two older ones built in 2010, one mid-aged, built

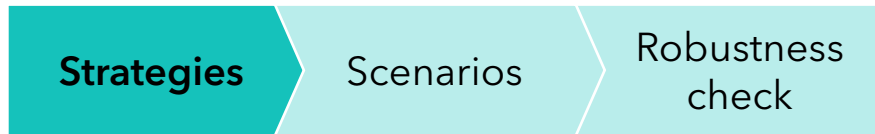
in 2015, and two modern ones delivered in 2020. All vessels in the existing fleet are conventional and fitted with open-loop scrubbers, without equipment for shore power connection.

The case study presented is simplified and for illustrative purposes only. Hence, we emphasize that to support real-world decision making, the study should cover a wider range of potential fleet strategies and, even more importantly, of potential scenarios.

The main new feature of the updated framework is that it captures risks not easily quantified in monetary terms, and provides a way to jointly assess such risks with cost quantification.

FIGURE 5-2
Heat-map of VLCC operations during the calendar year 2025, based on AIS-data





5.2.1 Step 1: Strategies

The owner can pursue a wide range of fuel and technology strategies to preserve the fleet’s net earning capacity. Importantly, separate strategies may be developed for the existing fleet and newbuilds. Here we consider two from among a vast number of potential strategies, including a wide array of solutions.

For both, we assume all five ships trade internationally in the spot market, with some limited EU/EEA

exposure⁵⁹. Fleet capacity is kept constant through a structured renewal programme in which each VLCC is replaced at 20 years of age, starting with the oldest ships from 2030 and continuing as vessels reach end of life.

Strategy A: HSHFO + scrubber

In the ‘HSHFO (high sulphur heavy fuel oil) + scrubber’ strategy, all newbuilds ordered include open-loop exhaust gas scrubbers with conventional fuel-oil technology (see Figure 5-3).

For the existing fleet, industry-standard energy-efficiency measures are implemented. This includes regular hull and propeller cleaning to control

biofouling, as well as weather routing to determine the most efficient voyages and speeds based on weather forecasts, wind direction, and wave heights. During each five-year dry-docking, hull is spot-blasted and new standard hull coating is applied. No retrofits requiring physical onboard installation are performed.

Newbuilds are ordered to the yard’s standard specifications, incorporating the industry-standard energy-efficiency measures applicable at the time of construction, and meeting the latest IMO Energy Efficiency Design Index (EEDI) regulations. These include propulsion-improvement devices designed to optimize hull-flow characteristics, as well as other

measures considered standard at the time. All vessels are ordered with conventional fuel-oil technology, including exhaust gas scrubber, enabling use of HSHFO, and they are not equipped for shore power connection.

Strategy B: Phase-in of dual-fuel LNG ships

In the ‘Phase-in of dual-fuel LNG ships’ strategy, all newbuilds ordered include dual-fuel LNG technology (see Figure 5-4).

For the existing fleet, the newest vessels (VLCC 3, VLCC 4 and VLCC 5) will be retrofitted during the 2026 dry-docking with pre- and post-swirl energy-saving devices to improve

FIGURE 5-3
Overview of Strategy A: HSHFO + scrubber

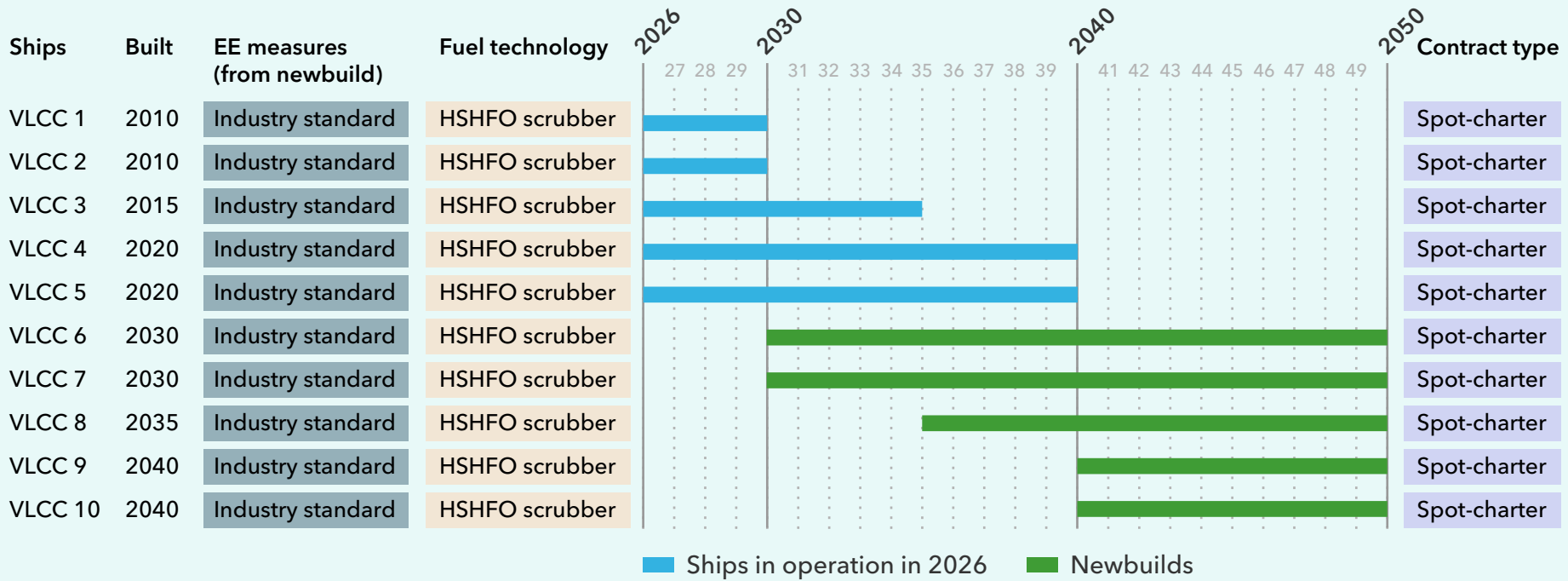
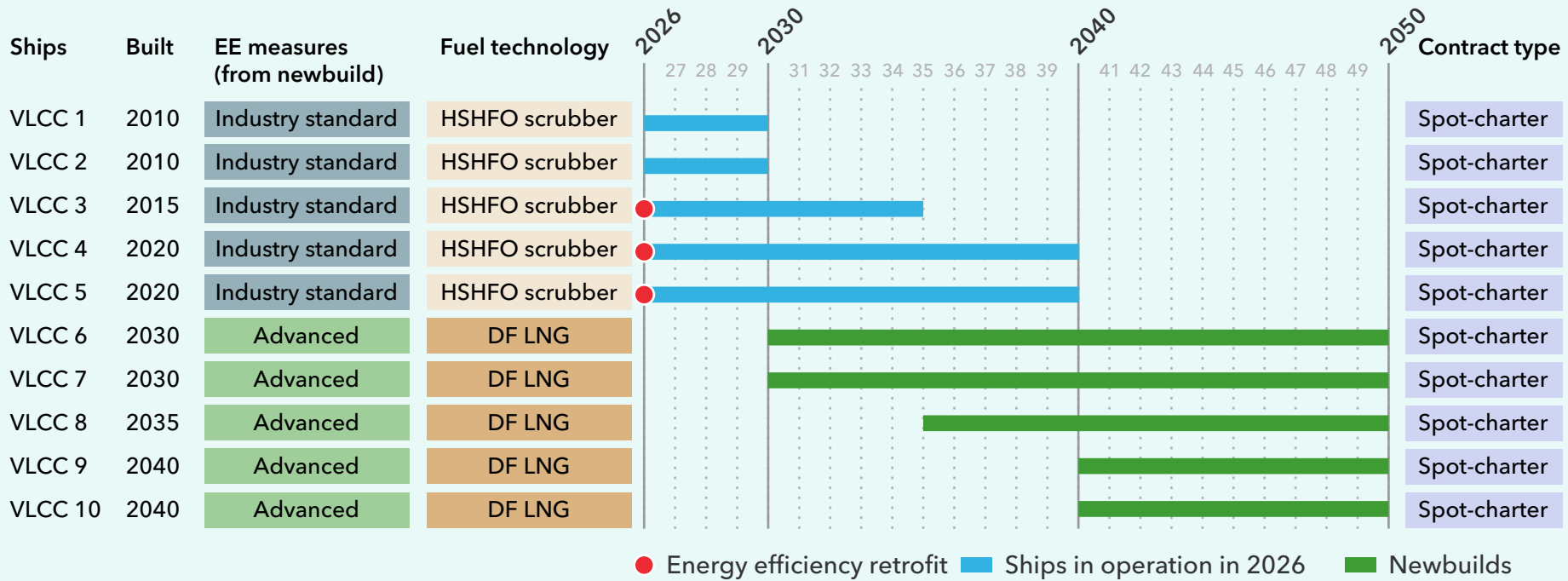


