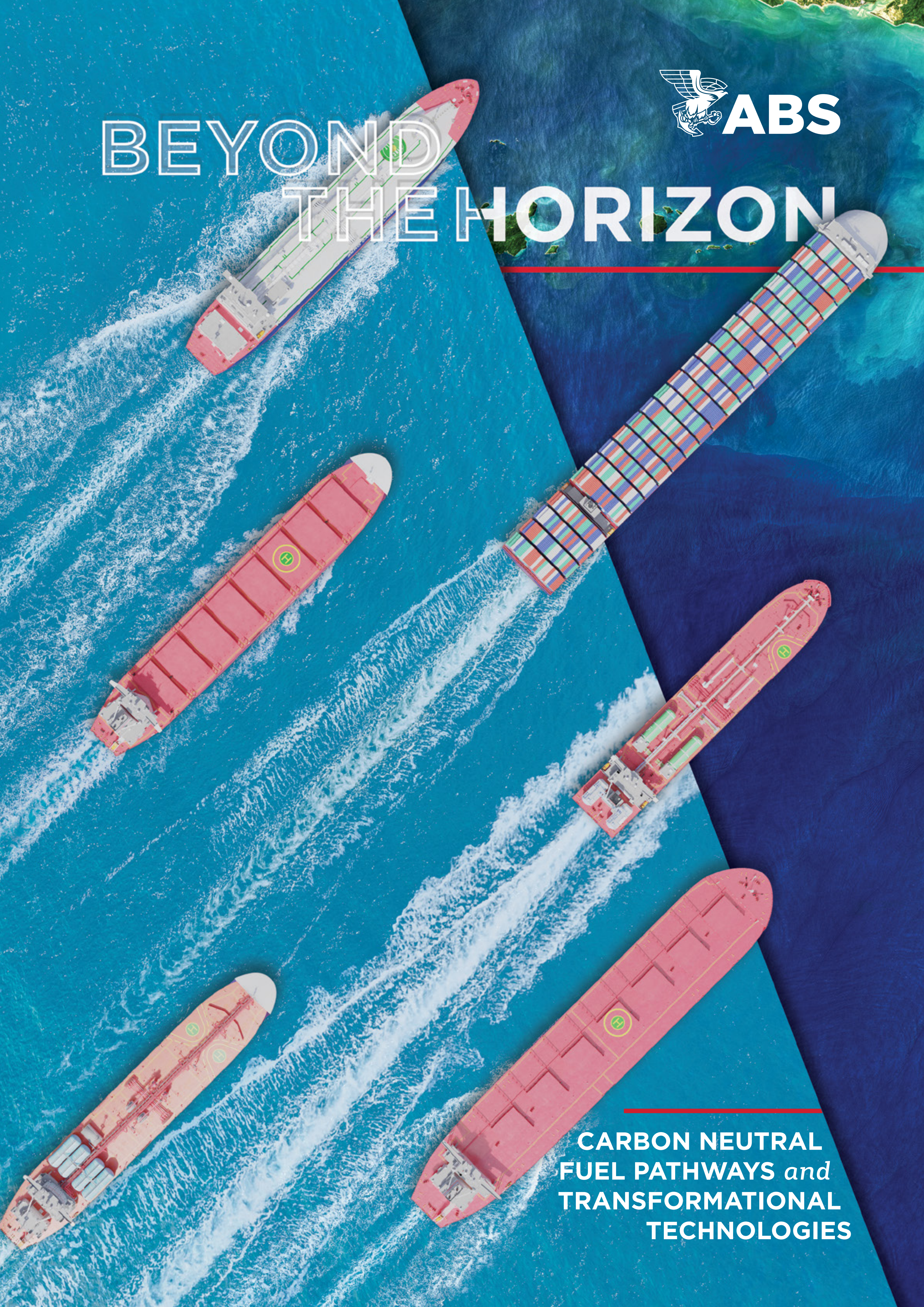
BEYOND THE HORIZON



CARBON NEUTRAL FUEL PATHWAYS *and* TRANSFORMATIONAL TECHNOLOGIES

TABLE OF CONTENTS

SECTION 1

INTRODUCTION

The maritime industry is currently undergoing an energy transition, which is being driven by the imperative to mitigate climate change and an ever-changing regulatory environment. An unprecedented transition from conventional fossil fuels to alternative energy sources and the implementation of cutting-edge technologies define the sector's endeavors.

A number of initiatives aimed at reducing greenhouse gas (GHG) emissions have been implemented or are in the process of being implemented in accordance with the revised GHG Strategy of the International Maritime Organization (IMO). Furthermore, ongoing developments of supplementary measures will support regional or national objectives. The necessity for decarbonization is driven by the numerous statutory requirements enforced on the industry.

1.1 Regulatory Updates

The regulatory landscape governing maritime decarbonization is characterized by a complex interplay between international mandates led by the IMO and regional initiatives that seek to address the unique challenges and opportunities within specific jurisdictions.

The IMO's adoption of a revised strategy in 2023 to achieve net-zero GHG emissions around 2050 marks a significant commitment to leading the industry toward a more sustainable direction. This strategy not only sets ambitious targets but also outlines a series of short-, mid- and long-term measures designed to facilitate the transition to low-carbon practices. This target requires a paradigm shift in operational, technological and fuel utilization across the sector.

Moreover, the regional regulatory landscape is evolving, with entities like the European Union (EU) integrating maritime emissions into its Emissions Trading System (ETS), and the United States focusing on renewable energy and clean technologies. These regulatory frameworks, while distinct in their approaches, underline a global consensus toward a sustainable maritime future.

