WHEN TRUST MATTERS

Energy Transition Outlook 2025

MARITIME FORECAST TO 2050

A deep dive into shipping's decarbonization journey

FOREWORD

Shipping's transformation is underway, powered by innovation, collaboration, and purpose

Maritime decarbonization continues to define our time. With global regulations gaining momentum and industry commitment accelerating, the pathway to net zero is no longer theoretical, it's unfolding in real time. The challenges are complex, but the direction is clear, and the pace of innovation, investment, and collaboration is picking up across certain parts of the value chain.

Earlier in 2025, the IMO took a momentous step by approving in principle what may become the most impactful global regulation in any industry – the Net-Zero Framework (NZF) for shipping. Building on the ambitions laid out in the 2023 IMO GHG Strategy, the NZF introduces the first global pricing mechanism for greenhouse gas emissions, alongside technical requirements for well-to-wake GHG intensity.

If adopted in October, this regulation will reshape investment decisions, operational strategies, and fuel choices across the industry, and this year's Maritime Forecast to 2050 highlights and analyses its potentially transformative impact.

The framework, while groundbreaking, is not without its imperfections, and urgently needs clarity across several key areas to ensure that all pathways to decarbonization are properly recognized and rewarded. The coming year will be pivotal as the IMO starts laying the groundwork for the supporting guidelines which will determine how effectively the framework can be implemented.

Crucially, the calculation method for the greenhouse gas fuel intensity (GFI) must be finalized to avoid inconsistencies and ensure comparability across fuel types. Life Cycle Assessment (LCA) guidelines, including well-to-tank (WtT) values for fossil LNG and other fuels, are essential to ensure that those who are making real strides towards emissions reductions today are rewarded and not penalized.

The emergence of low-GHG fuels can also be facilitated by practical and sensible guidelines around the sustainable fuels certification framework. Without a harmonized and credible system, the market for low- and zero-emission fuels will struggle to scale. The adoption of flexible Chain of Custody models can allow for the distribution of green fuels together with fossil fuels, removing the need for extra pipelines and infrastructure, potentially saving millions in CAPEX investments while reducing emissions.

More broadly, the reward mechanism for zero and near-zero (ZNZ) fuels, and for emission- and energy-saving technologies, should be clarified to incentivize innovation and early adoption. Governance and spending mechanisms must be defined to build trust in how revenues from the IMO Net-Zero Fund are managed and reinvested back into the industry to accelerate the transition.

As shown in this year's Maritime Forecast to 2050, there is no silver bullet for decarbonization, and a wide and diverse number of technological and operational pathways lie in front of us. While our natural instincts may compel us to seek the best singular solution, it is crucial that we embrace this diversity.

These solutions are not in competition – they are complementary. Maritime decarbonization demands a portfolio approach, where low-GHG fuels, energy efficiency, onboard carbon capture, and digital optimization work together to reduce emissions.

Significant progress has already been made and there is much to celebrate, particularly on the technology transition.

Drawing on insights from DNV's Alternative Fuels Insight database, this year's report shows how the number of vessels on order with alternative fuel capability is set to more than double by 2028, leading us to conclude that the old 'chicken-and-egg' dilemma – whether ships or fuels should come first – no longer applies.

By 2030, the alternative-fuelled fleet will be capable of consuming around 50 million tonnes of oil equivalent (Mtoe) of non-oil fuels annually. While this is still short of the total fleet consumption of 280 Mtoe per year, it is a remarkable achievement in a short time.

This progress shifts the spotlight to fuel producers. To meet the IMO's 2030 target of a 20% emissions reduction, shipping will need access to around 25 Mtoe of low-GHG fuels annually. This represents roughly a quarter to a third of the total projected global supply of 70–100 Mtoe of low-GHG fuels by 2030, highlighting the intense competition shipping will face from other sectors also racing to decarbonize.

The fuel transition will take time and while we hope that green versions of fuels such as methanol, LNG, hydrogen, and ammonia will eventually power a carbon-neutral fleet in the future, other avenues to emissions reductions must be explored in the meantime. This includes energy-efficiency measures, where a wide range of solutions can already be applied to ships, at relatively low cost, delivering emissions reductions today.

Great strides are being made in wind-assisted propulsion systems, and several pilot and third-party verification projects are already underway in 2025 to quantify their benefits. If successful, we could see a surge in their uptake, representing a breakthrough for sustainable shipping.

Onboard carbon capture is also growing in prominence. Research from this year's report shows that retrofitting this technology to the largest containers, bulkers, and tankers in the global fleet is feasible, with space requirements similar to a standard LNG fuel tank. If this is allayed with the development of CO_2 offloading infrastructure at 20 of the world's largest ports, emissions from these vessels could be reduced by 19%, equivalent to a 9% reduction in total fleet emissions.

We are still putting the pieces of this puzzle together. Progress isn't linear. It's built on innovation, lessons learned, collaboration, and relentless improvement. We each have a role to play and engagement and collaboration across all fronts are critical.

Let's keep working together and continue to move forward.

Knut Ørbeck-Nilssen
CEO Maritime
DNV

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1 EXECUTIVE SUMMARY

Maritime Forecast to 2050 is one out of DNV's suite of Energy Transition Outlook reports. With this latest edition we aim to improve our understanding of the International Maritime Organization's (IMO) Net-Zero Framework (NZF) and its implications, and to provide fresh insight into the status of the maritime fuel transition today – onboard and onshore.

The stage is set. The IMO has approved – but not yet adopted – the NZF and is heading towards implementation of the first ever global pricing mechanism for GHG emissions. Even as projects for the production of low-GHG fuels are facing headwinds, the shipping industry is moving forward. LNG- and methanol-capable ships are crowding the order book, while ammonia as fuel, onboard carbon capture, and modern sails are all being tested and readied to impact on the global shipping industry.

Ships contracted in the coming years need to consider the upcoming stringent requirements to retain their commercial attractiveness, asset value, and profitability in the following decades. As we move beyond 2030, ships in operation may need to consider retrofit options for using low-GHG emission fuels. The NZF regulations not only affect technology choices and operation of ships but also impact the development of shoreside infrastructure and the availability of low-GHG fuels and carbon dioxide (CO_2) storage.

The NZF aims to accelerate the adoption of low-GHG fuels and technologies, thereby supporting the achievement of the revised 2023 IMO GHG Strategy, namely a 20% reduction in emissions by 2030, a 40% reduction by 2040 (compared to 2008 levels), and net-zero emissions 'by or around' 2050. It is based on the GHG fuel intensity (GFI) metric expressed in gCO_2eq/MJ of all energy used on board in a calendar year on a well-to-wake (WtW) basis. Gradually stricter GFI targets are to be set every year from 2028. In effect, the NZF penalizes vessels with a GFI higher than the targets and incentivizes the use of low-GHG fuels and other technologies that can reduce the GFI.

Gotland Horizon X is designed for fuel flexibility.

A ship that has a higher GFI than the targets can buy remedial units (RU) to make up for compliance deficits, with the initial RU prices for the reporting periods 2028 to 2030 being set as follows:

- **Tier 1 RU:** 100 USD per tonne of CO_2eq
- **Tier 2 RU:** 380 USD per tonne of CO_2eq

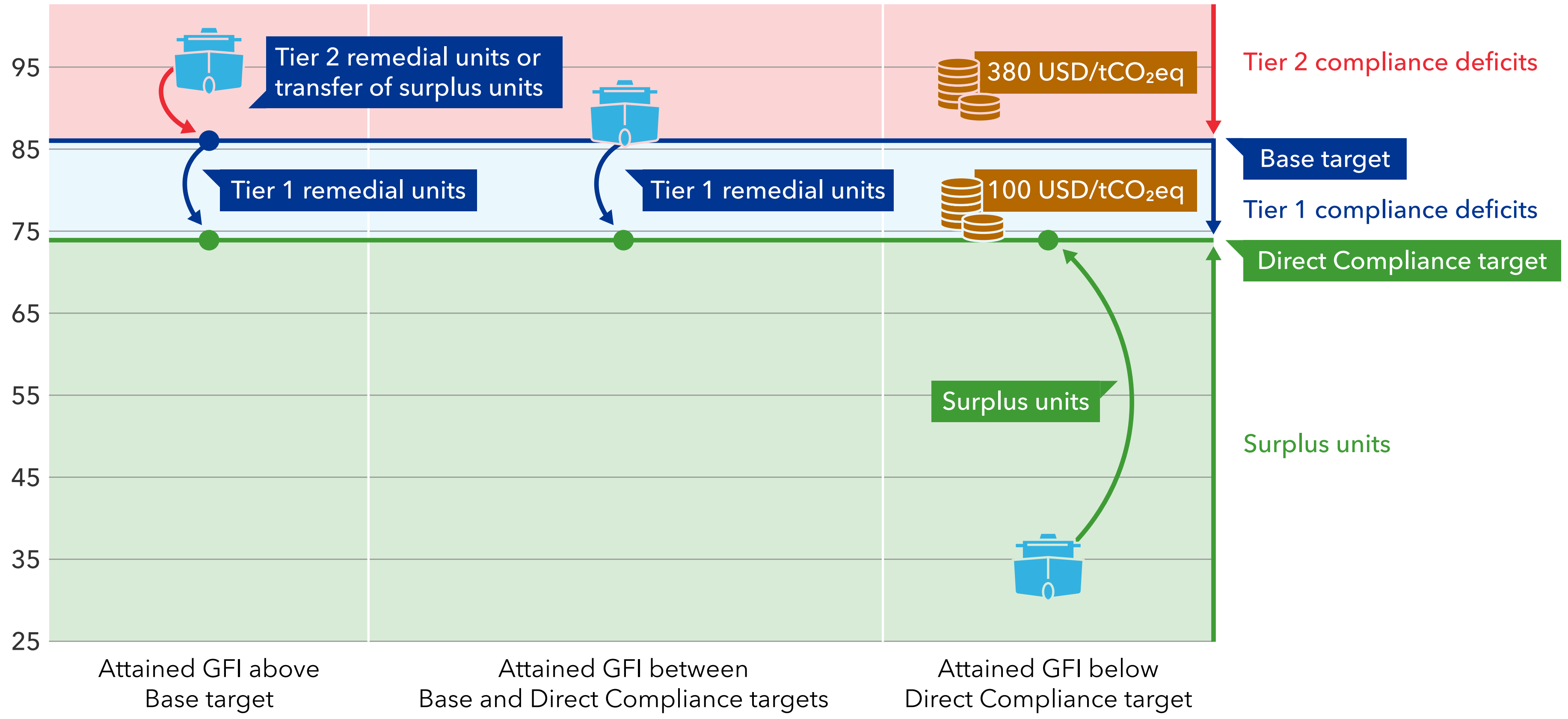
The proceeds from the sale of RUs to shipping companies – estimated to reach 10 to 15 BUSD/year – will go directly into the Net-Zero Fund, which will be set up and managed by the IMO. While the legal framework of the NZF has been established through the approved amendments to MARPOL Annex VI, much work remains to develop the necessary guidelines ahead of its entry into force.

We present a case study ship operating under the NZF, a chemical tanker of 18,000 DWT, and find that with present biofuel prices it will be a better business case to use biofuel rather than pay Tier 2 penalties. To reach the Base target from 2028 to 2040 by

FIGURE 1-1

Illustration of compliance approaches in the NZF exemplified for the 2030 targets

Units: GFI (gCO_2eq/MJ)



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increasingly blending in biofuels, the case study ship starts with 6% of biofuel in its energy mix in 2028, increasing to 78% in 2040. We find that a strategy of selling surplus units through maximal use of bio-LNG for the LNG version of the case study ship is not economically viable with our case study assumptions after 2031, without extra income from premium transport or rewards from the IMO Net-Zero Fund.

Overall, there is significant difference in progress made by each low-GHG fuel across ship technologies, fuel supply, and infrastructure – the three pillars necessary for the uptake of these fuels. For example, there are 1,539 vessels in operation that can run on bio-LNG or e-LNG, compared to three vessels capable of operating on blue ammonia or e-ammonia. Global annual production of biodiesel amounts to about 20 million tonnes oil equivalent (Mtoe)[1], while production of bio-methanol/e-methanol is only about 1 Mtoe. Similarly, on the infrastructure side, there are 106 bunkering facilities catering to bio-LNG and e-LNG, while for ammonia there is only one.

With the number of vessels capable of running on alternative fuels set to almost double by 2028, we are seeing a rapid increase in the capability to burn such fuels, led by a growing shift towards dual-fuel LNG.

There are, however, large differences between the ship segments. While three-quarters of the order book for large container vessels have dual-fuel capability, this is true for only one in five large tankers and only one in twenty large bulkers. For container vessels above 2,000 TEU, half the order book is LNG-capable, one quarter methanol-capable and only one quarter being built solely for conventional fuel.

This represents promising progress, but fuel availability and cost remain significant hurdles.

The maritime industry currently consumes an estimated 1 Mtoe per year of low-GHG fuels. To meet the IMO's 2030 Base target, DNV simulates that this needs to increase to as much as 25 Mtoe.

By 2030, the global fleet will have the capacity to consume over 50 Mtoe per year of low-GHG fuels (other than biodiesel) on ships with alternative fuel technology. Yet the development of low-GHG fuel production, particularly hydrogen and its deriv-

TABLE 1-1

Fuel transition status August 2025

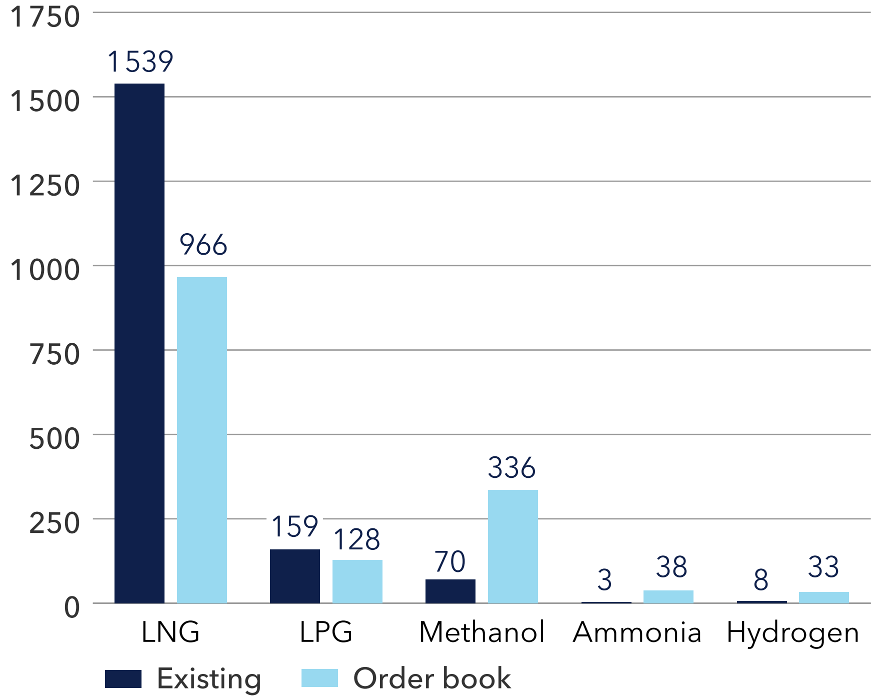
Progress status: Very high / High / Medium / Low

		Low GHG fuels				
		Bio-based diesel / e-diesel (mono-fuel vessels)	Bio-LNG/ e-LNG	Bio-methanol/e-methanol	Blue ammonia / e-ammonia	Blue H_2 / e-H_2
Ship technologies	Technical maturity	Conventional (mature)	Mature	Limited engine models available	Under development	Under development
	Safety regulations	Conventional (mature)	Mature	Interim IMO guidelines	Interim IMO guidelines (high-level)	Alternative design approval process
	Vessels in operation* (number of vessels)	Majority of vessels in operation	1 539	70	3	8
	Order book* (number of vessels)	Majority of newbuild order book	966	336	38	33
	Potential annual fuel consumption (Mtoe)*,**	Majority of potential annual fuel consumption	~40	~6	~0.2	~0.04
Fuel supply	Global fuel production (Mtoe)	~20***	~9	~1	~0.1	~3
	Supply to shipping (Mtoe)	~0.7	~0.1	~0.1	0	0
Infrastructure	Bunkering facilities (dedicated facilities only)	>670	106	3	1	1

 *values include vessels using cargo as fuel, e.g. liquefied natural gas (LNG) carriers, methanol tankers, and ammonia tankers; **includes vessels in operation and order book; ***only accounting for bio-based diesel produced from non-food and non-feed sources

FIGURE 1-2

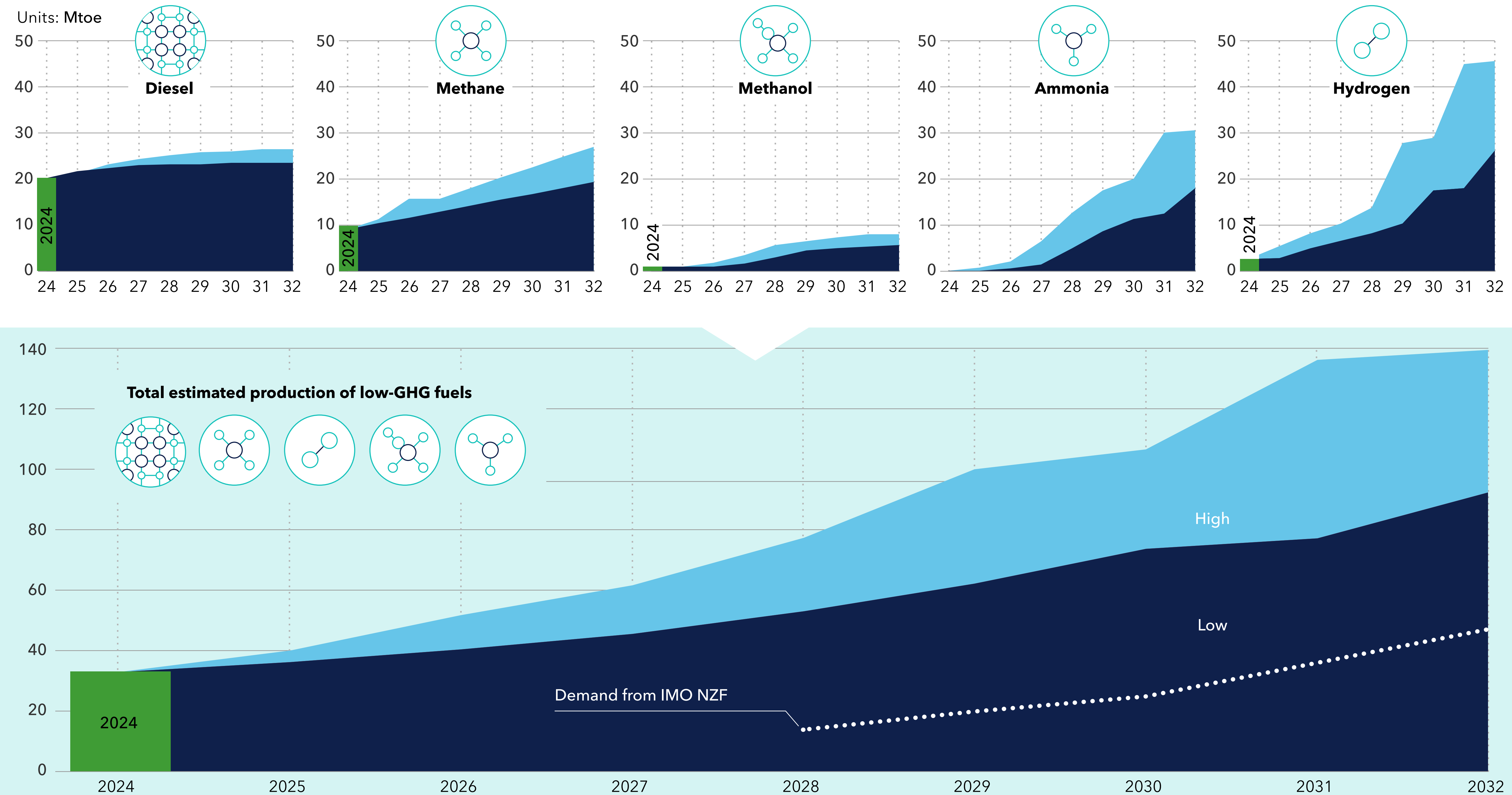
Number of ships with alternative fuel capabilities in the order book compared to the existing fleet (incl. LNGC)



 Source: Alternative Fuels Insight (AFI) - afi.dnv.com, as of August 2025

FIGURE 1-3

Estimated global production of low-GHG fuels across all sectors



atives, has encountered substantial headwinds, with no increase in estimated production by 2030 (when we exclude bio-methane) from our 2023 and 2024 estimates. Currently, only around 4% of the hydrogen-derived low-GHG fuel project pipeline has successfully reached final investment decision, with an even smaller fraction of approximately 1% reaching operational status.

Nonetheless, although the steady growth of the project pipeline has stalled, an estimated total production capacity of between 70 and 100 Mtoe for low-GHG fuels (for all sectors and including biodiesel) is expected in 2030.

As different industries move towards decarbonization, there will be competition for low-GHG energy and fuel. To illustrate this, we have calculated how the net GHG reduction achieved through electricity usage varies significantly depending on the sector, the end-use of electricity, and the displaced energy use.

> The maritime industry faces an urgent challenge in competence development, and additional training capacity is needed.

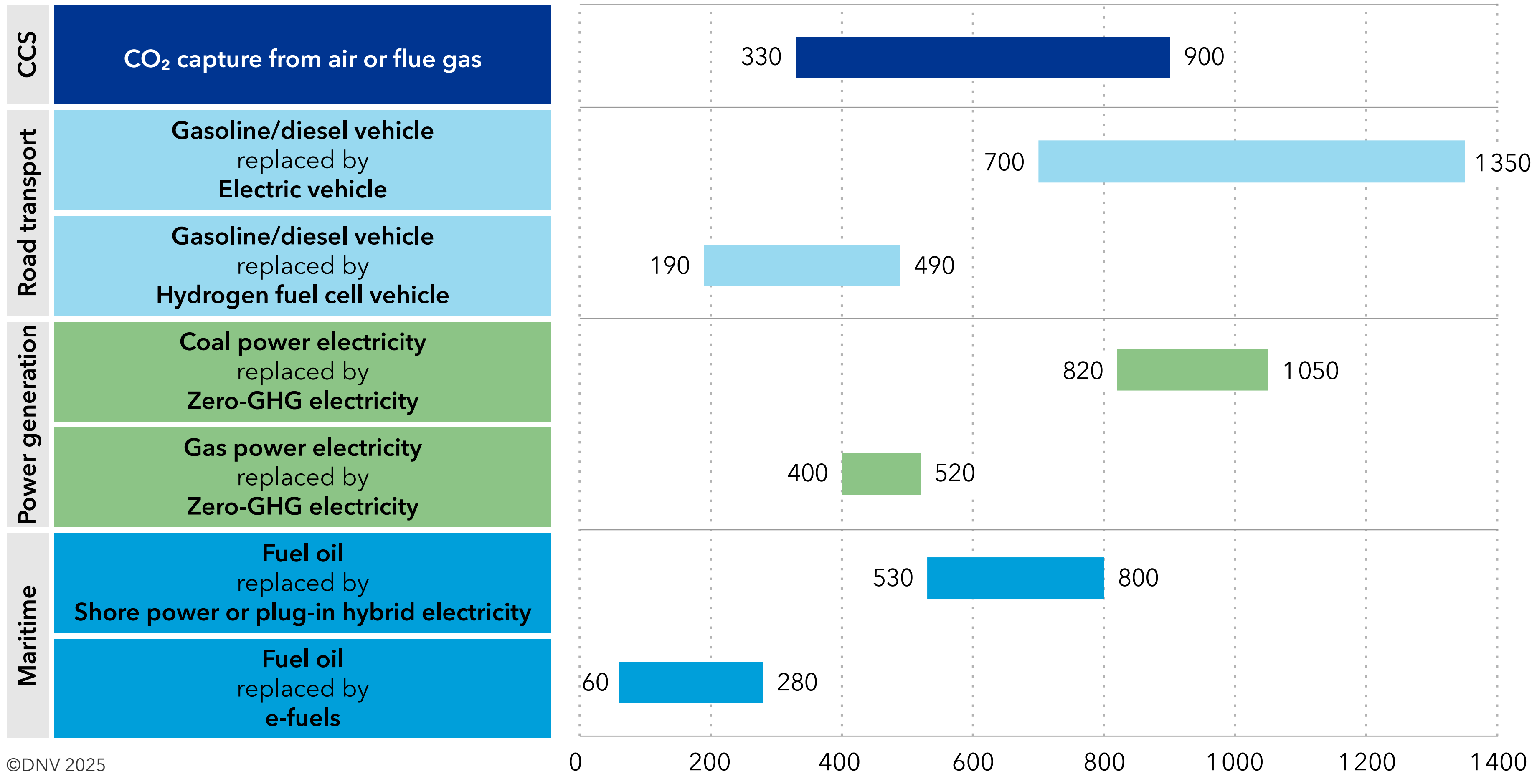
The adoption of low-GHG fuels requires substantial onshore investments and developments, both in production of low-GHG fuels and in bunkering and distribution infrastructure. The cost of establishing bunkering and distribution infrastructure for low-GHG fuels varies between fuel types and, in addition, the total costs will depend on the rules adopted for using different GHG-intensity versions of the same fuel, directly impacting the reusability of infrastructure.

These challenges can be mitigated through the adoption of flexible Chain of Custody models, which can trace and verify the sustainability of low-GHG fuels in the fuel supply chain. For example, in the case of LNG and bio-LNG, if a mass balance Chain of Custody model is applied to interconnected infrastructure, the fossil LNG terminals and natural gas pipelines can be used instead of building separate infrastructure for bio-LNG/bio-methane. This also has the added benefit of reducing energy

FIGURE 1-4

GHG reduction from use of 1 kWh of electric energy – not considering emissions from production of electricity

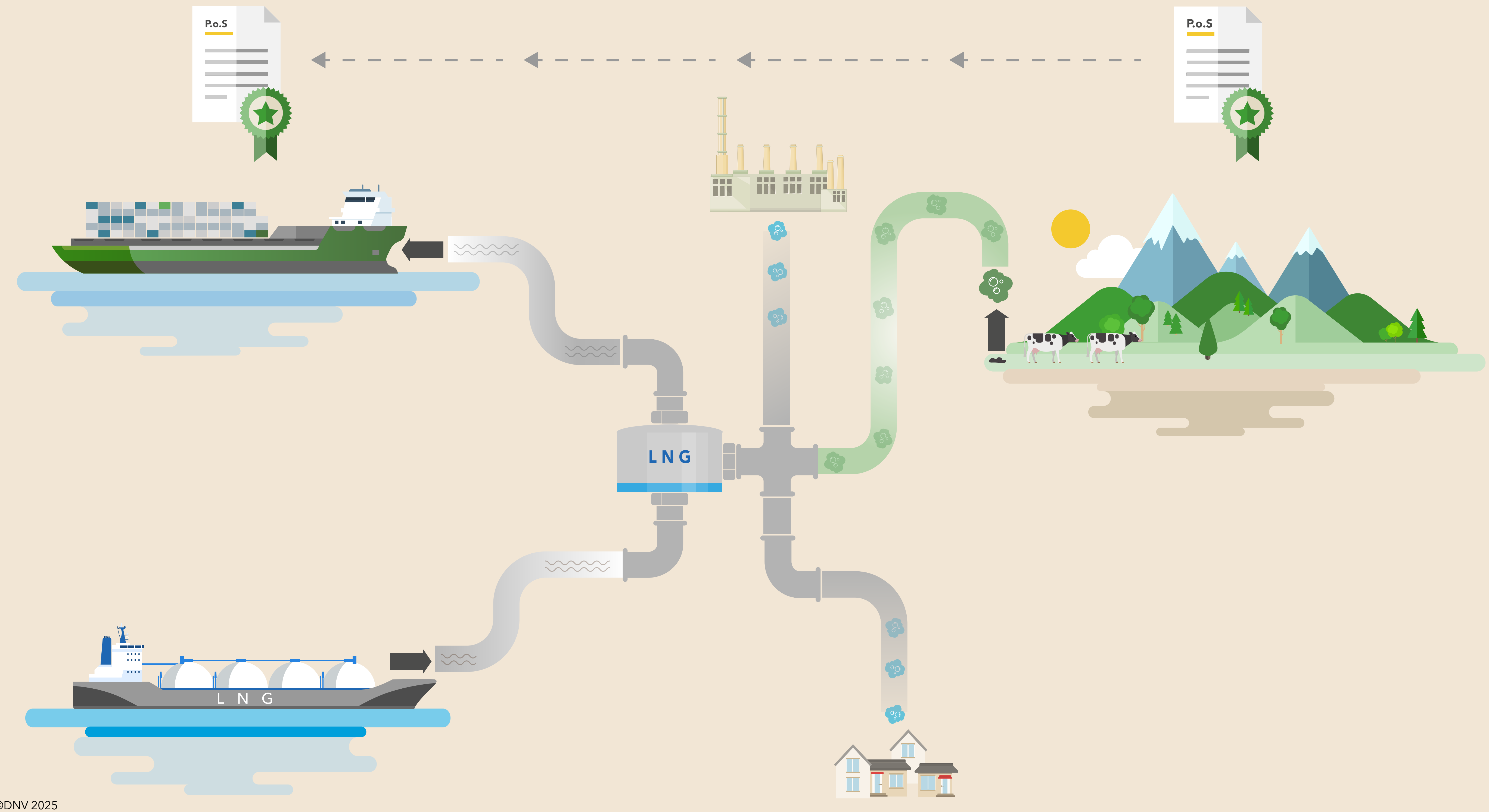
Units: gCO_2eq reduced per kWh zero-GHG electricity input



Shore power is supplied through a containerized system, supporting cleaner and more efficient port operations.

FIGURE 1-5

Mass balancing principle in the EU, where a ship can buy bio-methane injected into and transported on the natural gas grid: a Proof of Sustainability will accompany the bunker delivery note, ensuring the fuel counts as bio-LNG under the EU ETS and FuelEU Maritime regulations



consumption, emissions, and costs associated with further infrastructure expenditure, thereby further incentivizing the production of low-GHG fuels.

Allowing full flexibility, for example through the book-and-claim Chain of Custody model, would lead to even greater energy savings, amounting to approximately 0.55 Mtoe per year if all the bio-methane produced in the EU were to be used as fuel for ships, assuming 10% energy loss from liquefaction and 3% from regasification. Purchasing bio-LNG in this way would result in the bunkered volume having a Proof of Sustainability document, enabling reduced GHG intensity towards FuelEU Maritime and EU ETS.

Increased use of these models could also strengthen markets for bio-LNG, incentivizing further production for a fuel which provides an increasingly clear path to decarbonization as the number of LNG-fuelled ships in the global fleet continues to grow.

As alternative-capable newbuilds enter operation over the next three to four years, we estimate that around 33,000 additional seafarers will require additional training to operate these vessels. This indicates that the maritime industry faces an urgent challenge in competence development, and that additional training capacity is needed.

Growth in the uptake of alternative-fuelled vessels is also being mirrored by an increase in other technologies which can drive GHG emissions reductions. In simulations of the development of the world fleet, DNV sees retrofit numbers of energy-efficiency packages peaking at around 1,700 a year, similar to the scrubber retrofit peak.

Maritime wind energy can potentially contribute to reduced fuel consumption and this could be a breakthrough year for several wind-assisted propulsion systems (WAPS) with several pilot systems being tested and moving into commercial operation. With upcoming third-party verifications of these technologies providing confidence in their performance, and the IMO NZF driving shipowners to explore all routes to decarbonization, WAPS adoption is set to accelerate.

Uptake of onboard carbon capture (OCC) is also increasing but its contribution to maritime decarbonization requires the development of regulatory frameworks, the installation of equipment on ships, and supporting infrastructure on land. The IMO has launched a workplan to create a regulatory framework for OCC, targeted for completion by 2028. While the EU ETS provides incentives for OCC deployment, FuelEU Maritime currently does not, but this will be considered during its scheduled review in 2027.

The CO_2 storage capacity on a ship will limit how much can be captured on a given voyage, and to assess realistic tank sizes for storing CO_2 captured on board, we assume similar volumes as for existing LNG tank installations. By combining these tank sizes with estimated emissions from voyages to specific ports, we have found that by equipping 20 of the largest ports with CO_2 offloading infrastructure, over 75 million tonnes of CO_2 emissions could potentially be removed from large bulkers, tankers, and containerships with onboard CCS equipment, amounting to 9% of world fleet CO_2 emissions and equivalent to using 25 Mtoe of low-GHG fuel.

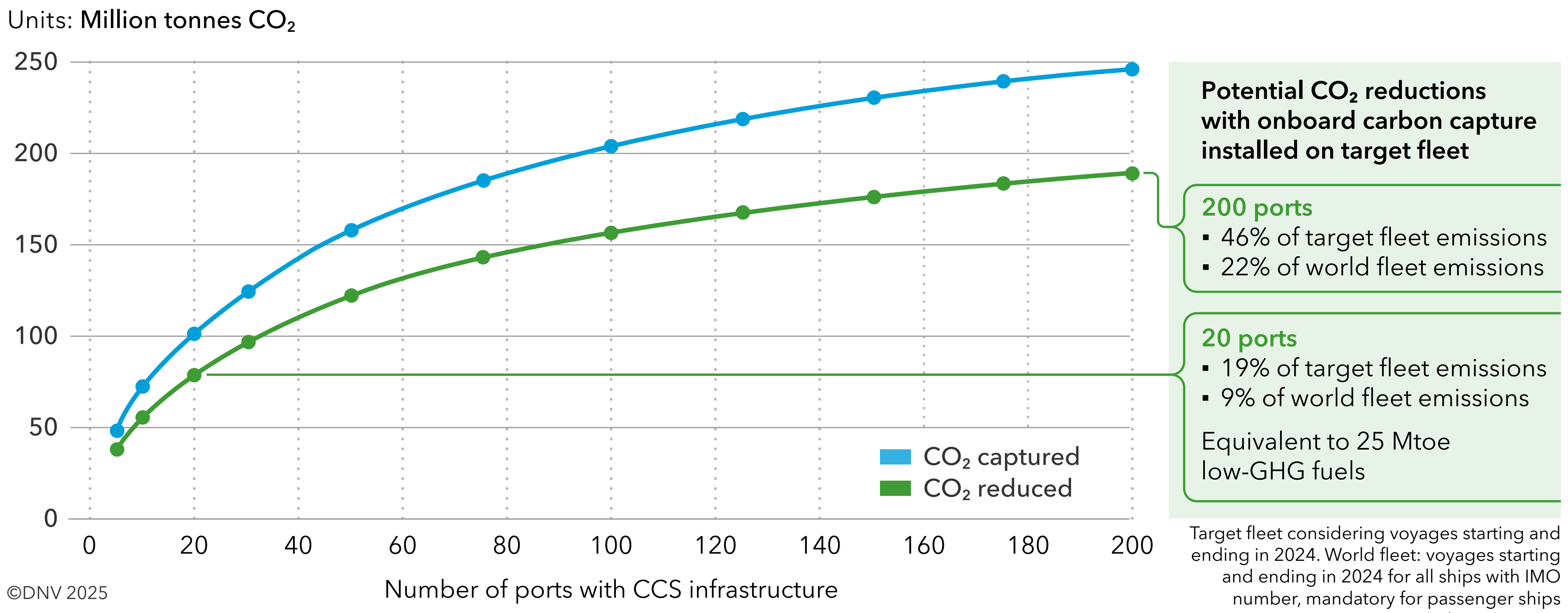
Shipping has started moving towards a cleaner future, with biofuels, LNG, and wind as good short-term measures. With the IMO NZF on the horizon, shipowners and other stakeholders need to investigate all options to find cost-effective solutions for the next two and a half decades.

This is a pivotal moment for maritime decarbonization. Success will depend on synchronized progress across ships, fuel supply, and port infrastructure, supported by investment, regulatory clarity, and industry-wide collaboration.

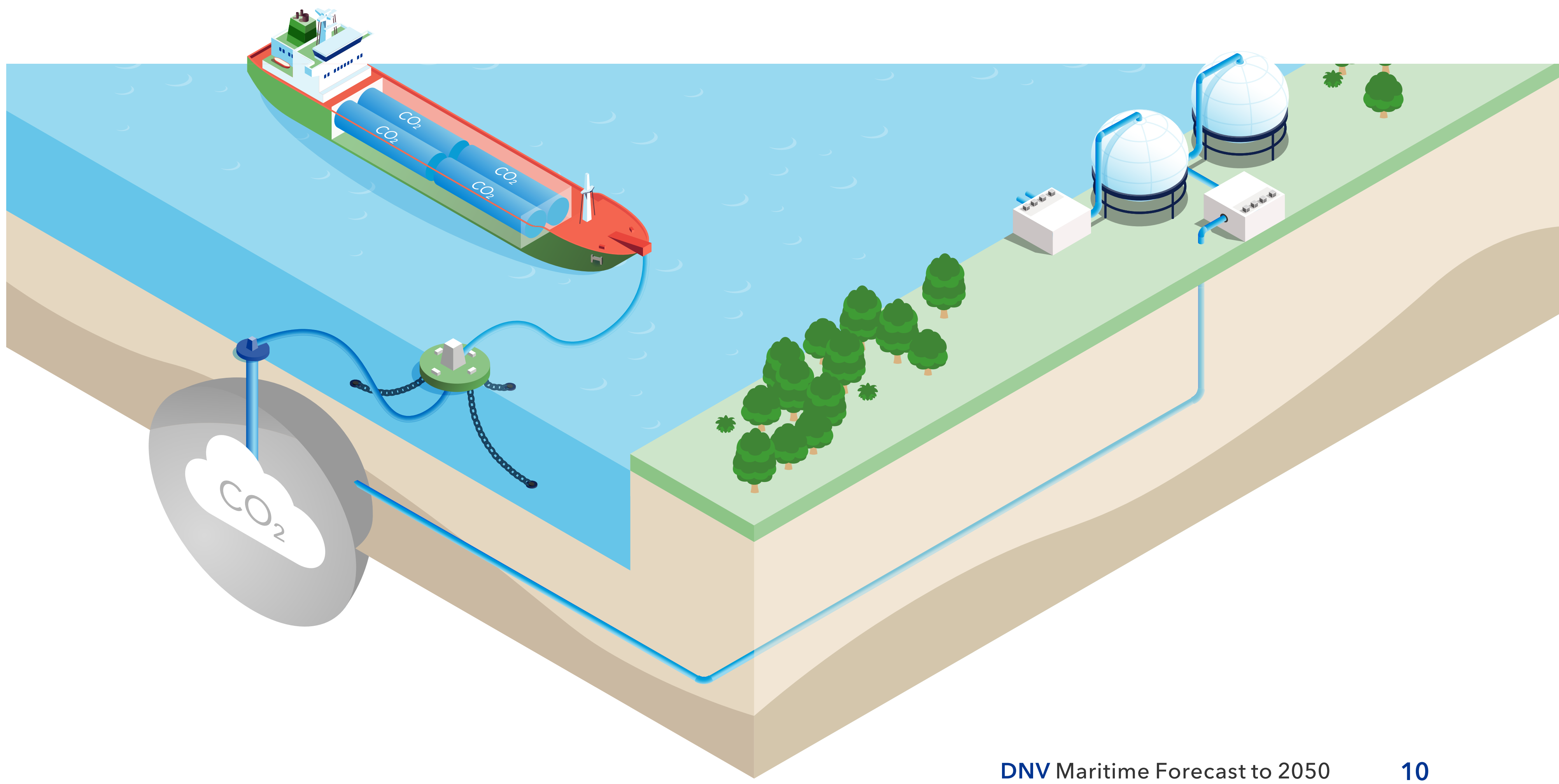
> With the IMO NZF on the horizon, shipowners and other stakeholders need to investigate all options for finding cost-effective solutions for the next two and a half decades.