FIGURE 5-4
Overview of Strategy B: Phase-in of dual-fuel LNG ships



Strategies

Scenarios

Robustness
check

5.2.2 Step 2: Scenarios

hull-flow performance. In parallel, variable-frequency drives (VFDs) will be installed on seawater pumps and engine-room fans to reduce electrical load and fuel consumption. All vessels will also undergo full hull blasting and application of low-friction, silicone-based coatings.

The newbuilds are ordered with advanced energy-efficiency measures, beyond what is considered industry average at the time of construction. These include, among others, the installation of shaft generators. All newbuilds are equipped with LNG dual-fuel technology, enabling operation on conventional fuel oils, LNG, bio-diesel, and liquefied bio- and e-methane, and are also equipped for shore power connection.

We define two out of a vast number of potential scenarios, looking at the time-period towards 2050. They are selected because they offer a clearly different impact on our strategies, thus illustrating the framework. They are not considered more likely than other scenarios. Additional scenarios could also be considered. The two selected here are defined as follows:

Scenario 1: Slow transition

Global action on climate change slows down considerably, and the delay at the IMO observed in 2025 solidifies into a prolonged regulatory standstill. Regional and national regulations nevertheless continue to advance, with FuelEU Maritime and the EU ETS remaining the dominant regulatory drivers for shipping.

Consequently, progress in the global marine low-GHG fuel market remains sluggish. Fuel availability and supporting infrastructure are largely confined to major bunker hubs and regions subject to GHG regulation. Biofuels remain the most economically competitive low-GHG fuel option for shipping, with prices broadly in line with current levels due to limited demand growth from shipping and other sectors.

With limited global attention on GHG emissions, VLCC charterers place limited value on greening their value

chains, and financial institutions show little focus on reducing portfolio carbon intensity. Conventional fuel-oil technology, including scrubber-equipped VLCCs, continues to be the industry norm.

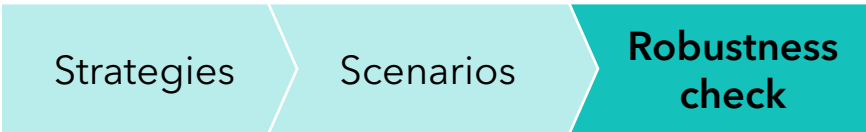
Scenario 2: Rapid transition

Global climate regulations tighten considerably. The delay at the IMO proves temporary, with its Net-Zero Framework back on track from 2029. The NZF is further strengthened as Tier 2 RU prices increase from 380 to 500 USD/tCO₂eq in 2033, and to 700 USD/tCO₂eq by 2040.

As regulations tighten, the fuel market develops rapidly. Biofuel demand rises sharply in maritime and rises in other industries, placing upward pressure on prices and limiting its availability for shipping. From 2040, e-fuels emerge as the main price-setters for low-GHG methane and low-GHG diesel.

As global attention on GHG emissions intensifies, VLCC charterers place increasing value on greener value chains, while financial institutions seek to reduce the carbon intensity of their portfolios. This drives a gradual shift in ordering behaviour towards LNG and methanol capable tonnage, enabling operation on both fossil and low-GHG variants of these fuels, besides conventional fuel oil and low-GHG diesel.





5.2.3 Step 3: Robustness check

The robustness check consists of two parts: a cost assessment and a risk evaluation. Below, we first cover key results from the cost assessment, followed by the risk assessment. Finally, we calculate a total score for each strategy. More information on assumptions is provided in Appendix B.

Cost assessment

We use the break-even daily rate to represent the cost performance of each strategy under each scenario, reflecting all relevant costs as a daily average, including GHG compliance, fuel, operating expenses, and capital costs. In our case study, we assume that all ships trade on the spot market and that the owner covers all relevant costs (including fuel and GHG compliance costs). Results show that the break-even daily rate varies significantly between ships.

Figure 5-5 illustrates the cost performance of each strategy under Slow transition (left) and Rapid transition (right). Break-even rates start around USD 52,000/day for both strategies in 2026. In Slow transition, they rise moderately to ~USD 61,000 (HSHFO + scrubber) and ~USD 67,000 (LNG) by 2049 – well within normal market volatility. In Rapid transition, costs increase sharply, reaching ~USD 167,000 (HSHFO + scrubber) and ~USD 144,000 (LNG),

far exceeding typical volatility. Overall, HSHFO + scrubber is cheaper in Slow transition, while LNG performs better in Rapid transition, with differences widening over time.

The key factors driving these differences vary depending on the scenario. In Slow transition, the ‘Phase-in of dual-fuel LNG ships’ strategy faces notably higher capital costs than in the ‘HSHFO + scrubber’ strategy, primarily because dual-fuel LNG newbuilds are more expensive than conventional scrubber-fitted ships. While dual-fuel LNG ships do gain some regulatory compliance advantages for EU-bound voyages, these benefits are modest

and insufficient to offset the higher capital costs. Furthermore, scrubber-fitted ships can use HSHFO, which is assumed to be less expensive than LNG. Although liquefied bio-methane is a cheaper fuel compared to bio-diesel, its limited use under the Slow transition scenario means it does not significantly impact overall costs or compensate for the higher expenses. In the Rapid transition scenario, the picture changes drastically. The scrubber-fitted VLCCs cannot capitalize fully from the use of HSHFO, as the fleet starts using low-GHG diesel to meet regulatory targets. The ‘HSHFO + scrubber’ strategy faces prohibitively high fuel prices towards 2049, resulting in payment of penalties rather than

use of low-GHG diesel at the assumed prices. Meanwhile, the ‘Phase-in of dual-fuel LNG ships’ strategy benefits from lower fuel consumption (higher energy efficiency) and the use of low-GHG methane, which is priced significantly cheaper than low-GHG diesel.

Risk assessment

The risk assessment highlights areas where real-world uncertainties could lead to outcomes that diverge from those predicted in the cost assessment. It also incorporates a broader spectrum of risks, including those that are difficult to quantify.

To carry out the risk assessment, we adopt a structured HAZID methodology, identifying events and risks involved with each strategy. Risk is assigned based on probability and consequence, on a scale from 1 to 3. It should be emphasized that the examples presented are not comprehensive; numerous events remain unassessed. We focus on events whose probabilities and/or consequences vary by strategy. To demonstrate the risk assessment process, we have selected some illustrative events from each risk category – charter risk, fuel cost, compliance risk, finance risk, and operational risk (see page 60).

The assessed risk of each event varies by strategy and scenario, as shown in Table 5-1. In the Rapid transition scenario, for example, being unable to bunker low-GHG diesel was identified as a high-risk event for Strategy A: HSHFO + scrubber, while in the Slow transition scenario, the impact is judged less likely

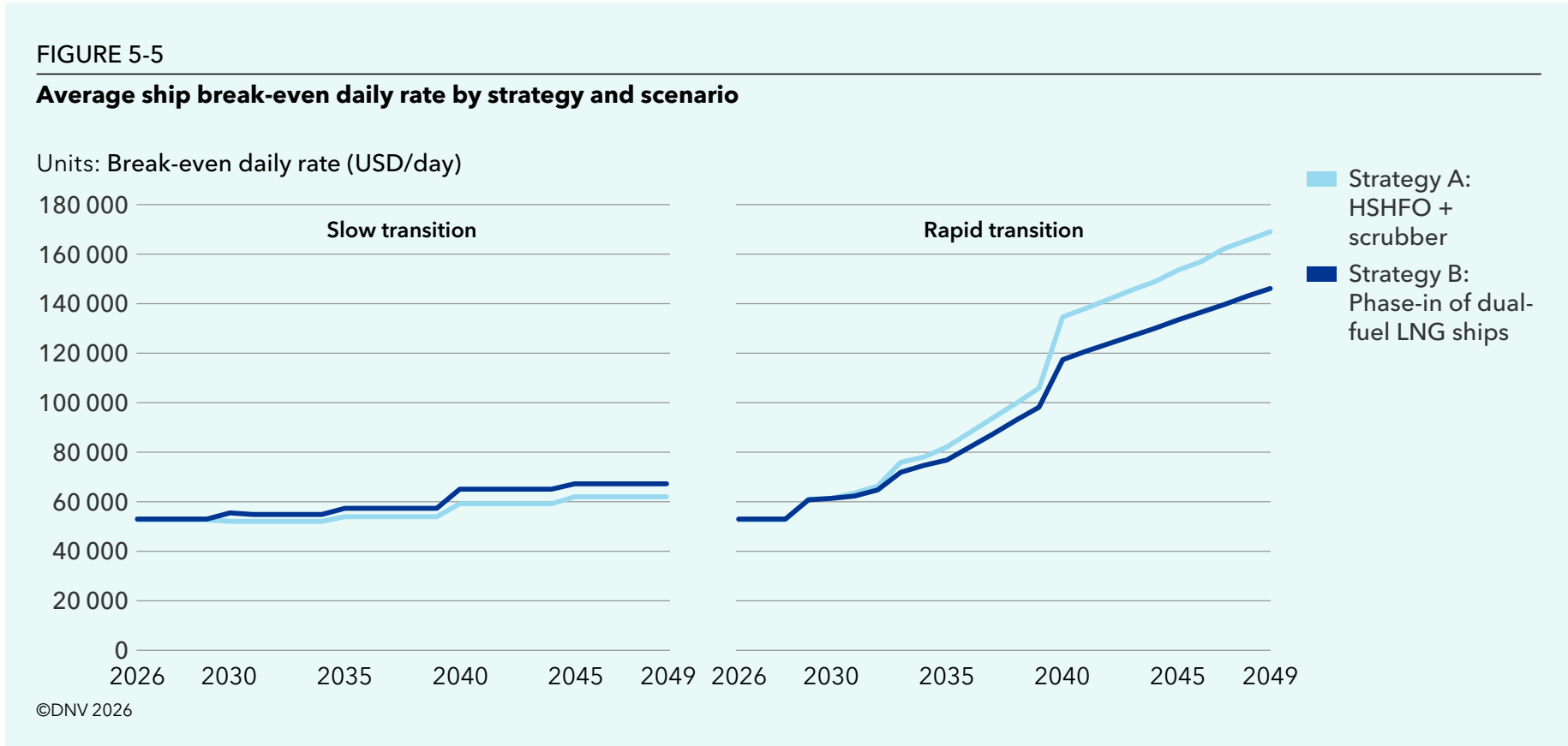


TABLE 5-1

Results from HAZID. Selected events are examples; many more could be identified and evaluated.

Category	Event	Cause	Impact	Scenario	Strategy A: HSHFO + scrubber			Strategy B: Phase-in of dual-fuel LNG ships		
					Probability	Consequence	Risk	Probability	Consequence	Risk
Fuel cost and compliance risk	Unable to bunker sufficient amount of low-GHG diesel (biodiesel / e-diesel)	Lack of availability or excessive prices in bunkering ports visited	Higher GHG compliance costs	Slow transition	1	1	Low	1	1	Low
				Rapid transition	2	3	High	2	2	Medium
	Unable to bunker sufficient amount of low-GHG methane (bio-methane / e-methane)	Lack of availability or excessive prices in bunkering ports visited	Higher GHG compliance costs	Slow transition				1	1	Low
				Rapid transition				2	2	Medium
	Unable to connect to shore power where mandated	Lack shore power equipment onboard ships	Limitations in trading area, potentially lower charter rate	Slow transition	2	2	Medium	1	2	Low
				Rapid transition	2	2	Medium	1	2	Low
	Unfavourable WtT GHG intensity factor assigned to LNG	Regulatory process	Reduced GHG intensity benefit from using LNG	Slow transition				1	1	Low
				Rapid transition				2	2	Medium
Operational risk	Damage to onboard machinery system	Off-spec bio-diesel bunkered, microbial growth in fuel	Shorter component lifetime, technical off-hire, lower chartering revenue	Slow transition	1	2	Low	1	2	Low
				Rapid transition	2	2	Medium	1	2	Low
	Challenges recruiting competent crew for dual-fuel ships	Shortage of competent crew	Higher crew wages	Slow transition	1	2	Low	2	2	Medium
				Rapid transition	1	2	Low	2	2	Medium
	Lack of available spare parts	Failure in fuel system components	Higher cost of spare parts. Technical off-hire	Slow transition	1	2	Low	2	2	Medium
				Rapid transition	1	2	Low	2	2	Medium
Charter risk	Ships are not competitive in the charter market	Charterer ESG policies exclude higher-emitting ships	Lower charter revenue	Slow transition	1	2	Low	1	2	Low
				Rapid transition	2	2	Medium	1	2	Low
Finance risk	Unable to secure financing for fleet and newbuilds	Focus of financial institutions on reduced carbon intensity	Higher capital costs	Slow transition	1	1	Low	1	1	Low
				Rapid transition	2	2	Medium	1	2	Low
	Diminishing second-hand value of ships in the fleet	Fleet is uncompetitive compared to competing fleet	Higher capital costs and low second-hand sales price	Slow transition	1	1	Low	2	1	Low
				Rapid transition	2	2	Medium	1	1	Low

and less severe. The risk of this event for Strategy B: Phase-in of dual-fuel LNG ships is less due to its lower reliance on low-GHG diesel. However, for this strategy, being unable to bunker low-GHG methane represents an almost equally high risk event. For Strategy A: HSHFO + scrubber, restrictions on open-loop scrubber use are also identified as a significant risk, as they could limit the use of HSHFO and force a switch to more expensive low-sulphur fuel variants, thereby increasing costs. The probability of such restrictions is higher in the Rapid transition scenario, although their severity is assessed as equally high in both scenarios.

There are multiple ways to help reduce either the probability or the consequence of the key risk events identified above. For example, when considering the risk of being unable to bunker low-GHG diesel, several measures can be implemented to mitigate this risk:

- Compliance pooling: By joining with other operators in a compliance pool, it is possible to collectively manage fuel availability and compliance obligations, thereby reducing individual exposure to supply shortages.
- Long-term offtake agreements at key bunkering hubs: Securing forward contracts for low-GHG fuels at major refuelling locations can improve certainty of supply and help ensure access to required volumes.
- Transferring GHG compliance cost liability to the charterer: Structuring agreements so that the responsibility for compliance costs lies with the

charterer can reduce financial exposure for ship-owners and operators.