FIGURE 1-5

The potential CO_2 capture from large[2] bulkers, tankers, and containerships in million tonnes (blue line) and the corresponding net CO_2 reduction (green line), as a function of number of ports with CO_2 deposit infrastructure



Target fleet considering voyages starting and ending in 2024. World fleet: voyages starting and ending in 2024 for all ships with IMO number, mandatory for passenger ships ≥ 100 GT, cargo ships ≥ 300 GT



2 INTRODUCTION

This publication is part of DNV's 2025 suite of Energy Transition Outlook (ETO) reports. This latest Maritime Forecast to 2050 provides an independent outlook on shipping's energy future and examines how the technology and energy transition will affect the industry.

With the Net-Zero Framework (NZF) approved by the International Maritime Organization (IMO) in April 2025, the course is being set for the global maritime fuel transition. The NZF aims to meet the emission reduction targets set out in the 2023 IMO GHG Strategy. Pending adoption in October 2025, a GHG fuel intensity (GFI) metric, in combination with a two-tier GHG pricing mechanism, will require operators to reduce their ships' GHG emissions intensity by 21% by 2030, with financial penalties for those who fail to do so. Beyond 2030, the requirements become rapidly stricter.

In response to the NZF, shipowners should carefully identify, evaluate, and use technologies, fuels, and solutions that help minimize energy consumption and lower GHG fuel intensity for ships. Many ships contracted in the coming years may still be in operation in 2050, and need to consider the upcoming stringent requirements to retain their commercial attractiveness, asset value, and profitability in the following decades. In addition, as we move beyond 2030, ships in operation may need to consider retrofit options to allow the use of low-GHG emission fuels.

In this year's report, we aim to improve our understanding of what the IMO Net-Zero Framework is, and its implications. We also want to provide fresh insight into the status of the maritime fuel transition today – onboard and onshore – so as to better understand the work that remains to be done to meet the requirements.

The report first provides an in-depth explanation of the new IMO NZF (Chapter 3), as well as an updated outlook on other GHG regulations and drivers for the maritime fuel transition. These regulations not only affect technology choices and operation of ships (Chapter 4) but also impact the development of shoreside infrastructure and the availability of low-GHG fuels and CO_2 storage (Chapter 5). Further insights into the key mechanisms of the IMO NZF are provided in Chapter 6, with an analysis of the economic impact on a case study vessel. Finally, in Chapter 7, we assess the potential of onboard carbon capture (OCC) to contribute to decarbonizing shipping.

Clarifying low-GHG vs. alternative fuels

Regulations are now maturing, and both the EU and the IMO have made rules that focus on the overall GHG emissions of fuels in a well-to-wake (WtW) perspective; the GHG fuel intensity (GFI) in the IMO; and WtW GHG intensity used in the EU. In this report we will use the term **low-GHG fuels** when referring to fuels with a significant improvement in WtW GHG emissions from conventional fossil fuel oils, while **alternative fuels** are fuels that require a different energy converter technology, such as LNG, LPG, methanol, ammonia and hydrogen, regardless of WtW GHG intensity.

3 OUTLOOK ON REGULATIONS AND DRIVERS

Highlights

As regulation drives shipping's decarbonization, we examine the potentially game-changing new IMO Net-Zero Framework (NZF) and other key developments, including:

- A detailed description of the NZF mechanisms on GHG fuel intensity and its two-tier emissions pricing scheme.
- Critical NZF guidelines to be developed in the coming years.
- The IMO's plans for a future regulatory framework on onboard carbon capture and storage.
- How the NZF's requirements differ from the EU ETS and FuelEU Maritime.
- The latest updates on completed and pending reviews of the Carbon Intensity Indicator for ships.

The bottom line for shipowners is that the IMO NZF and FuelEU Maritime both restrict ship GHG emissions, effectively forcing wider uptake of low-GHG fuels and technologies. Financially, the NZF's carrot-and-stick approach penalizes undercompliance and incentivizes Maritime's big emissions clean-up. In this chapter, we discuss the latest need-to-know details on regulatory and commercial drivers of maritime decarbonization.

Regulations and policies remain the key drivers for the decarbonization of shipping through direct requirements and incentives for ships and shipping companies. Currently, the EU has existing Emissions Trading System (ETS) and FuelEU Maritime regulations impacting costs of using fossil fuels and effectively forcing the use of low-GHG fuels (Figure 3-1).

3.1 IMO

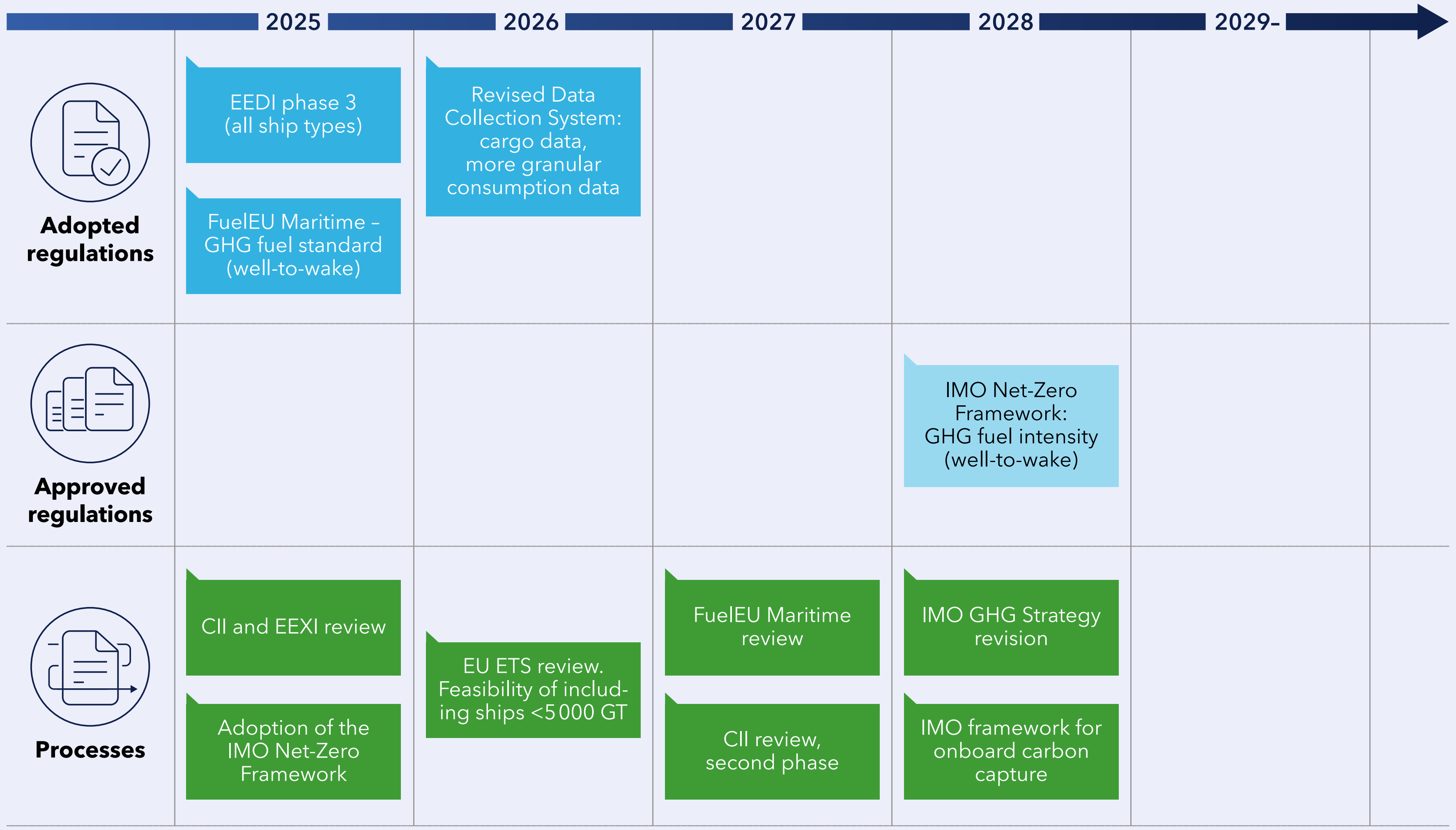
In this section we describe the major regulatory development in the IMO in 2025, the Net-Zero Framework, and then compare its consequences with those of EU regulations before describing other regulatory developments in the IMO.

3.1.1 Net-Zero Framework

The IMO's Marine Environment Protection Committee (MEPC) in April 2025 approved the Net-Zero Framework (NZF) which will be included as a new Chapter 5 in Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL Convention).[3] In addition to the new chapter, the NZF also includes consequential amendments to other regulations in MARPOL Annex VI covering definitions, survey/verification, certificate issuance, port state control, the Ship Energy Efficiency Management Plan (SEEMP), as well as the Data Collection System (DCS).

FIGURE 3-1

GHG regulatory timeline towards 2030



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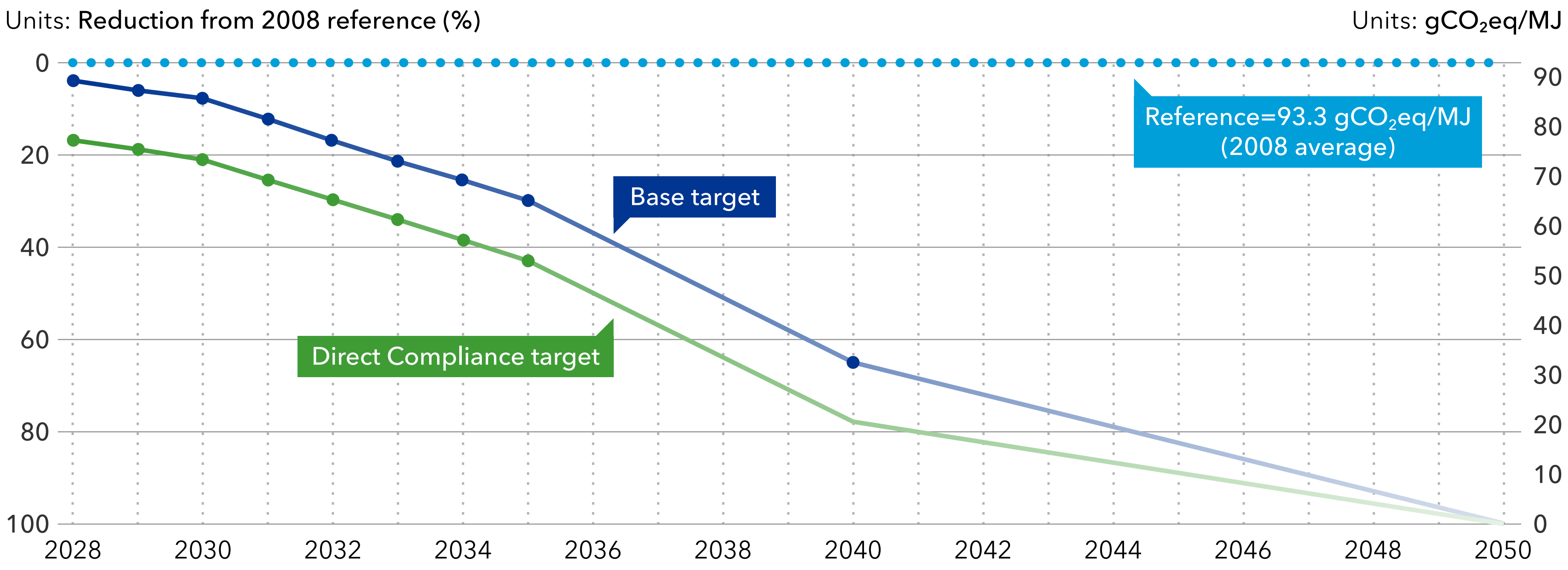
Key: Carbon Intensity Indicator (CII); Energy Efficiency Design Index (EEDI); Energy Efficiency Existing Ship Index (EEXI); Emission Trading System (ETS)

The amendments to MARPOL were approved by a majority vote and are due for adoption at an extraordinary session of the MEPC in October 2025. Adoption requires a two-thirds majority of parties to MARPOL Annex VI present and voting. While the amendments are expected to enter into force in March 2027, in practice the new requirements will apply to ships from 1 January 2028.

FIGURE 3-2

GFI reduction factors and reference value in the NZF



Year	2028	2029	2030	2031	2032	2033	2034	2035	...	2040
Base	4%	6%	8%	12.4%	16.8%	21.2%	25.6%	30%	...	65%
Direct	17%	19%	21%	25.4%	29.8%	34.2%	38.6%	43%	...	-

The NZF is the IMO's regulatory response to the 2023 IMO GHG Strategy, which sets out the ambition to reach net-zero GHG emissions by or around 2050. The stated goal of the NZF is to ensure that international shipping can meet the strategy's GHG emission reduction targets, to accelerate the uptake of so-called zero or near-zero GHG fuels, technologies and energy sources (ZNZs), as well as to support a just and equitable transition of the maritime sector.

The regulations provide a long-term trajectory to 2040 for the GHG emissions through setting GHG intensity reduction requirements for ships. The GHG fuel intensity (GFI) is a technology-neutral metric measured as well-to-wake GHG emissions per energy used on board a ship, supplemented by sustainability criteria. Several features in the NZF are similar to those in FuelEU Maritime, but there are important differences that we highlight in this chapter.

The NZF is ground-breaking in introducing a global technical requirement in combination with a GHG pricing scheme. It presents a new regulatory era where ships will be required to gradually adopt fuels that are considerably more expensive than conventional fossil fuels, or alternatively pay a contribution to the IMO Net-Zero Fund. Given the long lifespan of ships, shipowners should prepare now for the new regulations to ensure cost-effective compliance, both at the ship and the fleet levels.

Scope and metric

The new regulations apply to all ships above 5,000 gross tonnes (GT). They do not apply to ships trading solely domestically, to platforms including floating production, storage and offloading units (FPSOs), floating storage units (FSUs) and drilling rigs, or to semi-submersible vessels. As for other IMO requirements, it is the manager – in other words, the ISM company – which is responsible for compliance for the ship towards the flag. In case of change of company, it is the company at the end of each calendar year which is responsible for the full 12-month reporting period.

The GFI metric also includes electricity delivered to the ship, as well as wind propulsion and solar power. The attained GFI is to be reported annually by the ship as part of the DCS.

The reporting of the GFI will be enabled by expanding the current DCS scheme. Each ship will be required to develop or update its data collection and reporting plan to include the necessary elements to calculate the GHG intensity. The plan must be verified and kept on board together with a Confirmation of Compliance prior to the start of the first reporting period, which is 1 January 2028.

The regulations mandate that the GHG emissions factors and sustainability aspects should be certified by a recognized Sustainable Fuels Certification Scheme (SFCS). SFCSs are to be approved by the MEPC, and the IMO will publish a list of recognized SFCSs by 1 March 2027. This list will be periodically updated.

The GHG emissions factors and information on sustainability aspects should be provided on the Fuel Lifecycle Label (FLL) and accompany the Bunker Delivery Note when the fuel is delivered. Details on these aspects will be included in guidelines to be developed in the coming years.

Requirements

Two tiers of requirements are set on the annual attained GFI for a ship: a Base target and a Direct

Compliance target. Each ship is required to meet the Direct Compliance target, either through the use of low-GHG fuels, or through one of the alternative compliance approaches described later in this chapter. The Base target is used to separate between Tier 1 and Tier 2 compliance deficits.

The regulations include annual GFI reduction targets to 2035, as shown in Figure 3-2. A Base target for 2040 is also included and set to 65%. The annual reduction targets for the years 2036 to 2040 are expected to be set as part of the first review by 1 January 2032.

Compliance approaches

Based on the attained GFI and the targets, each ship will have to determine an annual compliance balance, expressed in tonnes CO_2eq. If a ship has a GFI lower than the Direct Compliance target, it will receive surplus units (SUs). Conversely, if a ship has a GFI above the Direct Compliance target, it has a negative compliance balance and accrues compliance deficits:

- For an attained GFI between the Base and the Direct Compliance targets, a ship generates a Tier 1 compliance deficit.
- For an attained GFI above the Base target, a ship generates both a Tier 1 compliance deficit (for the emissions between the Base and the Direct Compliance targets) and a Tier 2 compliance deficit (for the emissions above the Base target).

> Each ship is required to meet the Direct Compliance target, either through the use of low-GHG fuels, or through one of the alternative compliance approaches described later in this chapter.

To handle compliance deficits and surpluses, the NZF includes several compliance approaches as illustrated in Figure 3-3 .

A ship with a compliance surplus can transfer SUs to other vessels – including to ships under other companies – which have a compliance deficit (similar to FuelEU Maritime's concept of compliance pooling). The ship with a compliance surplus can also bank SUs for later use within the two subsequent calendar years, or it can cancel the SUs as a voluntary mitigation contribution (which prevents the SU being used to balance a deficit for another ship). Note that an SU can only be transferred once and can only be transferred to balance a Tier 2 compliance deficit. This avoids accumulation of SUs for later trading.

A ship can balance its Tier 2 compliance deficit with SUs from other ships, banked SUs from the previous reporting period, or it can buy remedial units (RUs) (similar to FuelEU Maritime's penalty) from the IMO Net-Zero Fund. The Tier 1 compliance deficit can only be compensated by Tier 1 RUs – in other words, SUs from other ships cannot be used to balance Tier 1 compliance deficit.

The initial RU prices for the reporting periods 2028 to 2030 are set as follows:

- **Tier 1 RU:** 100 USD per tonne of CO_2eq
- **Tier 2 RU:** 380 USD per tonne of CO_2eq

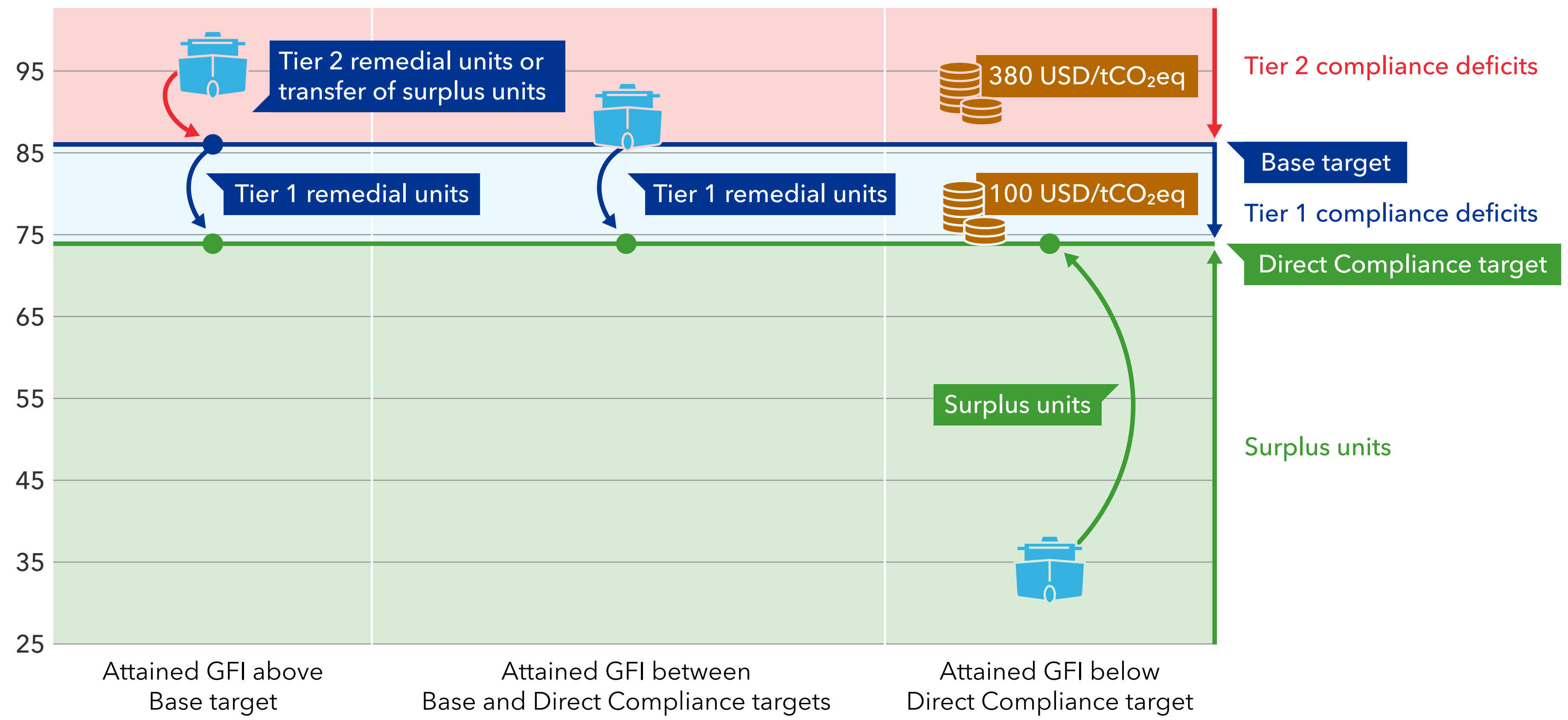
The MEPC will determine a mechanism by 1 January 2028 for reviewing and defining RU prices for 2031 and onwards.

The regulations are designed in this manner with the intention that most ships will use sufficient low-GHG emission fuels to reach the Base target and then buy Tier 1 RUs. This requires that the IMO sets the Tier 2 RU price higher than the price for low-GHG emission fuels. Alternatively, ships can buy SUs from other ships to cover the Tier 2 compliance deficit down

FIGURE 3-3

Illustration of compliance approaches in the NZF exemplified for the 2030 targets

Units: GFI (gCO_2eq/MJ)



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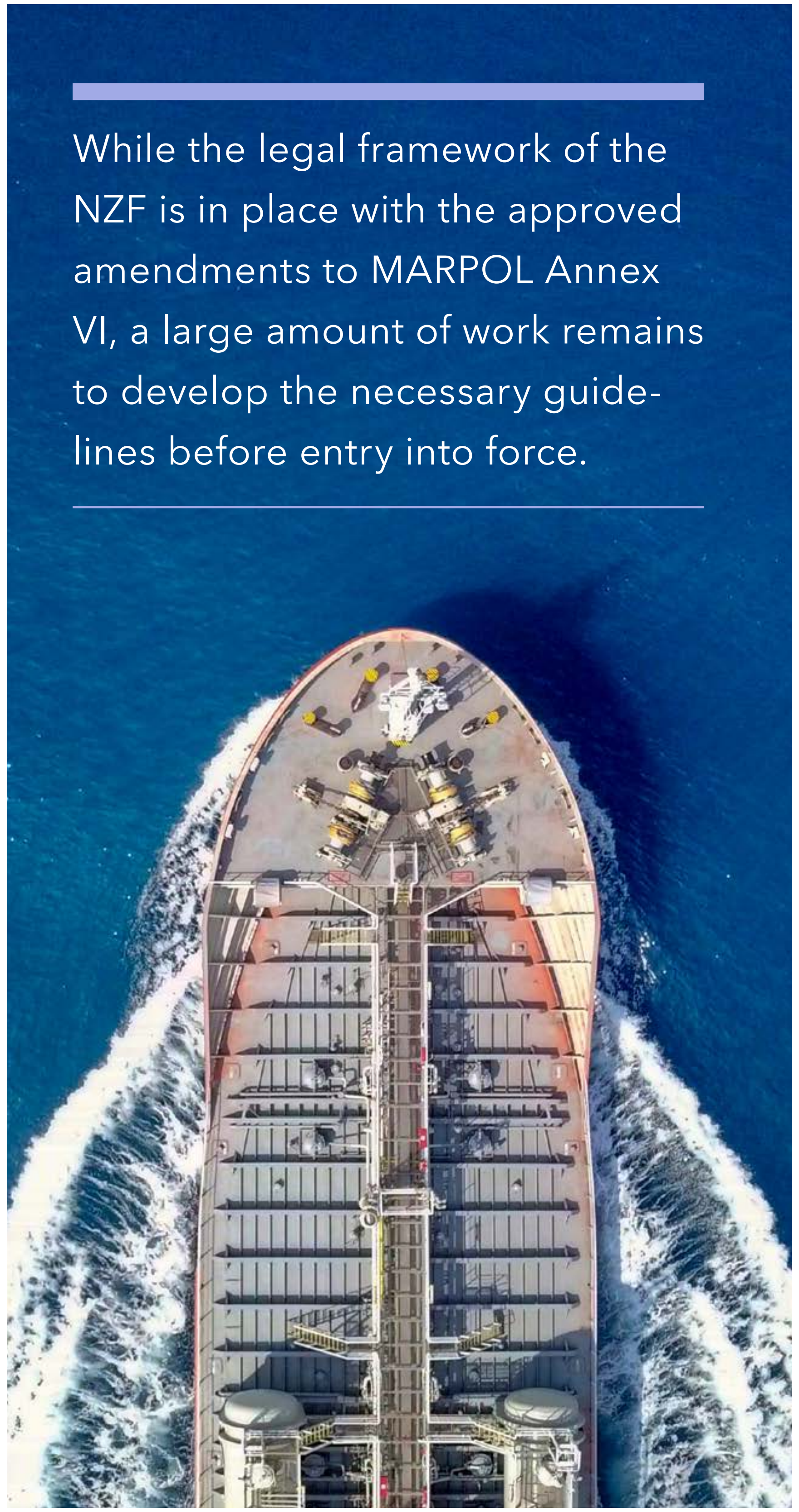
to Base target and then acquire Tier 1 RUs down to Direct Compliance target. This ensures that a certain amount of revenue is generated for disbursement purposes, while ensuring that the fleet achieves at least the Base target.

IMO Net-Zero Fund and rewards for using ZNZs

The proceeds from the sale of RUs, estimated to 10 to 15 BUSD/year[4], will go into the IMO Net-Zero Fund, to be set up and managed by the IMO. No revenues will be paid to IMO member states; the proceeds will all go directly from the shipping company into the Fund.

Part of the revenues are intended to be used for rewards for ships that use zero or near-zero GHG emission technologies, fuels and/or energy sources (ZNZs). This reward for use of ZNZs, and the methodology for determining the reward, will be defined by 1 March 2027, and will be reviewed every five years starting in 2032. The NZF defines ZNZs as technologies, fuels and energy sources with a GFI below 19 gCO_2eq/MJ until end 2034, and 14 gCO_2eq/MJ from 2035 onwards. Further details will be specified in new guidelines, and the IMO may approve additional specific ZNZs, making them eligible for rewards even if they do not fulfil the GFI threshold.

The remaining revenues will go to other purposes, focused on promoting a just and equitable transition in states by facilitating environmental and climate protection, adaptation and resilience building. This can include researching, developing



and making globally available and deploying ZNZs; enabling a just transition for seafarers and other maritime workforce; facilitating information-sharing, technology transfer, capacity-building, training and technical cooperation; implementation of national action plans; and addressing disproportionately negative impacts, including on food security.

IMO GFI Registry

The IMO will set up a registry which is responsible for handling the GHG emission reports, transfer of SUs, and sale of RUs. Transfer and trading of SUs and purchasing of RUs will commence in 2029 based on the GFI reported by ships for 2028.

Each ship in scope of these regulations needs to have an account with the IMO GFI Registry by 1 October 2027 and must pay an annual administration fee to the GFI Registry by 30 June every year starting in 2028. The administration fee is an additional payment to cover the registry's administrative cost and will be set in new guidelines.

Remaining work

While the legal framework of the NZF is in place with the approved amendments to MARPOL Annex VI, a large amount of work remains to develop the necessary guidelines before entry into force. This includes guidelines to make the GFI Registry and Net-Zero Fund – central features of the framework – fully operational no later than the end of the first reporting period in 2028. Many of the remaining details of the NZF will also be determined in guidelines, including the following issues:

- **Detailed method for calculation of GFI, including for wind propulsion and electricity:** The legal text in MARPOL provides an overall formula for calculating GFI, but the detailed calculation method is yet to be decided in a new guideline. This includes how wind propulsion and electricity should be taken into account.
- **Default emission factors:** The existing IMO Life Cycle Assessment (LCA) Guidelines are a critical part of the NZF and will need to be further developed to support implementation. This includes the development of default emission factors for fossil LNG. The LCA Guidelines are expected to remain under continuous review for the foreseeable future.
- **Certification of fuels:** The NZF mandates that the GHG emission factors and sustainability aspects of fuels delivered to a ship are to be certified by a recognized Sustainable Fuels Certification Scheme (SFCS), though the details on how to do this are to be decided in guidelines. These include guidelines on requirements and procedures for recognition of certification schemes/standards. This is a central part of the NZF, as robust certification is critical to ensure trust in the calculation of ship's attained GFI and compliance balance.
- **Reward for use of ZNZs:** Ships that use ZNZs may receive an annual compensation from the Net-Zero Fund. However, the type and level of reward are yet to be decided in guidelines. The reward and the methodology for determining the reward will

be defined by 1 March 2027, when the NZF enters into force. The reward will then be reviewed every five years starting in 2032 based on a study by the IMO Secretariat on use of ZNZs. The percentage of the Net-Zero Fund that will be allocated to rewards will be decided in the Fund's governing provisions, and this will be reviewed periodically.

- **Mechanism for determining the RU prices:** The NZF has set initial RU prices from 2028 to 2030, and the IMO will by 1 January 2028 determine the mechanism for reviewing and defining RU prices from 2031 onwards. The Tier 2 RU price is important as it sets an upper ceiling for a competitive price of low-GHG and ZNZ fuels, while the RU Tier 1 price determines the main part of the revenue for the IMO Net-Zero Fund. The Tier 1 RU price is expected to be set lower than the alternative cost of low-GHG and ZNZ fuels in order to be the preferred compliance approach, while the Tier 2 RU price will be set higher than the alternative cost in order to ensure that GHG emission reduction is the most feasible solution. To achieve this, the RU price-setting mechanism needs to take into account the price of available low-GHG fuels, and the RU prices may increase in the future.

The new regulations on the IMO NZF in MARPOL Annex VI will be reviewed every five years. The review will consider potential amendment of the annual GFI reduction factors, amendment of the ZNZ threshold values, and the possible inclusion of ships down to 400 GT.

3.1.2 Comparison of the NZF requirements with FuelEU Maritime

In addition to the NZF requirements, ships that also fall under the scope of the EU ETS and FuelEU Maritime will have to continue to adhere to these regulations before a potential alignment with the NZF. These ships will then have to both surrender emission allowances for the EU ETS and will have to potentially pay a penalty under FuelEU Maritime in case of undercompliance.

FuelEU Maritime applies a similar metric and mechanism to the NZF. However, an important aspect to note is that the default emission factors and reference values are not the same in the NZF and FuelEU Maritime, meaning that it is difficult to compare the trajectories based on the reduction factors only. Instead, in Figure 3-4 and Figure 3-5, we compare the stringency by showing the share of low-GHG fuels, as a percentage of total energy used, needed to meet the IMO NZF Base target and FuelEU Maritime requirements. This implies that the ship buys Tier 1 RUs under the IMO NZF requirements. The comparison is shown in 2030 and 2035 for a conventional MGO-fuelled vessel, and an LNG-fuelled vessel with a low methane slip – having a default factor of 0.2% under FuelEU and 0.15% under NZF – and using 5% MGO as pilot fuel. For both bio-MGO and bio-LNG we assume a GFI of 15 gCO_2eq/MJ. Since the IMO LCA Guidelines have not yet determined the

FIGURE 3-4

Percentage of low-GHG fuels needed to meet the IMO NZF Base target or FuelEU Maritime requirement in 2030 and 2035 for an MGO-fuelled vessel

Units: Percentage of annual energy (%)

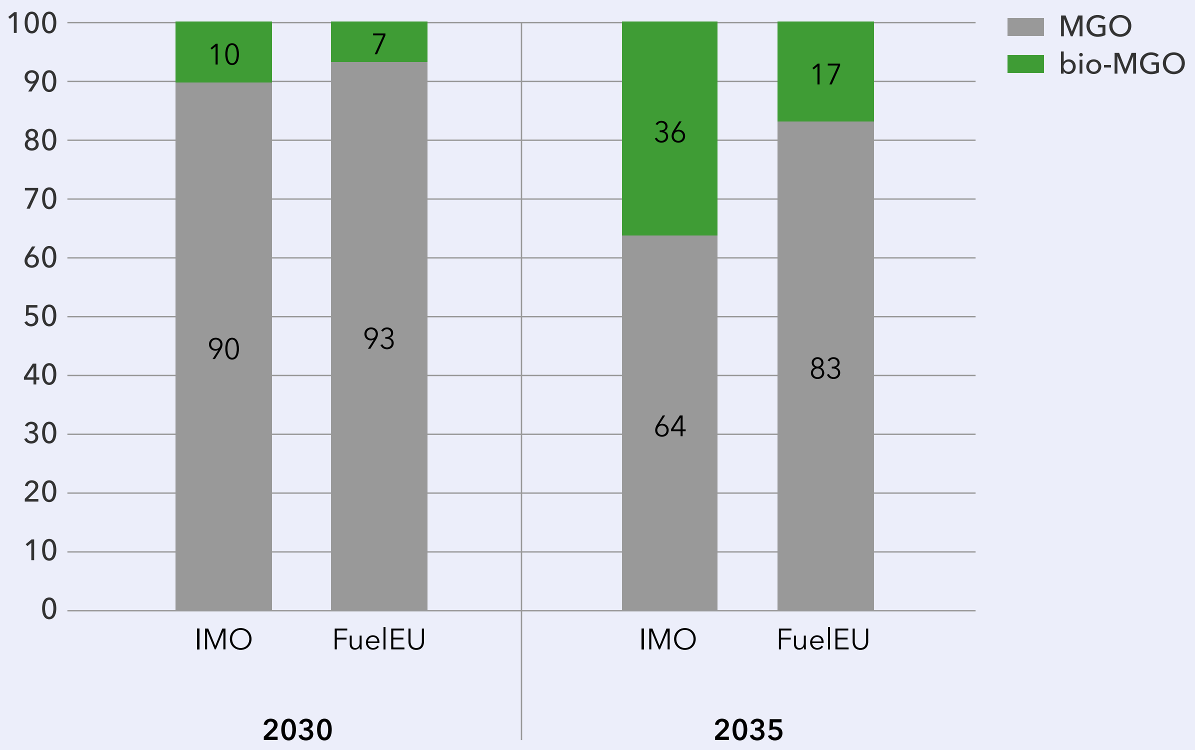


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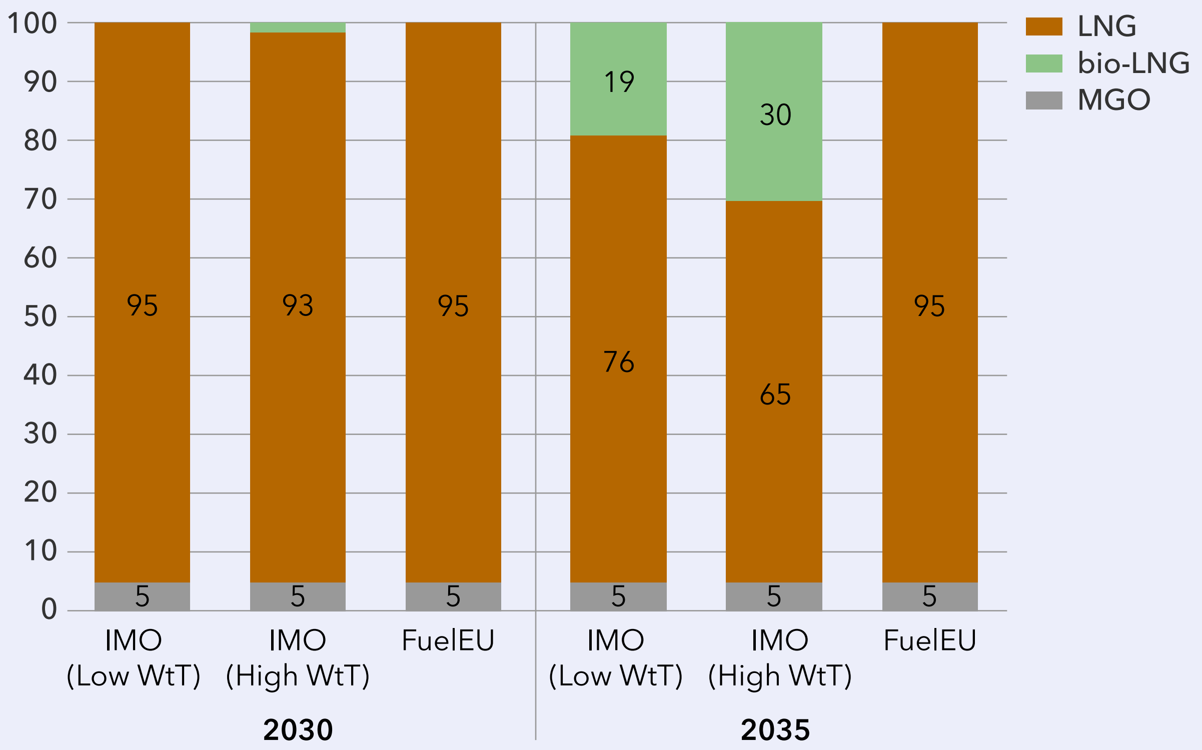
FIGURE 3-5

Percentage of low-GHG fuels needed to meet the IMO NZF Base target or FuelEU Maritime requirement in 2030 and 2035 for an LNG-fuelled vessel

Units: Percentage of annual energy (%)



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Key: well-to-tank (WtT)

WtT[5] GHG intensity factor for fossil LNG fuel we provide two values, a low WtT factor of 17.4 gCO_2eq/MJ and a high WtT factor of 28 gCO_2eq/MJ. These are the same assumption as used in the case study in Chapter 6.

In 2030, the NZF requires using more than 50% more bio-MGO compared to FuelEU, and in 2035 the amount of bio-MGO needed under the NZF is 36% of the total fuel consumption. With LNG, and assuming low methane slip, 0% to 2% bio-LNG is needed under the NZF requirements in 2030, while 17% to 29% is needed in 2035, depending on the WtT emission factor. No bio-LNG is needed for FuelEU in 2030 or 2035.

It should also be noted that FuelEU has a higher penalty of about 650 EUR/tCO_2eq (about 730 USD/tCO_2eq), for not reaching the GHG intensity requirements, compared to 380 USD/tCO_2eq for the NZF. See Chapter 6 for more on the cost implications.

3.1.3 Review of the CII and SEEMP

MEPC 83 completed the first phase of the review of the short-term GHG measures (CII, SEEMP, EEXI) by considering gaps and challenges. Most importantly, the CII reduction (Z) factors were set for the years 2027 to 2030 as shown in Table 3–1. No changes were made to the CII metric or references lines, or the compliance and enforcement, which are left for a more thorough review in a second phase, expected to be completed by 2028. The IMO is also expected to consider the synergies between the CII regulation and the NZF as part of the review.