- Proactive purchase of surplus compliance units: Entering into early agreements to acquire additional compliance units can provide a buffer against unforeseen shortfalls and support continuous regulatory compliance.

Evaluating total score

Cost and risk assessment outputs can be combined into an overall strategy score in several ways. One practical approach is to convert each strategy’s results under each scenario into standardized 1–5 scores, where 1 represents strong performance (lower cost

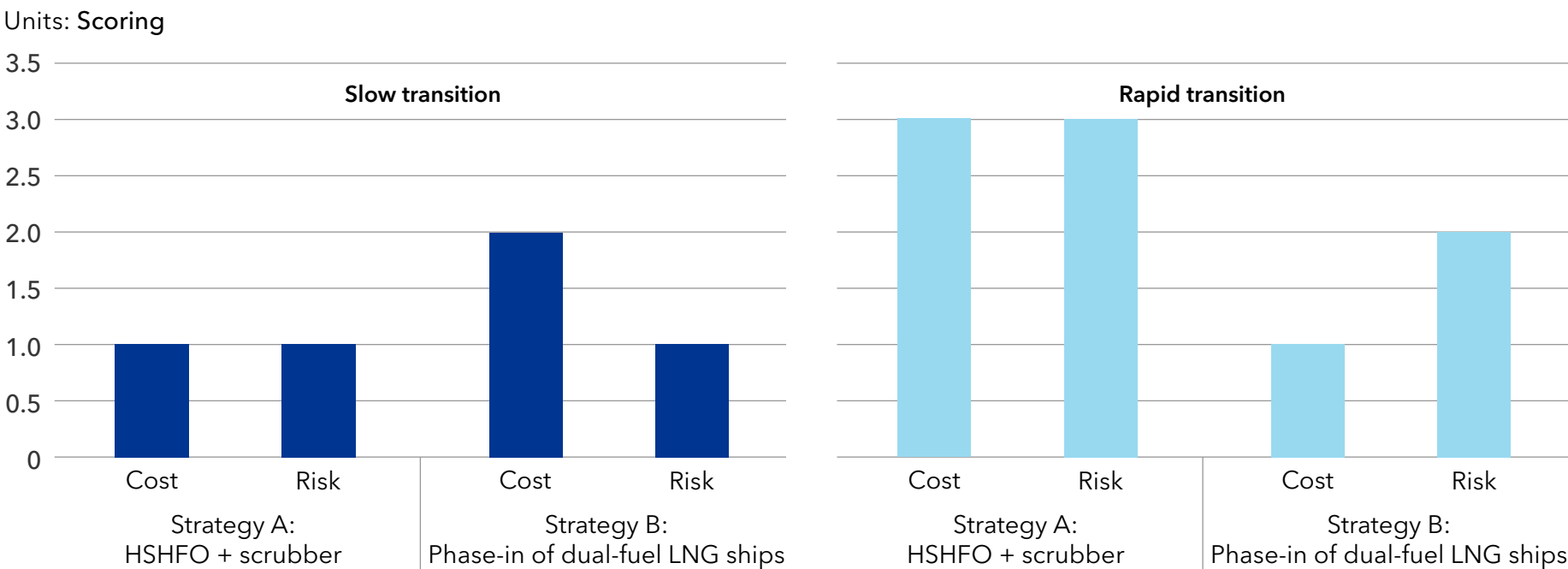
or lower risk) and 5 represents weak performance. For example, cost could be scored relative to the lowest-cost strategy in that scenario, while risk is scored based on the aggregated likelihood and impact of identified risks. Using a common 1–5 scale for both ensures they are directly comparable.

Figure 5-6 illustrates how this method works for Strategy A vs Strategy B under the Slow and Rapid transition scenarios.⁶⁰ Under Slow transition, both strategies have similar risk scores (indicating comparable risk levels), but Strategy B receives a higher cost score due to its higher costs. Under Rapid transition, the pattern reverses: Strategy A’s cost and risk scores are higher than Strategy B’s, indicating

Strategy A performs relatively worse on both dimensions under Rapid transition.

A single cost and risk score can be calculated for each strategy. Scenario likelihoods may be applied as weighting factors, allowing the framework to reflect different views of how the future may unfold (e.g. if Rapid transition is judged more likely than Slow transition, the overall score would give more weight to the Rapid scenario scores). This supports a structured comparison of strategies and makes the trade-offs between cost efficiency and exposure to transition risks explicit. The resulting total score provides a relative measure of each strategy’s robustness.

FIGURE 5-6
Assessed cost and risk score for Slow transition (left) and Rapid transition (right)



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APPENDIX A

Marine market for low-GHG fuels

Method for deriving potential supply and cost of low-GHG fuels

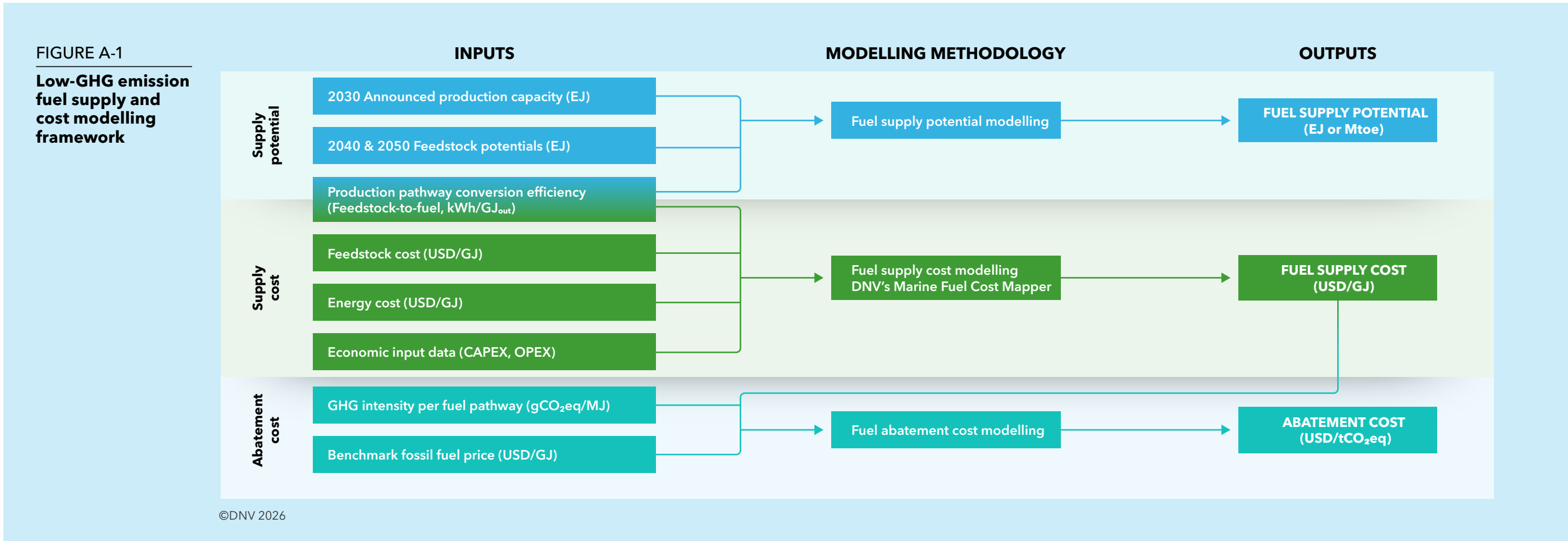
The overall method for estimating potential supply and abatement cost for each fuel pathway is illustrated in Figure A-1.

Fuel supply potential is estimated using different methods for short- and long-term horizons. For 2030, a project-based approach aggregates announced

and planned production capacities. Under this approach, fuel supply potential for each fuel pathway is derived from identified production projects, based on information compiled from industry reports and databases.⁶¹ It takes into account key project-level information, including technology pathway, project status, commissioning year, and planned capacity. We only include low-GHG hydrogen production projects relevant for the transportation sector. For

bio-methane and bio-diesel, we use projected production due to lack of data on production plants in the pipeline.

For 2040 and 2050, we derive the potential supply of biofuels primarily from DNV (2023a), using the average of low and high scenarios. These estimates are based on physical constraints on the availability of suitable feedstocks—such as



agricultural residues and municipal waste, taking into account economic boundary conditions and technical limitations.

This potential has been supplemented by projected biofuel production from sugarcane, maize, and vegetable oils from (OECD, 2025), as well as other sources (Clean Fuels, 2023) to consider all relevant feedstock sources.

Assumptions on conversion efficiencies (defined as feedstock energy input per unit of fuel energy output) and CO₂ input requirements (defined as CO₂ input per unit of fuel mass output) for carbon-containing e-fuels are aligned with those applied in DNV’s Marine Fuel Cost Mapper, which is also used for the fuel supply costs projection.

DNV’s Marine Fuel Cost Mapper models the full production and delivery chain. The general methodology of the model is described in the 2024 edition of DNV Maritime Forecast to 2050 (DNV, 2024b) and is continuously updated. In this year’s analysis, model inputs have been further refined by differentiating across individual feedstock categories and their corresponding cost assumptions based on several sources (DNV, 2025g; Fastmarkets, 2026a; Fastmarkets, 2026b; IEA, 2021; IMO, 2026; MESD CoE, 2022; MMMCZCS, 2024; SPHERA, 2024; World Bank Group, 2026).

Based on the resulting fuel supply costs, abatement costs are subsequently derived by combining supply cost outputs with low-GHG fuel GFI values from regulatory and industry sources (EBA, 2024; EUC, 2024; IFEU, 2022; MMMCZCS, 2022). See page 44 for abatement cost formula. The analysis provides a structured supply-side assessment and is not intended to forecast actual market outcomes.

Input assumptions for the GHG Pathway Model

The model is populated with the global fleet of ships above 400 GT that operate internationally based on AIS data for 2025. The model simulates the fleet development and fuel and technology uptake year by year, selecting the options with lowest net present value based on inputs such as regulations, seaborne trade growth, fuel emission factors and fuel and technology prices.

The seaborne trade growth from 2025 to 2050 is shown in Table A-1.

The aim of the simulation is not to assess the uptake of individual fuel types – but to estimate the overall demand for low-GHG fuels. Because of this, a reduced set of fuels and technologies are included in the model, along with energy-efficiency measures and speed reduction as other abatement options. We have not included abatement technologies such as onboard carbon capture and nuclear propulsion.

We use fuel prices derived from DNV’s Marine Fuel Cost Mapper (DNV, 2024b). Over the period 2025 to 2050, the assumed fossil fuel prices range from about 300 to 590 USD/toe, while low-GHG fuel prices range from about 1,100 to 2,200 USD/toe. These price assumptions are used as a starting point for deriving total low-GHG fuel demand and therefore do not align with the detailed supply costs for individual fuel pathways presented in Section 4.2. Higher assumed prices for low-GHG fuels primarily lead to greater uptake of energy-efficiency measures, which in turn reduce total demand for low-GHG fuels.

Low-GHG fuels are assumed to have a WtW GHG intensity of 15 gCO₂eq/MJ in the period 2025 to 2040, and then a linear decline to 0 gCO₂eq/MJ from 2041 to 2050. This assumption is due to a modelling constraint, and made so that the fleet can reach the assumed base target under IMO NZF in 2050. The fuel GHG intensities and regulatory requirements closer towards 2050 are highly uncertain.

All other assumptions, including the cost of fuel technologies and energy-efficiency measures, are as described in the Comprehensive Impact assessment of IMO’s mid-term GHG reduction measures (DNV, 2024a).

TABLE A-1
Seaborne trade growth based on DNV’s Energy Transition Outlook 2025 (DNV, 2025g)

Maritime transport segment	Growth 2025-2030 (% tonne-miles)	Growth 2031-2040 (% tonne-miles)	Growth 2041-2050 (% tonne-miles)
Crude oil tanker	14%	-16%	-24%
Oil products tanker	2%	-17%	-12%
Gas carrier	28%	28%	-19%
Bulk carrier	3%	-4%	-1%
Containership	13%	13%	9%
Other cargo vessels	12%	7%	3%

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APPENDIX B

VLCC fleet case assumptions

Key input assumptions

Below, we outline key input assumptions applied for the illustrative VLCC fleet example in Chapter 5. All cost modelling was carried out using DNV’s FuelPath model. Table B-1 shows the assumed low-GHG fuel price assumptions used for both the ‘Slow transition’ and ‘Rapid transition’ scenarios, while Table B-2 indicates the assumed GHG intensity per fuel type.

In Table B-3, we provide main assumptions on applicable regulations, EU Carbon Permits Allowance (EUA) prices, and Tier 2 RU costs by scenario.⁶²

We apply newbuild prices as of the two years before the year of delivery for each vessel, based on Clarksons Research newbuild price assessment for VLCCs. We assume that the base newbuild cost for

TABLE B-1
Low-GHG fuel price assumptions by scenario (USD/GJ), based on DNV’s Marine Fuel Cost Mapper

Scenario	Fuel	2026	2030	2040	2050
Scenario I: Slow transition	Low-GHG diesel	44	44	44	44
	Low-GHG methane	38	38	38	38
	LNG	11	11	11	11
	HSHFO	9	9	9	9
	LSHFO	12	12	12	12
Scenario II: Rapid transition	Low-GHG diesel	44	44	79	71
	Low-GHG methane	38	38	60	56
	LNG	11	11	11	11
	HSHFO	9	9	9	9
	LSHFO	12	12	12	12

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TABLE B-2
GHG intensity of each relevant fuel type

Maritime transport segment	GHG intensity by regulations (gCO ₂ eq per MJ)		
	EU ETS (TtW)	FuelEU Maritime (WtW)	IMO NZF (WtW)
Low-GHG diesel	1	18	18
Low-GHG methane	4	19	19
LNG	59	77	78
HSHFO	78	92	93
LSHFO	78	92	95

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TABLE B-3
Assumptions on applicable regulations, EUA prices, and Tier 2 RU costs by scenario

Scenario	Applicable regulations	EUA price assumptions	Tier 2 RU cost assumption
Slow transition	FuelEU Maritime and EU ETS	Constant at 89 USD/EUA, representative of the price as of April 2026 ⁶²	Not applicable
Rapid transition	FuelEU Maritime, EU ETS, and IMO NZF (from 2029)	Increases gradually from 89 USD/EUA in 2026 to 229 USD/EUA in 2049, in line with DNV’s Energy Transition Outlook study (DNV, 2025f)	2029-2032: 380 USD/RU 2033-2039: 500 USD/RU From 2040: 700 USD/RU

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all future newbuilds is about USD 130 million (representative of current prices as of Q1 2026). Dual-fuel LNG VLCCs are assumed to have an additional CAPEX of USD 20 million.

Assumed annual fuel consumption of each VLCC varies from 12,300-17,900 toe depending on strategy (and associated energy-efficiency measures) and year of newbuild.

Capital costs for energy-efficiency measures, implemented at the newbuild stage or retrofit ‘Phase-in of dual-fuel LNG ships strategy’, are based on DNV’s Abatement Insight database.

Non-fuel OPEX costs for VLCCs, covering manning, insurance, lubricating oils, etc., are based on data from (Drewry, 2024).

Seaspan Energy conducts ship-to-ship LNG bunkering in the Port of Vancouver.