Installation of a carbon capture system on board the Clipper Eris.

TABLE 3-1

CII reduction factors from 2027 to 2030

Year	2027	2028	2029	2030
Reduction factor	13.625%	16.250%	18.875%	21.500%

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Onboard carbon capture and storage

Onboard carbon capture and storage (OCCS) has seen increased interest as a possible solution for decarbonizing shipping. Currently, only the EU ETS include provisions for deducting carbon captured and permanently stored from the total amount of required emissions allowances. FuelEU Maritime does not provide incentives for using OCCS, but this will be considered in the upcoming review in 2027.

At MEPC 83 in April 2025, the IMO approved a work plan for the development of a regulatory framework for the use of OCCS. The work plan will address both ship and land (e.g. reception facilities, transport, storage) considerations pertaining to OCCS, taking into account their incorporation into existing and future regulatory frameworks such as the EEDI. The aim is to complete the work plan by 2028, but priority tasks will be completed as soon as possible. This implies that incentives for OCCS could take effect from around 2030.

In addition to the items in the work plan, how to account for onboard carbon capture when calculating the fuel GHG intensity of ships will be incorporated in the IMO LCA Guidelines for use when calculating the GFI.

3.2 Other national and regional GHG regulations

The FuelEU Maritime Regulation has now been effective since 1 January 2025, setting GHG emission intensity (gCO_2eq/MJ) requirements for ships over 5,000 GT transporting cargo or passengers for commercial purposes in the EU/EEA (DNV, 2024b). 2025 is also the first year in which shipping companies are required to surrender allowances under EU ETS, for reported emissions in 2024.

Both FuelEU Maritime and EU ETS include provisions that the regulations will be reviewed if the IMO adopts similar measures. The EU will review the ambitions of the IMO regulations in light of the Paris agreement target and examine if the ETS and FuelEU Maritime should be aligned with the NZF, including avoiding any duplication of the GHG regulations.

The UK plans to incorporate ships over 5,000 GT into the UK Emissions Trading Scheme starting in 2026. This will apply to domestic voyages, meaning voyages that begin and end at UK ports, as well as port calls within the UK also including vessels doing international journeys. Consideration is being given to covering 50% of UK/EEA voyages (UK ETS Authority, 2024). The scheme will include tank-to-wake (TtW) emissions of CO_2, CH_4, and N_2O, with well-to-wake (WtW) emissions under review. Responsibility will lie with the 'Registered Owner', unless delegated to the 'ISM Company', similar to the EU ETS. Further consultations are underway, with detailed design decisions and additional implementation specifics expected in 2025, including UK monitoring, reporting and verifying (MRV) requirements and processes. In May 2025 the EU and UK agreed to establish a link between their respective ETS systems.[6] However, no timeline has been established and the implications for the UK ETS and UK MRV remain unclear.

> The UK plans to incorporate ships over 5,000 GT into the UK Emissions Trading Scheme starting in 2026.

The Turkish parliament has approved a scheme to include shipping into its Emission Trading Scheme TR ETS for ships. The scope of the measures, including ship types, size thresholds, and the reporting procedures remain to be developed by the government. The overall TR ETS is expected to launch as a pilot in 2026.[7]

Djibouti and Gabon have introduced a carbon tax of 17 USD/tCO_2eq on half of the emissions on voyages in and out of their ports through the African Sovereign Carbon Registries initiative. Other African countries are also considering joining this carbon tax scheme.[8]

3.3 Commercial drivers

Up until 2025, the uptake of low-GHG fuels has largely been voluntary, driven by expectations from cargo owners and financial institutions in certain segments, who are themselves subject to regulations and expectations from investors and customers. The uptake of biofuels has increased considerably in the last few years, with the voluntary market as the main driver. As discussed in a recent DNV white paper on biofuels in shipping (DNV, 2025a), this voluntary market for biofuels is largely comprised of commercial service offerings with reduced scope 3 GHG emissions in return for a higher transport price. Such services are focused on container shipping and car carrier trades, with cargo owners willing to pay a premium for reduced scope 3 GHG emissions.

Another example of a commercial driver for the uptake of low-GHG fuels is buyers' alliances, such as the Zero Emission Maritime Buyers Alliance (ZEMBA). ZEMBA aims to kick-start the market for zero-emission fuels with targeted tenders, including specific requirements on the use of zero-emission fuels.[9] This involves pooling of buyers to create sufficient transport volumes, enabling shipowners to buy large volumes of fuels in a longer time perspective. ZEMBA's first tender was concluded in April 2024, won by Hapag-Lloyd using certified waste-based bio-methane. The contract involves 600 million TEU-nm per year for two years, with an expected 82,000 tCO_2eq in emission reduction compared to Low Sulphur Fuel Oil (Aspen Institute EEP, 2024). ZEMBA's second tender opened at the end of February 2025 and is focused on e-fuels. Before MEPC 83, ZEMBA encouraged the IMO to approve ambitious new regulations, highlighting the importance of regulatory certainty for cargo owners and the need for global requirements for scaling of low-GHG fuel uptake (ZEMBA, 2025).

Financial institutions, including both banks and insurers, continue to support maritime decarbonization through initiatives such as the Poseidon Principles, as well as through green, sustainability-linked and transition loans and bonds. These initiatives rely on IMO GHG frameworks, including the verified data collected from ships through the IMO Data Collection System (DCS) and, in the future, the IMO LCA Guidelines.

Further, many ports and canals around the world have implemented incentive schemes to encourage the adoption of low-GHG fuels as part of their sustainability initiatives. Notable examples of incentive schemes include:

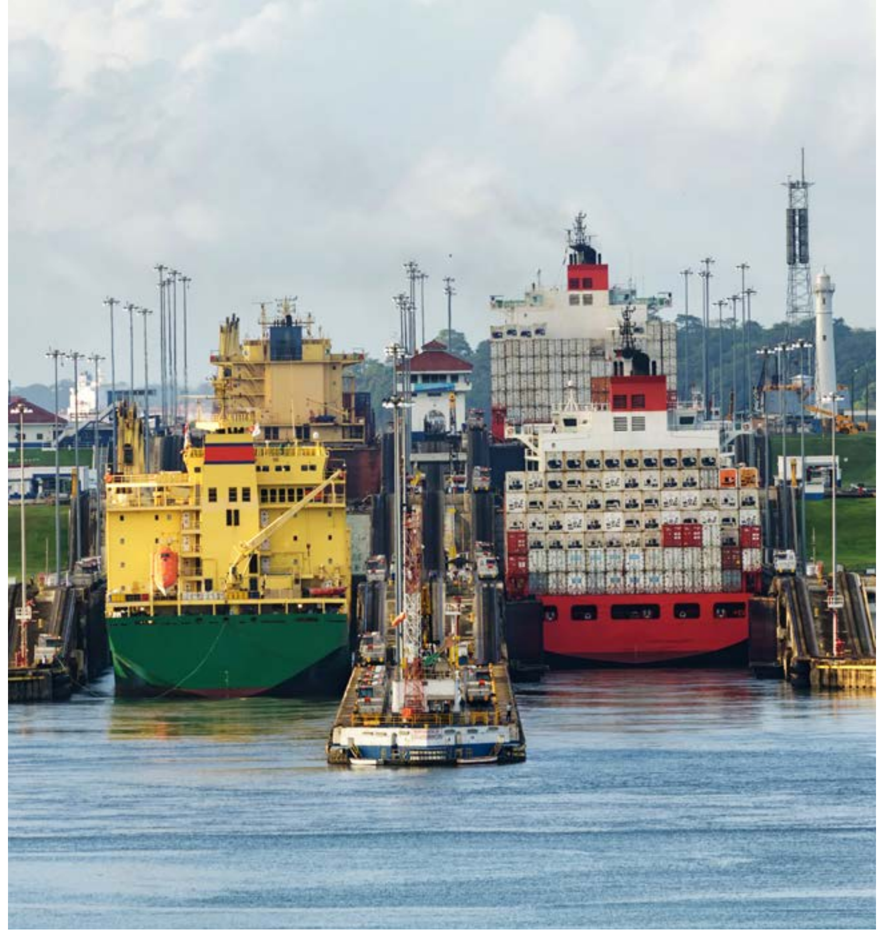
- The Panama Canal Authority has launched an initiative – the NetZero Slot – in which vessels using at least one low-carbon fuel with a carbon intensity of less than 75 gCO_2eq/MJ are eligible to compete for a dedicated transit slot, to be offered weekly.[10]

- Many ports provide financial incentives, for example through the Environmental Ship Index (ESI) for vessels that reduce emissions beyond IMO regulations. Rewards are based on scores derived from nitrogen oxides, sulphur oxide, and carbon dioxide emissions reductions, with an additional bonus for ships fitted with onshore power supply installations.[11]

- Under its Maritime Singapore Green Initiative, the Maritime and Port Authority of Singapore offers reductions in port dues for ships using low-carbon fuels like LNG or biofuel blends, with greater reductions for zero-carbon fuels such as hydrogen. Additionally, harbour craft using low- or zero-carbon fuels can qualify for a five-year waiver of port dues.[12]

- The Port of Rotterdam (Netherlands) has established a EUR 5 million incentive scheme to support the development and use of 'climate-friendly fuels', including low-carbon and zero-carbon alternatives. This programme targets shipping companies and fuel suppliers implementing innovative projects to reduce emissions.[13]

- The ports of Los Angeles and Long Beach (USA) have developed the Technology Advancement Program (TAP) which provides incentives for ships demonstrating zero or near-zero emission technologies.[14]



Green shipping corridors – often public-private initiatives – are expected to continue to be an important enabler for the initial development of the fuel market and related infrastructure, through addressing barriers at a smaller scale. So far, 80 green shipping corridors have been announced globally, with some having advanced to a demonstration phase, though most are still in the early planning phase.[15]

These initiatives and other commercial drivers are important in the years leading up to the IMO Net-Zero Framework's entry into force in 2028, which will necessitate a transition for ships in international trade to low-GHG fuels.

4 OUTLOOK ON SHIP TECHNOLOGIES AND FUELS

Highlights

We assess alternative fuel uptake by shipping's major emitters and other decarbonization technology trends, finding:

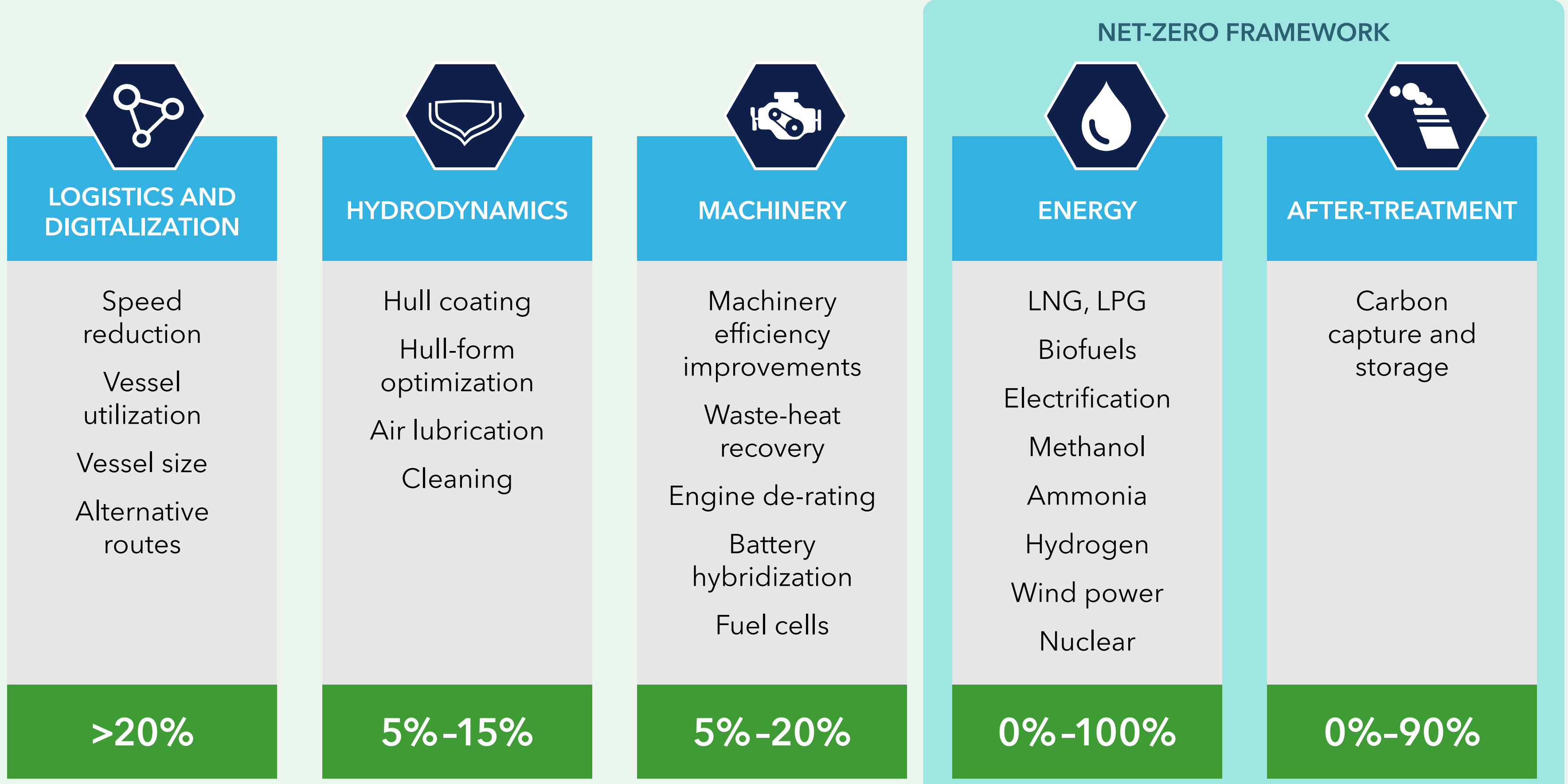
- LNG fuel use is scaling, methanol ships are sailing, and ammonia, hydrogen, and onboard CO_2 capture are in early trials.
- Nearly as many alternative-fuel ships are on order as in service.
- Dual-fuel ships account for 75% of large containership orders, 20% of tankers, and 5% of bulkers.
- Half of containerships above 2,000 TEU are LNG-capable and a quarter methanol-capable.
- Wind propulsion is gaining ground and biofuels are expanding in ports.
- More alternative-fuel ships create urgent need for better crew training and competence.

Our latest data shows owners of shipping's major emitters – large bulkers, tankers and container vessels – ordering more ships that can run on clean alternatives to conventional fuels. We analyse related issues including challenges in using biofuels and modern sails, and identify an already critical need for enhanced crew training for the new fuels.

With the approval of the IMO's Net-Zero Framework (NZF) setting ship-specific requirements for GHG fuel intensity, shipowners face increasing pressure to identify, evaluate, and adopt technologies and fuels that minimize energy use, decarbonize vessels, and fulfil other environmental mandates. The path toward maritime decarbonization is firmly set, with forthcoming additional regulations set to tighten compliance and impose costs on ship emissions. Understanding the current emissions landscape and developing robust decarbonization strategies could be a key success factor. For shipowners and other stakeholders, responses could involve implementing energy-efficiency practices in the short term while preparing for future fuel transitions.

FIGURE 4-1

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



4.1 Status of technology transition

Decarbonizing shipping will predominantly require new fuels and the uptake of onboard carbon capture and storage, but also greater energy efficiency and improved logistics. Pending final adoption, the IMO NZF requires operators to reduce their ships' GFI by 21% by 2030, with financial penalties for those who do not. Beyond 2030, the requirements become even stricter.

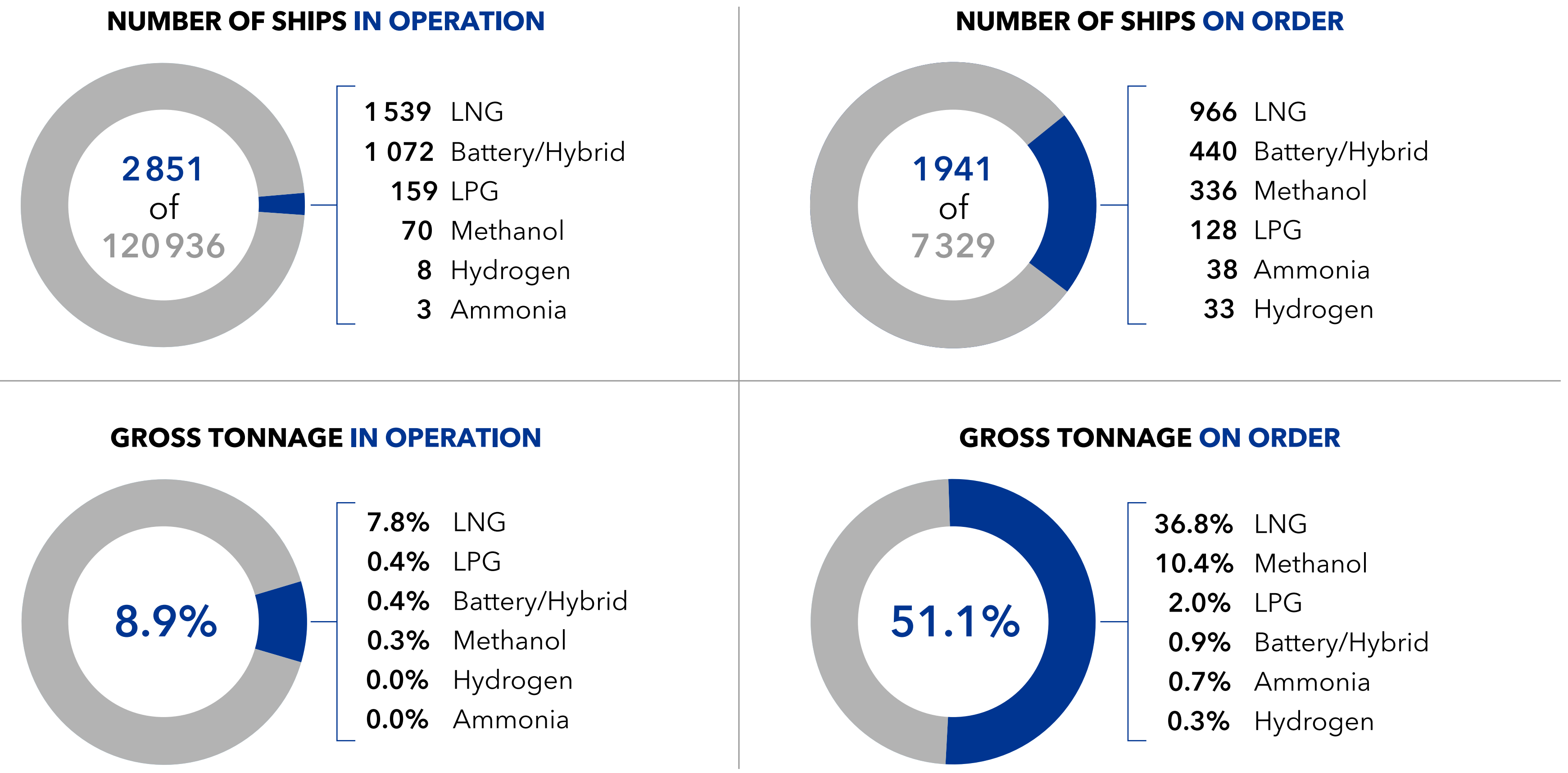
If the supply of sustainable biofuels cannot be increased enough to meet the demand for low-GHG fuels generated by these regulations, there will be a demand for scaling other energy sources to produce alternative low-GHG fuels or storage for CO_2 from onboard capture. This includes 'blue fuels' from reformed natural gas with carbon capture and storage and 'green fuels' (electrofuels (e-fuels) from renewable or nuclear electricity with sustainable carbon or nitrogen); producing fuel types such as ammonia, e-MGO, methanol and methane.

The use of alternative fuels and onboard carbon capture and storage will require new capital-intensive and space-demanding technologies on board, with a corresponding need for training and risk management. There are many solutions that can reduce emissions to meet GHG regulations, reduce penalties, and ensure the long-term profitability of shipowner assets, each with different barriers to implementation and use. Figure 4-1 categorizes decarbonization solutions and highlights which ones will be directly influenced by the IMO's Net-Zero Framework.

The fuels' potential for reducing GHG emissions varies widely in a well-to-tank perspective, depending on the primary energy source, fuel processing, the supply chain, and the onboard energy converter[16]. Low-GHG fuels can be produced from several primary energy sources and production pathways, and the IMO is in the process of devel-

FIGURE 4-2

Alternative fuel technology uptake in the world fleet in the number of ships (upper) and gross tonnage (lower)



Sources: S&P Global, Alternative Fuels Insight (AFI) - afi.dnv.com, as of August 2025

The LNG-fuelled Star of the Seas.

oping Life Cycle Assessment Guidelines[17], detailing how the WtT and TtW GHG emissions of marine fuels should be calculated. Ships will use the LCA Guidelines to calculate their compliance balance (attained GFI and the targets) and potential penalties to be paid. More details are provided in Chapter 3, and modelling cases are presented in Chapter 6. In addition, FuelEU Maritime has already entered into force, establishing well-to-wake GHG emission intensity requirements for ships operating in EU waters, based on the EU's fuel standard.[18]

The transition to new fuels will have to coincide with a corresponding development in onboard fuel technology. As indicated below, the fuel technology transition has begun, with dual-fuel engine technology for LNG a fully mature option and methanol growing rapidly. The use of batteries to store energy for propulsion and as part of energy-efficient hybrid power systems for ships frequently in port is also on the rise. However, the fuel technology shift will take time, even if dual-fuel engines are commercially available and marine fuel cells are emerging as an alternative. Converting existing ships to new fuel technologies is technically complex and costly, and the selection of fuel technologies should take into account that these ships may remain in operation for more than 30 years. Meanwhile, drop-in fuels can be used in existing conventional diesel engines (biodiesel/e-diesel) and in dual-fuel engines for LNG or methanol (bio-methane/e-methane or bio-methanol/e-methanol, in addition to biodiesel/e-diesel), depending on availability and bunkering infrastructure for these fuels.

4.1.1 Fuel technology transition in the order book

The increasing trend of ordering larger ships with dual-fuel propulsion capabilities continues, with a similar share of the gross tonnage on order being alternative fuel-capable, indicating that the fuel technology transition is progressing at a similar rate to last year. By alternative fuels, we mean those for which ships need changes to the machinery system to use them – in other words, fuels that are not oil fuels such as heavy fuel oil (HFO), low sulphur fuel oil (LSFO), MGO, biodiesel or e-MGO. The uptake of LNG is dominating, followed by methanol-capable vessels. Orders for dual-fuel vessels with LPG and ammonia are also shown in the statistics. Figure 4-2 presents the status and details of the uptake of alternative fuel technologies in the world fleet[19] and the order book as of August 2025.

Measuring by gross tonnage, 8.9% of ships currently operating can use fuels other than fuel oil (i.e. alternative fuels), and 51.1% of vessels in the order book. These are slight increases on last year's respective shares, 7.4% and 49.5%. Measured by the number of ships, the percentages are lower: 2.4% in operation and 26.5% for the order book, indicating that larger ships are more frequently opting for dual-fuel solutions.

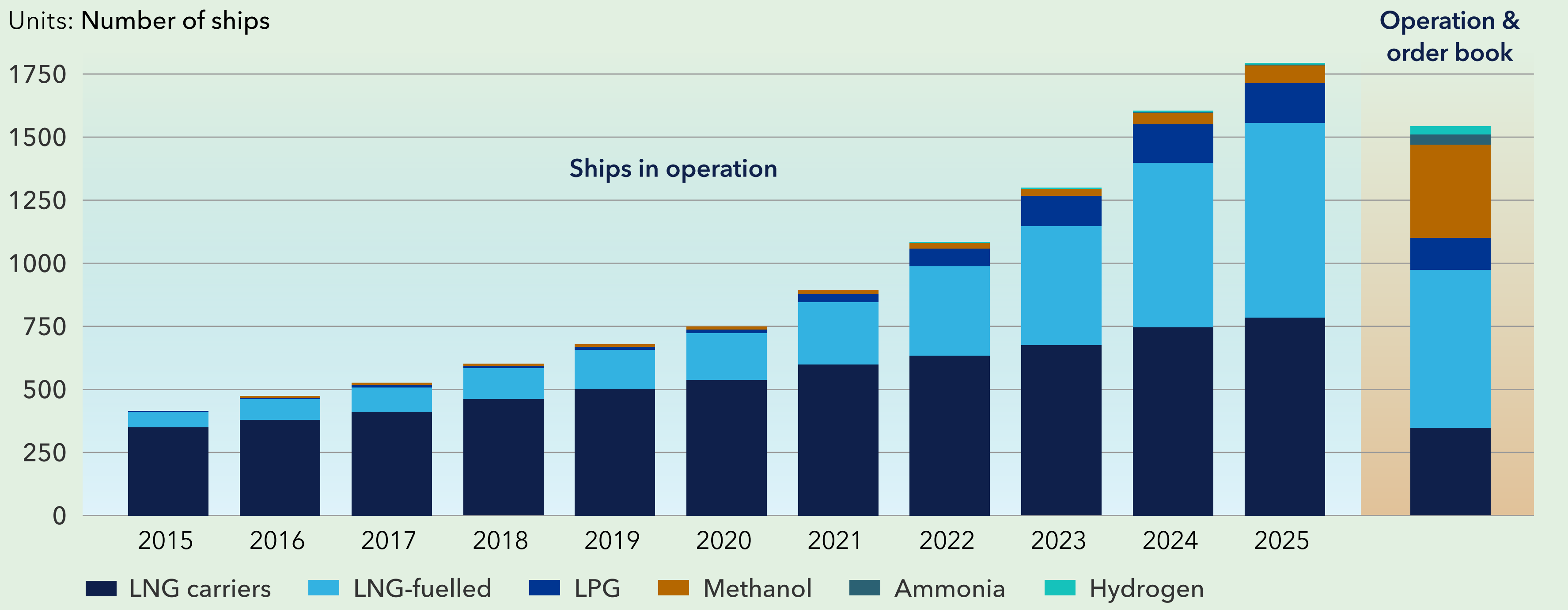
Figure 4-3 shows that the fuel technology transition is continuing, with an increasing number of ships capable of operating on alternative fuels entering the fleet towards 2028. The current order book is set to almost double the number of ships with the alternative fuel capabilities indicated above, with more details shown in Figure 4-4.

After examining the choice of fuel technology options for ships in service and those ordered, we find that:

- In the world fleet, 91.1% of the operational tonnage can only use oil fuels. This means they must rely on drop-in fuels (bio-MGO or e-MGO) to decarbonize fully unless they are converted to use alternative fuel types or onboard carbon capture. For vessels currently on order, 48.9% of the tonnage and 73.5% of the ships are similarly affected.
- Ships with dual-fuel LNG technology account for 7.8% of the total tonnage of ships in operation, while the share is 36.8% in the order book. Excluding LNG carriers that predominantly use boil-off from the cargo as fuel, the respective figures are 3.2% and 27.7%. LNG continues to be a favoured fuel technology option in the containership category, with 359 vessels currently ordered, up by 171 from last year. Other segments show similar figures as last year: the car carrier segment has 106 vessels on order, along with 90 tankers and 16 bulk carriers using LNG as fuel. The cruise ship sector has 25 ships on order. LNG carriers constitute 768 of the LNG-fuelled ships in service, while another 343 are on order. In total, 1,539 LNG-capable ships are currently sailing, while 966 are on order.
- The use of LPG as a marine fuel is restricted to LPG carriers. LPG uptake has yet to be seen for other ship types. Currently, 159 LPG carriers can use their LPG cargo as fuel, representing 0.42% of the total world fleet tonnage. Additionally, with 128 LPG carriers on order, 2.0% of the order-book tonnage has LPG-burning capacity.
- Methanol-capable (dual-fuel) vessels account for 0.3% of the world's fleet tonnage in operation and 10% of the tonnage ordered. The containership segment continues to have the highest number of methanol-fuelled ships on order, totalling 210. The number of methanol-capable bulk carriers in the order book has roughly doubled from 24 to

FIGURE 4-3

Growth of alternative fuel technology uptake



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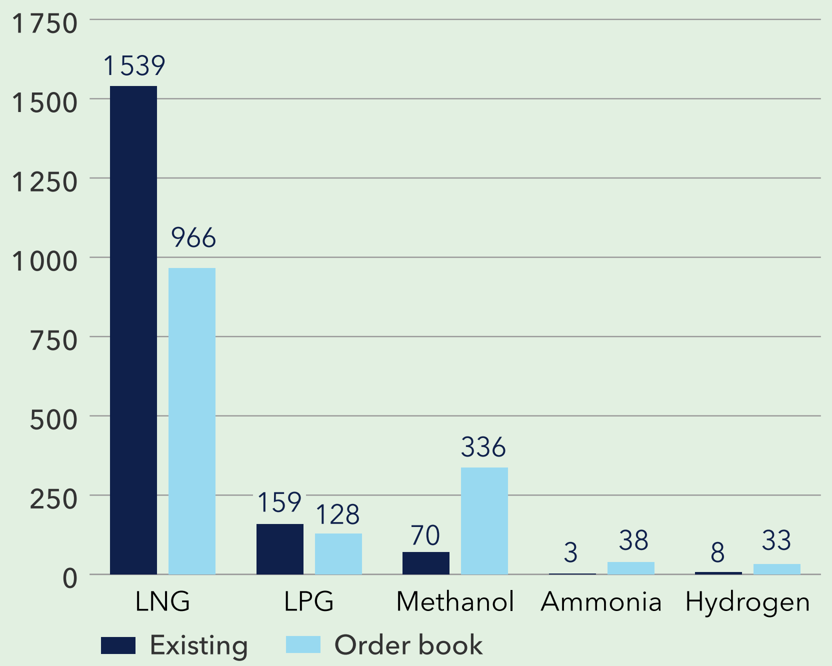
> 91.1% of the operational tonnage can only use oil fuels. They must rely on drop-in fuels (bio-MGO or e-MGO) to decarbonize fully unless they are converted to use alternative fuel types or onboard carbon capture.

FIGURE 4-4

Number of ships with alternative fuel capabilities in the order book compared to the existing fleet (incl. LNGC)



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59 ships, while the car carrier segment remained steady at 23 ships.

- Ferry operator Torghatten is set to receive two 120-metre ferries powered by compressed hydrogen in 2025 as a result of a public procurement of green ferry services. Meanwhile, Dutch logistics provider Samskip has placed an order for two 700 TEU containerships at the Cochin shipyard in India, with plans to equip them with hydrogen-fuelled fuel cells. Additionally, various hydrogen initiatives are being developed for smaller vessels.

- 38 ammonia-capable (dual-fuel) vessels are on order, with 12 bulk carriers and 21 LPG carriers constituting the majority.

- In addition to vessels that can utilize alternative liquid and gaseous fuels, there are currently 1,072 vessels in operation equipped with batteries, predominantly in hybrid systems with varying potential for electric propulsion and/or energy optimization of engines. 440 ships on order will incorporate batteries. Examples of battery-hybrid vessels with up to 100% electric propulsion in operation includes many of the battery-powered ferries in Norway.

- The number of LNG bunker vessels serving the existing fleet of LNG-fuelled ships grew from 53 to 62 ships over the last year, with new vessels sized to fit the fuel carriage capacity of large ships. The order book shows that 30 new LNG bunker vessels are scheduled for delivery over the next few years. The tank capacity is increasing with the increase in large capacity LNG-fuelled ships. Bunkering vessels on order have capacities ranging from 7,500 m³ to 20,000 m³, with the majority falling within the upper range. The number of bunker barges capable of carrying methanol has increased from 7 to 10 vessels over the last year, with 5 more in the order book. Almost all of them have their home port in Singapore.

It is important to note that most ships capable of using alternative fuels have dual-fuel solutions. Battery-electric ships (plug-in hybrids capable of sailing on batteries charged with shore power) almost always include oil-fuelled generator sets as backup. Furthermore, the alternative fuel may still originate from fossil energy sources, emphasizing the necessity for regulations that address GHG emissions from a well-to-wake perspective.

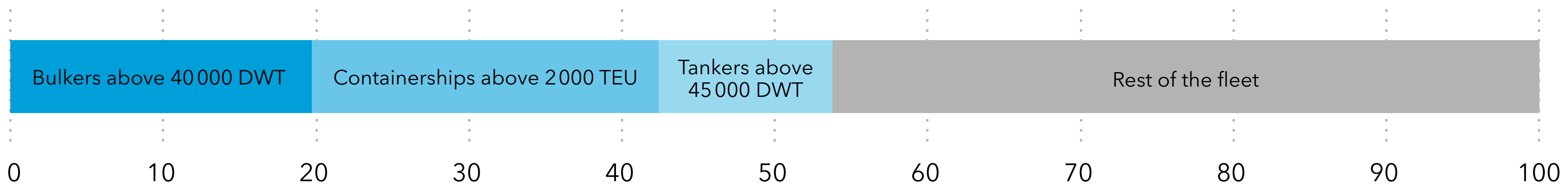
4.1.2 Status of fuel technology transition for large bulkers, tankers and containerships

Transitioning to low-GHG fuels or implementing onboard carbon capture is crucial for significantly lowering total emissions from shipping, surpassing what energy-efficiency measures alone can achieve. As outlined in Chapter 5, in principle, all vessels designed with the capability to operate on fuel oil can utilize drop-in biofuels (biodiesel), but the global

FIGURE 4-5

Share of emissions from bulkers, tankers, and containerships compared to total world fleet CO_2 emissions (TtW)

Units: Share of world fleet CO_2 emissions (%)



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Yara Eyde – a 1,400 TEU ammonia-fuelled containership set to operate between Norway and Germany from mid-2026.

supply is uncertain and may not satisfy demand. Therefore, conversion to alternative and low-GHG fuels, along with carbon capture and storage (CCS), might be required.

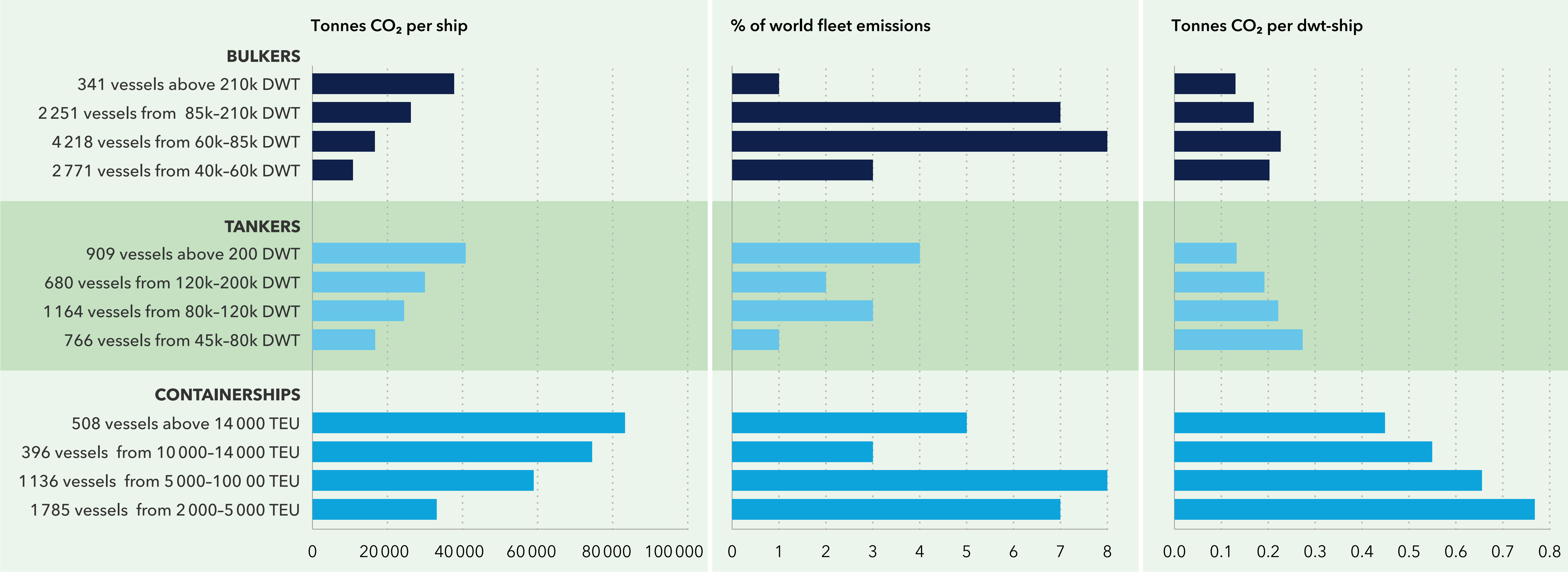
The industry is, to some degree, reacting to this, as reflected in half of the order book consisting of dual-fuel capable vessels. Furthermore, some conventionally fuelled ships are being constructed, with measures implemented to facilitate easier conversion to alternative fuels or CCS technologies.

Tankers, bulk carriers, and containerships feature relatively uniform designs, powerful main engines, and are built in large quantities. As a result, they contribute substantially to the GHG emissions from shipping. Analysing the decarbonization efforts in these sectors could provide a more nuanced understanding of the uptake of alternative fuel technologies among major GHG emitters. Figure 4-5 shows the emissions from larger vessels within these segments (bulk ships over 40,000 DWT, tankers over 45,000 DWT, and containers with a capacity of 2,000 TEU or more) in relation to the total world fleet emissions.

Their emissions account for approximately 54% of the global fleet's tank-to-wake CO_2 emissions. In Figure 4-6, we break this down further, looking at CO_2 emissions per ship, what percentage of total emissions each size segment represents, and their 'environmental effectiveness' measured as CO_2 emission per DWT per ship.