REFERENCES

Africa Sovereign Carbon Registry Foundation. (2026). *Sovereign Carbon Initiatives*. <https://asc-registry.org/en>

BCG. (2025). *Beyond shipping: How other sectors will fuel maritime decarbonization*. Boston Consulting Group. <https://www.bcg.com/publications/2025/how-other-sectors-will-fuel-maritime-decarbonization>

Clean Fuels. (2023). *UCO Supply Outlook*.
https://cleanfuels.org/wp-content/uploads/GlobalData_UCO-Supply-Outlook_Sep2023.pdf

Department for Energy Security & Net Zero.
(2025). *UK ETS scope expansion: domestic maritime - main Authority response*. <https://www.gov.uk/government/consultations/uk-ets-scope-expansion-maritime-sector/outcome/uk-ets-scope-expansion-domestic-maritime-main-authority-response-accessible-webpage>

DNV. (2018). *Maritime Forecast to 2050 - Energy Transition Outlook 2018*. <https://www.dnv.com/maritime/maritime-forecast/>

DNV. (2021). *Maritime Forecast to 2050 - Energy Transition Outlook 2021*. <https://www.dnv.com/maritime/maritime-forecast>

DNV. (2023a). *Exploring the potential of biofuels in shipping*. <https://www.dnv.com/expert-story/maritime-impact/Exploring-the-potential-of-biofuels-in-shipping>

DNV. (2023b). *Pathway to Net Zero Emissions*. <https://www.dnv.com/publications/pathway-to-net-zero-emissions-report-2023-249543>

DNV. (2024a). *Comprehensive impact assessment of the basket of candidate mid-term GHG reduction measures – Task 2: Assessment of impacts on the fleet, work for IMO, Final report. DNV Report no 2024- 1567 - Rev. 2.*

DNV. (2024b). *Maritime Forecast to 2050 - Energy Transition Outlook 2024*. <https://www.dnv.com/maritime/maritime-forecast>

DNV. (2024c). *White Paper. The Potential of Onboard Carbon Capture in Shipping*. <https://www.dnv.com/maritime/publications/the-potential-of-onboard-carbon-capture-in-shipping-download>

DNV. (2025a). *Maritime Forecast to 2050 – Energy Transition Outlook 2025*. <https://www.dnv.com/maritime/maritime-forecast>

DNV. (2025b). *White Paper. Energy-efficiency measures and technologies*. www.dnv.com/maritime/publications/energy-efficiency-report-download

DNV. (2025c). *White Paper. Wind-assisted propulsion systems (WAPS): How WAPS can help to comply with GHG regulations.*

www.dnv.com/maritime/publications/waps-white-paper-download

DNV. (2025d). *White Paper. Methanol Fuel in Shipping. Barriers and pathways to low-GHG methanol as a marine fuel.*

<https://www.dnv.com/maritime/publications/methanol-fuel-in-shipping-download>

DNV. (2025e). *White Paper. Biofuels in Shipping. Current market and guidance on use and reporting.*

<https://www.dnv.com/maritime/publications/biofuels-in-shipping-white-paper-2025-download>

DNV. (2025f). *White Paper. Safe Introduction of Alternative Fuels: Focus on ammonia and hydrogen as ship fuels.*

<https://www.dnv.com/maritime/publications/safe-introduction-of-alternative-fuels-focus-on-ammonia-and-hydrogen-as-ship-fuels-download>

DNV. (2025g). *Energy Transition Outlook* 2025. <https://www.dnv.com/energy-transition-outlook>

DNV. (2025h). *White Paper. Maritime Nuclear Propulsion - Technologies, commercial viability, and regulatory challenges for nuclear-powered vessels*. <https://www.dnv.com/maritime/publications/maritime-nuclear-propulsion-download>

DNV. (2025i). *White Paper. Ammonia in Shipping. Tracing the emergence of a new fuel.* <https://www.dnv.com/publications/ammonia-in-shipping-white-paper>

DNV. (2026a). DNV Energy Transition Outlook 2026 – Hydrogen to 2060. <https://www.dnv.com/energy-transition-outlook/hydrogen/download>

DNV. (2026b). *Energy Transition Outlook 2026* (forthcoming). <https://www.dnv.com/energy-transition-outlook/>

DNV. (2026c). *White Paper. Methane in Shipping. LNG-fuelled ships and the switch to low-GHG methane*. www.dnv.com/publications/methane-in-shipping

DNV. (2026d). *White Paper. Shore Power in Shipping. Technology, regulation and implementation*. <https://www.dnv.com/maritime/publications/shore-power-in-shipping-download>

DNV. (2026e). *CO₂ Abatement Potential from OCCS Application on Vessels of Five Container Liners on the North Europe-Asia Corridor*, Document no.: 2025.260. www.portofrotterdam.com/sites/default/files/2026-02/DNV-Liners-OCCS-Report.pdf

Drewry. (2024). *Ship Operating Costs - Annual Review and Forecast*. Drewry.

EBA. (2024). *Biomethane for emission abatement by 2040*. https://www.europe-anbiogas.eu/wp-content/uploads/2025/06/Common-Futures_Biomethane-for-emission-abatement-by-2040.pdf

EMSA. (2026). *Onboard Carbon Capture and Storage Systems Study*, European Maritime Safety Agency, Lisbon. www.emsa.europa.eu/publications/item/5634-onboard-carbon-capture-technologies.html

EUC. (2024). *EU Renewable energy directive*.
<https://eur-lex.europa.eu/eli/dir/2018/2001/oj/eng>

EUC. (2025). *A renewed agenda for European Union – United Kingdom cooperation Common Understanding*. https://ec.europa.eu/commission/presscorner/detail/en/statement_25_1267

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EUC. (2026). *EU Industrial Maritime Strategy*. COM(2026) 111 final. https://transport.ec.europa.eu/news-events/news/commis-sion-launches-industrial-maritime-strat-egy-competitive-sustainable-and-resil-ient-eu-maritime-2026-03-04_en

Fastmarkets. (2026a). *Soybean oil prices*. <https://www.fastmarkets.com/agriculture/veg-oils-and-meals/soybean-oil-prices>

Fastmarkets. (2026b). *Used cooking oil prices*. <https://www.fastmarkets.com/agri-culture/biofuels-and-feedstocks/used-cook-ing-oil-prices>

GMF. (2026). *The human side of operational efficiency in shipping*. Global Maritime Forum (GMF). <https://globalmaritimeforum.org/report/the-human-side-of-operational-effi-ciency-in-shipping>

Hupka, Y., Popova, I., Simkins, B., & Lee, T. (2023). *A review of the literature on LNG: Hubs development, market integration, and price discovery*. Journal of Commodity Markets, 31, 100349.

ICAP. (2025). *Status Report 2025: June Update*. International Carbon Action Part-nership. <https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-icap-status-report-2025>

IEA. (2021). *Global Assessment of Direct Air Capture Costs*. <https://ieaghg.org/publications/2021-05%20Global%20Assessment%20of%20Direct%20Air%20Capture%20Costs.pdf>

IEA. (2025a). *World Energy Outlook*. Interna-tional Energy Agency. <https://www.iea.org/reports/world-energy-outlook-2025>

IEA. (2025b). *Renewable Energy Progress Tracker*. <https://www.iea.org/data-and-sta-tistics/data-tools/renewable-energy-pro-gress-tracker#overview>

IEA. (2025c). *Outlook for Biogas and Bio-methane - a global geospatial assessment*. Paris: IEA. <https://www.iea.org/reports/outlook-for-biogas-and-biomethane>

IFEU. (2022). *Biomethane in Europe*. https://www.ifeu.de/fileadmin/uploads/ifeu_ECF_biomethane_EU_final_01.pdf

IMO. (2020). MEPC 76/6/1, Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2019).

IMO. (2021). MEPC 77/6/1, Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2020).

IMO. (2022a). *Just-in-time arrival: Emissions reduction potential in global container shipping*. IMO GreenVoyage2050 Programme.

IMO. (2022b). MEPC 79/6/1, Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2021).

IMO. (2023). MEPC 81/6, Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2022).

IMO. (2024). MEPC 82/6/38. Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2023).

IMO. (2025). MEPC 84/6/1. Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2024).

IMO. (2026). MEPC 84/7/16 - Report of the third meeting of GESAMP-LCA Working Group.

IRENA. (2024). *World Energy Transitions Outlook 2024: 1.5°C Pathway*.

Kanchiralla, F.M. et al. (2026). *Marine fuel choices and related life-cycle environmental impacts under global shipping policies*. Nature Energy.

Kramel, D. et al. (2026). *Maritime sector pathways toward net-zero emissions within global energy scenarios*. Nature Energy.

Longva, T., Eide, M. S., Endresen, Ø., Sekkesæter, Ø., Helgesen, H., & Rivedal, N. H. (2024). *Marginal abatement cost curves for CO₂ emission reduction from shipping to 2050*, Maritime Transport Research, Volume 6, 2024, 100112, ISSN 2666-822X. <https://doi.org/10.1016/j.martra.2024.100112>

MESD CoE. (2022). *Role of bio-LNG in shipping industry decarbonisation*. https://safety4sea.com/wp-content/uploads/2022/10/Sea-LNG-Role-of-bio-LNG-in-shipping-industry-decarboni-sation-2022_10.pdf

MMMCZCS. (2022). *Navigate WtW Position Paper*. <https://www.zerocarbon-shipping.com/files/navigate-wtw-postion-paper.pdf>

MMMCZCS. (2024). *Biogas as a Source of Biofuels for Shipping*. https://www.zerocar-bonshipping.com/files/biogas-as-a-source-of-biofuels-for-shipping_5 techno-econom-ic-trends.pdf

MMMCZCS. (2026). *Countdown: The fuel supply waiting for a market*: <https://www.zerocarbonshipping.com/news/countdown-the-fuel-supply-waiting-for-a-market>

Nordic Roadmap. (2024). *Fuel Transition Roadmap for Nordic Shipping*. https://futurefuelsnordic.com/wp-content/uploads/2024/12/Fuel-Transition-Roadmap-for-Nordic-Shipping_Dec2024.pdf

OECD. (2025). *OECD-FAO AGRICULTURAL OUTLOOK 2025-2034 Statistical Data*. https://www.oecd.org/content/dam/oecd/en/publications/support-materials/2025/07/oecd-fao-agricultural-outlook-2025-2034_3eb15914/statistical-data-2025.pdf

Rehmatulla, N., & Smith, T. (2015). *Barriers to energy efficiency in shipping: A triangulated approach to investigate the principal agent problem*. <https://www.sciencedirect.com/science/article/pii/S030142151500169X>

Ricardo & DNV. (2023). *Study on the read-iness and availability of low- and zero-carbon ship technology and marine fuels*. <http://futurefuels.imo.org>

Seas at Risk. (2026). *A Global Fleet Under Wind: Scaling Wind Propulsion for Emission Reduction, Energy Demand and Equity*. https://seas-at-risk.org/wp-content/uploads/2024/09/A-global-Fleet-Un-der-Wind_Seas_At_Risk-1.pdf

SPHERA. (2024). *1st Life Cycle GHG Emission Study on the Use of Ammonia as Marine Fuel*. <https://sphaera.com/resources/report/1st-life-cycle-ghg-emission-study-on-the-use-of-ammonia-as-marine-fuel>

UCL & UMAS. (2024). *Port congestion, waiting times and operational efficiency*. UCL Energy Institute & UMAS.

World Bank. (2025). *Keys to Energy-Efficient Shipping*. <http://hdl.handle.net/10986/43773>
License: CC BY-NC 3.0 IGO.

World Bank Group. (2026). *Commodity Markets*. <https://www.worldbank.org/en/research/commodity-markets>

ZEMBA. (2026). *RFP 2*. <https://www.ship-zemba.org/how-we-work/rfp-2>

ENDNOTES

- 1

For details on the MEPC 84 deliberations, see the MEPC 84 meeting report, available from IMODOCS at <https://webaccounts.imo.org>
- 2

IMO Resolution MEPC.377(80), 2023 IMO Strategy on Reduction of GHG Emissions from Ships. Available from: <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf>
- 3

Read more at: <https://www.dnv.com/news/2026/imo-mepc-84-revisiting-the-net-zero-framework>
- 4

Read more at: <https://www.zerocarbonshipping.com/news/countdown-what-did-we-learn-from-the-first-year-of-fue-leu>
- 5

Information provided by the European Commission in a presentation to the European Sustainable Shipping Forum on 19 May 2026.
- 6

See more details from Hecla at: [https://www.hecla-em.com/blog/compliance-market-indicator-\(cmi\)-week-22](https://www.hecla-em.com/blog/compliance-market-indicator-(cmi)-week-22)
- 7

See for example: <https://et-fuels.com/article-rfocean-secures-e-methanol-from-etfuels>
- 8

Read more at: [Zero-Emission Requirements for Passenger Ships in World Heritage Fjords - regjeringen.no](#)
- 9

Read more at: [Fra 1. januar blir det nullutslippskrav i offentlige anskaffelser](#)
- 10

Read more at: [Innfører klimakrav til offshorefartøy - regjeringen.no](#) (in Norwegian)
- 11

Read more at: <https://icapcarbonaction.com/en/ets/turkish-emission-trading-system>
- 12

Read more at: <https://icapcarbonaction.com/en/ets/china-shanghai-pilot-ets>
- 13

Read more at: <https://icapcarbonaction.com/en/ets/korea-emissions-trading-system-k-ets>
- 14

Read more at: <https://icapcarbonaction.com/en/ets/brazilian-green-house-gas-emissions-trading-system>
- 15

Read more at: <https://north-standard.com/insights-and-resources/resources/archive/articles/china-msa-regulation-on-ship-energy-consumption-data-and-carbon-intensity-management-measures-effective-from-22-dec-2022-valid-for-5-years-4829>
- 16

For more information from the Maritime Safety Administration of the People's Republic of China, see: <https://www.msa.gov.cn/html/cnmsa/xxgk/article/2026/b096e4423f2947cab0db-94c383b95c97.html?hav=1JnAGGcEugnOhbjbyC> (in Chinese)
- 17

Read more at: https://transport.ec.europa.eu/transport-themes/clean-transport/sustainable-transport-investment-plan_en
- 18

Read more at: https://transport.ec.europa.eu/transport-themes/clean-transport/alternative-fuels-sustainable-mobility-europe/alternative-fuels-infrastructure_en
- 19

Read more at: https://www.gov.cn/gongbao/2025/issue_12406/202511/content_7048917.html (in Chinese)
- 20

Read more at: <https://www.irs.gov/inflation-reduction-act-of-2022>
- 21

See, for example, Boston Consulting Group (BCG), The \$10 Billion Opportunity in Green Shipping, available at: <https://www.bcg.com/publications/2025/the-10-billion-opportunity-in-green-shipping>
- 22

Based on average low sulphur heavy fuel oil (LSHFO) prices in Singapore from 1 January 2024 to 30 April 2026
- 23

Based on vessel-level data from Clarksons Research, World Fleet Register
- 24

See example from MSC: <https://www.msc.com/en/newsroom/press-releases/2024/msc-sustainability-report-highlights-alignment-of-new-operations-and-achievement-of-key-milestones>
- 25

See example from Maersk: <https://www.maersk.com/news/articles/2025/10/02/maersk-rolls-out-efficiency-programme-for-its-time-chartered-fleet>
- 26