FIGURE 4-6

Annual emissions from large bulkers, tankers, and containerships (in total 17 025 vessels*)



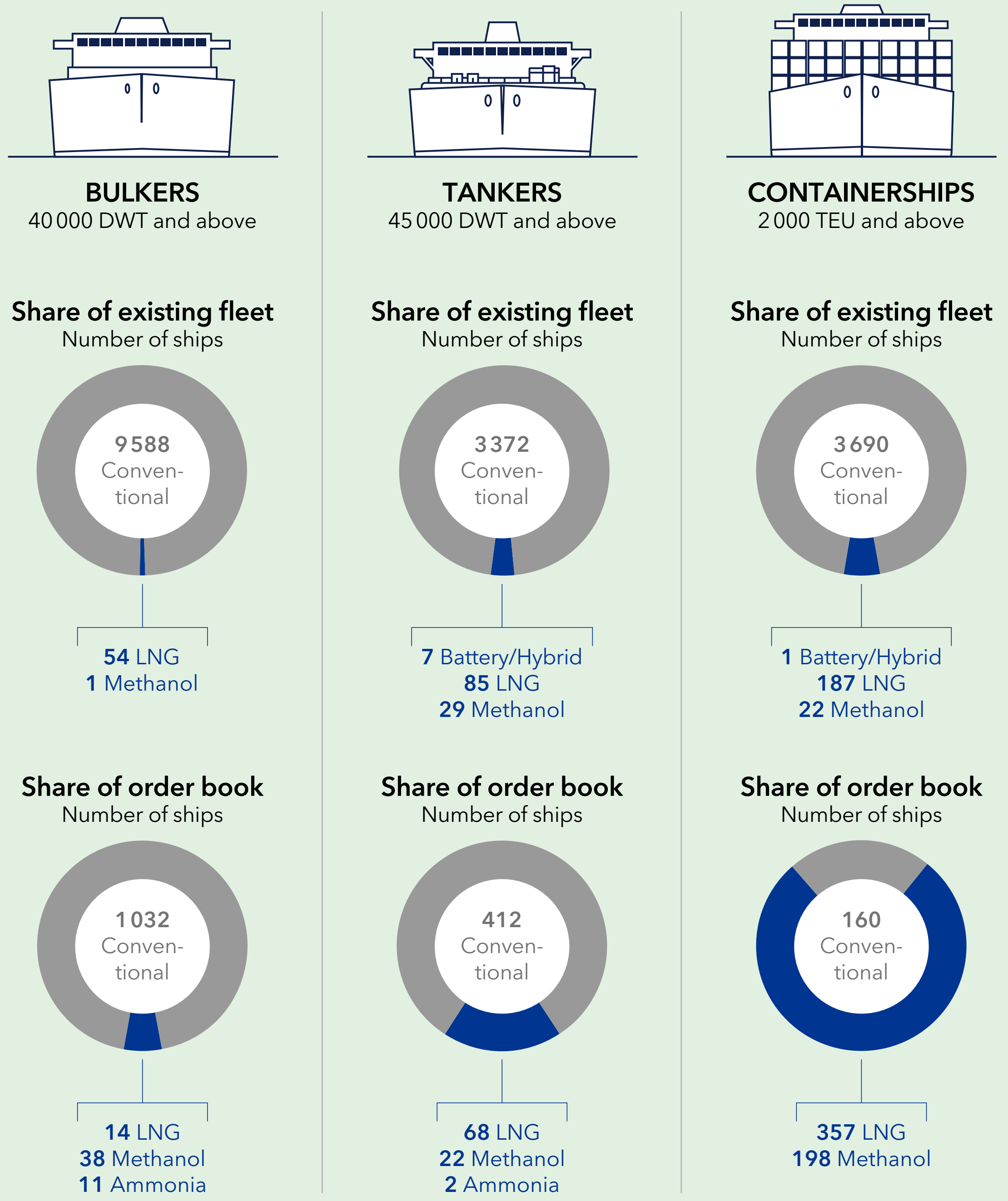
Source: 2024 AIS data; *World fleet is all ships with an IMO number, which is mandatory for passenger ships of 100 GT and above and cargo ships of 300 GT and above

The container segment has the highest emissions per ship on average, as well as per deadweight tonnage capacity, because they typically have the largest engines and high service speeds. Even the smaller container feeders contribute significantly to emissions due to relatively high installed engine power. The largest containerships (14,000 TEU and above) generate the most emissions per vessel across all three vessel categories. Nevertheless, when considering emissions per deadweight tonnage, these vessels are almost twice as efficient as container feeder vessels.

Containerships with capacities between 5,000 and 10,000 TEU, along with the bulkers in the 60k to 85k DWT segment, account for the highest share of total emissions. The largest tanker size segments, very large crude carriers (VLCCs, of 200,000+ DWT) have both the highest average emissions per ship and the highest total emissions within the ship segment. Again, it is worth noticing the increase in efficiency in terms of CO_2 emissions per deadweight tonnage when the size of the vessels increases. The bulk segment has a large number of ships and a large share of the total fleet emissions. Bulkers between 60k and 85k DWT are significant contributors to fleet emissions due to the large number of vessels.

FIGURE 4-7

Uptake of alternative fuel technologies for large bulkers, tankers and containerships



Source: Alternative Fuels Insight (AFI) - afi.dnv.com, as of August 2025

> Trading patterns, cargo owners' willingness to pay a premium for green transport, asset value, and technical challenges affect shipowners' willingness to invest in alternative fuel-capable ships.

Considering the findings on page 27, decarbonization efforts for large ships in the tank, bulk and container segments will have a significant effect on the overall emissions from shipping. As illustrated in Figure 4-7, we have isolated these three segments to examine how each segment evolves in terms of adopting alternative fuel technologies.

As indicated in Figure 4-2, vessels capable of operating on alternative fuels account for 2.3% of the existing world fleet, while the share is 28% for the total order book.

Examining the bulk carrier segment of 40,000 DWT or larger, only 0.6% of the vessels can utilize alternative fuels other than drop-in oil-based green options, while the share is 5.2% in the order book.

In the existing tanker segment, ships of 45,000 DWT or larger have an alternative fuel share of 3.4% in terms of the number of vessels, with a corresponding share of 18% in the order book.

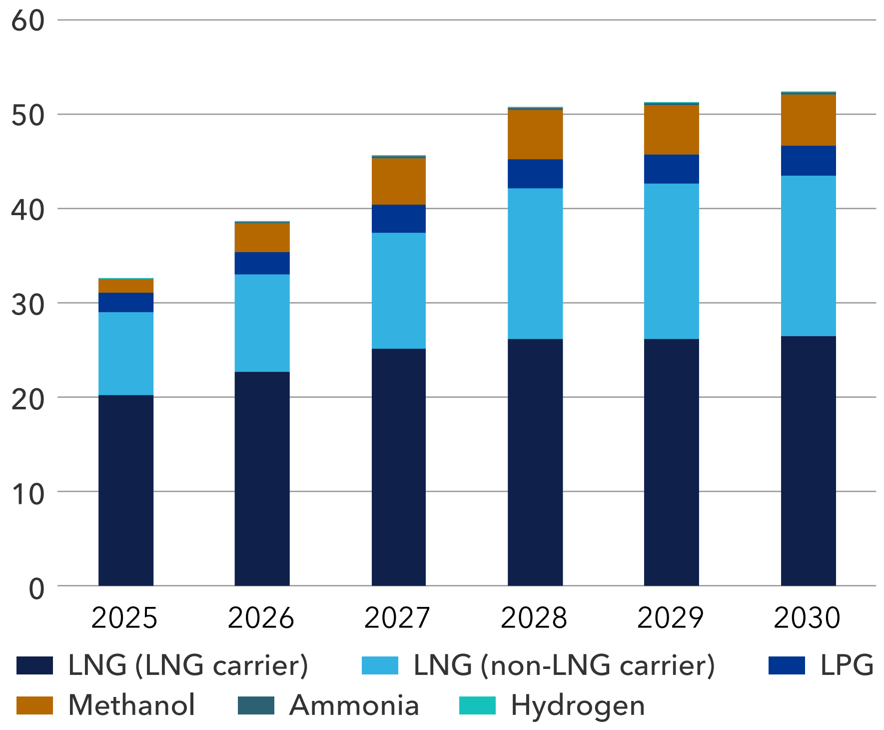
The ratio is higher for containerships with a carriage capacity of 2,000 TEU and above compared to tankers and bulk carriers, and it is also significantly higher than the world fleet average. Currently, 4.7% of existing containerships and 76% of the order book have alternative fuel storage and power generation systems.

This picture fits the arguments that trading patterns, cargo owners' willingness to pay a premium for green transport, asset value, and technical challenges affect shipowners' willingness to invest in alternative fuel-capable ships. Vessels with lower asset value make it harder for owners to justify any increase in capital expenditure, and irregular trading patterns are detrimental in relation to potential fuel availability. This is reflected in the bulk carrier segment exhibiting the least uptake in terms of ships in operation and the order book. The higher uptake of alternative fuel-capable ships in the segment for large container vessels indicates that there can be a higher willingness from freight buyers in this segment to pay a premium to reduce their scope 3 emissions from ocean freight.

FIGURE 4-8

Maximum consumption of LNG, LPG, methanol, ammonia and hydrogen for the world fleet and vessels in the order book

Units: Maximum consumption by fuel-type (Mtoe)



 Source: Alternative Fuels Insight (AFI) - afi.dnv.com, as of August 2025

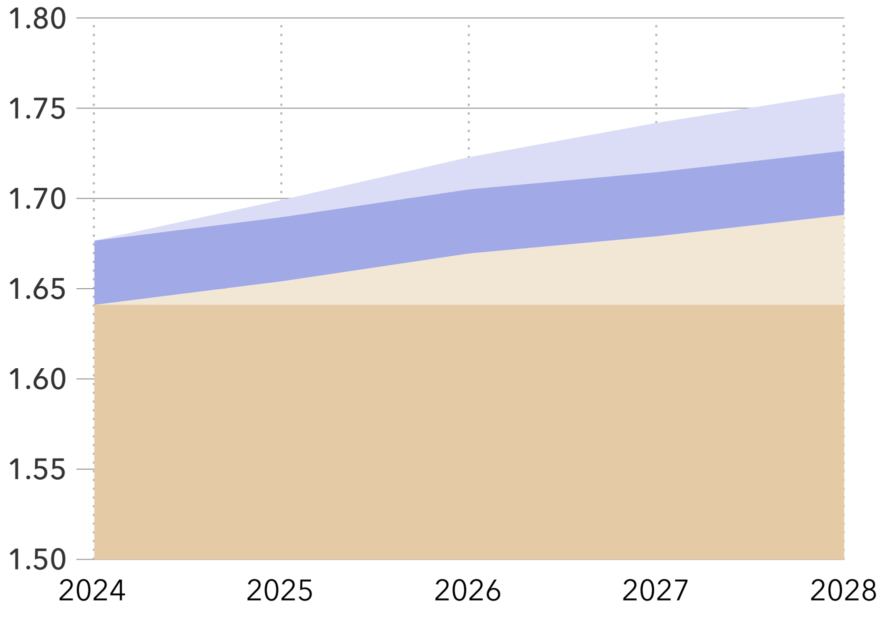
Potential fuel consumption for fleet in operation and order book

Figure 4-8 shows the estimated potential fuel consumption of the fleet in operation and order book, assuming all vessels utilize their maximum capacity to operate on alternative fuels. In total, we estimate a total potential alternative fuel consumption of about 50 Mtoe when the order book is delivered by 2030. LNG accounts for the highest potential fuel consumption, partly due to the existing LNG carrier fleet, followed by methanol and LPG, and finally ammonia and hydrogen.

FIGURE 4-9

Seafarers on existing and ordered seagoing ships by fuel type

Units: Number of seafarers (millions)



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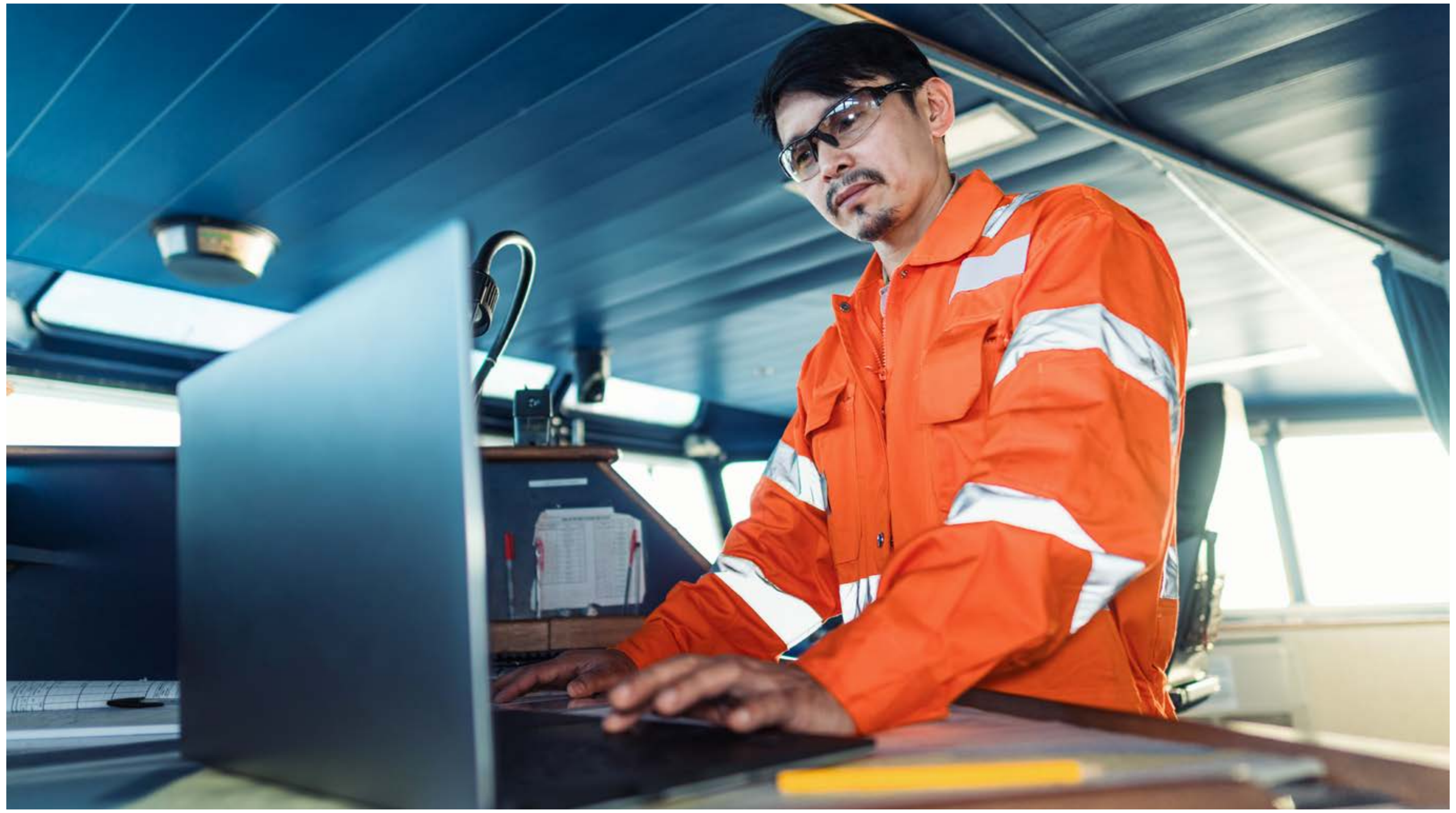
4.1.3 The competence development challenge

Based on the current order book, the number of alternative fuel-capable vessels is set to nearly double between 2024 and 2028. As a result, we estimate that around 33,000 additional seafarers require alternative fuel training over the next three to four years, to operate the alternative fuel-capable newbuilds set to enter operation during this time[20] (see Figure 4-9). This indicates that the maritime industry faces an urgent challenge in competence development, and that additional training capacity is needed.

As dual-fuel operations are expected to become common, shipping organizations must foster a proactive safety culture along with effective safety management. This relies heavily on the robustness of the company's Safety Management System (SMS) and its capability to recognize improvements by learning from non-conformities, accidents and hazardous occurrences related to alternative fuels. Consequently, the Maritime Technologies Forum (MTF) has developed guidelines[21] to strengthen the SMS for alternative fuels on ships, together with industry stakeholders. More recently, the MTF has published SMS guidelines[22] specifically for ammonia-fuelled ships, with key recommendations related, for example, to mechanisms for continuous improvement, clear lines of communication, training and familiarization, procedures and contingency planning.

The IMO STCW (Standards of Training, Certification, and Watchkeeping) convention and its associated model courses sets the standard for the training and certification of seafarers worldwide. At present, there are no STCW courses available for fuels like methanol, ammonia, and hydrogen. However, interim generic guidelines for the development of training provisions for seafarers on ships using alternative fuels and technologies were submitted to MSC 110 in June 2025 for approval. The development of fuel-specific guidelines will continue in 2026. Until STCW courses for seafarers on ships utilizing methanol, ammonia or hydrogen as fuels are in place, training should be developed based on existing resources in consultation with the Flag Administration. In the meantime, other stakeholders, including the European Maritime Safety Agency EMSA, Flag Administrations and classification societies, are working on defining competence requirements and recommendations. DNV has developed a competence standard for methanol fuel (DNV-ST-0687) and a recommended practice for the onboard use of ammonia as fuel (DNV-RP-0699).



4.2 Biofuels

Biofuels present an attractive decarbonization option in shipping due to their compatibility with existing vessels, offering a drop-in capability.[23] For biodiesels and bioliquids replacing distillates and fuel oils, drop-in capability varies based on feedstock, production processes, and refining levels. Users must evaluate each biofuel type individually to ensure that fuel specifications and quality match the intended applications, thereby preventing damage to equipment and power loss.

Various biofuels are available for maritime use, with fatty acid methyl ester (FAME) and hydrotreated vegetable oil (HVO) being the most recognized and widely used today. FAME, often called biodiesel, is made from fats, oils, and greases (FOGs) through transesterification, and its exact characteristics

TABLE 4-1

CII reduction factors from 2027 to 2030

(Baseline: MGO)	FAME	HVO
Energy content	Lower	Comparable
Cetane number	Comparable	Higher
Density	Comparable	Slightly lower
Viscosity	Slightly higher	Slightly lower
Material compatibility	Incompatible with certain materials*	Comparable
Flash point	Higher	Comparable
Lubricity	Good**	Poor
Cold flow properties* **	Poor	Good / Comparable
Storage stability	Poor	Good / Comparable

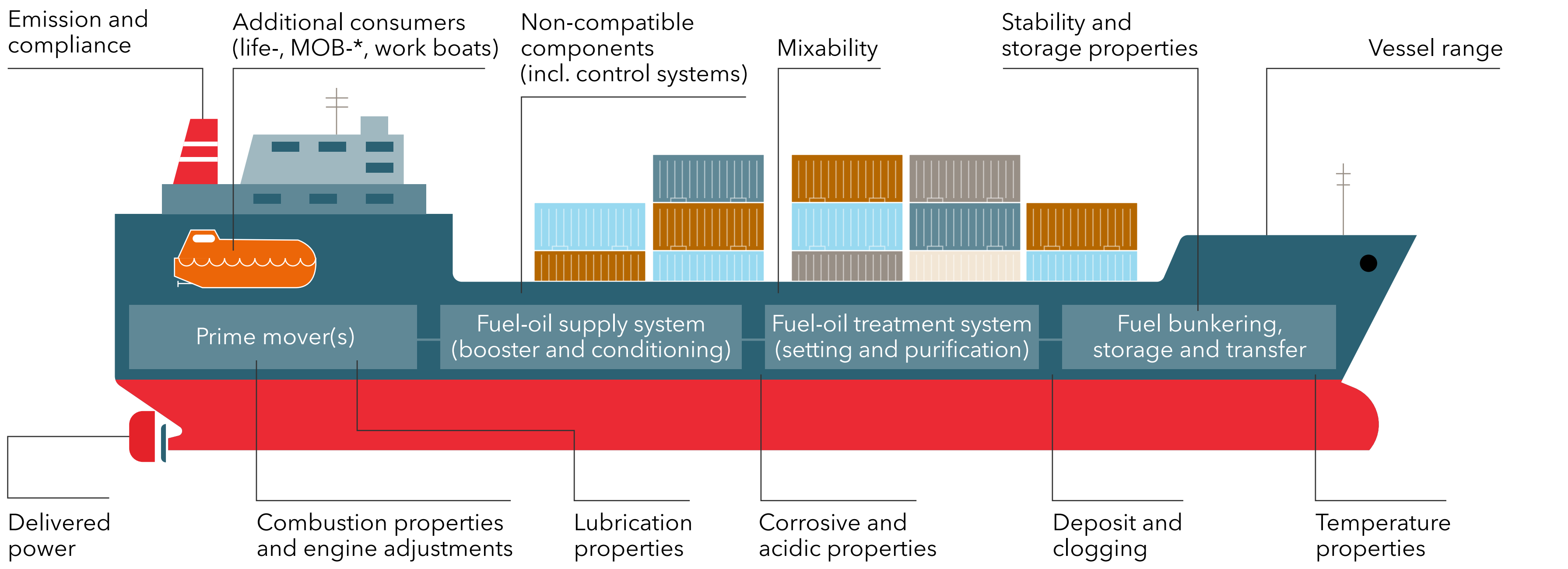
*Corrosive activity varies with quality indicators such as acidity; **FAME maintains good lubricity despite having a very low sulphur content; ***Cloud Point (CP), Pour Point (PP), and Cold Filter Plugging Point (CFPP) depend on the feedstock. HVO, or renewable diesel, is produced from FOGs via hydrotreatment, resulting in paraffinic hydrocarbons suitable for most current fuel systems and engines. The fuel properties differ among biofuel products and blend ratios. Table 4-1 shows fuel properties of pure HVO and FAME compared to MGO.

HVO and FAME possess distinct properties, some of which may present challenges for onboard system components. HVO is recognized as a drop-in fuel and can, in practice, serve as a substitute for fossil diesel grades in the majority of MGO-compatible engines. Compared to MGO, HVO has a similar flashpoint, good cold temperature tolerance, robust stability, and oxidation properties, and is generally comparable in terms of microbial growth and material compatibility. Although HVO is a high-quality product, its potentially lower density, viscosity and lubricity mean some adjustments may be needed before it can be used.

FAME comes with relatively good combustion and lubricity properties. Still, it poses some challenges compared to standard oil fuels, particularly in terms

FIGURE 4-10

Essential factors to consider before and during the use of biofuels on ships: these topics may affect one or multiple onboard systems and are not specific to any particular fuel or blend



*MOB boat: man overboard rescue boat

of stability (degradation), corrosivity, and cold flow properties.

It is emphasized that FAME and HVO are fundamentally different fuels with distinct properties. Their technical compatibility with onboard systems varies not only from each other but also from ship to ship, necessitating individual assessments. Nevertheless, industry feedback indicates that operations generally proceed without significant problems, provided the transition is well-planned and executed. Figure 4-2 highlights key factors relevant to a ship during this process.

Using the four subsystems illustrated in Figure 4-10, Table 4-2 goes further into detail and summarizes technical and operational considerations for each subsystem.

Biofuels can, in many cases, be a technically feasible and practical solution for meeting the requirements to reduce GHG emissions. With the growing emphasis on sustainability, it may be beneficial to maintain transparency with charterers by indicating whether a ship is equipped and ready to operate on biofuels.[24] The summary provided in Table 4-2 should be considered general advice, as the considerations for introducing HVO or FAME will vary from ship to ship. It is always recommended to verify the details with the original equipment manufacturer and, if necessary, conduct a risk assessment before introducing the new fuel.

TABLE 4-2

Summary of general and subsystem-specific factors to consider before and during the use of FAME and HVO on ships: the general considerations may be relevant for several subsystems

<table>
<tr><th>Sub-system</th><th>FAME</th><th>HVO</th></tr>
<tr><td rowspan="2">General considerations</td><td>• Material compatibility: Verify the compatibility of metals, elastomers, and rubber compounds, and replace them as needed.
• Cold flow properties: Verify according to expected conditions due to poor low-temperature tolerance.</td><td>• Flash point: To be confirmed within the applicable limit (60°C).</td></tr>
<tr><td colspan="2">• Filters: To be monitored according to established routines during normal operation, with extra attention during initial trials.
• Fuel mixing: Avoid or minimise mixing to the extent possible.
• Fuel specification: Utilise recognised standards and specify additional requirements based on anticipated conditions. Avoid off-spec fuels.
• Fuel analysis: Request supplier pre-test and conduct drip or bunker sampling to verify fuel quality.</td></tr>
<tr><td rowspan="2">Storage and transfer</td><td>• Stability: Monitor temperature and avoid water ingress and contaminants.
• Storage time: To be monitored. Fuel analysis may be relevant if storage is prolonged (typically beyond 3 months, depending on various factors).</td><td></td></tr>
<tr><td colspan="2">• Prepare tanks: Empty, clean, and dry to the extent possible before introducing the new fuel. Maintain proper housekeeping measures.
• Thermal management: Monitor fuel temperature to accommodate for cold flow properties.</td></tr>
<tr><td rowspan="2">Treatment and purification</td><td>• Purification: Review compatibility and adjust as needed according to fuel specifications.</td><td>• Purification: Review compatibility and adjust as needed according to fuel specifications. Note that the density of HVO may be lower than that of MGO.</td></tr>
<tr><td colspan="2">• Thermal management: Monitor fuel temperature to accommodate cold flow properties.
• Tank drainage and preparation: Empty, clean and dry to the extent possible. Regular draining of water and potential sludge.</td></tr>
<tr><td>Fuel supply</td><td>• Viscosity: Ensure proper viscosity control. FAME may have slightly higher viscosity than MGO.</td><td>• Viscosity: Ensure proper viscosity control. HVO may have slightly lower viscosity than MGO.</td></tr>
<tr><td rowspan="2">Consumers</td><td>• Fuel consumption: Increased consumption may result from a lower calorific value (LCV).
• Lubricity: Verify according to the original equipment manufacturer's recommendations. Lubricity is considered good despite its low sulfur content.</td><td>• Lubricity: Verify according to the original equipment manufacturer's recommendations. HVO has low lubricity due to low sulfur content.</td></tr>
<tr><td colspan="2">• LCV: Adjust according to energy content to ensure efficient operation, as power output, limiters, and engine power limitation may be affected if changes in LCV are not accounted for.
• Internal leakages: May become evident due to factors such as low viscosity (HVO), incompatible materials (FAME), or worn pump and injection components.</td></tr>
</table>

* Corrosive activity varies with quality indicators such as acidity; ** FAME maintains good lubricity despite having a very low sulfur content; *** Cloud Point (CP), Pour Point (PP), and Cold Filter Plugging Point (CFPP)

4.3 Wind

Wind-assisted propulsion system (WAPS) technologies on the market or under development all operate based on the same physical principle of generating aerodynamic thrust for the vessel by directly harnessing wind power.[25] The importance of this technology will increase with high penalties for emissions and uncertain levels of production of low-GHG fuels. Under the IMO's Net-Zero Framework, wind propulsion will be included in the GFI calculation, which is likely to improve significantly the business case for WAPS.

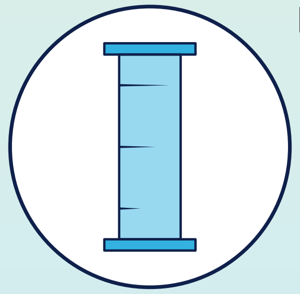
Typically, WAPS are categorized into five groups, each with distinct characteristics that determine their suitability for specific use cases. These characteristics may influence their installation on specific ships or ship types, their operation in particular geographic areas, weather zones, or trades, or their compliance with specific prerequisites, conditions, or restrictions. Most modern systems installed on seagoing ships now utilize state-of-the-art intelligent control and automation systems to operate safely and efficiently, minimizing the need for direct human interaction. A combination of advanced aerodynamics, automation, computer modelling and modern materials is unlocking a new generation of innovative sail systems.

Designing for WAPS

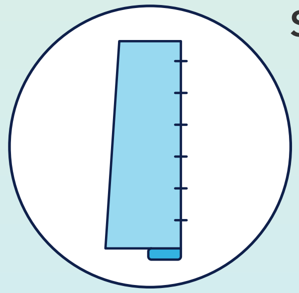
When assessing the feasibility of a specific WAPS installation, it is important to identify the design and operational challenges that must be addressed for the successful implementation of the system. Installing WAPS on a vessel imposes specific requirements for the ship's structure and design and will have implications for the vessel's operation, as well as for compliance with safety and environmental regulations. The ship type and size, along with their main particulars, dictate varying technical considerations and constraints. Whether constructing a new vessel or retrofitting an existing one significantly impacts the range of feasible solutions. The choice of specific WAPS technology influences onboard integration and related engineering challenges. Additionally, the desired level of supplemental wind power for ship propulsion affects the scale of the sail unit and the complexity of machinery systems. Finally, the operational trade routes, including prevailing winds, weather patterns, and local regulations, also affect the technical and economic feasibility.

The importance of WAPS will increase with high penalties for emissions and uncertain levels of production of low-GHG fuels.

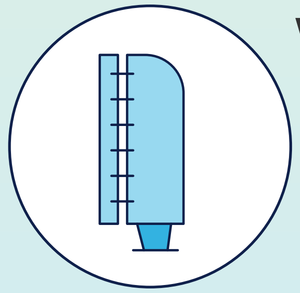
Overview of WAPS technologies



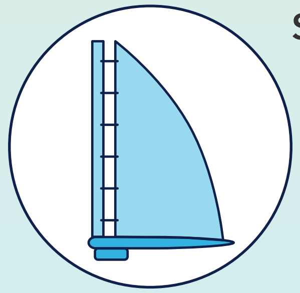
Rotor sails – A rotor sail is a cylindrical structure rotating around its axis. Aerodynamic lift[26] is generated by the so-called 'Magnus Effect', which produces a pressure differential through surface friction enhanced by rotation. The rotor does not need trimming against the wind angle, making operation relatively simple. Clockwise and anticlockwise rotation is required when the wind is coming from the port or starboard side. Rotor sails require a continuous supply of electrical power to maintain their spinning speed. Nonetheless, this power consumption is marginal in comparison to the propulsion power output. The aerodynamic efficiency of a rotor sail relies on the ratio between wind speed and surface speed, with revolutions being limited for practical reasons. Disconnecting the electrical power supply halts rotor operation and lift generation. Rotor sails can come equipped with a tilting mechanism to aid port operations, passing under bridges, or to reduce air draft.



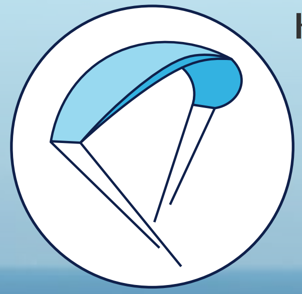
Suction sails – The suction sail is a short-span wing- or oval-shaped vertical structure. An electric-powered suction system delays aerodynamic flow separation by sucking air through the leeward perforated surface, increasing the generated lift and reducing drag. Suction sails need to align with the incoming wind direction with an optimum angle of attack. The operation of the suction fan requires a continuous supply of electrical power, although this is small compared to the propulsion power output. To achieve aerodynamic efficiency, wind suction flow volumes need to be optimized for different wind conditions. Cutting off the electrical power supply stops the operation and lift generation. Suction sails can be fitted with a tilting mechanism to facilitate port operations or reduce air draft.



Wing sails – A wing sail is a foil structure that typically features high-lift devices like flaps to enhance lift generation. Well explored through aeronautical applications, the aerodynamic efficiency is relatively high compared to conventional sails. Wing sail aerodynamics are very similar to those of airplane wings. Rigid wing sails are constructed from hard shells, whereas soft and hybrid wing sails utilize modern textile materials. This results in distinct characteristics, particularly regarding weight. Wing sails need to align with the incoming wind direction with an optimum angle of attack. A wing sail is made up of several elements that can be cambered to enhance aerodynamic forces. Wing sails often need to be tiltable for port operations, to reduce air draft, or to protect them from high winds.



Soft sails – Soft sails come in a wide variety of configurations and form the historical foundation of sailing technology. A soft sail is a flexible fabric suspended between a supporting mast and a boom, often stabilized by sail battens. The materials and manufacturing of sailcloth can be customized to meet specific demands, such as high performance, stretch, or durability. Soft sail systems fitted on seagoing vessels must also adhere to the overall objective of functioning without physical human interaction.



Kites – A kite is a tethered sail made of lightweight material, guided by ropes and flying at high altitudes. Often, aerodynamic performance is enhanced by dynamic motion. In contrast to the other systems introduced, a kite performs best only in the downwind sector.

The tables below describe several requirements and implications related to ship design and operation. As described before, the importance or applicability of each depends on the specific project. However, understanding these requirements in the early project phase is crucial for determining the feasibility of an installation on a specific ship.

Adoption of WAPS is anticipated to increase significantly over time due to international and regional GHG regulations.

Uptake of Wind-Assisted Propulsion Systems

Today, 64 ships have installed modern wind-assisted propulsion systems (Figure 3-1). Although this represents only a small fraction of the global fleet, the adoption of WAPS is anticipated to increase significantly over time due to international and regional GHG regulations.

The recent rapid uptake is demonstrated by the 56 ships built or retrofitted after 2020, with retrofitting accounting for approximately 75% of these. Large ships prevail, as indicated by a total of 3.8 million DWT with installed WAPS. Figure 3-2 shows that three different technologies characterize the uptake. For bulk carriers and tankers, the predominant WAPS technologies today are rotor sails with 54% market

TABLE 4-3

Design and operational considerations for WAPS installations

Design considerations	
Free air and deck space	WAPS require airflow that is as undisturbed as possible, and sufficient deck space to place the foundation.
Structural integration	WAPS generate substantial forces. Particularly for retrofits, individual extra deck reinforcements are unavoidable.
Intact stability	By their excitation or aerodynamic forces, WAPS must be included in intact stability calculations.
Installation in hazardous zones	Specific requirements apply to electrical installations in hazardous zones of ships, requiring equipment to comply with applicable standards.
Added weight	WAPS increase the lightship weight, leaving less for cargo.
Air draft	WAPS will, in many cases, increase the vessel’s air draft. Depending on the trade route and its potential obstructions (e.g. bridges), the WAPS may require a retraction system.
Mooring	WAPS may influence the equipment numeral, thereby influencing requirements for mooring and anchoring equipment, and retrofits might obstruct the mooring configurations.
Performance optimization	It is essential to carefully consider the placement of the WAPS on the deck. Ensuring free airflow is essential, and the longitudinal positioning can significantly affect course stability.
Navigational; line of sight, navigation lights, radar sector	WAPS are quite substantial obstacles and may impair some navigational regulations.

Operational considerations	
Robustness/reliability/ operational safety	WAPS need to be robust, reliable and safe in operation to comply with SOLAS. Note that the crew size in most cases will not be increased when such systems are installed.
Interference with deck/cargo handling	For ships where cargo handling involves the use of grab cranes or belt conveyors, WAPS should be designed to move out of their operational range.
Engine and propeller derating	Additional thrust from WAPS may impact the optimal operation profile of the engine and propeller, and therefore reduce the efficiency of the existing propulsion engine and propeller (retrofits).
Manoeuvrability	WAPS impose large side forces on a ship and may impair its manoeuvrability.
Crew training	Even though most WAPS are automated and fail-safe, the crew should be educated on operation, possible emergency scenarios, and the physics behind sailing.
Port operations, pilots, towage, channels, locks	There might be restrictions, special rules, or extra costs for WAPS-equipped ships.
Interference with helicopter/ evacuation procedures	Free access must be granted to enable operations.

share, while for general cargo ships, 67% of WAPS solutions are suction sails. This may, however, be attributed not only to the type of ship but also to available WAPS sizes; rotor sail manufacturers offer larger units commercially. Rotor sails account for almost 50% of the current WAPS uptake overall.

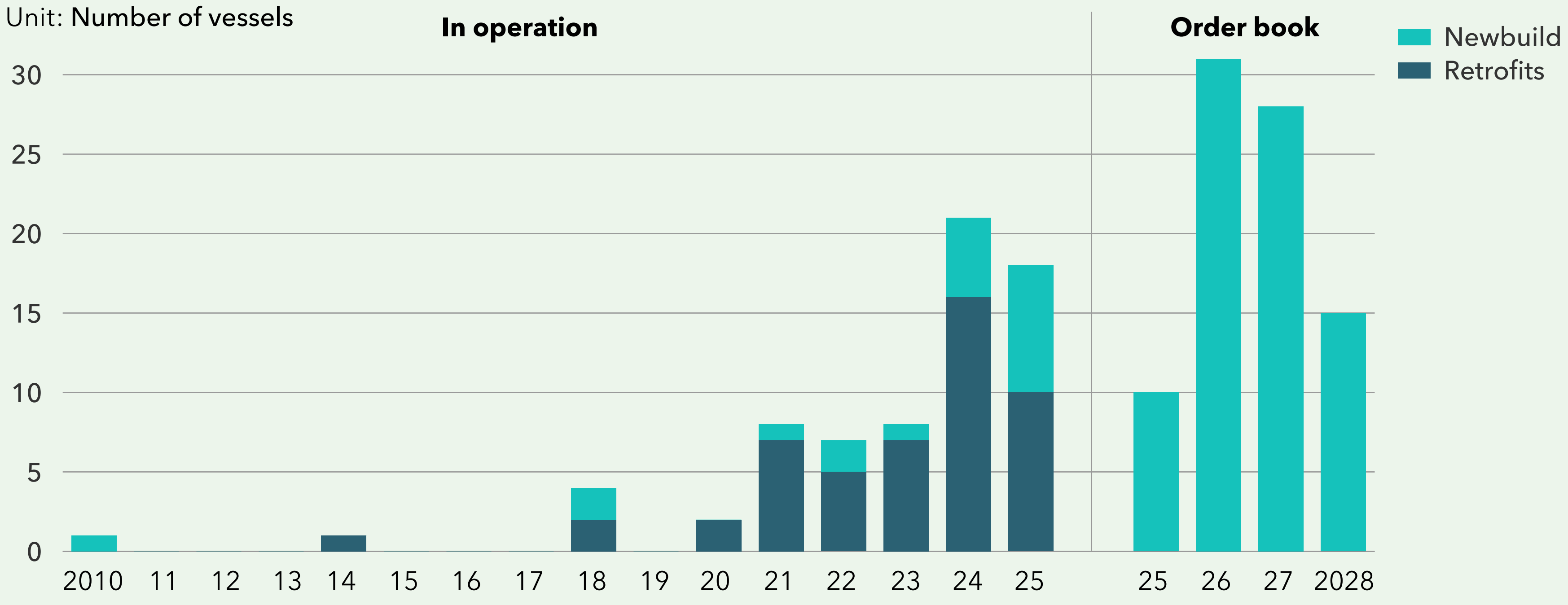
Considering the current order book, we observe 84 ships featuring WAPS technologies (Figure 4-12) of which more than half are tankers and bulk carriers. A significant increase in newbuilds is anticipated in 2025 over 2024, with substantial numbers also present in the current order book for 2026 and 2027 (Figure 4-11). As retrofits are not included in the order book, the WAPS fleet is projected to expand more than indicated by the order book in the years ahead.

In recent years, developments in the industry have demonstrated that the installation of WAPS is not limited to particular types of ship. Retrofitting WAPS can be accomplished on nearly any vessel that provides adequate deck space and unobstructed airflow, even if the ship was not originally designed to accommodate sails. This adaptability allows for implementing WAPS across a diverse range of existing ships and ship types. However, slower speeds and comparatively lighter ships gain a greater advantage from wind propulsion, enabling them to maximize the efficiency of wind assistance.

Newbuilds represent an even greater opportunity for enhancing the emission-reduction potential. By integrating WAPS into the design and construction phases, these vessels can be customized to achieve superior performance, exceeding the efficiency of

FIGURE 4-11

Number of vessels operating and on order with WAPS 2010-2028



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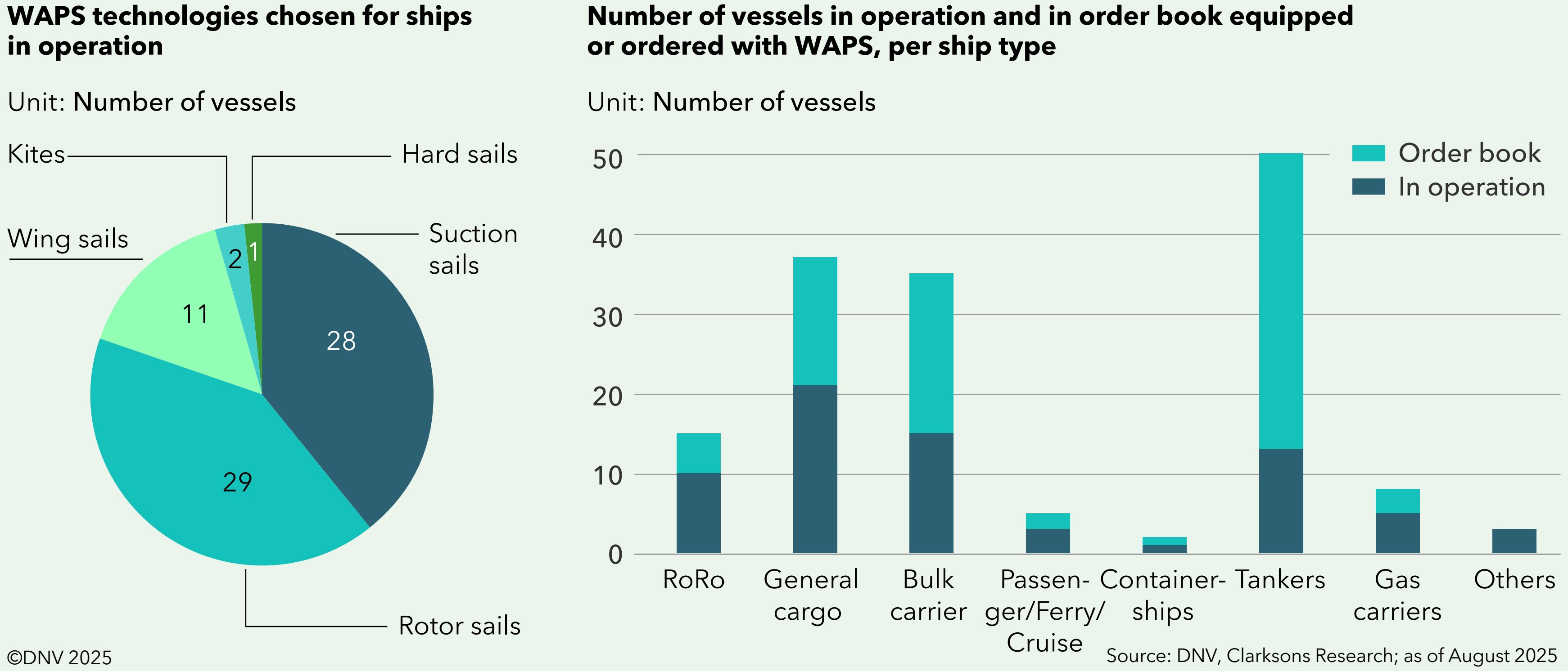
Source: DNV, Clarksons Research; as of August 2025

FIGURE 4-12

WAPS technologies in operation and in order book



©DNV 2025

Source: DNV, Clarksons Research; as of August 2025 retrofits. Purpose-designed hull forms, improved aerodynamics, more seamless system integration, and aligned structural elements to optimize wind power can unlock the full potential of this sustainable propulsion technology.

WAPS fuel-reduction potential

The fuel-reduction potential of vessels utilizing WAPS depends on such factors as those described in Table 4-4.

The rationale for investing in WAPS or other energy-efficiency measures rests on the potential for fuel cost savings within a reasonable payback period. While capital expenditure and return on investment expectations may vary among stakeholders, these factors are crucial in the investment decision-making process. Wind-assisted propulsion has already delivered annual fuel savings of between 5% and 20% for certain ships, according to vessel owners, operators and technology makers. Under given operational conditions, the potential is large, and DNV has verified[27] WAPS reaching peak values of about 30% reduced energy consumption per nautical mile in favourable conditions.

It is crucial to ensure that the wind-assisted propulsion system can reliably deliver the projected savings across various operational and environmental conditions. To accurately evaluate the performance of a WAPS, high-frequency automated data collection must capture all parameters required to do so. Consequently, automated data logging and processing are essential. Moreover, it is essential to ensure data accuracy and integrity, particularly for regulatory reporting and financial evaluations. By accurately measuring and quantifying the effects of WAPS in real-world operations, along with independent third-party verification of these effects, stakeholders can build trust and confidence in its performance, while also providing knowledge for future investments. This, in turn, can speed up the adoption of such measures and support the development of new collaborative business models.

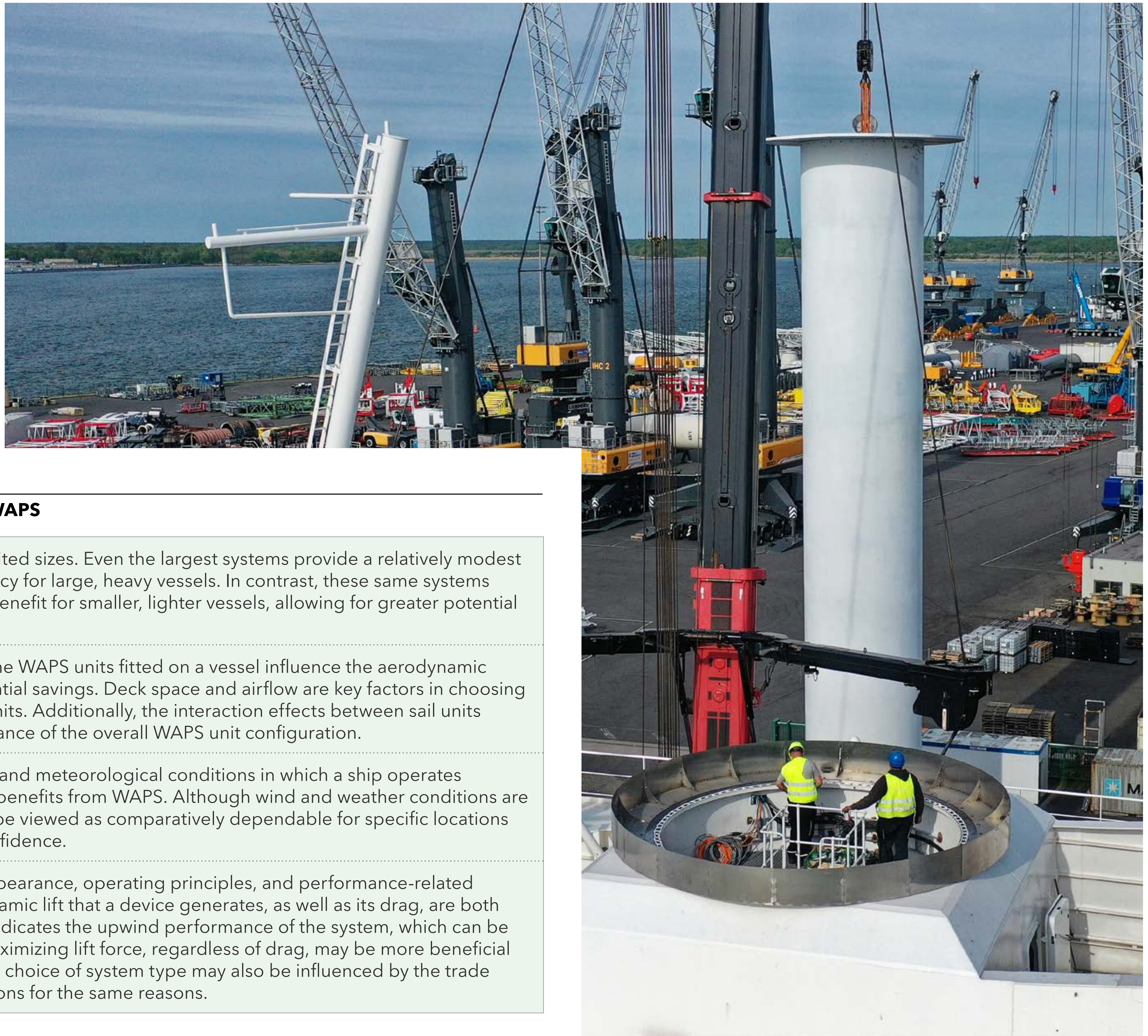


TABLE 4-4

Factors affecting the fuel-reduction potential of vessels utilizing WAPS

Ship size and displacement	Current WAPS are available in limited sizes. Even the largest systems provide a relatively modest increase in thrust and fuel efficiency for large, heavy vessels. In contrast, these same systems yield a more substantial relative benefit for smaller, lighter vessels, allowing for greater potential savings.
Number and size of WAPS	The quantity and dimensions of the WAPS units fitted on a vessel influence the aerodynamic thrust produced, impacting potential savings. Deck space and airflow are key factors in choosing the optimal number and size of units. Additionally, the interaction effects between sail units impact the aerodynamic performance of the overall WAPS unit configuration.
Trade routes	The geographical region, season and meteorological conditions in which a ship operates significantly impact the potential benefits from WAPS. Although wind and weather conditions are fundamentally random, they can be viewed as comparatively dependable for specific locations and times, and with statistical confidence.
Type of WAPS	The systems available differ in appearance, operating principles, and performance-related characteristics. The pure aerodynamic lift that a device generates, as well as its drag, are both important. The lift-to-drag ratio indicates the upwind performance of the system, which can be advantageous for faster ships. Maximizing lift force, regardless of drag, may be more beneficial for slower ships. Furthermore, the choice of system type may also be influenced by the trade route and prevailing wind conditions for the same reasons.

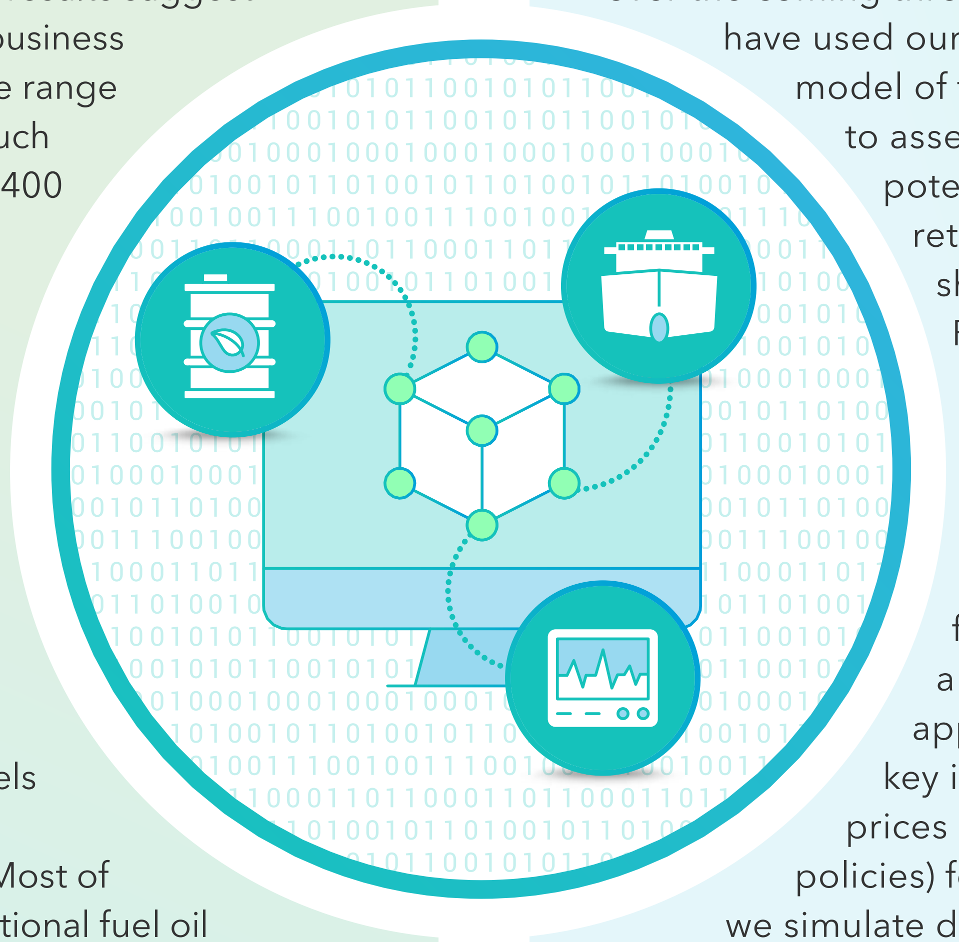
4.4 Modelling examples

4.4.1 Modelling alternative fuel and CCS conversions

With new regulatory drivers, the economic potential of converting ships to use alternative fuels or onboard carbon capture will change, and we have used our GHG Pathway model of the world fleet to assess what the potential demand for retrofits of existing ships could be. Future economic factors remain uncertain, such as the costs of fuel and emissions, and to account for this, we apply a scenario-based approach. By varying key inputs (e.g. fuel prices and regulatory scenarios) over each scenario, the modelled results have different outcomes for newbuild fuel choices and annual retrofit volumes. The scenarios used have previously been presented in (DNV, 2024a) and (DNV, 2024c), and explored a range of conditions, providing a broad perspective on annual retrofit needs across the global fleet.

The simulated number of retrofits peaks at up to 3,500 annually around 2030 for alternative fuels and onboard carbon capture. This is a significant number, comparable to the SO_x scrubber boom (2018–2020), when over 3,500 scrubbers were installed in two years (not one). Given the complexity of retrofitting ships for alternative fuels and CCS, it remains uncertain whether such volumes are feasible for shipyards and suppliers. A report by Lloyd's Register estimates a yard retrofit capacity on the order of 400–500 annual retrofits to alternative fuels (Lloyd's Register, 2025). Still, the simulation results suggest substantial retrofit potential if the business case is strong. The lower end of the range of simulated retrofits provides a much more manageable number of 100–400 annual retrofits. In the simulations, some scenarios include the option to pool emissions from a fleet and collectively decarbonize. In these scenarios, there are fewer retrofits than in those where each ship must comply individually. For individual compliance, more ships must contribute some, rather than a few doing a lot.

According to DNV's Alternative Fuels Insight platform, 52 alternative fuel conversions have occurred so far. Most of these conversions involved conventional fuel oil technology being adapted to allow operation on LNG or LPG. Looking ahead, there are 37 fuel conversions in the order book, most of which aim to enable conventional ships to operate on methanol.



4.4.2 Modelling energy-efficiency conversions

Will we see a boom for wind retrofits over the coming three years? We have used our GHG Pathway model of the world fleet to assess what the potential demand for retrofits of existing ships could be. Future economic factors such as the costs of fuel and emissions remain uncertain, and to account for this, we apply a scenario-based approach. By varying key inputs (e.g. fuel prices and regulatory policies) for each scenario we simulate different outcomes for newbuild vs. retrofit. The scenarios used have previously been presented in (DNV, 2024a). They explored a range of scenarios, providing a broad perspective on annual retrofit needs across the global fleet.

Here we present a simulated number of retrofits to new energy-efficiency measures, simulated as different energy-efficiency packages representing several technologies, such as wind-assisted propulsion, batteries, and waste heat recovery. The simulations show varying demand for such retrofits. Compared to alternative fuels or onboard carbon capture retrofits, the retrofit of energy-efficiency measures can, in many cases, be less time-consuming. Hence, a higher number of WAPS retrofits could be more realistic as long as the business case is advantageous for a significant share of the world fleet. We see a peak over the range of scenarios of 1,700+ ships a year retrofitting energy-efficiency measures, which is close to the historical peak seen in the annual number of retrofits of SO_x scrubber systems.

5 OUTLOOK ON FUEL PRODUCTION, SUPPLY CHAINS AND INFRASTRUCTURE

Highlights

For shipping, we analyse the status and future for low-GHG fuel production and permanent CO_2 storage, finding:

- Meeting IMO and EU targets will need major investment in renewable power, low-GHG fuels production, and CO_2 storage.
- Biofuel and LNG bunkering is well established in many locations: methanol, ammonia, and hydrogen need investment in bunkering infrastructure.
- Flexible Chain of Custody models can boost low-GHG fuel availability and reduce the investment needs for storage and bunkering infrastructure.
- Bio-methane via mass balancing in EU ports reduces the energy loss for liquefaction and gasification and will support European bio-methane production.
- Our 2030 CO_2 storage forecast is raised, but maritime players should engage early with storage or utilization project developers.

Shipowners interested in low-GHG fuels and onboard carbon capture need to know if, where, and when they can bunker fuel and offload CO_2 stored on board. We present the latest developments concerning these questions and discuss the importance of Chains of Custody to prove the provenance and specification of alternative fuels.

Existing and coming regulations will force shipowners to use low-GHG fuels or onboard carbon capture. This inescapable reality presents challenges in both the availability of fuels and competition from other decarbonizing industries such as aviation and heat-intensive manufacturing. Without a scale-up of the production of low-GHG fuels and CO_2 storage infrastructure, it will be difficult for the shipping industry to decarbonize fully. Our analysis dives in some depth into what the future may hold in this regard and suggests ways to reduce the cost and infrastructure investment needs of alternative fuels.

Höegh Aurora is designed for future operation on ammonia to enable zero-carbon shipping.

5.1 Supply of low-GHG fuels

Existing fuel use in the maritime sector

The reported fuel-oil consumption for ships in international trade of 5,000 GT and above was 211 Mt in 2023 (IMO, 2024). Almost all this fuel was fossil, including heavy fuel oil, light fuel oil, and diesel/gas oil, which together constitute almost 93.5% of the total consumption by mass. LPG and methanol consumption increased to 0.24 Mt and 0.09 Mt respectively in 2023, while use of LNG increased by 17% from 2022, to around 13 Mt (16 Mtoe) in 2023, constituting around 6% of the total fuel consumption.

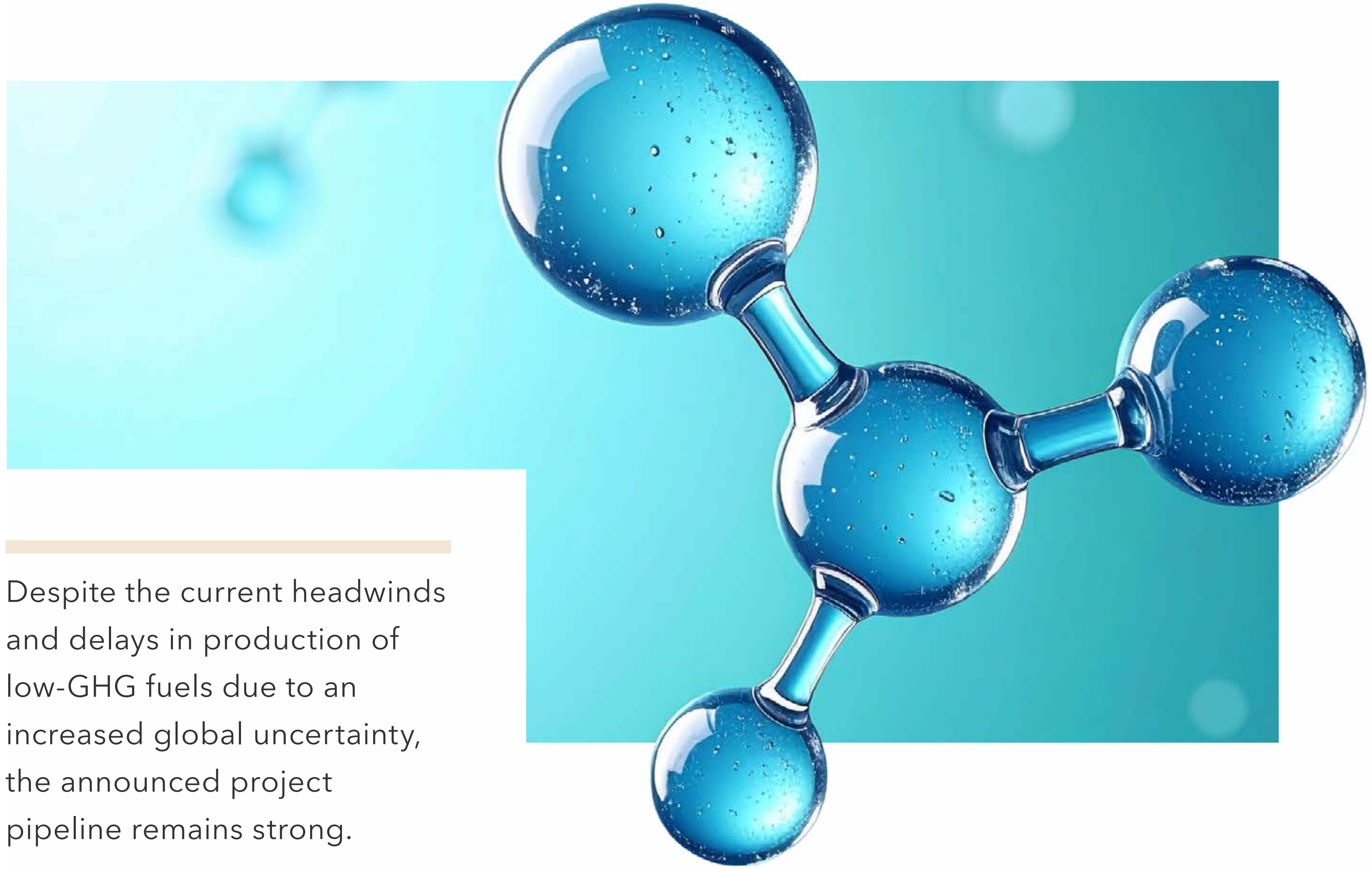
The use of biofuels in shipping has also risen significantly in the last couple of years, as evidenced by bunkering statistics provided by the two largest bunkering hubs worldwide, the Ports of Singapore and Rotterdam. In total, use of biofuels within the maritime industry amounted to about 0.7 Mtoe in 2023 (IEA, 2024). Relative to 2023, Singapore and Rotterdam reported an almost 30% increase in bio-blended bunker sales in 2024. Applying the same relative increase on global biofuel use in shipping would yield a figure of about 0.9 Mtoe for 2024. Most of the biofuel is sold as blends, but the total consumption is calculated as 100% biofuel equivalents, representing 0.3% of the total energy use of the marine shipping sector.

Maritime demand for low-GHG fuels and coming competition from other industries

In 2023, the total global energy consumption was approximately 10,600 Mtoe where transport and industry accounted for about 65% of this demand (DNV, 2024d) (IEA, 2024a). With the maritime industry accelerating its transition towards decarbonization, the competition for low-GHG fuels is intensifying across multiple industries. Achieving net-zero emissions will require substantial access to renewable electricity (for e-fuel production), biofuels and/or blue fuels (from fossil with CCS), but maritime is not the only industry vying for these resources. Maritime transport accounts for roughly 11% of total transport energy demand or about 3% of total global energy demand.

However, such fuels are also sought after by aviation and heavy-duty trucking, where aviation has fewer technically viable alternatives to fossil fuels. Sustainable aviation fuel (SAF) production remains limited and costly, while trucking companies are exploring hydrogen and liquid and gaseous biofuel alternatives in addition to battery-electric solutions.

The industrial sector, responsible for 37% of global energy demand, is another major competitor for low-GHG energy carriers and molecules, both as an alternative energy source for high-temperature processes and for feedstock in the production of different products. This might also be the reason for the industrial sector's high interest in the European Hydrogen Bank's pilot auction for renewable hydrogen, in which more than 63% of all bids had 'industry' categorized as their main off-taker[28]. The category mobility, which includes all forms of transport, represented less than 30% of the bids. In the second round of its Hydrogen Bank auction, the EU included a separate basket for projects having maritime off-takers. This part of the auction attracted 8 bids out of a total of 61. Of these, only 3 projects, all located in Norway, received funding. This indicated that transport, including maritime, will not be the primary off-taker for hydrogen and derivatives in the EU.



Despite the current headwinds and delays in production of low-GHG fuels due to an increased global uncertainty, the announced project pipeline remains strong.

Recent development in low-GHG fuel production

To assess the state of and plans for production of low-GHG fuels, DNV established a database in 2023 of existing and planned production sites, with estimates of future production presented in (DNV, 2023) (DNV, 2023) and (DNV, 2024a). The estimates are based on existing and announced production volumes, with planned production being probability adjusted with a high or a low set of probabilities, according to the present level of commitment, adjusting for the fact that not all projects will be completed. In addition, the high estimate assumes a one-year delay in start-up, while the low estimate assumes three years of delay (in the 2023 and 2024 editions of this report we used a two-year delay assumption in the low estimate).

The development of low-GHG fuel production, particularly hydrogen and its derivatives, has encountered substantial headwinds recently. Developers are facing increased cost pressures across the supply chain, compounded by broader industry-wide economic challenges. These factors, coupled with fluctuating and uncertain demand dynamics, have created a difficult market environment, significantly impacting the rate of project maturation.

Currently, only around 4% of the hydrogen-derived low-GHG fuel project pipeline has successfully reached the Final Investment Decision (FID), with an even smaller share of approximately 1% reaching operational status. For example, at the time of writing, none of the projects receiving funding through the European Hydrogen Bank pilot auction[29] have announced reaching FID. These projects have a maximum time to entry into operation of five years after signing the grant agreements, else they will lose the grant and need to pay a penalty. This will encourage them to be operational before 2030. The second auction included stricter requirements, of a maximum of 2.5 years from signing the grant agreements to reach FID, meaning by early 2028. At the same time, studies show that approximately one fifth of all European hydrogen projects have been stalled, delayed, or cancelled, pushing the mass build-out of hydrogen projects further into the future[30].

Despite the current headwinds and delays in production of low-GHG fuels due to an increased global uncertainty, the announced project pipeline remains strong. Although the steady growth of the project pipeline has stalled, it comprises an estimated total production capacity between 70 and 100 Mtoe for low-GHG fuels (for all sectors) in 2030.

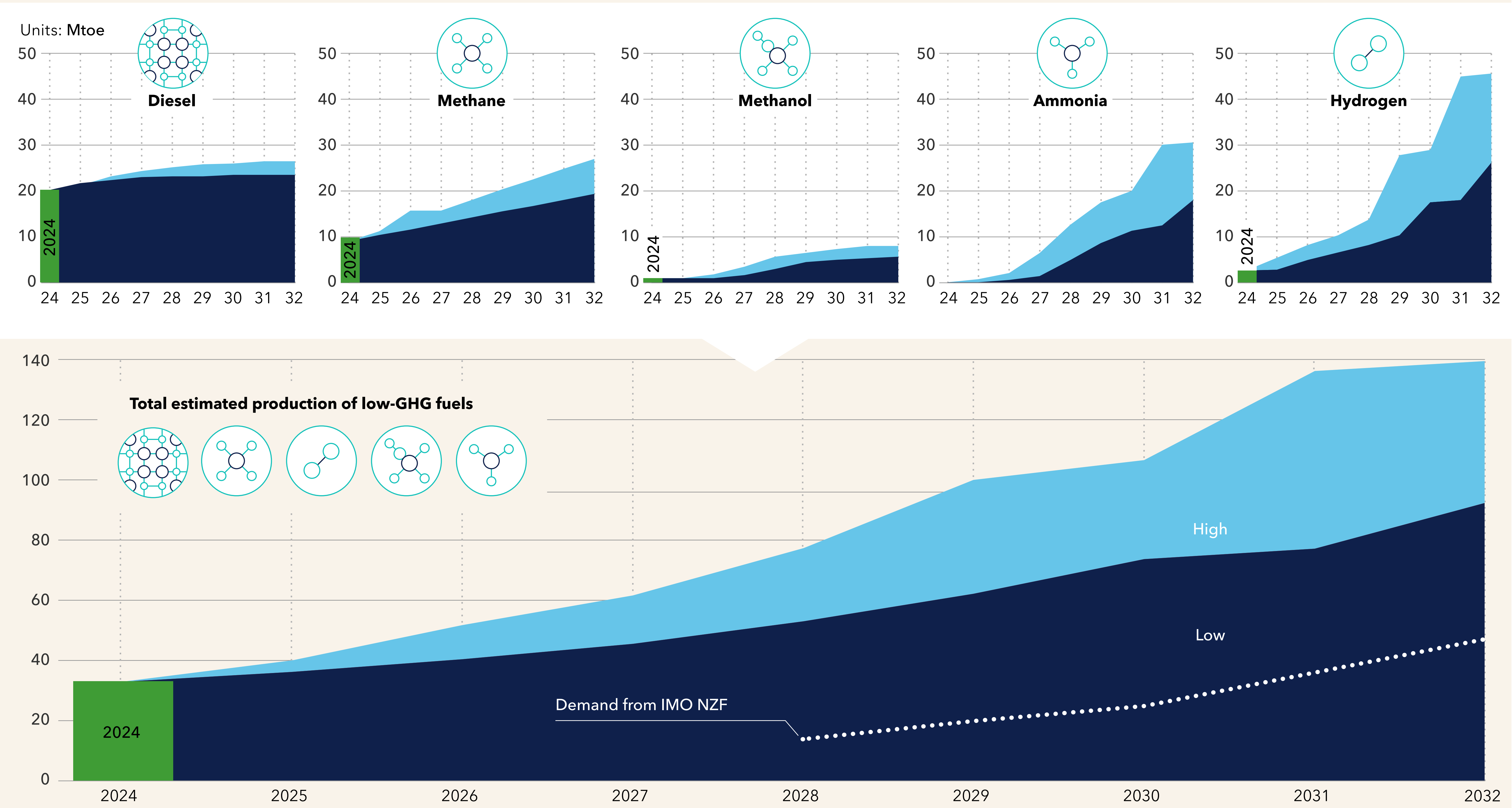
This is an increase of 50% from last year's report, due mainly to bio-methane now being included (see box in Section 5.4 for explanation of difference between biogas, bio-methane and bio-LNG). Our present estimate of the production capacity of low-GHG fuels in 2023, when we exclude bio-methane, is the same as the estimates we presented in 2023 and in 2024.

Excluding the biodiesel volume, the estimated total production capacity of low-GHG alternative fuels in 2030 is between 50 and 80 Mtoe, and by 2032, half of the high estimate is for hydrogen and ammonia. With ongoing delays and market uncertainty, it is estimated that a significant proportion of the capacity originally planned to come into operation by the late 2020s and in 2030, will be pushed further into the future, especially for hydrogen and the hydrogen derivatives. To take the increased delays into consideration, the estimation in this year's Maritime Forecast includes a three-year delay in all projects in the Low scenario, increased from the previous editions' two-year delay for the Low Scenario.

The total estimated global production of low-GHG fuels, including an estimate of each main fuel type, is shown in Figure 5-1. These high and low estimates are based on the current production capacity including a probability adjusted estimated production capacity, based on the status of all projects in the project pipeline meeting the sustainability criteria set by the EU in the second Renewable Energy Directive RED II.[31] Estimated demand for low-GHG fuels from shipping due to the IMO's Net-Zero Framework is also included.[32]

FIGURE 5-1

Estimated global production of low-GHG fuels across all sectors



5.2 Status and outlook on carbon storage facilities

Building on last year's Maritime Forecast, the latest analysis of global CO_2 storage projects (excluding enhanced oil recovery) in Figure 5-2 indicates a 25% increase in projected storage capacity by 2030, now estimated to range between 49 and 85 Mt per year[33], from last year’s 47 and 67 Mt, see (DNV, 2024a). Note that the Low scenario has increased the delay to three years, relative to last year’s two-year delay in the low scenario. Although the total global geological storage capacity is a limiting factor, the Intergovernmental Panel on Climate Change estimated that the total theoretical storage resource potential globally is 1,000 $GtCO_2$[34], and that this should be enough to meet the world’s ambitious climate targets.

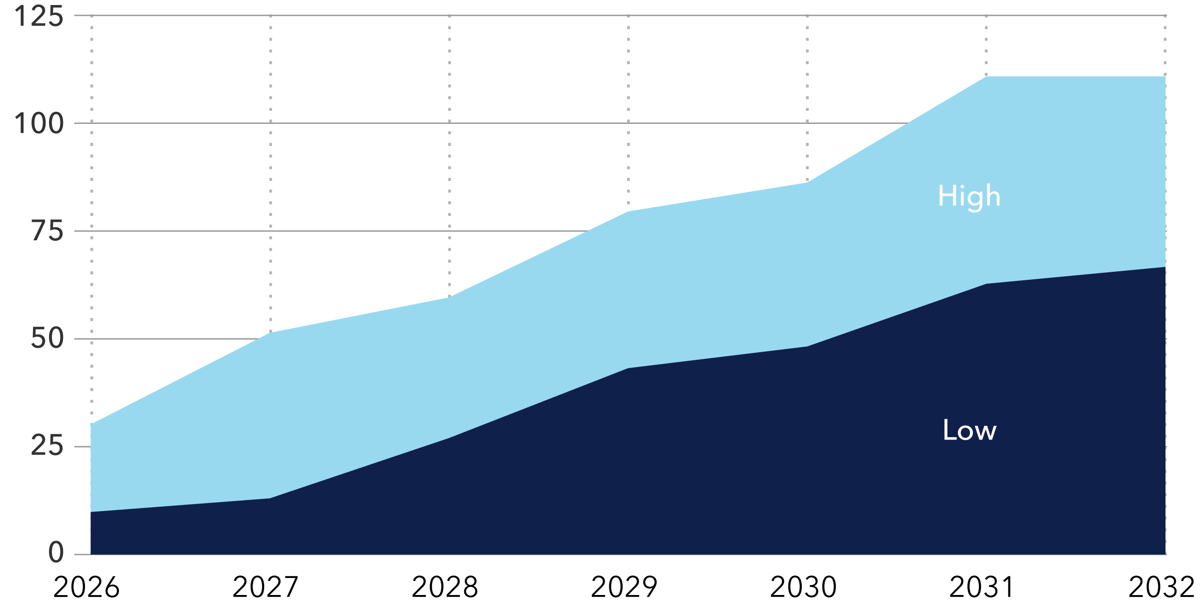
As an example, Northern Lights, one of Europe's CO_2 transport and storage projects, is on track to begin operations in 2025 with Phase 1. The project is the first cross-border and open-access site, which enables industries in Europe to ship CO_2 to a central site for permanent storage. In addition, the project has recently reached a FID on Phase 2[35], which will increase its storage injection capacity to 5 million tonnes per year. These milestones demonstrate growing confidence and commitment to expanding the storage infrastructure for carbon dioxide.

While there is a positive development, it is essential to differentiate between total capacity and available capacity, as capacity in storage projects is typically reserved in advance. Carbon capture projects and storage infrastructure are often developed in parallel to ensure alignment between capture, transport and storage. Which also means that it can be a challenge for the maritime industry to have firm enough commitments for storage use from several ships rather than a few large industrial emitters. Without secured access to storage sites, shipowners and operators risk having limited access to permanent storage for the captured carbon dioxide. This can also lead to the first onboard carbon capture projects aiming for utilization of CO_2 rather than permanent storage.

FIGURE 5-2

Estimated global CO_2 storage capacity (excluding enhanced oil recovery)

Units: Million tonnes



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Norhern Lights’ onshore storage tanks.

5.3 GHG reduction from different uses of electricity

In order to provide the necessary low-GHG fuels, shipping is also competing for the feedstocks to make them: sustainable biomass for biofuels, and sustainable carbon and low-GHG intensity electricity for green fuels. There is also a competition for CCS capacity for production of blue fuels.

Once generated from a diverse range of primary energy sources (e.g. nuclear, wind, natural gas) electricity is very versatile and highly efficient in transporting energy. Electricity is regarded as a high-quality form of energy because it can be easily converted into many useful forms, such as motion, heat, light, and chemical energy. This versatility has made it indispensable in modern industrialized societies. In this section we consider various electricity end-uses and the associated reductions in greenhouse gas (GHG) emissions achieved by displacing current activities; Table 5-1 describes the examples spanning several sectors, including land-based carbon capture and storage, power generation, automotive and maritime industries.

In Figure 5-3, we present calculations of the GHG emissions avoided by using one kilowatt-hour (kWh) of zero-GHG intensity electric energy[36] in the specified manner. The results demonstrate that the net GHG reduction achieved through electricity usage varies significantly depending on the sector, the end-use of electricity, and the displaced energy use. This conclusion is echoed by a recent report from

TABLE 5-1

Potential end-uses of low-GHG electricity to reduce GHG emissions

Sector	End-use of electricity	Displaced activity
Carbon capture and storage	CO_2 capture from concentrated sources	None
	CO_2 capture from air	
Power generation	Replace existing power generation	Coal power generation
		Gas power generation
Road transport	Charging batteries in electric vehicles	Gasoline/diesel cars
	Production of hydrogen fuel for use in fuel cell electric vehicles	
Maritime	Shore power for ship	Onboard oil-fuelled power generation
	Charging batteries in ships (plug-in hybrid)	Oil-fuelled ship propulsion
	Production of liquefied hydrogen fuel for ships (fuel cell)	
	Production of e-ammonia fuel for ships (internal combustion engine/ICE)	
	Production of e-LNG fuel for ships (ICE)	
	Production of e-methanol fuel for ships (ICE)	
	Production of e-MGO fuel for ships (ICE)	

the green climate think tank CONCITO (CONCITO, 2025), and for more analysis on the use of energy in making e-fuels see (Lindstad, 2021).

The calculation method is based on efficiencies in terms of electric energy needed for each type of end-use, with a high and low estimate for each case. This is then compared to a high and low estimate for energy conversion efficiency and associated GHG intensity for the displaced activities, yielding a range of GHG reduction per kWh for each end-use. More information about calculation methods and key assumptions is provided in Appendix A.

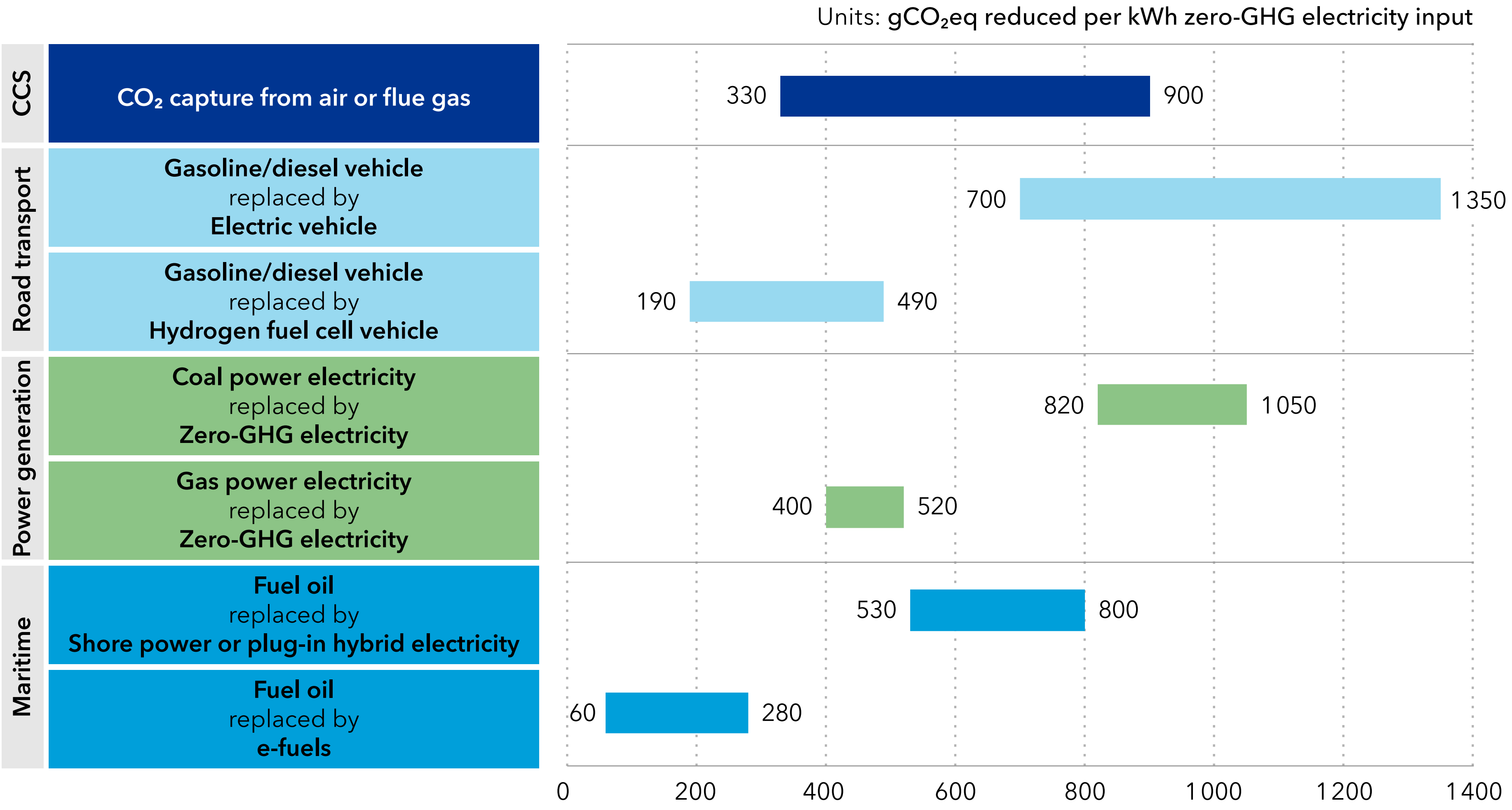
Direct applications of electricity tend to yield higher net GHG reductions compared to applications involving fuel production (e.g. e-MGO). For instance, using one kWh of clean electricity to produce e-fuels for maritime use can achieve a GHG reduction of about 60–280 gCO_2eq. In contrast, the direct use of electricity in an electric vehicle (EV) delivers a substantially higher reduction, ranging from 700 to 1,350 gCO_2eq.