See example for Hapag-Lloyd: <https://www.dnv.com/expert-story/maritime-impact/hapag-lloyd-tackles-huge-fleet-upgrade-programme-with-dnv-support>
- 27

Read more at: <https://smartmaritimework.com/2026/03/20/hapag-lloyd-reports-5-fuel-saving-through-engine-optimisation>
- 28

See for example: https://www.renewableenergymagazine.com/energy_saving/dnv-study-validates-energy-efficiency-gains-for-20240212
- 29

Read more at: <https://www.iea.org/reports/assessing-emissions-from-lng-supply-and-abatement-options>
- 30

See example from Wallenius Wilhelmsen: <https://www.walleniuswilhelmsen.com/insights/our-new-shaper-class-vessels-pave-the-way-for-our-journey-to-near-zero>
- 31

See example from Höegh Autoliners: <https://www.offshore-energy.biz/hoegh-autoliners-taps-kongsberg-for-propulsion-upgrade-of-10-pctcs>
- 32

Read more at: <https://cruising.org/news/cruise-lines-international-association-clia-releases-annual-environmental-technologies#:~:text=Uptake%20of%20alternative,%20zero-%20and,-fleet%20and%2065%25%20of%20capacity>
- 33

See for example: <https://www.seatrade-maritime.com/dry-bulk/shandong-shipping-orders-10-methanol-fuelled-vlocs>
- 34

Read more at: <https://www.dnv.com/expert-story/maritime-impact/maximizing-energy-efficiency-in-the-tanker-segment/#:~:text=at%20optimum%20loads-,%E2%80%A2,by%20large-angle%20rudder%20movements>
- 35

Numbers on uptake in the fleet (*AFI*) include all sail systems except the kite, onboard vessels above 500 GT. Furthermore, since some early WAPS pilot cases and prototypes may have been uninstalled from the vessels, the projects listed are all verified by DNV to have the WAPS system installed today. Because the verification is challenging with kites, this system is excluded from the overview.

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36	It should be noted that the fleet and order book data originate from two different sources. Because the order book is not known down to ship name level, there is a risk that some vessels and installations may appear in in both if, for example, an installation is happening in the near future. The order book numbers presented are, however, providing a good indication of the order of magnitude of future installations, which gives important insights into the market's position towards WAPS technologies.	42	Read more at: https://mykn.kuehne-nagel.com/news/article/hapagllloyd-studies-windassisted-propulsion-fo-11-Nov-2024	48	Read more at: https://incat.com.au/history-made-as-worlds-largest-battery-electric-ship-powers-up				
37	Read more at: https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fuel-maritime/questions-and-answers-regulation-eu-20231805-use-renewable-and-low-carbon-fuels-maritime-transport-en	43	See for example: https://www.oceanwings.com/product/ow-re-rigid-elevator-wingsail	49	Read more at: https://www.buquebus.com/info/buque-electrico				
38	See for example: https://www.seatrade-maritime.com/wind-powered-ships/regulations-and-shipowner-experience-driving-wind-power-adoption	44	Read more at: https://www.dnv.com/news/2025/Rapid-WAPS-uptake-driven-by-stricter-emission-regulations-and-industry-innovation	50	Read more at: https://interestingengineering.com/innovation/vision-battery-electric-cruise-concept				
39	DNV AFI, https://afi.dnv.com , accessed August 2026	45	See for example: https://www.rivieramm.com/news-content-hub/rotor-sail-leasing-initiative-aims-to-improve-access-to-wind-assisted-power-78375	51	The annual utilization rate is calculated based on reported LNG consumption from DCS data (IMO, 2020; IMO, 2021; IMO, 2022b; IMO, 2023; IMO, 2024; IMO, 2025), divided by the theoretical maximum LNG consumption if the vessels operated in gas mode continuously, using data from DNV's AFI platform.				
40	Clarksons Research, World Fleet Register, accessed August 2026	46	In operation: Only ships over 100 GT are included. Only ships delivered in 1980 or later are included (this is the same cut-off year as in the previous two Maritime Forecasts). All ship types except naval vessels are included. On order: Only ships over 100 GT are included. Only ships contracted in 2017 or later are included (in the previous two Maritime Forecasts, we used 2016 and 2015 as cut-offs). All ship types except naval vessels are included. To avoid double counting, and as in the two previous Maritime Forecasts, alternative fuel ships on order do not include retrofit projects to avoid double counting (same as in the previous two years).	52	The annual utilization rate is calculated based on reported methanol consumption from DCS data (IMO, 2020; IMO, 2021; IMO, 2022b; IMO, 2023; IMO, 2024; IMO, 2025), divided by the theoretical maximum methanol consumption if the vessels operated in methanol mode continuously, using data from DNV's AFI platform.				
41	Read more at: https://anemoimarine.com/successful-installation-of-anemoi-rotor-sails-on-u-mings-grand-pioneer-vloc-at-cosco-zhoushan-shipyard	47	DNV AFI, https://afi.dnv.com , accessed August 2026	53	Based on DNV's Alternative Fuels Insight platform (https://afi.dnv.com), IEA Renewable Energy Progress Tracker (https://www.iea.org/data-and-statistics/data-tools/renewable-energy-progress-tracker), e-NG Coalition (https://www.eng-coalition.org/news/first-global-project-map-of-electric-natural-gas-facilities), and IEA's Gas 2025 report (https://www.iea.org/reports/gas-2025). For hydrogen, we only include an assumed share of 10% relevant for the mobility sector, derived from IEA's Hydrogen Production and Infrastructure Projects Database (https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database#hydrogen-production-projects).				
				54	According to the Renewable Energy Progress Tracker, approximately 0.7 Mtoe of FAME biofuel was consumed by ships in 2024. In contrast, the IMO reports around 1.2 Mtoe of the bio-blended fuel consumption, although the specific blend compositions are not specified (IMO, 2025)				
				55	TCO includes capital, operational, fuel and regulatory expenses for the ship over a 20-year period from 2029 to 2048.				
				56	Read more at: https://www.fsb-tcfd.org				
				57	A HAZID (Hazard Identification) is a structured, qualitative risk assessment method used to systematically identify potential hazards and their causes, consequences, and safeguards in a system or operation.				
				58	The owner manages ownership, technical operations, crewing, and commercial activities in-house.				
				59	We assume 20% of fuel energy use is on voyages from/to EU ports, implying about 10% of total fuel consumption and GHG emissions fall within the scope of EU ETS and FuelEU Maritime.				
				60	Score-setting is based on (i) cost, expressed as the fleet-average break-even daily rate relative to the lowest-cost strategy among those assessed, and (ii) risk, represented by an index averaged across the scenario and strategy. Cost scores are defined as follows: 1 = 100-104%; 2 = 104.1-110.0%; 3 = 110.1-120.0%; 4 = 120.1-150.0%; and 5 = >150.0%. Risk scores are defined on an index scale: 1 = 1.00-1.39; 2 = 1.40-1.79; 3 = 1.80-2.19; 4 = 2.20-2.59; and 5 = 2.60-3.00. Individual risk events are assigned scores of 1 (low), 2 (medium), or 3 (high), and aggregated by averaging across the relevant scenario and strategy.				
				61	Based on DNV Alternative Fuels Insight platform (https://afi.dnv.com), IEA Renewable Energy Progress Tracker (https://www.iea.org/data-and-statistics/data-tools/renewable-energy-progress-tracker), e-NG Coalition (https://www.eng-coalition.org/news/first-global-project-map-of-electric-natural-gas-facilities), IEA Gas 2025 report (https://www.iea.org/reports/gas-2025), and SIA Observatoire international des e-fuels 2025 (https://www.sia-partners.com/system/files/document_download/file/2025-04/2025_Observatoire_international_e-fuels.pdf).				
				62	For more data on historic price developments for EU emission allowances, see https://tradingeconomics.com/commodity/carbon				

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