The GHG reduction per kWh is calculated for various e-fuels, including e-MGO, e-methanol, e-LNG, e-ammonia, and e-LH_2 (liquefied hydrogen). For all e-fuels, except for LH_2 where we assume a fuel cell, it is assumed that ships use internal combustion engines (ICE).

For carbon capture and storage, the GHG reduction per kilowatt-hour (kWh) of electricity consumed varies greatly depending on the CO_2 concentration of the source. For instance, capturing flue gas with a CO_2 concentration of 8.5% (by volume) for permanent storage can achieve a reduction of approximately 900 g CO_2eq/kWh. In contrast, direct air capture (DAC) with permanent CO_2 storage results in a significantly lower reduction, at around 330 gCO_2e/kWh. The estimates are made under the assumption that electric energy is used to generate the heat needed for the CO_2 capture process. If alternative heat sources were to be used (e.g. waste heat), this will reduce the required electricity input.

FIGURE 5-3

GHG reduction from use of 1 kWh of electric energy – not considering emissions from production of electricity



5.4 Infrastructure and Chain of Custody for low-GHG fuel bunkering

The transition to low-GHG fuels requires substantial onshore investments and developments, both in production of low-GHG fuels and CCS, and in bunkering and CO_2 offloading infrastructure. The cost of establishing bunkering infrastructure for low-GHG fuels varies between fuel types (e.g. oil fuels, methanol, ammonia), as they have varying degrees of existing infrastructure and terminals. In addition, the total costs will depend on the rules adopted for using different GHG intensity versions of the same fuel – e.g. blending in tanks, in transport, or purchasing certificates rather than physical versions of the low-GHG fuel – directly impacting the reusability of infrastructure.

Biodiesel can use existing fuel oil infrastructure, and methane can benefit from the development of LNG infrastructure for distribution, storage, and bunkering. Methanol, ammonia, and hydrogen will require more complex bunkering facilities than fuel oil, which may come at significantly higher costs. However, the already existing terminal infrastructure for methanol and ammonia could be a starting point for a distribution network for use as fuel in ships, bringing down the 'last-mile' distribution cost.

When using low-GHG fuels, a Chain of Custody is used to ensure the validity of emission reduction and sustainability claims in a supply chain. The standard ISO 22095:2020[37] has different Chain of Custody models (see (DNV, 2024a) Section 5.5) with varying degrees of flexibility. These range from an '**identity preserved model'** in which any given low-GHG fuel needs to be separated from other GHG intensity grades (especially fossil fuels), to other models with increasing flexibility, such as **mass balancing** allowing for mixing of fuels but maintaining an overall GHG balance, or a book-and-claim model in which certificate book-keeping is not necessarily connected to the physical flow of fuels through the supply chain.

Full use of existing infrastructure will therefore require a flexible Chain of Custody model, allowing mixing of fuels with different GHG intensities. If only the Identity Preserved model is allowed, transition from fossil energy to bio- and e-fuels will need significant additional investments in separate storage tanks, pipelines, and bunkering infrastructure.

Bunkering infrastructure

Since 2015, biofuel bunkering has occurred in at least 60 different ports (DNV, 2025a), mainly in fuel blends with biofuel (mostly FAME) and conventional oil-based fuel (distillate or residual fuel). The most common blends range from 20% (B20) to 30% (B30) biofuel content by volume. Biofuel bunkering largely takes place using conventional fuel oil infrastructure. As per MARPOL[38] Annex II and the IBC[39] code, biofuel blends containing FAME delivered by bunkering barges or vessels classified as 'oil tankers' are restricted to a maximum biofuel share. Until recently, this maximum share was 25% FAME (by

The current bunkering methods includes ship-to-ship bunkering, truck-to-ship bunkering, and terminal pipeline-to-ship bunkering.

volume); however, at MEPC 83 an interim circular[40] allowing up to 30% (by volume) was approved. For bunkering of blends with higher FAME share from bunkering ships (e.g. B50 or B100), IMO Type 2 chemical tankers are needed, which can limit the bunkering capacity for these fuels.

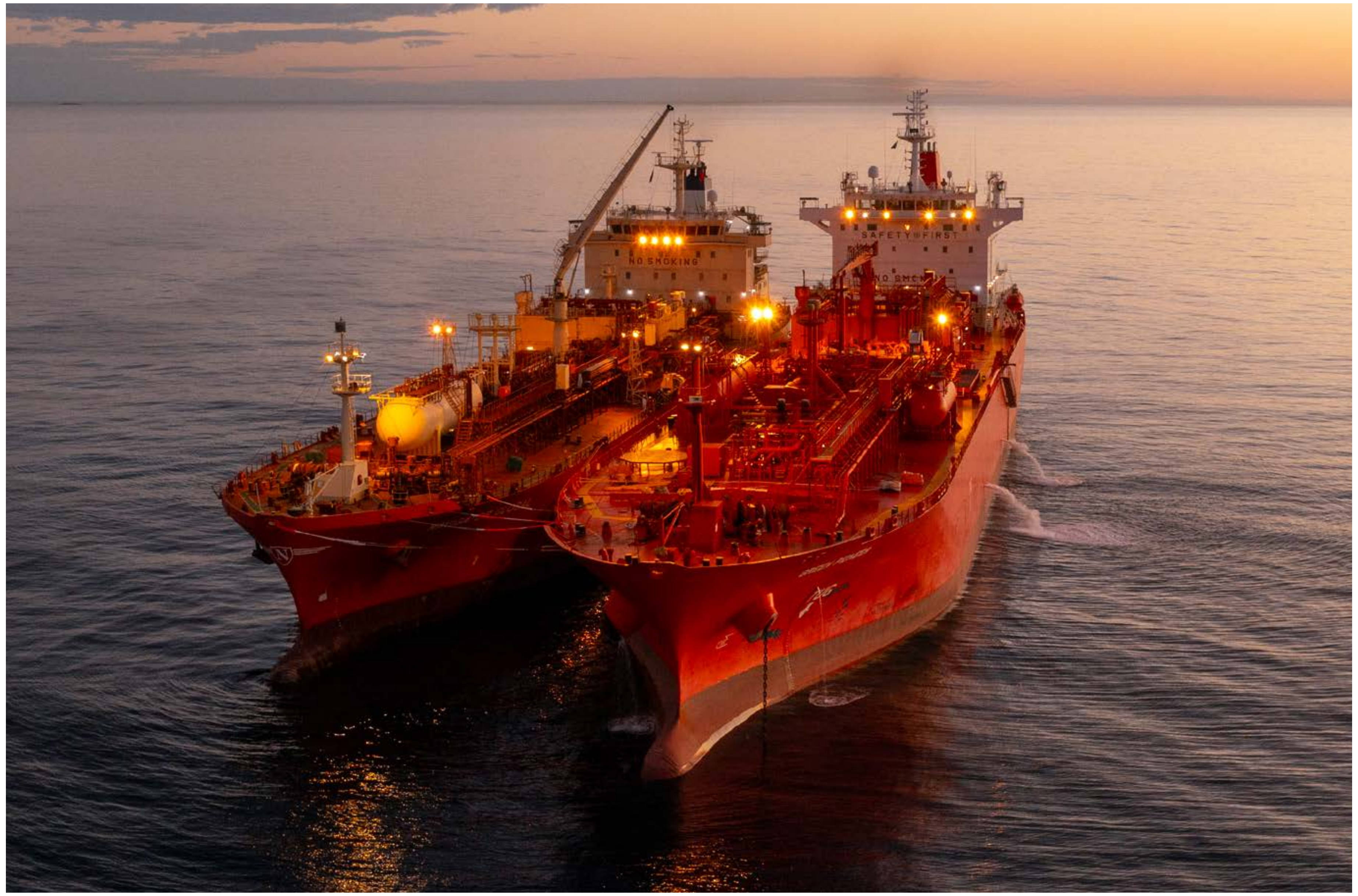
The current bunkering methods include ship-to-ship bunkering, truck-to-ship bunkering, and terminal pipeline-to-ship bunkering; where ship-to-ship bunkering is the most common method of delivering marine fuels to ships (Yang & Lam, 2023). Truck-to-ship bunkering is mostly relevant if the required fuel volume is limited. Figure 5-4 shows ports where biofuel bunkering operations have taken place or where biofuel suppliers have indicated that biofuels are available.

LNG bunkering infrastructure is also well developed compared to other alternative fuels. For example, the Port of Singapore has established robust infra-

FIGURE 5-4

Locations where biofuel bunkering has taken place since 2015 (green) and where biofuel suppliers have indicated biofuel availability (red); each location represents one port; bunkered biofuels include FAME, HVO, bio-methane, and bio-methanol (DNV, 2025a)

Source: DNV; as of December 2024



The world's first ship-to-ship ammonia transfer at anchorage was completed between Navigator Global and Green Pioneer at Port Dampier's outer anchorage in September 2024.

structure for LNG bunkering, including dedicated terminals and vessels. Beyond biofuel and LNG bunkering, there have been recent developments in bunkering of methanol and ammonia for the two largest bunkering hubs:

- Singapore, the world largest bunker hub, has recently demonstrated multi-fuel bunkering capability, with the world's first ship-to-containership methanol bunkering operation in July 2023, followed by ordering of methanol-capable bunker vessels.[41] In March 2024, the first ammonia bunkering trials were initiated, when the Fortescue Green Pioneer was loaded with liquid ammonia from the existing ammonia facility at Vopak Banyan Terminal on Jurong Island.[42]
- Rotterdam, the second largest bunkering hub, has made progress in supplying methanol, as well as working on ammonia bunkering. Ship-to-ship bunkering of methanol has already taken place several times, and a dedicated methanol bunker barge is planned to be deployed in the port.
- A milestone was also reached in September 2024, when the world's first ship-to-ship ammonia transfer using vessels at anchorage in a working port environment was completed in Australia.[43]

Interviews with shipowners that have ammonia or methanol dual-fuel ships on order have confirmed that the availability of these alternative fuels in the major bunker hubs are improving. The general view among shipowners is that both ammonia and methanol will be available for ships in sufficient quantities in the major bunkering hubs within two years. In addition, many ports are starting to accept bunkering simultaneously with cargo operations as for conventional fuels (SIMOPs). It is still, however, a challenge to secure low-GHG fuel at competitive prices compared with conventional fuels as production volume of the former remains low.

Chain of Custody – bio-methane as fuel in shipping

To document a fuel's WtW GHG factor, different Chain of Custody models can be used. Trust is crucial, so robust governance is needed to ensure actual compliance and real emission reductions. The main goal for shipping is to reduce emissions as much and as fast as possible. Therefore, it is essential to secure maximum availability for different low-GHG fuels at a minimum cost as early as possible, which can only be achieved by allowing for flexible Chain of Custody models. This will also further incentivize investments in fuel production in parts of the world with high access to renewable energy, CCS or biomass, and will reduce the investment needs for infrastructure for transportation, storage, distribution and bunkering.

To ensure compliance with EU RED II and to mitigate risks of irregularities and fraud in renewable fuel transactions, the Union Database for Biofuels (UDB) was developed and officially launched in 2024. The UDB is a centralized system in the EU designed to track the sustainability and origin of liquid and gaseous transport fuels applications. When fully implemented, it will ensure that all renewable fuel transactions are transparent, verifiable, and compliant with EU regulations. The UDB will help prevent double counting and supports the EU's renewable energy targets by integrating data from various national registries and voluntary schemes.

Bio-methane can play an important role in the decarbonization of the shipping industry as the fleet of dual-fuel LNG ships in operation and on order are increasing in number. As shown in the graphs for estimated future production of low-GHG fuels in Figure 5-1, there is a potential for scaling up the bio-methane production in the short and medium term and the potential is even higher towards 2050.

To illustrate the importance of allowing for flexible Chain of Custody models that are described in Chapter 5.5 in Maritime Forecast 2024 (2024, DNV), bunkering of bio-LNG from bio-methane in EU can be used as an example:

- For ships to be able to use methane as fuel it needs to be liquefied, which is done by cooling to -163 °C.
- If an identity preserved Chain of Custody model were to be applied, the bio-methane produced all over Europe would need to be transported in separate pipelines (or trucks) to a liquefaction plant where more than 10% of the energy is lost in transportation and cooling before it can be used as fuel on ships (Pospisil, 2019). At the same time,

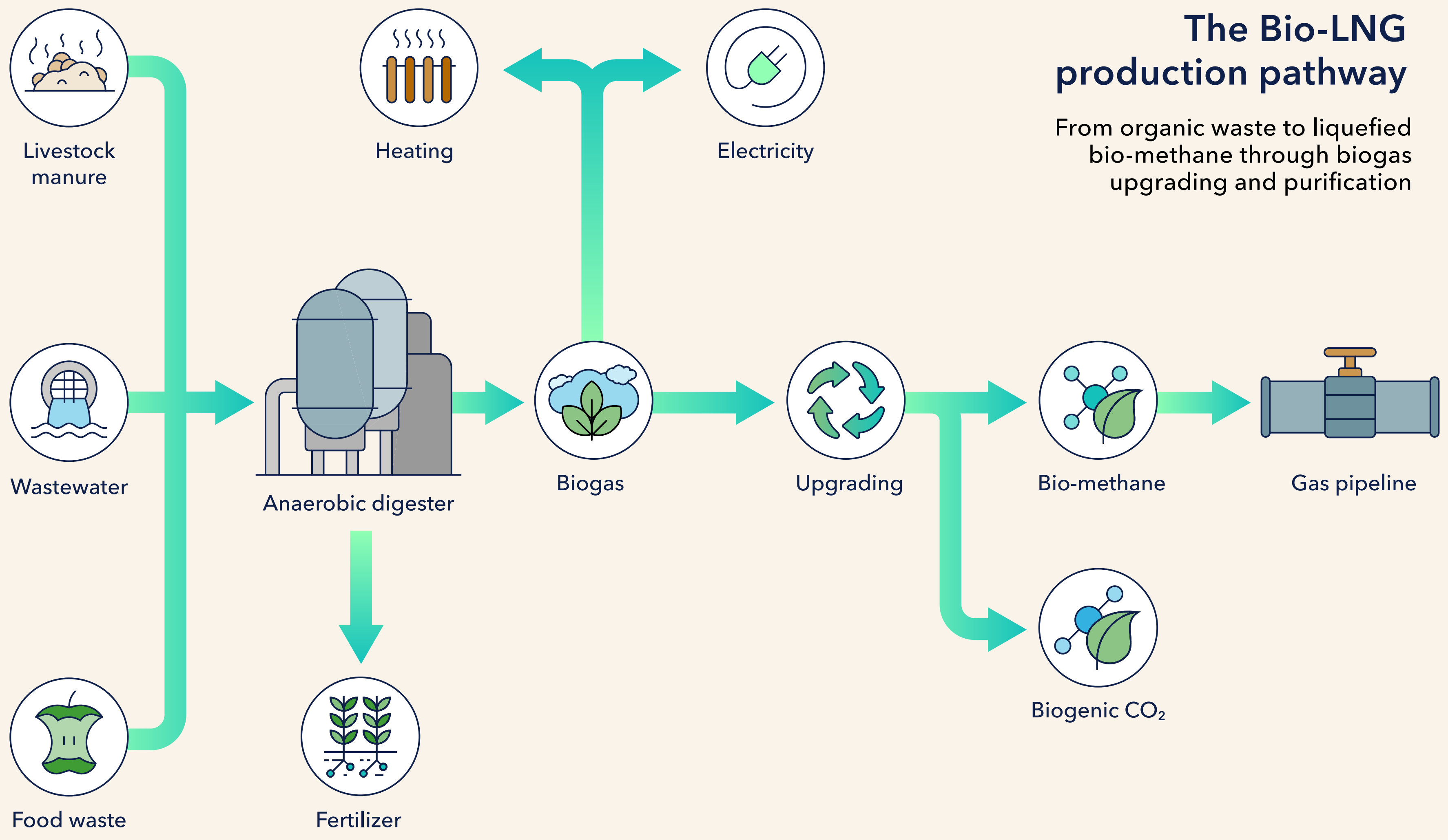
Biogas ⊙ bio-methane ⊙ bio-LNG

Biogas is a blend of gases, primarily methane, generated by bacteria breaking down organic waste in an oxygen-free environment, a process known as anaerobic digestion. Organic matter sources include animal manure, municipal waste, food waste, processed wastewater, and sewage sludge. The biogas composition varies based on the organic matter mix, bacteria used, and processing conditions. Methane typically constitutes 45% to 75% of biogas (by volume), with the remainder being CO_2, water vapour, and trace gases.

Biogas is flammable and can be directly burned to produce electricity or heat. However, its energy output is only 50-75% that of pure methane, depending on the concentration of other gases. Through a process called upgrading, biogas can be converted to nearly pure bio-methane by removing CO_2, water vapour, and trace gases, resulting in 98% pure bio-methane. Due to its high purity, bio-methane can be injected into existing natural gas networks. As it is produced from organic waste, it has the potential to be a net-zero emissions energy source. Some biogas production methods can even represent ‘better than zero’ by not only replacing fossil-fuel CO_2 emissions with zero- or low-GHG intensity CO_2 but also avoiding the alternative pathway of biogenic methane slip with far higher GHG intensity than the CO_2 from its combustion. In addition, the biogenic CO_2 can be used as feedstock for production of different e-fuels such as e-methanol, e-methane and e-diesel. Globally, about 90% of bio-methane is derived from upgraded biogas, while the remainder comes from gasification and methanation of forest residues. Finally, in the same way that LNG is made by liquefying methane, bio-LNG can be made by liquefying bio-methane.

The Bio-LNG production pathway

From organic waste to liquefied bio-methane through biogas upgrading and purification



large amounts of LNG are imported to Europe from other parts of the world, and it is already liquefied for the transportation. The imported LNG will then need to be regasified before it can enter the EU gas pipeline network, also requiring extra energy to heat the gas.

- If a mass balance Chain of Custody model is applied for the interconnected infrastructure, the fossil LNG terminals and natural gas pipelines can be used instead of building separate bio-methane transport infrastructure, avoiding investments and energy use for transport on, for example, trucks compared to application of the identity preserved model.[44]

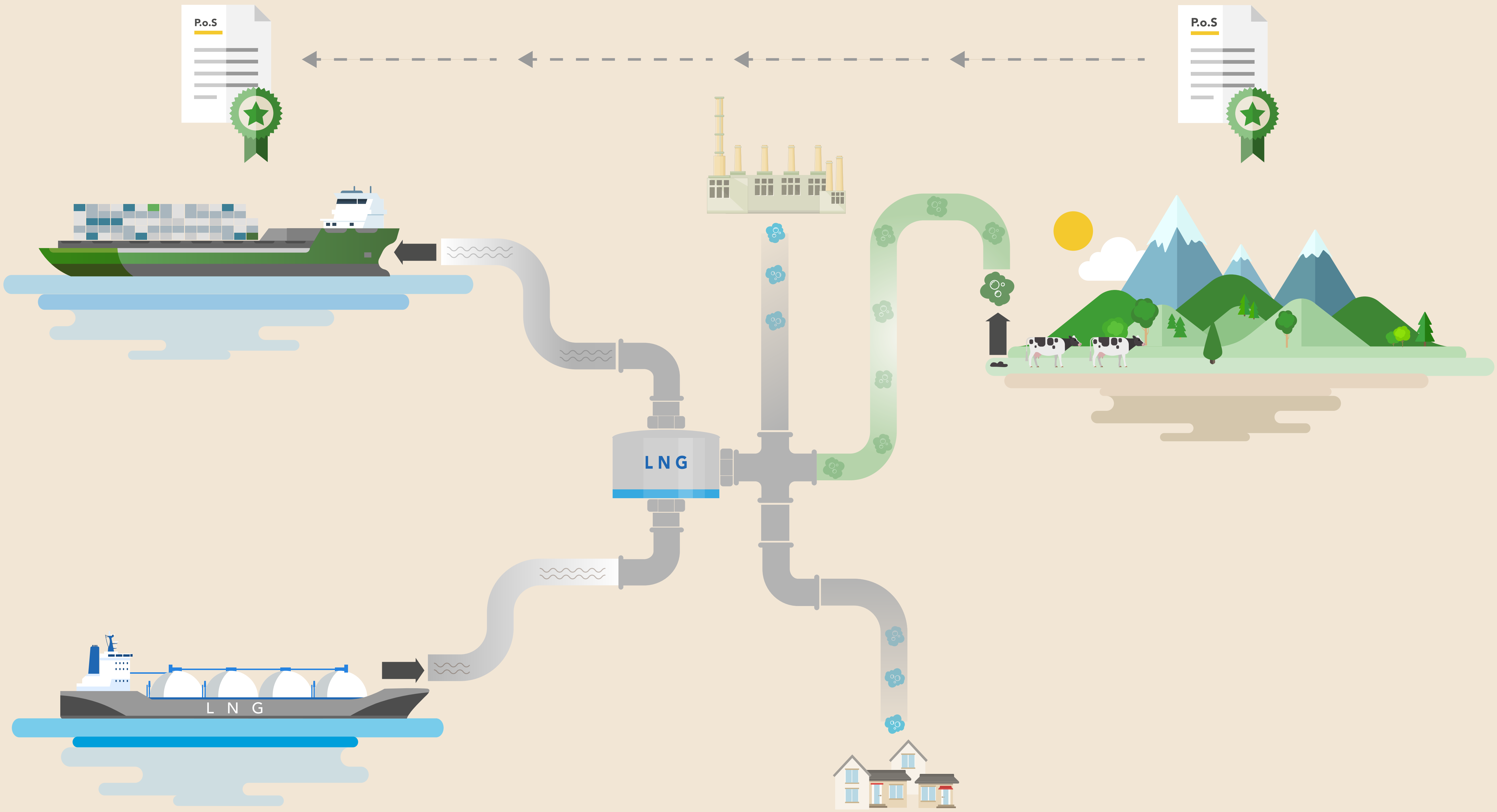
- Allowing full flexibility – for example using a book-and-claim Chain of Custody model – would save energy corresponding to approximately 0.55 Mtoe per year if all the bio-methane produced in the EU (4.3 Mtoe, (European Biogas Association, 2024)) were to be used as fuel for ships, assuming 10% energy loss from liquefaction and 3% from regasification, for a total of 13% energy loss (Pospisil, 2019).

- When purchasing bio-LNG in this way, the bunkered volume will have a Proof of Sustainability documenting a reduced GHG intensity towards the EU ETS and FuelEU Maritime, see Figure 5-5.

- At the same time, the availability of bio-methane for ships will increase significantly as well as the incentives for further increase of biogas production.

FIGURE 5-5

Mass balancing principle in the EU, where a ship can buy bio-methane injected into and transported on the natural gas grid: a Proof of Sustainability will accompany the bunker delivery note, ensuring the fuel counts as bio-LNG under the EU ETS and FuelEU Maritime regulations



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6 CASE STUDY – IMO NET-ZERO FRAMEWORK COMPLIANCE STRATEGIES AND COST IMPACT

Highlights

Our case study of an 18,000-DWT chemical tanker compares several strategies for complying with the IMO's NZF and finds:

- Fuel and compliance costs rise significantly from 2028 to 2040, varying by strategy.
- Fuel choice is crucial to emissions performance and economic impact, and depends on factors like price, GHG intensity, and availability.
- Costly onboard technologies may be more financially viable in ships eligible for game-changing economic incentives and revenue-earning potential under the NZF.
- Shipowners and stakeholders should make an early start to exploring cost-effective compliance options for the NZF.

Shipowners need evidence-based insight to choose effective and economical emissions-compliance strategies for ships and fleets. Here we present a chemical tanker (18,000 DWT) case study to demonstrate the consequences of the new IMO NZF regulations. This modelling explores key mechanisms such as buying Tier 1 and Tier 2 remedial units (RUs), using low-GFI fuels, and selling surplus units (SUs).

Early consideration of the compliance options is advisable as the newly approved, but not yet adopted, IMO NZF regulations will have a major effect on shipowners and charterers in the coming years (see Section 3.1). The IMO has introduced a new metric on which to measure the climate impact of using different fuels and to penalize the use of fossil fuels, the **GFI** (GHG fuel intensity), and in this chapter we use the term 'low-GFI fuels' for 'low-GHG fuels', i.e. fuels with significantly lower WtW GHG emissions compared to conventional fossil fuels.

Our modelling builds on a case study presented in (DNV, 2024a) and on databases and analysis tools in DNV's decarbonization toolbox for the economic assessment. We emphasize that the case study is high level; our analysis uses fixed fuel prices and includes only a limited set of available NZF compliance strategies. The aim of the case study is thus only to illustrate the mechanism in the NZF and the cost impact of different compliance strategies, given certain assumptions: it is not to rank different compliance strategies or fuels. In a more targeted fuel and compliance strategy analysis, with the aim of ranking alternatives (considering, for example, fuel prices, technology development, regulations, newbuilding vs. retrofits, operational parameters), we recommend assessing various fuel strategies, fuel price scenarios, and also include all relevant GHG regulations.

First, we present the case vessel assumptions, then we present an economic analysis of four NZF compliance strategies excluding the impact from EU GHG regulations. Finally, we compare the impact of IMO and EU GHG regulations on the case study vessel.

6.1 Case study vessel – chemical tanker newbuild (18,000 DWT)

We use a chemical tanker of 18,000 DWT operating internationally to examine the annual expenses for a set of NZF compliance strategies (excluding EU regulations) over the period 2028 to 2040, see Table 6-1 for details on the ship and Chapter 3 for more details on the IMO NZF.

We assess several compliance strategies for the case vessel (see Table 6-2), using either mono-fuel conventional engine or a dual-fuel LNG engine for propulsion/auxiliary/boiler (no shorepower), and present key insights on the cost impact of each compliance strategy. For each strategy, we assume that the technology and fuels are available for the case vessel. In Appendix B, we provide more details on the assumptions on applied future fuel prices and capital expenditure (CAPEX).

The fuel prices used are based on average prices over the period 2028 to 2040 in DNV's FuelPrice Mapper, a model developed to assess the cost of producing low-GHG fuels (DNV, 2022). However, we emphasize that future fuel prices are inherently uncertain.

TABLE 6-1

18 000 DWT chemical tanker – operational assumptions

Capacity	18 000 DWT
First year of operation	2028
Period assessed	2028 to 2040
Annual fuel consumption	2 465 t MGO equivalent (105 255 GJ)
Area of operation	Internationally (no EU port calls)

Further, in the case study we make the following IMO NZF-specific assumptions:

- the initial RU prices remain the same also from 2031 onwards
- a linear interpolation of the Base target between 2035 to 2040
- the Direct Compliance target continues to remain 13 percentage points below the Base target to 2040. These values may be strengthened during future reviews of the NZF.

TABLE 6-2

Overview of fuel technologies and NZF compliance strategies analysed in the case study

Fuel technology	Compliance strategy	Fuel options
MF MGO	1. Use MGO + buy Tier 1 and Tier 2 RUs	MGO
MF MGO	2. Use MGO and bio-MGO + buy Tier 1 RUs	MGO / bio-MGO
DF LNG	3. Use LNG and bio-LNG + buy Tier 1 RUs	LNG / bio-LNG (MGO as pilot fuel)
DF LNG	4. Maximum bio-LNG use + SU revenue	bio-LNG (MGO as pilot fuel)

Key: dual-fuel (DF); mono-fuel (MF); liquefied natural gas (LNG); marine gas oil (MGO); surplus unit (SU); remedial unit (RU)

6.2 Case study results

In this section, we present the case study results for our four selected NZF compliance strategies:

- Use of fossil MGO only and buy Tier 1 and Tier 2 RUs
- Use of fossil MGO and bio-MGO to achieve Base target and buy Tier 1 RUs
- Use of fossil LNG and bio-LNG to achieve Base target and buy Tier 1 RUs
- Maximum bio-LNG use and selling SUs

Compliance strategy 1: Use MGO + buy Tier 1 and Tier 2 RUs

The case vessel uses fossil MGO from 2028 to 2040 and buys Tier 1 and Tier 2 RUs in all years. Figure 6-1 presents the annual expenses and attained GFI for this compliance strategy. We use this as our reference case in the other compliance strategies analysed.

The figure shows that the annual Tier 2 RU cost increases with stricter Base target requirements over time, from 0.2 MUSD in 2028 to 2.5 MUSD in 2040. The annual Tier 1 RU cost, however, is constant at 0.13 MUSD from 2028 to 2040, due to constant Tier 1 compliance deficits generated from 2028 to 2040. In 2036, the cost of Tier 1 and Tier 2 RUs is more than the annual MGO fuel cost for the vessel.

FIGURE 6-1

Annual expenses and attained GFI for the 'Use MGO + buy Tier 1 and Tier 2 RUs' compliance strategy

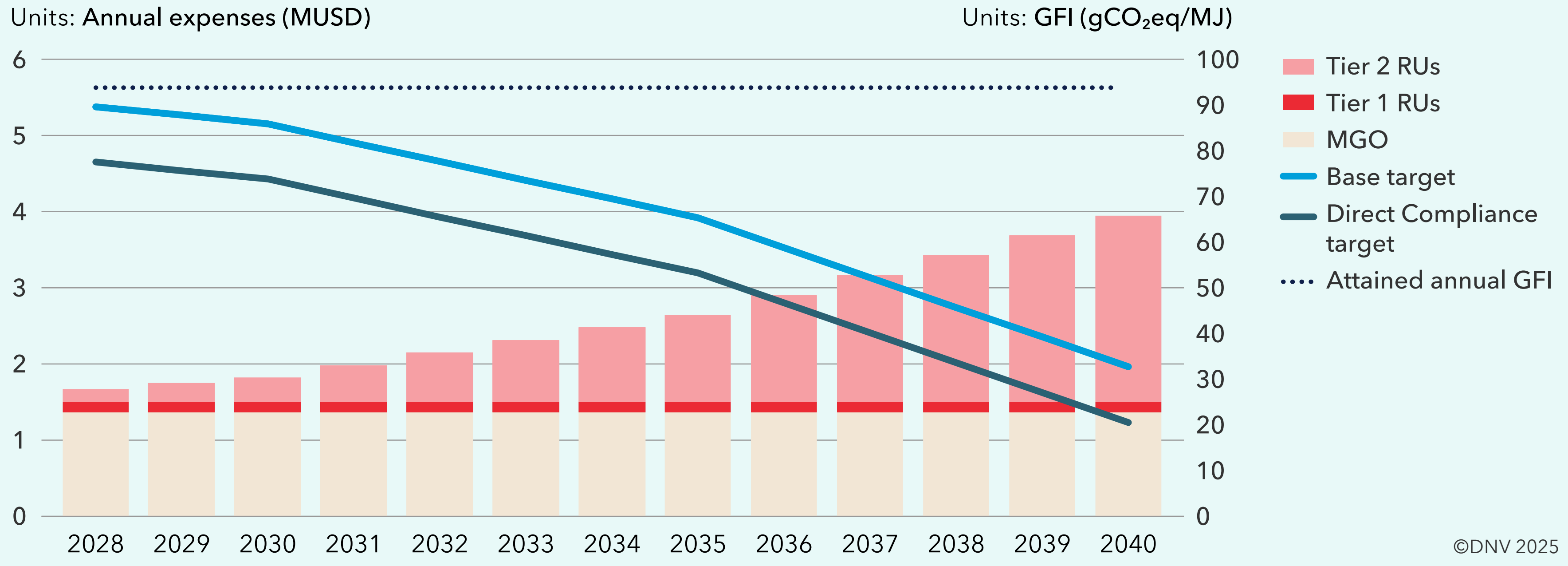
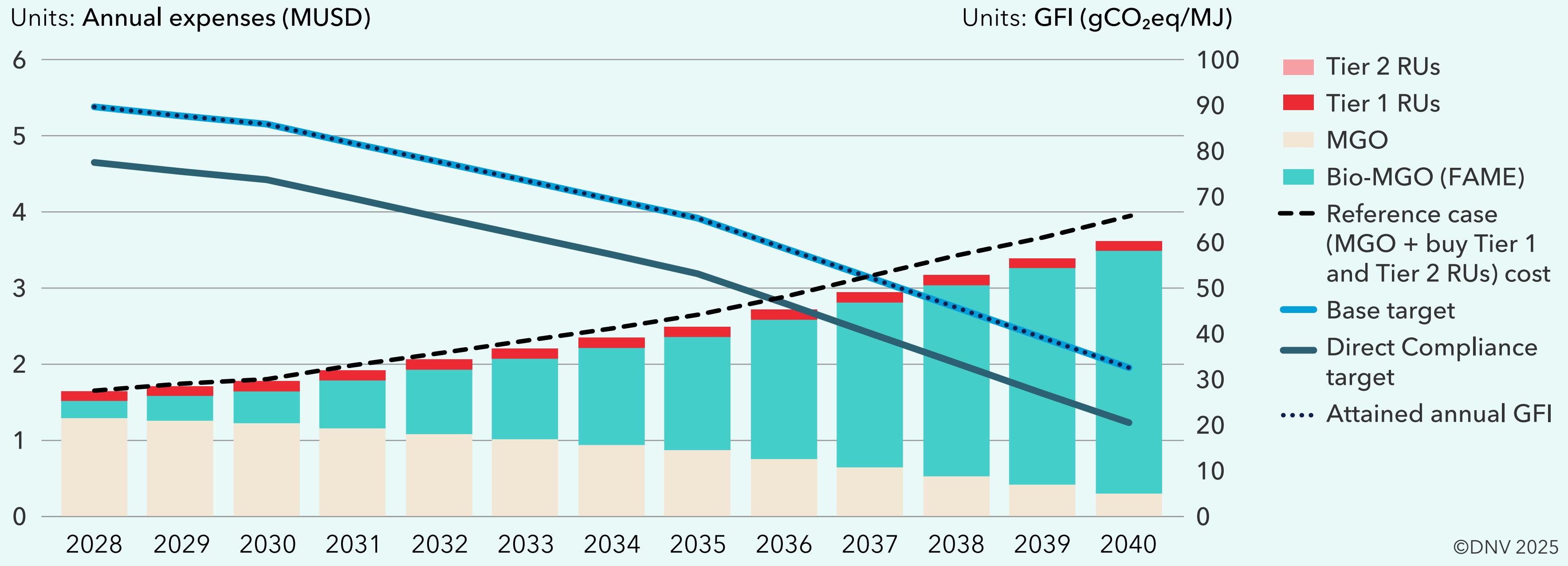


FIGURE 6-2

Annual expenses and attained GFI for the 'Use MGO and Bio-MGO + buy Tier 1 RUs' compliance strategy



Compliance strategy 2: Use MGO and Bio-MGO + buy Tier 1 RUs

The case vessel runs on a mix of MGO and bio-MGO (FAME biodiesel) from 2028 to 2040 and uses bio-MGO to achieve the Base target and buys Tier 1 RUs to maintain NZF compliance. Figure 6-2 presents the annual expenses and attained GFI for this compliance strategy.

As described in Chapter 3, the NZF is designed in a manner so that most ships will use sufficient low-GHG emission fuels to reach the Base target and then buy Tier 1 RUs. Thus, in this case study we do not look into the compliance approach of using low-GFI fuels to achieve the Direct Compliance target as this will be a more expensive option than using low-GFI fuels to achieve Base target and buy Tier 1 RUs. The reason for this is that with the assumptions used, the abatement cost for the fuels is above the Tier 1 RU price of 100 USD/tCO_2eq. With the biofuel price and GFI used in this case study, the abatement cost[45] is 329 USD/tCO_2eq.

The figure shows that to achieve the Base target from 2028 to 2040, the vessel gradually increases the bio-MGO share of the fuel mix, starting at 6% of the energy mix in 2028 and rising to 78% in 2040. This increases the annual fuel cost from around 1.5 MUSD in 2028 to above 3.5 MUSD in 2040. The annual Tier 1 RU is constant at 0.13 MUSD from 2028 to 2040, due to constant Tier 1 compliance deficits generated from 2028 to 2040. As indicated with the stippled line in the figure, this compliance strategy is less expensive than the 'Fossil MGO + buy Tier 1 and Tier 2 RUs' in all years from 2028 to 2040, with the given assumptions in the case study.

The NZF is designed in a manner so that most ships will use sufficient low-GHG emission fuels to reach the Base target and then buy Tier 1 RUs.

Compliance strategy 3: Use LNG and bio-LNG + buy Tier 1 RUs

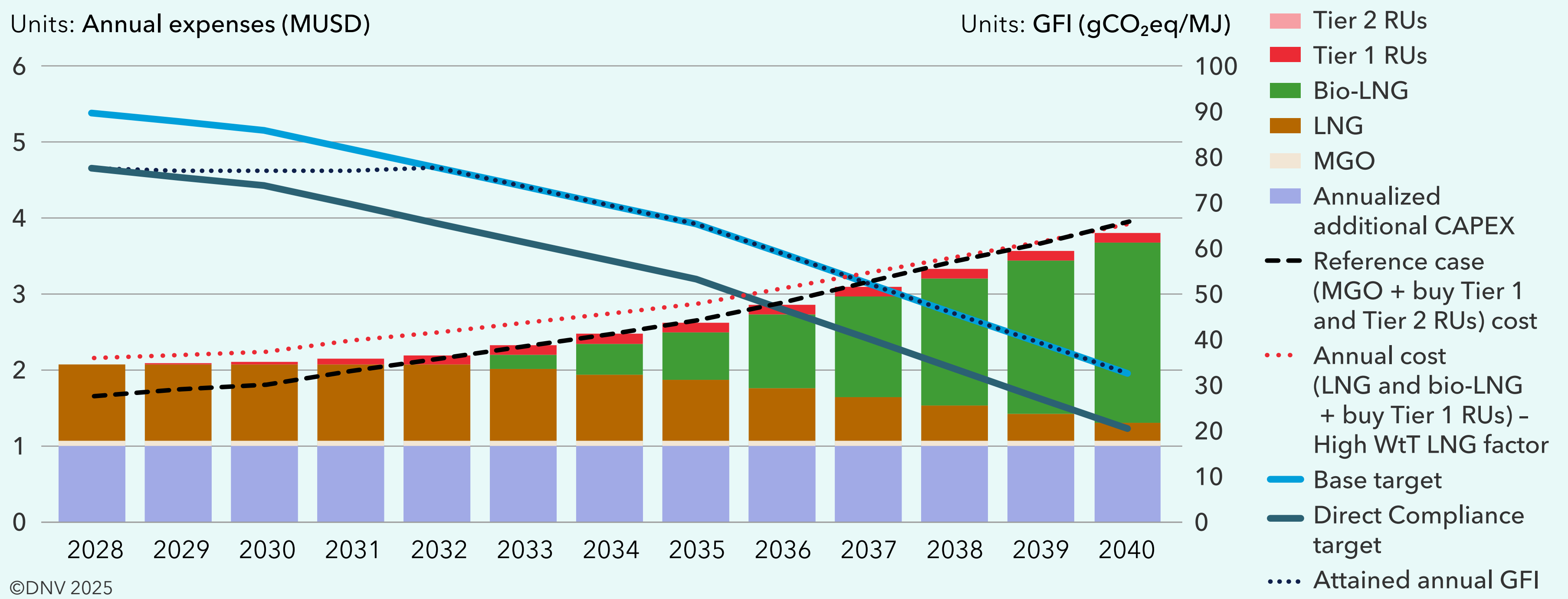
For the third and fourth compliance strategies, the case vessel is built with dual-fuel LNG engine and runs on a mix of LNG and bio-LNG from 2028 to 2040, using MGO as pilot fuel. In the third compliance strategy the ship uses bio-LNG to achieve the Base target and buys Tier 1 RUs to maintain NZF compliance. Figure 6-3 presents the annual expenses and attained GFI for this compliance strategy. Compared to the previous two cases, building this vessel as an LNG vessel adds extra CAPEX to the newbuild. This extra CAPEX is included in the cost analysis as an annualized additional CAPEX.

The IMO LCA Guidelines have not yet determined the WtT GHG intensity factor for fossil LNG. In this case study we use a low WtT GHG intensity factor for the main results but also present the results for a high WtT GHG intensity factor with a dotted line.

The figure shows that to achieve the Base target from 2028 to 2040, the vessel gradually increases the bio-LNG share of the fuel mix, starting at 6% of the energy mix in 2033 and rising to 73% in 2040. This increases the annual fuel cost from around 1.1 MUSD in 2028 to above 2.7 MUSD in 2040. The annual Tier 1 RU cost increases to 0.13 MUSD in 2033 and is constant at this value to 2040. As shown in the figure, the annualized additional CAPEX to make this vessel LNG capable has a significant impact on the annual cost, and results in a higher annual cost for this compliance strategy compared to the MGO reference case in the first five years. Also, as indicated in the figure, with a high WtT factor for LNG, the annual cost for this compliance strategy increases.

FIGURE 6-3

Annual expenses and attained GFI for the 'Use LNG and bio-LNG + buy Tier 1 RUs' compliance strategy



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Compliance strategy 4: Maximum bio-LNG use + SU revenue

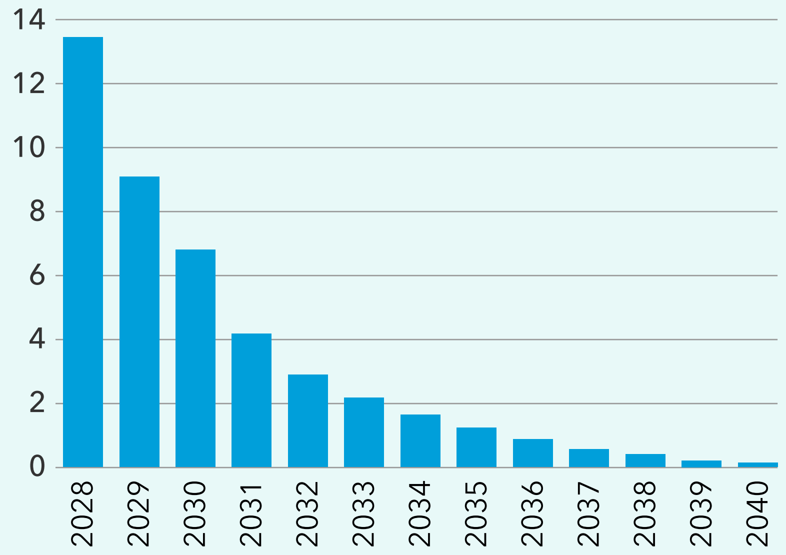
In this strategy we investigate if the business case for the LNG-fuelled case vessel can further improve if the vessel is using its full bio-LNG capacity and obtaining revenue from selling SUs to vessels with Tier 2 compliance deficits.

Vessels that have an attained GFI below the Direct Compliance target receive SUs that they can sell to ships with Tier 2 compliance deficit. To illustrate the SU potential, the case vessel that runs fully on bio-LNG over the years 2028 to 2040 transfers SUs to other vessels that use only fossil MGO. For simplicity, the bio-LNG vessel and the MGO vessels are assumed to have the same annual energy requirement. As shown in Figure 6-4, the bio-LNG vessel can offset the annual Tier 2 compliance deficits for a total of 13 fossil MGO vessels in 2028, 9 in 2029, 6 in 2030, and just 1 vessel in 2035. This reduction is due to the NZF reduction requirements becoming more stringent, reducing the annual SUs generated by the bio-LNG vessel, as well as increasing the Tier 2 compliance deficits for the vessels on fossil MGO.

FIGURE 6-4

Maximum number of fossil-MGO vessels that one bio-LNG vessel can help down to Base target in the period 2028 to 2040

Units: Annual number of fossil-MGO vessels



To make buying SUs an attractive option for owners of vessels running on MGO, the price for the SUs must be financially advantageous compared to the other compliance alternatives. For an MGO-fuelled vessel, as we have seen in compliance strategies 1 and 2 above, the two main alternatives for achieving Base target are:

i. use drop-in fuels with lower GFI (e.g. bio-LNG)
ii. buy Tier 2 RUs

Therefore, the added cost for each of these two options can be used as a reference point when setting the SU price[46]. We use a high and low price for SUs which are calculated either from the Tier 2 RU price (high SU price) or the abatement cost of running on bio-MGO (low SU price). Note that the low SU price is sensitive to the price and GFI for bio-MGO and the price for fossil MGO.

With these limitations to the SU price, the question is then if the business case for the bio-LNG vessel running on its full capacity can be economically competitive with the compliance strategy 'Use LNG and bio-LNG + buy Tier 1'.

In Figure 6-5 we present the annual expenses for the case vessel running on its full bio-LNG capacity from 2028 to 2040, using MGO as pilot fuel, including revenue from selling SUs for a high and low price.

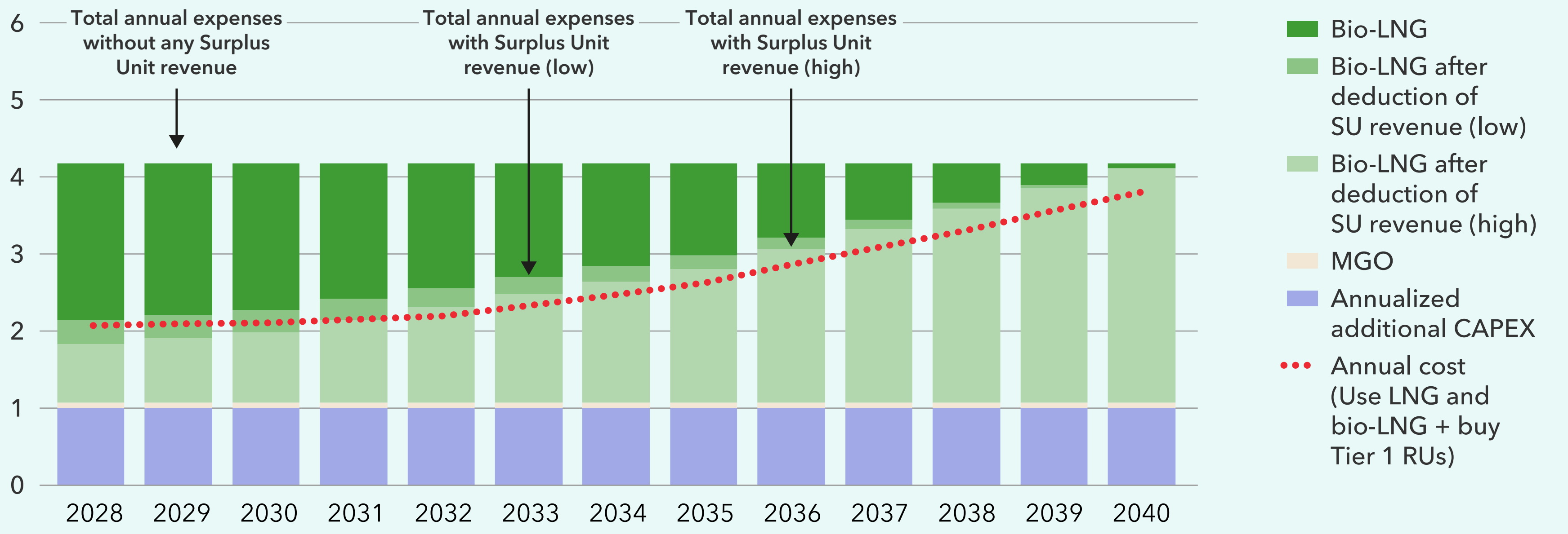
As shown in Figure 6-5, with SU revenue, the annual expenses for the LNG vessel running on its full bio-LNG capacity can reduce significantly, although they are still higher than for the 'Use LNG and bio-LNG + buy Tier 1 RUs' strategy in most years.

With the present case study assumptions on fuel and RU prices (emphasizing that the results are sensitive to the input assumptions), we find that a lower bio-LNG price or additional revenue is necessary to justify using a maximal amount of low-GHG fuels and selling surplus units, after 2031. Shipowners investing in alternative fuel-capable ships should seek to obtain a green transport premium (see Section 3.3). Additionally, the ZNZ reward mechanism that will be developed in the IMO NZF, see Section 3.1, can contribute to closing the cost gap between using just enough to fully utilizing the capability to use alternative low-GHG fuels.

FIGURE 6-5

Annual expenses for the LNG vessel running on the full bio-LNG capacity including SU revenue (high and low SU price)

Units: Annual expenses (MUSD)



6.3 Cost comparison of IMO and EU GHG regulations

In this section we compare the annual expenses for our 18,000 DWT chemical tanker case study vessel for being compliant with **either** the IMO NZF **or** EU regulations (FuelEU Maritime and the EU ETS) separately. Importantly, ships that fall under the scope of the EU ETS and FuelEU Maritime will have to continue to adhere to these regulations before a potential alignment with the NZF, see Section 3.2.

Table 6-3 describes the three fuel options and compliance strategies used in each GHG regulation scenario used for illustrating the annual expenses for complying with the IMO or EU GHG regulations.

When considering the EU GHG regulations, we assume the case study vessel operates 100% of its time between EU/EEA ports. For more information on the FuelEU Maritime Regulation see our DNV White Paper on FuelEU Maritime[47]. In Figure 6-6, the annual expenses for the three fuel options elaborated on in Section 6.2 are presented for either IMO NZF regulations or the EU ETS and FuelEU Maritime.

For the MGO-fuelled vessel opting to pay penalties, buying FuelEU penalty and EU Allowances (EUAs) is more expensive than buying IMO Tier 1 and Tier 2 RUs for the case vessel in the years 2028 to 2040. This is

TABLE 6-3

Compliance strategy description in IMO's NZF and the EU's FuelEU Maritime Regulation and EU ETS

Fuel strategies	Compliance strategies in each regulation	
	IMO NZF The case vessel operates internationally with no EU/EEA port calls.	FuelEU Maritime + EU ETS* The case vessel operates 100% between EU/EEA ports (excluding the cost for IMO NZF)
Fossil MGO	Run on fossil MGO and buy Tier 1 and Tier 2 RUs.	Run on fossil MGO, pay FuelEU Maritime penalty and buy EUAs.
Fossil MGO + blend in bio-MGO	Blend in bio-MGO to achieve Base target and buy Tier 1 RUs.	Blend in bio-MGO to achieve FuelEU Maritime requirement and buy EUAs.
Fossil LNG + blend in bio-LNG	Blend in bio-LNG to achieve Base target and buy Tier 1 RUs.	Blend in bio-LNG to achieve FuelEU Maritime requirement and buy EUAs.

Assuming an EU Allowance (EUA) price of 100 USD/tCO_2eq

largely because of the EU ETS cost and the consecutive FuelEU penalty multiplier, where the penalty is progressively increased by 10% for each consecutive reporting period in which the ship has a compliance deficit.

For the vessel using MGO and bio-MGO, the EU regulations impose higher costs than the NZF in the first years, owing to the EU ETS cost. However, with stricter GFI targets in the NZF the vessel needs to increase the share of bio-MGO in the fuel mix, more than due to the FuelEU (see Figure 3-4), with IMO NZF costs becoming more expensive from 2036 and onwards.

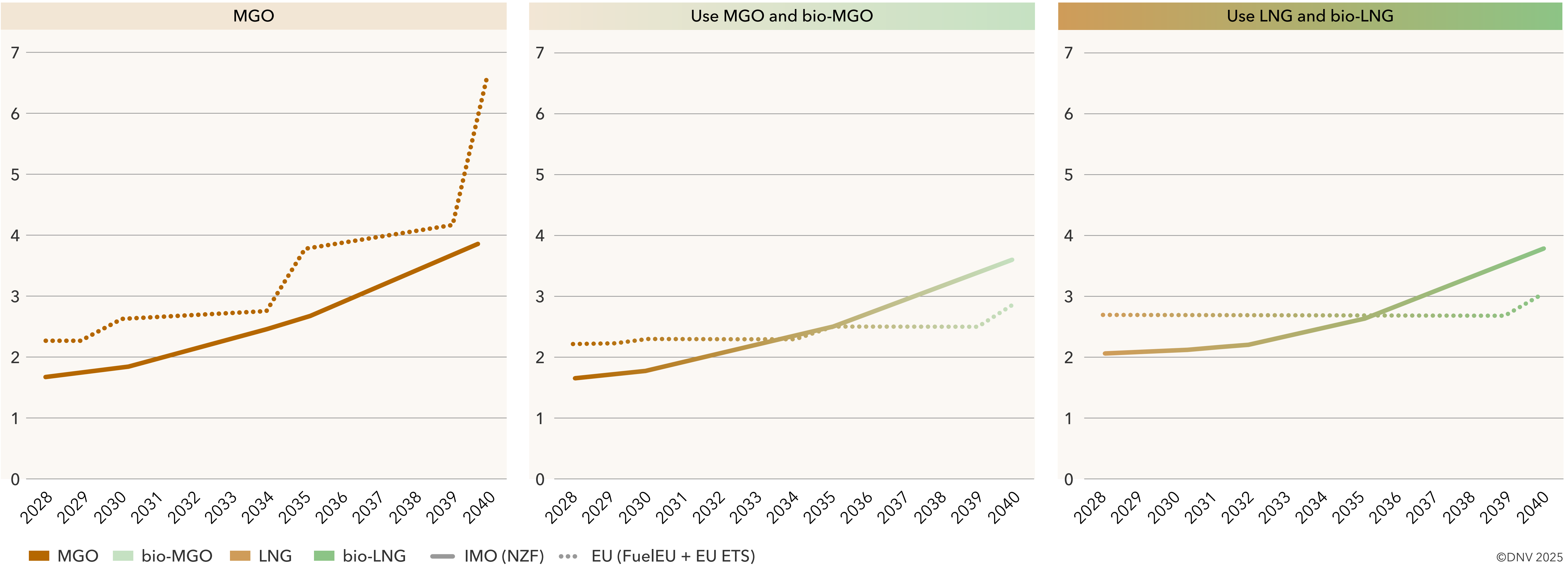
For the LNG vessel using LNG and bio-LNG, the annual expenses in IMO NZF start out lower than in EU-only regulations, mainly due to the EU ETS cost, but from 2035 and onwards the IMO NZF costs are higher, due to more bio-LNG required in the fuel mix.

We emphasize that these results are highly sensitive to the input assumptions, such as fuel prices, fuel GHG intensities, and fuel availability. A potential strengthening of the RU prices and the GFI targets will also have a significant impact on these results.

FIGURE 6-6

Comparison of annual expenses from 2028 to 2040 for the case vessel under the IMO NZF and under EU's FuelEU Maritime and EU ETS

Units: Annual expenses (MUSD)



7 POTENTIAL FOR ONBOARD CARBON CAPTURE FOR LARGE BULKERS, TANKERS AND CONTAINERSHIPS

Highlights

We model the potential impact of onboard carbon capture (OCC) for ships responsible for a large share of global fleet CO_2 emissions, and find:

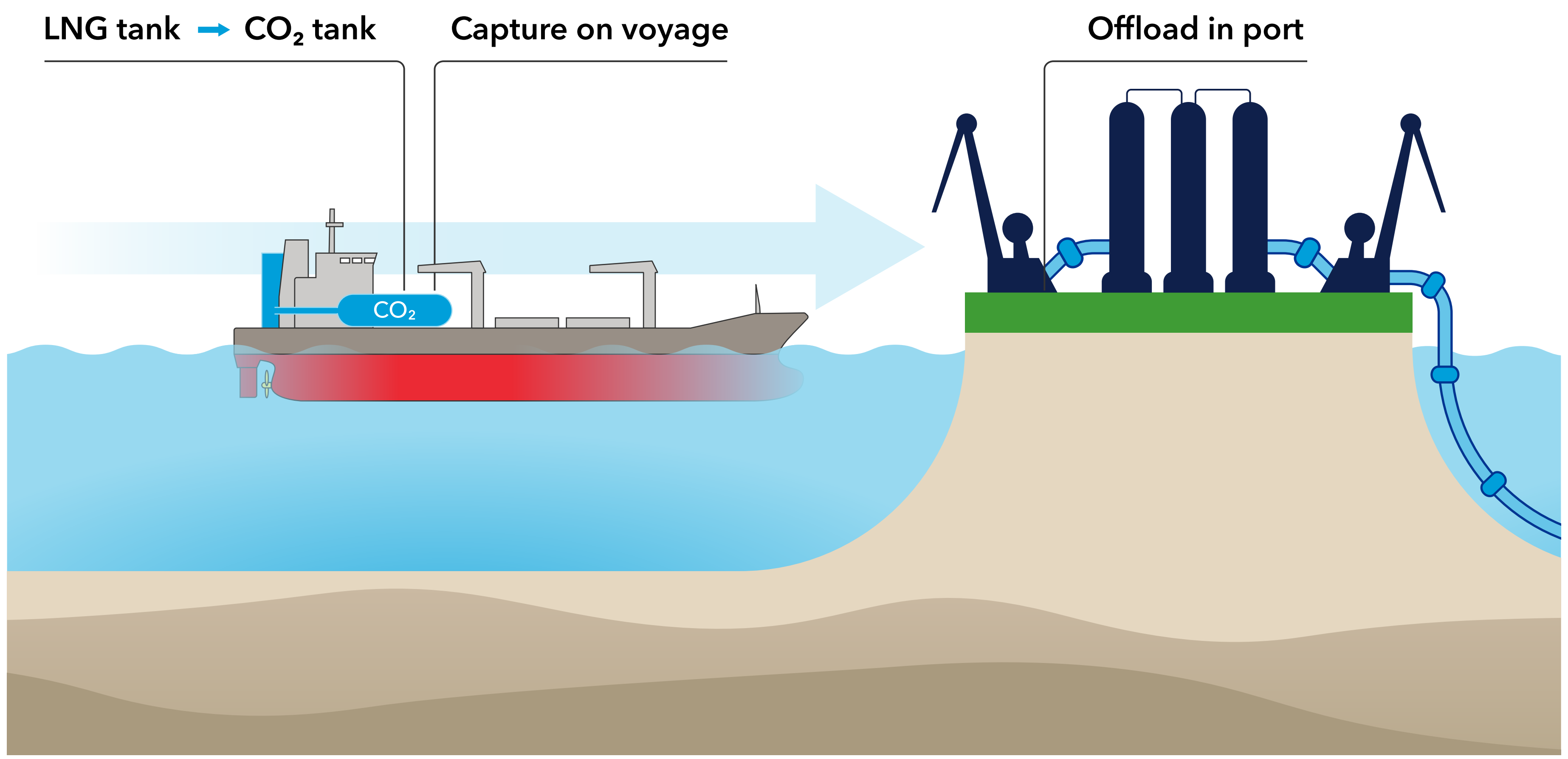
- If they can offload CO_2 on route, allocating space for onboard carbon capture may be no harder than for LNG tanks.
- They could then capture significant amounts, or potentially all, of the CO_2 emissions using tank sizes comparable to existing LNG systems.
- With CO_2 offloading in the 20 busiest ports, widespread use of onboard carbon capture on the world's largest ships could cut global fleet emissions by an amount similar to that needed to meet the IMO's 2030 goal.
- Raising the number of such ports to 200 could almost halve emissions from the ships studied, around a fifth of global shipping emissions.

As onboard carbon capture is being piloted[48], we analyse two major barriers to its wider adoption: technical implementation on ships and developing infrastructure for offloading CO_2 prior to its permanent storage or utilization. In supplementing our discussion on regulation (Section 3.1) and cost (DNV, 2024a), this chapter adds further insight for industry stakeholders making critical decisions on onboard carbon capture.

To investigate these issues and to quantify the possible impact of onboard carbon capture, we look at three ship categories accounting for a large share of world fleet CO_2 emissions: large bulkers, tankers and containerships[49] (see Chapter 4). The concept for analysis is illustrated in Figure 7-1, where we first use LNG fuel tank volume capacities on existing LNG-capable vessels as a proxy for the amount of CO_2 that can be practically stored on the ships. Secondly, we assess the CO_2 deposit potential[50] of major ports by estimating total amounts of CO_2 that can be captured on vessels on incoming voyages to each port.

FIGURE 7-1

Using existing LNG tank installations to find realistic CO_2 storage volumes on ships and AIS analysis with estimated emissions per voyage, we can estimate decarbonization potential of onboard carbon capture



7.1 Realistic CO_2 tank sizes for large bulkers, tankers and containerships

Is it feasible to store enough captured CO_2 onboard to decarbonize ships when each tonne of conventional oil fuel burned yields more than three tonnes of CO_2 and a large ship may generate several hundred tonnes of CO_2 each day of operation? Of course, the definitive answer to this question will have to be addressed by ship designers, taking into account all the considerations necessary for a ship to successfully ply its trade (see e.g. (Bureau Veritas, 2024), (DNV, 2024e)). But here, we use capacity of existing LNG tank installations to explore what level of decarbonization could be achieved with the same tank sizes being used to store liquefied CO_2 instead.[51]

As a proxy for achievable CO_2 storage tank sizes, we have utilized volume capacity data on 50 LNG tank installations for bulkers above 40,000 DWT, tankers above 45,000 DWT, and containerships above 2,000 TEU. In doing so, we assume that the placement and available space for CO_2 storage is comparable to the placement and available space for LNG tanks on these vessels.

While LNG can be stored in different types of tanks, we here assume that the liquefied CO_2 is stored in cylindrical Type C tanks[52]. The CO_2 tank is then assumed to be placed at the same location as the LNG tanks, which is at the aft deck for bulkers and the forward deck for tankers, while container vessels can have large LNG tanks that are not cylindrical Type C tanks and are located below the superstructure. To assess the equivalent CO_2 capacity for container vessels, we assume that the same space used for the large LNG tanks is used for both storing fuel oil and for accommodating a Type C tank for liquefied carbon dioxide.[53]

Following the assumptions, estimates of tank sizes are presented in Table 7-1 based on reported LNG tank sizes within each segment and size category.[54] Since it is assumed that the feasible tank capacity will depend on the size of the vessel, an estimated capacity per DWT has been calculated and then scaled up by the average DWT in each segment and size category.

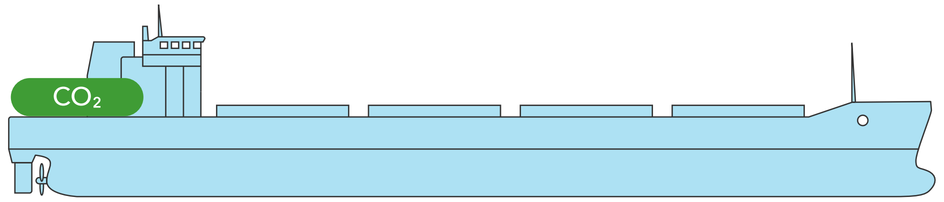
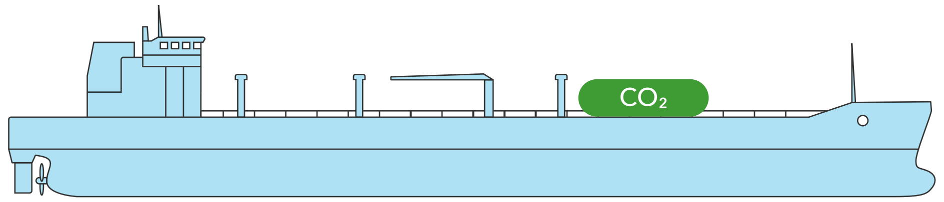
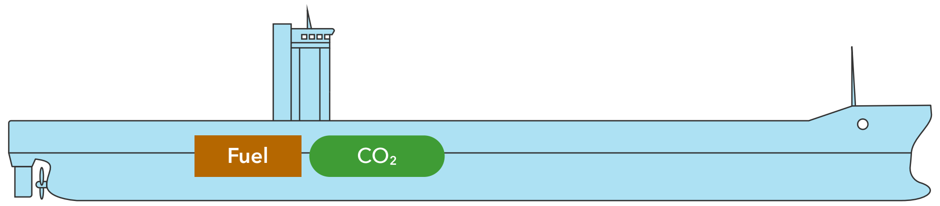
The CO_2 emission per ship and per voyage is modelled by AIS analysis and DNV's MASTER model (see Appendix C). The maximum captured CO_2 depends on the emissions between each deposit/offloading of CO_2, which is given by the operational pattern of each individual ship. With our estimated tank sizes, and a theoretical assumption that the ship can offload CO_2 in every port, we calculate the CO_2 reduction potential for each ship in the evaluated segments (i.e. for each of the 17,025 ships seen in Figure 4-6). We can then find the maximum amount of its annual CO_2 emissions that the ship can capture, taking into account voyages that are too long for a given tank size to be able to hold all the CO_2 generated on that voyage. The maximum reduction potential for each voyage has been reduced to match a fuel penalty of 30% (increased energy use to capture and liquefy the CO_2, see e.g. (Feenstra, 2019)).

The maximum annual CO_2 capture (as a percentage) with our estimated tank sizes has been calculated for each ship and aggregated by segment category in the histograms shown in Figure 7-2, Figure 7-3, and

The maximum captured CO_2 depends on the emissions between each deposit/offloading of CO_2, which is given by the operational pattern of each individual ship.

TABLE 7-1

Volumes of LNG tank-equivalent CO_2 tanks for bulkers above 40 000 DWT, tankers above 45 000 DWT and containerships above 2 000 TEU

Segment	Estimated CO_2 tank volume (m^3)	Tank location
BULKERS		
40-60k DWT	350	
60-85k DWT	450	
85-210k DWT	4 500	
above 210k DWT	8 000	
TANKERS		
45-80k DWT	1 800	
80-120k DWT	2 600	
120-200k DWT	3 600	
above 200k DWT	6 900	
CONTAINERSHIPS		
2-5k TEU	400	
5-10k TEU	1 000	
10-14k TEU	1 500	
above 14k TEU	5 100	

Berge Bulk has successfully installed a carbon capture system on its 63,000 DWT Berge Yotei.

Figure 7-4. Most of the bulkers will be able to capture between 10% to 50% of their emissions, even though a quite substantial number are able to capture 95% to 100%. Most containerships exhibit a CO_2 capture potential in the range of 25% to 60% with the chosen tank sizes, whereas the majority of tankers show a significantly higher potential, typically above 60%.

Crucially, the tank sizes applied in our calculations are not an actual maximum CO_2 tank size for the vessels in question but instead reflect the sizes of tanks that have already been installed for LNG as fuel. Shipowners could find it technically feasible and economically viable to install larger CO_2 storage tanks. We have not considered costs related to loss of cargo capacity or increased fuel consumption due to the weight of CO_2 (Sadi Tavakoli, 2024).

It should also be noted that the amount of CO_2 that a ship can offload during a year is not a simple function of the number of port calls, but crucially depends on the presence of offloading facilities; for example, a 'debunkering vessel' that transports the CO_2 from the ship to a certified storage facility some distance away. The logistics of offloading operations can be developed to enable ships to capture a portion of their emissions, allowing them to avoid penalties during the initial years following the planned implementation of the IMO Net-Zero Framework in 2028, see Section 3.1. This may enable ships to install carbon capture and intermediate storage equipment on board and gradually increase the share of emissions captured as logistics for offloading CO_2 are expanded, thereby gradually decreasing the emissions of the ship in tandem with the development of the CCS infrastructure.

FIGURE 7-2

Number of bulkers above 40000 DWT (9480 ships in total) with different annual CO_2 reduction potentials from onboard CO_2 capture, assuming given tank volumes and 100% capture rate

Units: Number of ships

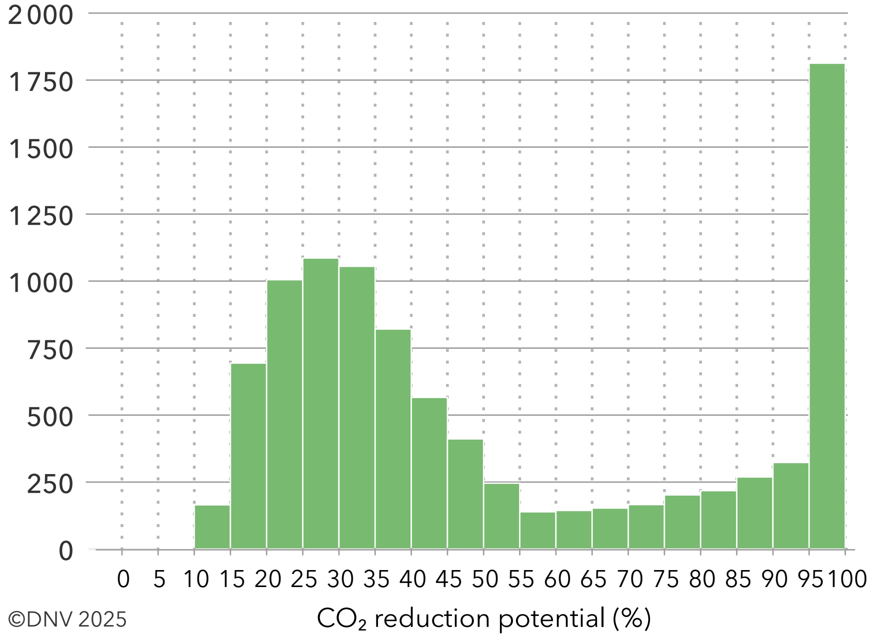


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FIGURE 7-3

Number of tankers above 45000 DWT (2489 ships in total) with different annual CO_2 reduction potentials from onboard CO_2 capture, assuming given tank volumes and 100% capture rate

Units: Number of ships

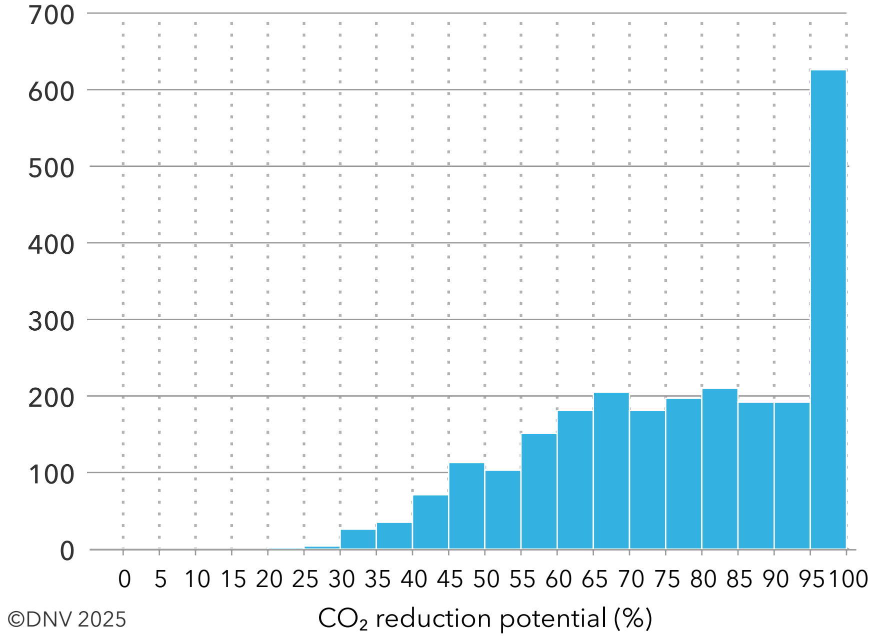

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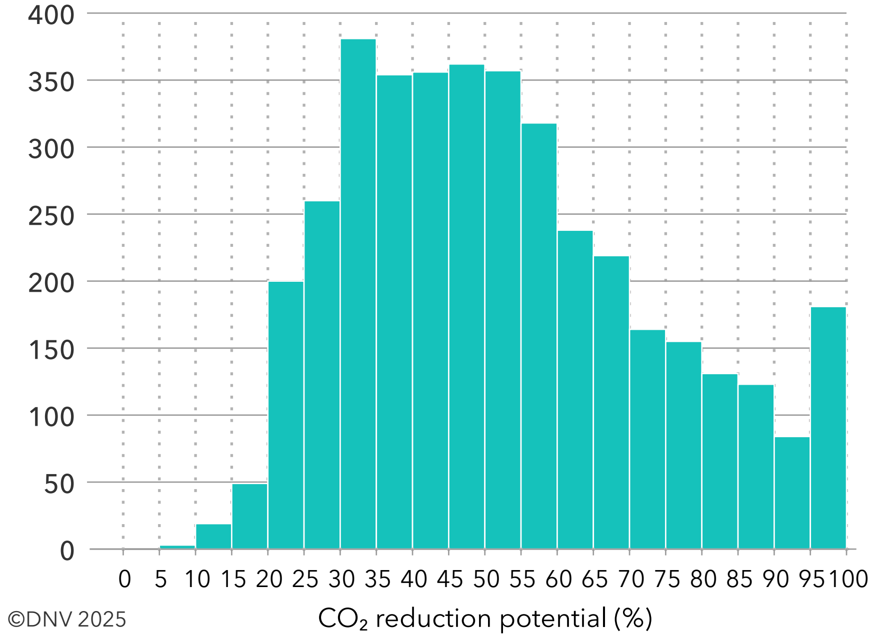
FIGURE 7-4

Number of containerships above 2000 TEU (3954 ships in total) with different annual CO_2 reduction potentials from onboard CO_2 capture, assuming given tank volumes and 100% capture rate

Units: Number of ships



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The amount of CO_2 that a ship can offload during a year is not a simple function of the number of port calls, but crucially depends on the presence of offloading facilities.

7.2 CO_2 infrastructure development and impact on decarbonization of the world fleet

The potential for onboard carbon capture as a decarbonization pathway is dependent not only on the onboard CO_2 storage capacity but also on the development of infrastructure for CO_2 deposits. In this chapter, we have analysed the decarbonization potential for onboard carbon capture for bulkers above 40,000 DWT, tankers above 45,000 DWT, and containerships above 2,000 TEU, given various levels of port infrastructure for CO_2 deposits.

To estimate this, we have built an analysis on top of DNV's MASTER model and Voyage model (see Appendix C for details), with a basis in the activity of the fleet in 2024. To find the potential for CO_2 capture in total, we assume that all vessels in the fleet under consideration are equipped with onboard carbon capture systems that could capture all[55] the CO_2, incurring a 30% fuel penalty[56]. Each ship is also assumed to be fitted with CO_2 storage capacity sized according to the estimated capabilities in Table 7-1.

Further, we assume that a given number of ports have CO_2 deposit infrastructure. The ports are selected based on having the highest total CO_2 emissions from incoming voyages.[57] Every time a ship arrives at one of these ports, it deposits all captured CO_2 since its last deposit. At maximum, the captured CO_2 between two deposits can reach the capacity of the estimated onboard CO_2 storage tanks. Based on this, we calculate the possible CO_2 emissions that can be captured and delivered for storage for various numbers of ports with CO_2 deposit infrastructure.

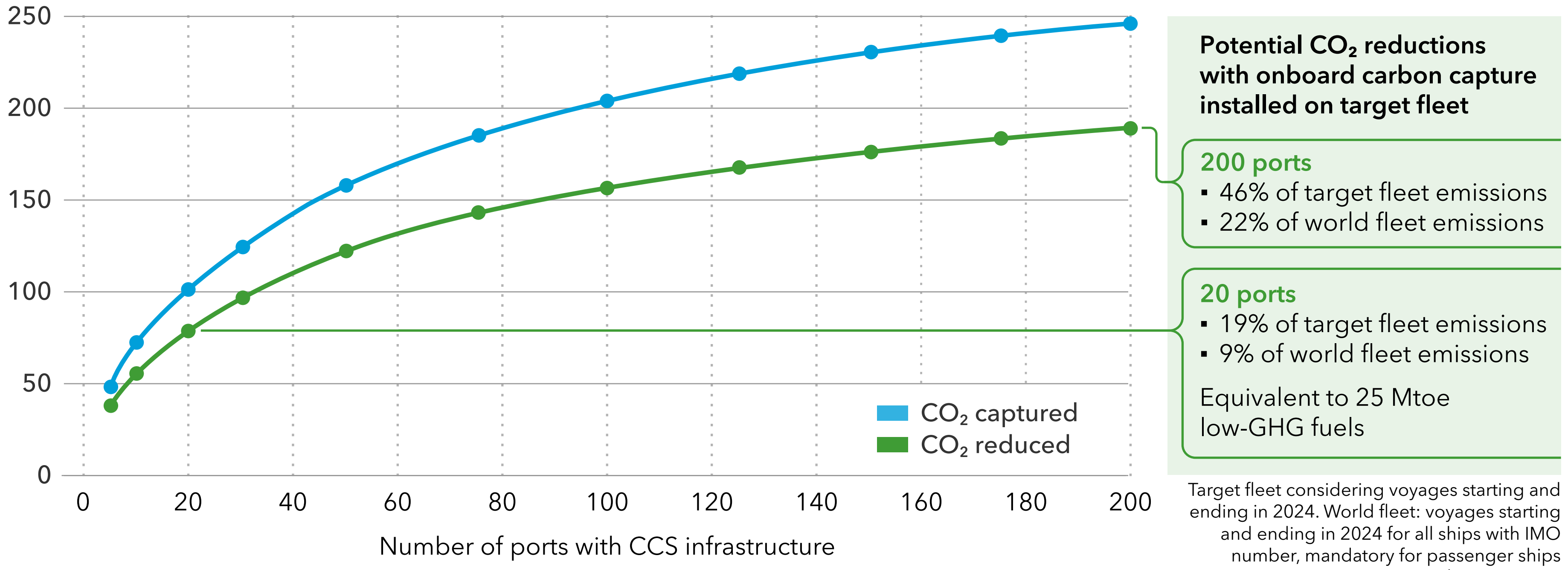
The potential amount of CO_2 captured for various numbers of ports with deposit infrastructure is shown with the blue line in Figure 7-5. Since operating a carbon capture system requires additional fuel (we assume 30%), the net CO_2 reduction is lower, shown with the green line in the same figure.

For comparison, the total emissions from these segments are about 410 $MtCO_2$[58], representing approximately half of our estimated total world fleet emissions of 870 $MtCO_2$. **Hence, given the current operational pattern, almost 10% of the CO_2 emissions of the world fleet could be captured and delivered with deposit infrastructure in 20 of the largest ports.** This is equivalent to the reduction in emissions from using 25 Mtoe of low-GHG fuel[31], which according to the analysis presented in Figure 5-1 is the estimated demand for low-GHG fuels to meet the IMO Net-Zero Framework requirements in 2030. To double the captured CO_2, the number of ports needs to be increased to 200. Routes between these ports could also be the best candidates for carbon capture corridors (CC Corridors), a variety of Green Corridors.

FIGURE 7-5

The potential CO_2 capture from large[59] bulkers, tankers, and containerships in million tonnes (blue line) and the corresponding net CO_2 reduction (green line), as a function of number of ports with CO_2 deposit infrastructure

Units: Million tonnes CO_2



Target fleet considering voyages starting and ending in 2024. World fleet: voyages starting and ending in 2024 for all ships with IMO number, mandatory for passenger ships ≥ 100 GT, cargo ships ≥ 300 GT

APPENDIX A

Methodology for calculating GHG reduction from different uses of electricity

For each considered electricity end-use case, we calculate the GHG emissions avoided by using one kilowatt-hour (kWh) of zero-carbon electric energy[60] from the following formula:

$$GHG\ reduction\ per\ kWh = \eta_{fuel} \times \eta_{con} \times GHGIE_{enduse} \times (1\text{-}\eta_{grid})$$

where the variables are given in Table A-1.

For all electricity use cases, we account for a loss of electricity from grid amounting to 8% ($\eta_{grid}=0.08$).

In Table A-2, we provide the assumed values of the electricity-to-e-fuel energy efficiency per fuel type. Electricity-to-e-fuel energy efficiency is defined as the proportion of electric energy utilized in the production of synthetic fuels (e-fuels) that is ultimately retained in the fuel itself as fuel energy.

It considers the thermodynamic losses incurred during the conversion process, including the steps of electrolysis (to produce hydrogen) and synthesis (to combine hydrogen with other elements, such as carbon or nitrogen, to create e-fuels like e-methanol or e-ammonia). The efficiency metric highlights how much of the input electricity is effectively converted into energy stored (lower heating value, LHV) in the resulting e-fuel. The low and high efficiencies

FIGURE A-1

System boundary applied for calculations

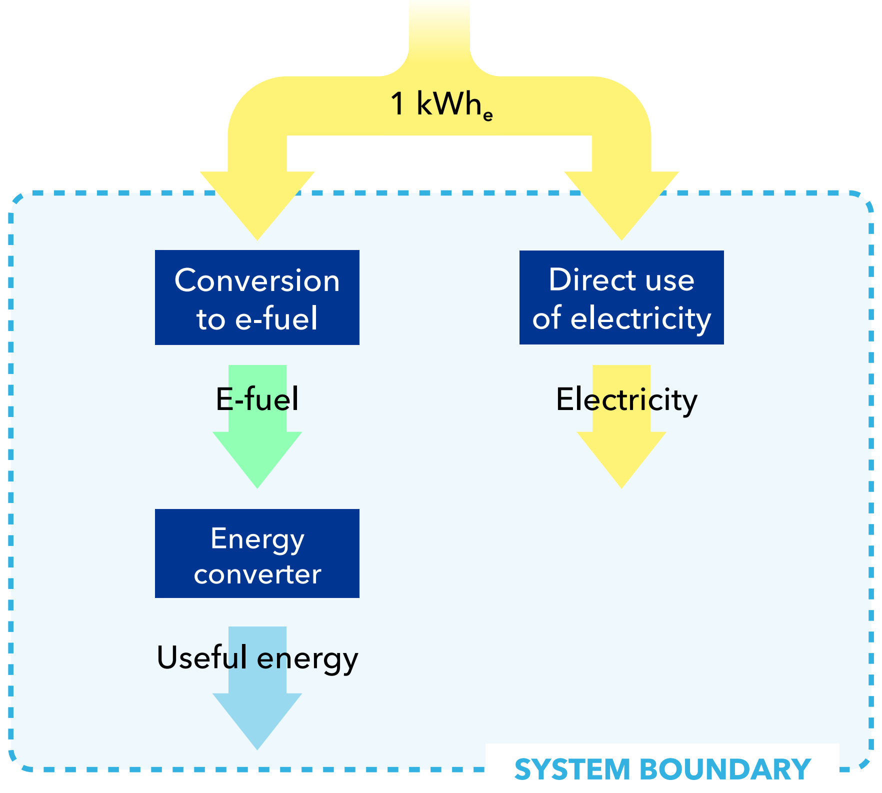


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TABLE A-1

Variables for calculating GHG reduction from different uses of electricity

Variable	Description	Unit
GHG reduction per kWh	GHG emissions avoided per kWh	gCO_2eq/kWh
η_{fuel}	Electricity-to-e-fuel energy efficiency	–
η_{con}	Fuel-to-useful-energy conversion efficiency	–
$GHGIE_{enduse}$	GHG emissions per usable energy output of the displaced activity or the GHG abated from carbon capture and storage per electrical energy input	gCO_2eq/kWh
η_{grid}	Efficiency of grid electricity transmission	–

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TABLE A-2

Electricity-to-e-fuel energy efficiency by fuel-type (LHV)

Fuel-type	Low	High
e-MGO	30%	42%
e-methanol	35%	50%
e-LNG	38%	53%
e-ammonia	45%	55%
e-LH_2	45%	54%
e-CH_2	54%	66%
No fuel conversion	100%	100%

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TABLE A-3

(LHV) Fuel-to-useful-energy conversion efficiency

Sector	End-use	Low	High
Road transport	Gasoline/diesel cars	20%	30%
	Electric vehicles	70%	90%
	Fuel cell electric vehicles	35%	50%
Maritime	Onboard power generation	35%	45%
	Ship propulsion	35%	50%
	Shore power for ship	93%	93%
	Plug-in hybrid ships	88%	88%
	Ships with fuel cells	40%	60%

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reflect different electrolyser efficiency levels and CO_2 source for production of carbon-based e-fuels (i.e. direct capture from air or capture from point source).

In Table A-3, we provide the fuel-to-useful-energy conversion efficiency values applied in the study. Fuel-to-useful-energy conversion efficiency refers to the percentage of energy stored in a fuel that is successfully converted into useful work or energy output during its consumption. This can include mechanical work, electricity generation, or heat, depending on the application. The efficiency depends largely on the technology applied for converting fuel to useful energy (e.g. internal combustion engine (ICE) or fuel cell (FC)), with high and low levels reflecting possible variations.

Table A-4 gives the GHG emissions per usable energy output of the displaced activity or the GHG abated from carbon capture and storage per electrical energy input (given in gCO_2eq/kWh). This metric quantifies the reduction in GHG emissions achieved by displacing an existing activity or by capturing CO_2 for permanent storage. The values given in Table A-4 are calculated from several sources providing data on GHG emissions for different end-uses or energy use for CCS (CONCAWE, 2022; NREL, 2021; IEA, 2024b; Danish Energy Agency and Energinet, 2021), combined with the energy conversion efficiencies given in Table A-2.

TABLE A-4

GHG emissions per usable energy output of the displaced activity (for carbon capture and storage: abated GHG emissions per electrical energy input).

End use	GHG intensity per end-use usable energy (gCO_2eq/kWh)	
	Low	High
Oil-fuelled ship propulsion	650	930
Onboard oil-fuelled power generation	730	930
Gasoline/diesel cars	1 090	1 630
Gas power generation	440	570
Coal power generation	890	1 140
CO_2 capture from air*	360	470
CO_2 capture from concentrated sources*	980	2 460
MGO as ship fuel	653	932
MGO as ship fuel (generator)	725	932
Diesel as car fuel	1 088	1 631
Electricity - gas power	438	569
Electricity - coal power	892	1 137
CCS - DAC	363	472
CCS - Point source/ flue gas	975	2 460

*Estimate includes energy use for distribution and storage of carbon dioxide.

APPENDIX B

Chapter 6 case study

Below we list key input assumptions used in in the case study presented in Chapter 6.

TABLE B-1

Description of annual expense components and revenue included in the case examples

Item	Description
Annualized additional capital expenditure (CAPEX)	We consider the annualized additional CAPEX relative to a conventional MGO-fuelled vessel (see Table B-4). In the case examples, the additional CAPEX is annualized by assuming 100% debt financing with an interest rate of 7% and paydown time of 14 years (due to 2040 being the latest year with an IMO NZF GFI target) (see Table B-3).
Operational expenditure (OPEX)	We assume each compliance strategy has the same OPEX (excl. fuel cost) and hence do not show it as a cost element in the case examples.
Fuel cost	Calculated based on the fuel price assumptions in Table B-2.
Tier 1 remedial unit (RU) cost	Included for compliance strategies with GFI above Direct Compliance target.
Tier 2 remedial unit cost	Included for compliance strategies with GFI above Base target.
Surplus unit (SU) revenue	For the compliance strategies with attained GFI below Direct Compliance target, we assume a reduction in annual expenses proportional to the revenue from selling surplus units.

TABLE B-2

Input assumptions for each fuel-type considered

Fuel molecule	Feedstock	Methane slip (%)* (NZF)	Well-to-wake GFI (gCO_2eq/MJ)		Share of pilot fuel oil (by energy)	Fuel price (USD/GJ)***	Fuel price (USD/tonne MGOeq)
			IMO NZF	FuelEU			
MGO (diesel)	Fossil	–	93.93	90.77	–	13	555
	Biogenic	–	15	15	–	39	1 665
LNG (methane)	Fossil	0.15%	76.09–86.64**	76.08	5%	10	427
	Biogenic	0.15%	15	15	5%	31	1 324

*We apply a tank-to-wake methane slip of 0.15% (IMO NZF / LCA Guidelines) and 0.2% (FuelEU Maritime), as per default factors for LNG Diesel (dual-fuel slow-speed) engines. For the sake of simplicity, higher methane slip values for the LNG Otto (dual-fuel medium-speed) engines on board has not been included.
**Based on a high and low WtT intensity, ranging from 17.4 to 27.95 gCO_2eq/MJ. The IMO LCA Guidelines have not yet determined the WtT GHG intensity factor.
***Prices based on DNV's FuelPrice Mapper. Average values for all regions in the years 2028 to 2040.

TABLE B-3

Economic assumptions

Interest rate	7%
Paydown time	14 years

TABLE B-4

Cost assumptions for the case vessel

Newbuild design option	CAPEX (MUSD)	Additional CAPEX (MUSD)
Mono-fuel MGO	46	–
Dual-fuel LNG	55	9

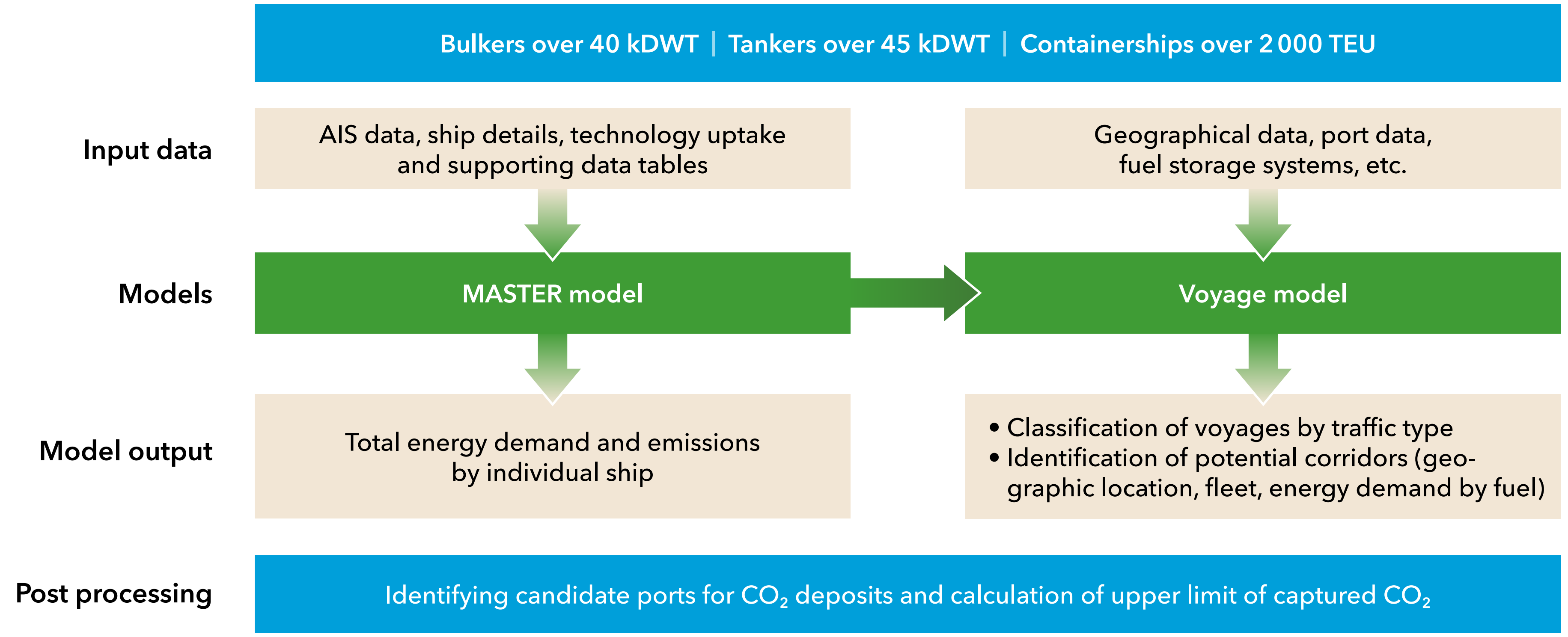
APPENDIX C

AIS analysis for estimating CO_2 storage demand

To estimate the potential captured volume of CO_2 from voyages of bulk carriers above 40,000 DWT, tankers over 45,000 DWT, and containerships over 2,000 TEU in Chapter 7, an analysis using DNV's MASTER model (Mapping of Ship Tracks, Emissions and Reduction potentials) and DNV's Voyage model has been done. The models allow for analysis of fuel consumption and emission on individual ships, aggregation of results on ship types and size categories, geographical areas, and enable detailed voyage and port analysis. An overview of the modelling framework and methodology is illustrated in Figure C-1, followed in the subsequent sections by a short description of the modelling and post-processing steps.

FIGURE C-1

Overview of the calculation method using the MASTER and Voyage models to estimate potential for onboard carbon capture using our estimated tank sizes based on actually installed LNG tanks



C.1 Calculating fuel consumption and emissions – DNV's MASTER model

DNV's MASTER model (DNV, 2008), (Mjelde, Martinsen, & Endresen, 2014) and (DNV GL, 2018), illustrated in Figure C-2, (Mapping of Ship Tracks, Emissions and Reduction potentials) is a Python based model that uses global ship-tracking data from AIS, enriched with other data sources, including ship-specific data from S&P Global, to model energy use and emissions from individual ships. AIS data provides a detailed overview of current sailing speeds, operating patterns, sailed distances (nautical miles) and time spent at sea or in port by each vessel. The information from AIS data is combined with technical databases for detailed information on the individual ships, such as installed power on main and auxiliary engines and boilers, machine configuration (diesel-electric versus diesel-mechanical / direct-driven, and the fuel used), specific fuel consumption, ship design speed, tonnage, and so on.

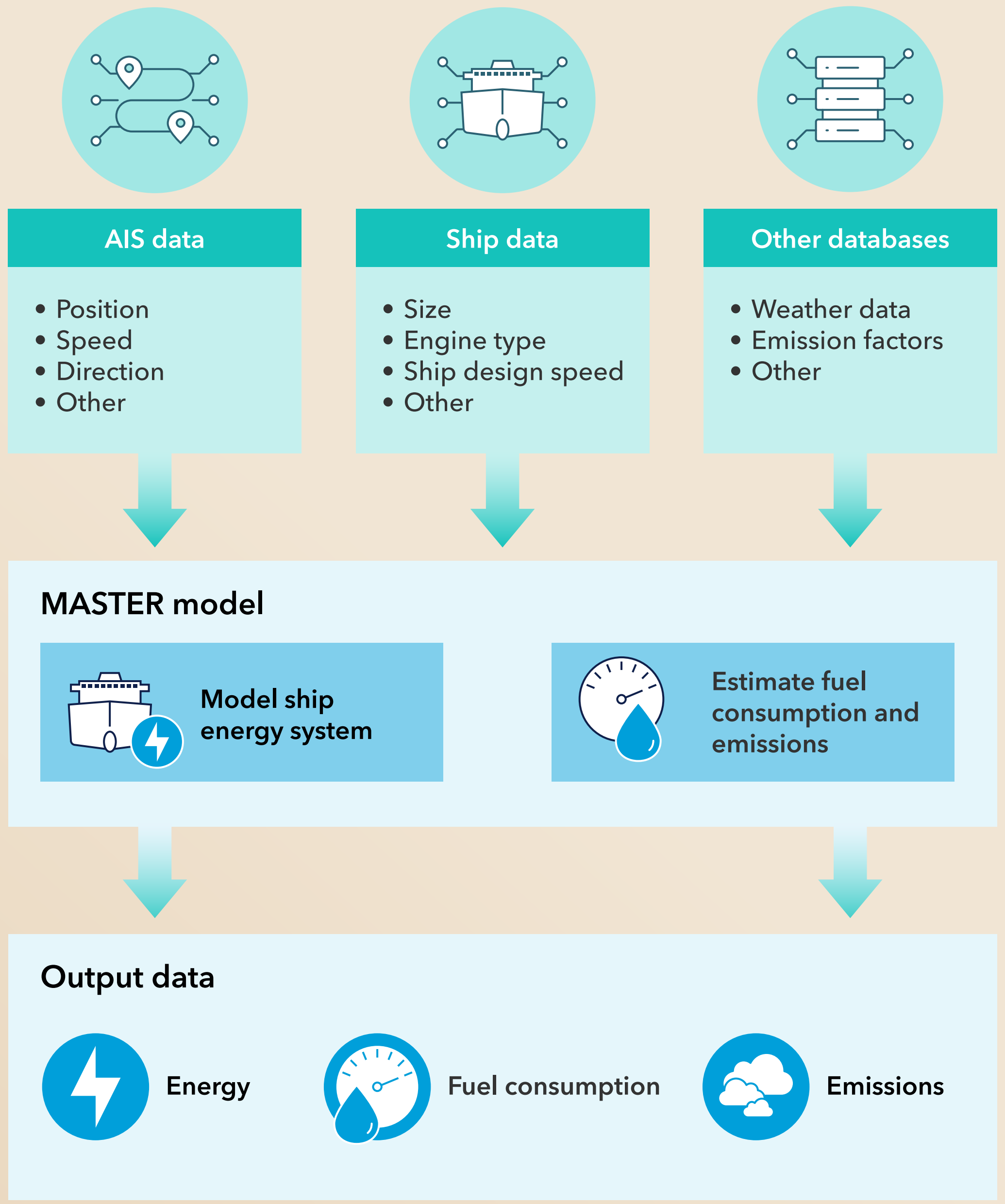
The ship main engine energy demand is modelled using two approaches, dependent on ship type. One is the power model, used mainly for conventional ships like tankers, bulkers, and container-ships, where ship resistance modelling (calm water resistance, air resistance, etc.) is used to estimate power requirements for the main engine. The other approach is the cubic rule method used for other ship types, where the main engine power requirement at given service speed is calculated as the cube of the ratio between the reported ship speed and the service speed of the vessel multiplied with the maximum continuous rating (MCR) of the vessel. The auxiliary and boiler energy use are derived from reported data and depend on operation mode, ship type and size. The energy demand is translated into fuel consumption and emissions, based on the most likely type of fuel used by each vessel.

The output of the MASTER model has been validated against actual reported distance sailed and fuel consumption from around 5,000 vessels of all types.

Quality assurance and control efforts have been taken to minimize the uncertainties in the modelled results. The uncertainties are mainly related to quality of input data, the model algorithms applied to estimate energy consumption, fuel consumption and emissions, and the systematics for distribution of modelled results on individual ship voyages. Frequent update of the databases, validation and calibration routines are established to secure that the input data meet and maintain the highest possible standard.

FIGURE C-2

Conceptual figure of the MASTER model



C.2 From AIS points to voyages – DNV's Voyage model

DNV's Voyage model categorizes the MASTER model results into port visits and port-to-port voyages for individual ships. The ports are defined utilizing DNV's Port Shape database where all ports above a certain size across the world are defined with GPS coordinate shapes, as illustrated by the example in Figure C-3. AIS positions are handled at a frequency of one position every 10 minutes, and when a vessel has four or more consecutive AIS positions within the same rectangle with a 100m diagonal, this is regarded as a stop. When a stop is located inside a port shape, this is regarded as a port visit. A voyage is defined as the vessel's operation between two port visits. This is illustrated in Figure C-4. For each voyage and port visit, the model estimates fuel oil consumption and CO_2 emissions by aggregating data from DNV's MASTER model.

FIGURE C-3

Example port shape from DNV's Port Shape database, showing the Port of Barcelona, Spain

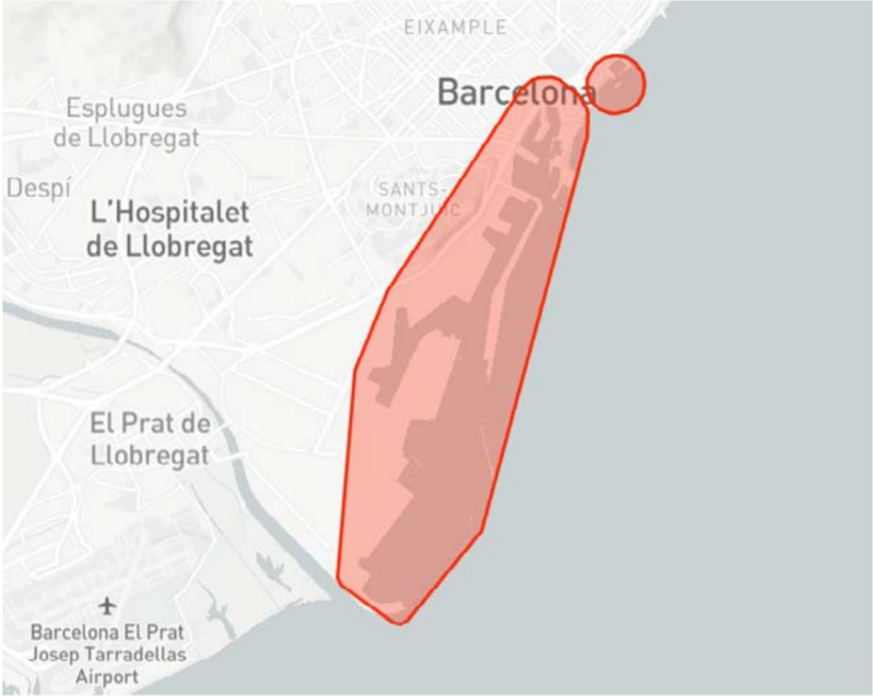
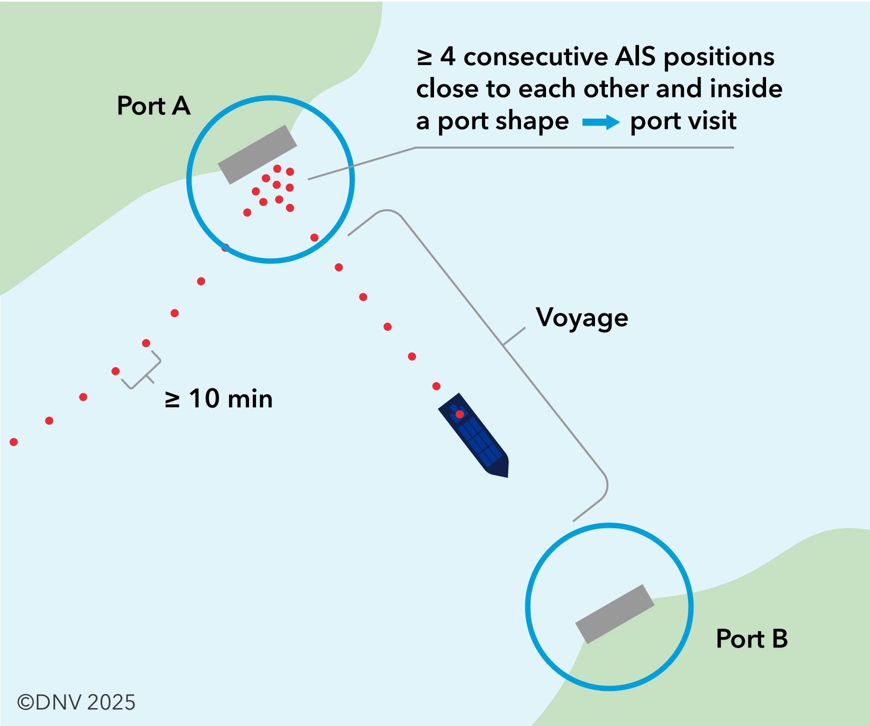


FIGURE C-4

Illustration of voyage detection in Voyage model



C.3 Calculation method for upper limit of captured CO_2

After identifying voyages and calculating their corresponding CO_2 emissions in 2024, the possible amounts of CO_2 that can be captured and delivered given various number of ports with CO_2 deposit infrastructure were estimated. The stepwise method for this is summarized below. The method has been applied sequentially for N equals 5, 10, 20, 30, 50, 75, 100, 125, 150, 175 and 200.

1. Identify the top N ports with the highest total CO_2 emissions from all voyages going into the port in 2024. Assume that these ports have CO_2 deposit infrastructure and are capable of receiving any amount of captured CO_2 emissions.

2. For each ship, calculate the total emissions for activity between each time the ship visits one of these ports.

3. Calculate the possible captured CO_2 for each of the trips between these ports as:
   a. When the emissions between two of the N ports are higher than the capacity of the CO_2 tank, the capture potential is capped at the CO_2 tank capacity.
   b. When the emissions between two of the N ports are lower than the capacity of the CO_2 tank, all emissions are captured.
   c. Ships with no port calls to the N ports do not capture any CO_2 emissions.

4. Sum the captured CO_2 of all the voyages between the N ports for all the ships.

The results are presented in Figure 7-5 in Section 7.2.

Click on a reference to navigate to the related page !

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ENDNOTES

Click on an endnote number to navigate to the related page

1 Only accounting biodiesel produced from advanced feedstocks (i.e. non-food and non-feed sources)

2 Bulkers > 40,000 DWT, tankers > 45,000 DWT, container vessels > 2,000 TEU.

3 IMO Circular Letter No.5005: Draft revised MARPOL Annex VI.

4 The estimate is based on a total energy use for the fleet in scope in 2030 of 8.77 EJ, based on the reported energy use from DCS in 2023 (MEPC 82/6/38) and a projected growth in energy use based on Scenario 24 of Task 2 of the Comprehensive Impact Assessment (MEPC 82/INF.8/Add.1). This scenario assumes low seaborne trade growth (scenario OECD_RCP2.6_G from the Fourth IMO GHG study) and a moderate uptake of energy-efficiency measures. If all ships achieve the Base target and buy Tier 1 RUs, the total Tier 1 RU revenue will be 10.6 BUSD. If 20% of the fleet in terms of energy runs on MGO and also buys Tier 2 RUs, the additional revenue is 5 BUSD. If 20% of the fleet chooses to generate SUs, the Tier 1 RU revenue will be zero from these ships, reducing the total revenue by 2.1 BUSD. In total, we assess the revenue in 2030 to be between 10 and 15 BUSD.

5 Well-to-tank, i.e. the emissions associated with production of liquefied natural gas. There are discussions on what the real emissions of methane during production and transport to ship are.

6 https://ec.europa.eu/commission/presscorner/detail/en/statement_25_1267

7 https://icapcarbonaction.com/en/ets/turkish-emission-trading-system

8 https://asc-registry.org/en

9 ZEMBA used the following definition of zero-emission fuels for the inaugural tender: "fuels that have the potential to achieve GHG (CO_2, CH_4 and N_2O) emissions reductions equal to, or greater than, 90% when compared to a commonly used reference fuel" (Aspen Institute EEP, 2024).

10 https://pancanal.com/en/promotes-sustainable-maritime-shipping-with-the-net-zero-slot

11 https://www.environmentalshipindex.org/info

12 https://www.mpa.gov.sg/maritime-singapore/sustainability/maritime-singapore-green-initiative

13 https://sustainableworldports.org/project/port-of-rotterdam-incentive-scheme-for-climate-friendly-shipping

14 https://cleanairactionplan.org/technology-advancement-program/tap-guidelines-and-funding-opportunities

15 DNV's internal Green Shipping Corridor Database (accessed May 2025).

16 Chalmers and IVL (2023), Life Cycle Assessment of Marine Fuels in the Nordic Region,

17 Resolution MEPC.391(81): 2024 Guidelines on life cycle GHG intensity of marine fuels (2024 LCA Guidelines).

18 DNV – https://www.dnv.com/maritime/publications/fueleu-maritime-white-paper-download

19 In service: 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 does not include retrofit projects.

20 Number of vessels based on the existing fleet (up to 2024) and order book (as of April 2025). Alternative-fuel vessels feature dual-fuel, dedicated gas engines, or batteries. The average projected crew on board is estimated to be 23 in 2030.

21 https://www.maritimetechnologiesforum.com/documents/2024-mtf-ism-guideline-report-April-4-2024.pdf

22 https://www.maritimetechnologiesforum.com/documents/mtf-ammonia-specific-ism-guidelines-1.pdf

23 For more details see DNV 2025 whitepaper on biofuels: (DNV, 2025a).

24 This can, for example, be demonstrated through DNV's biofuel class notation.

25 For more details see DNV 2025 whitepaper on wind-assisted propulsion systems: (DNV, 2025b).

26 The sail experiences apparent wind that generates a total aerodynamic force. This force can be broken down into drag (the component aligned with the apparent wind) and lift (the component perpendicular (90°) to the apparent wind).

27 https://www.bartechnologies.uk/commercial-ships/dnv-validates-energy-savings-of-windwings

28 https://ec.europa.eu/commission/presscorner/detail/en/ip_24_2333

29 https://ec.europa.eu/commission/presscorner/detail/en/ip_24_2333

30 https://hydrogen-central.com/westwood-insight-over-a-fifth-of-all-european-hydrogen-projects-stalled-or-cancelled

31 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

32 The estimate is based on a total energy use for the fleet in scope in 2023 of 8.69 EJ (MEPC 82/6/38) and a projected growth in energy use based on Scenario 24 of Task 2 of the Comprehensive Impact Assessment (MEPC 82/INF.8/Add.1). This scenario assumes low seaborne trade growth (scenario OECD_RCP2.6_G from the Fourth IMO GHG study) and a moderate uptake of energy efficiency. Further, each ship is assumed to use sufficient low-GHG emission fuel at 20 gCO_2eq/MJ, in order to reach the Base target

33 These scenario results are lower than those of the DNV report "Energy Transition Outlook CCS to 2050", mostly due to difference in database, delays added on announced start-up dates, and the success rates used.

34 https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf, C.4.6, page 32: "The technical geological CO_2 storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor."

35 https://www.equinor.com/news/20250327-northern-lights-phase-2

36 As a simplification, in the calculations, we assume that the generation of 1 kWh of electricity has a GHG footprint of zero. In reality, there will be GHG emissions related to construction and decommissioning of the power plant and related infrastructure, as well as operational GHG emissions depending on the source of primary energy.

37 https://www.en-standard.eu/bs-iso-22095-2020-chain-of-custody-general-terminology-and-models/?msclkid=44075f551e981f-9cfe6b397b07b36879

38 International Convention for the Prevention of Pollution from Ships.

39 International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk.

40 MEPC.1/Circ.917 on Interim guidance on the carriage of blends of biofuels and MARPOL Annex I cargoes by conventional bunker ships.

41 https://www.mpa.gov.sg/media-centre/details/successful-first-methanol-bunkering-operation-in-the-port-of-singapore

42 https://www.offshore-energy.biz/fortescues-ammonia-powered-vessel-completes-set-of-sea-trials

43 https://www.yara.com/corporate-releases/the-worlds-first-ship-to-ship-ammonia-transfer-at-anchorage-a-major-milestone-to-decarbonize-shipping-fuel

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

44 Allowing full flexibility in Europe would save energy corresponding to approximately 0.55 Mtoe per year if all the bio-methane produced in the EU (4.3 Mtoe, European Biogas Association) were to be used as fuel for ships, assuming 10% energy loss from liquefaction and 3% from regasification, for a total of 13% energy loss.

45 The abatement cost of a fuel when not considering CAPEX, in terms of USD per tCO_2eq reduced relative to a fossil fuel, can be calculated as the difference in price divided by the difference in GFI. For example, for bio-MGO with a price of 39 USD/GJ and a GFI of 15 gCO_2eq/MJ, relative to fossil MGO priced at 13 USD/GJ and a GFI of 93.93 gCO_2eq/MJ ($kgCO_2eq/GJ$), the abatement cost is (39 – 13)USD/GJ / (0.09393 – 0.015) tCO_2eq/GJ = 329 USD/ tCO_2eq.

46 In Chapter 7 of the 2024 edition of Maritime Forecast to 2050 (DNV, 2024a) we present more details on the pricing mechanism for surplus compliance units in the FuelEU Maritime regulation.

47 DNV white paper – FuelEU Maritime – Requirements, compliance strategies, and commercial impacts. The publication can be downloaded here: https://www.dnv.com/maritime/publications/fueleu-maritime-white-paper-download

48 Solvang chemical tanker Clipper Eris with Wärtsilä capture system, capturing in operational vessel since February 2025: https://www.wartsila.com/media/news/07-05-2025-wartsila-launches-carbon-capture-solution-to-shipping-market-after-world-first-full-scale-installation-success-3582634. In January 2024, the containership MV Ever Top was retrofitted with OCCS, and is both operational and running a capture system: MEPC 83/INF.13, A case of onboard carbon capture system and the offloading of captured CO_2, https://www.linkedin.com/feed/update/urn:li:activity:7343511792909807616, https://www.linkedin.com/posts/lynn-loo-1711562_fuels-carboncapture-decarbonisation-activity-7343535586198044679-VP9B?utm_source=share&utm_medium=member_ios&rcm=ACoAAADGi40Bpwss-TomTubT64ww8Kzg3nP5BdRk

49 Bulk ships over 40,000 DWT, tankers over 45,000 DWT, and container vessels with a capacity of 2,000 TEU or more.

50 The CO_2 deposit potential of a port is defined as the total amount of captured CO_2 that can be offloaded in a given port, if the port has access to CCS infrastructure allowing permanent storage of CO_2 generated on all incoming voyages made by ships

51 Liquefied CO_2 can be stored at different pressures, but the density is typically between 1.1 and 1.2 tons per m^3, while LNG has a density of around 0.45 tons per m^3. See Table 2.1 (DNV, 2025b)

52 https://www.marineteacher.com/post/cargo-tank-types-that-may-be-found-on-gas-carriers

53 In order to assess the volume that can be used for a cylindrical CO_2 tank based on volumes of LNG tanks installed in large container vessels, we assume that the volume taken by the LNG tank has to be used for both carrying fuel (HFO, VLSFO, MGO) and carbon dioxide. Since the volumetric energy density of LNG is approximately half that of MGO, the available space for fuel is estimated to be half of the LNG tank volume. When assuming that the pressurized CO_2 is stored in a cylindrical Type C tank that fits into the remaining space, the tank volume needs to be reduced by approximately an additional one third. This results in our estimate that one third of the LNG tank volume of large container vessels will be available for storing liquefied carbon dioxide.

The volume of a cylinder is the area of the circular cross section times its length. The volume of the same box is the area of the square cross section times its length. The area of the circle is πr^2, while the area of the square is $(2r)^2=4r^2$. As an approximation, the cylinder in the box loses one third of the volume available (1/2 of LNG tank), i.e. one third of LNG tank volume available for CO_2 tank is estimated.

54 There are other limitations on the size of tanks for liquefied carbon dioxide. There are discussions in the industry of building single tanks up to 7,500 m^3 in volume, https://www.provaris.energy/news/provaris-and-yinson-aim-to-break-co2-carrier-capacity-ceiling-with-new-order-in-the-works. Bulkers and tankers with LNG today often use two tanks.

55 CO_2 capture systems may not be able to capture 100% of the CO_2 and the fuel penalty may not be as high as 30%. This analysis includes ships that could only offload once a year, which clearly would not be economical. On the other hand, ships could collect CO_2 from other voyages and not have to unload in the exact port we have used in our analysis.

56 Extra fuel consumption required to operate an onboard carbon capture system.

57 This analysis was performed for the top 5, 10, 20, 30, 50, 75, 100, 125, 150, 175 and 200 ports; i.e. ranking ports by the sum of CO_2 emissions from voyages ending in the given port.

58 Target fleet emissions are only for voyages starting and ending in 2024.

59 Bulkers > 40,000 DWT, tankers > 45,000 DWT, container vessels > 2,000 TEU.

60 As a simplification, in the calculations, we assume that the generation of 1 kWh of electricity has a GHG footprint of zero. In reality, there will be GHG emissions related to construction and decommissioning of the power plant and related infrastructure, as well as operational GHG emissions depending on the source of primary energy.

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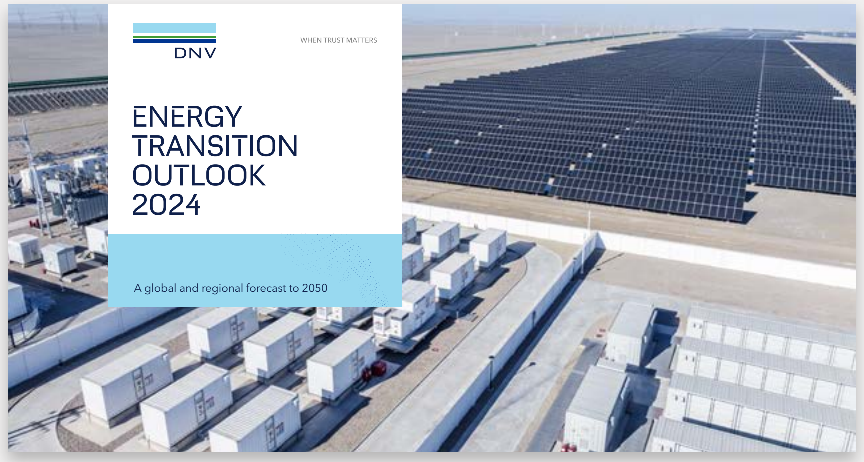

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