The path to decarbonization, however, contains several challenges, including technological constraints, the need for significant investments, and the global nature of maritime operations that demands cohesive international regulatory frameworks.

The introduction of novel propulsion methods and alternative fuels strategies stands at the forefront of this transition. However, the industry's journey is also marked by geopolitical tensions and economic challenges that could impact operational and regulatory trends. As we look through 2024 and beyond, understanding the connection between current and future regulatory landscapes and their impact on maritime decarbonization becomes increasingly important.

1.1.1 IMO Latest Developments: MEPC 81

The IMO Marine Environment Protection Committee (MEPC) held its 81st session from March 18 to 22, 2024, and included a program of regulatory developments that will shape the maritime sector for years to come.

Key to the IMO's strategy are the indicative checkpoints set for 2030 and 2040, designed to ensure that the maritime industry is on track to meet its 2050 emissions reduction target. These checkpoints highlight the necessity of rapid adoption of zero or near-zero GHG emission technologies and fuels, alongside significant improvements in energy efficiency onboard vessels. The strategy also highlights the role of mid-term measures, including carbon pricing and GHG fuel standards, which are critical to creating the economic and regulatory incentives that the industry needs in order to invest in cleaner alternatives.

During the period between MEPC 80 and 81, the Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG) worked on further developing:

a. The candidate mid-term measures.

b. The life cycle GHG assessment (LCA) framework.

c. Consider proposals related to onboard carbon dioxide (CO_2) capture.

Further consideration of the development of candidate mid-term measure(s)

The MEPC is advancing in accordance with the established work plan for the development of mid-term measures, anticipating the results of the Comprehensive Impact Assessment (CIA) set to be unveiled during MEPC 82 (September 2024). This assessment aims to estimate the impact of the measures currently under consideration with particular attention paid to the needs of developing countries, especially Small Island Developing States (SIDS) and Least Developed Countries (LDCs).

The following eight candidate mid-term measures are currently considered:

1. **GHG Fuel Standard (GFS) with its Flexibility Compliance Mechanism** as the technical element, in combination with a GHG pricing mechanism covering all GHG emissions as the economic element.

2. **International Maritime Sustainable Fuels and Fund (IMSF&F) Mechanism**, with technical elements and economic elements integrated into a single measure.

3. **Feebate Mechanism**, developed as an economic element separately from a technical element and comprising of a mandatory contribution on GHG emissions and reward for zero emission vessels by the Zero Emission Shipping Fund (ZESF), to be complemented by the GFS as technical element.

4. **Universal mandatory GHG levy as economic measure,** acting in combination with a simplified Global GFS, as technical measure.

5. **Simplified Global GFS with an energy pooling compliance mechanism**, to be developed as a separate technical measure together with a separate maritime GHG emissions pricing mechanism.

6. **ZESF and Fund and Reward (Feebate) mechanism** to be adopted as a separate maritime GHG emissions pricing mechanism as economic measure, in addition to a Global GFS as technical measure.

7. **Green Balance Mechanism**, designed to work as part of an integrated measure or incorporated into complementary, but separate technical and economic measures.

8. **Maritime GHG Pricing Mechanism** as a direct per-tonne-of-CO_2-equivalent regulatory charge on the Tank-to-Wake (TtW) GHG emissions reported by each ship, determined by adjusting a universal GHG price signal according to each fuel type and pathway's Well-to-Wake (WtW) emissions profile.

Table 1.1 presents the different mid-term measures currently under consideration by the IMO.

Proposals for Mid-Term Measures	Description	Technical Measure	Economic Measure
GHG Fuel Standard (GFS) with its Flexibility Compliance Mechanism	Incentivizes the uptake of sustainable low- and zero-carbon fuels, offering flexibility mechanisms such as rewarding of overcompliance for early movers via Surplus Reward Units (SRUs) and alternative compliance options such as GFS Remedial Units (GRUs).	X	
International Maritime Sustainable Fuels and Fund (IMSF&F) mechanism	Aims at the promotion of sustainable marine fuels by setting up an annual GHG fuel intensity target for shipping, while providing flexible compliance approaches (pooling, banking and fund contribution/reward).	X	X
Feebate Mechanism	Comprises of a mandatory contribution on GHG emissions and reward for zero emission vessels by the ZESF, to be complemented by the GFS as technical element.		X
Universal mandatory GHG levy	A mandatory levy on all GHG emissions from international shipping will address the price differential between business-as-usual emission-based technology options, including fuels and decarbonize alternatives.		X
Simplified Global GFS with an energy pooling compliance mechanism	A performance standard, independent of fuel type, which includes a voluntary energy pooling compliance mechanism and may help increase the production and uptake of all types of low-, near-zero and zero-GHG fuels.	X	
Zero Emission Shipping Fund (ZESF)	Funds collected from mandatory contributions by ships per tonne of CO_2 equivalent emitted will be utilized to provide rewards to ships using eligible zero/near-zero GHG fuels through a “feebate” mechanism narrowing the cost gap with conventional fuels.		X
Green Balance Mechanism	Uses a cost balancing approach to reconcile emissions reductions with economic realities. It can be fully integrated with a GHG fuel-intensity standard.		X
Maritime GHG Pricing Mechanism	A direct per-tonne-of CO_2 equivalent regulatory charge on the TtW GHG emissions reported by each ship, determined by adjusting a universal GHG price signal according to each fuel type and pathway's WtW emissions profile.		X

Table 1.1: Mid-term measures currently under consideration.

The Working Group agreed on progressing the development of the basket of measures using the following key five elements:

1. Goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG intensity.
2. Flexible compliance strategies and relevant reporting and verification requirements.
3. (Other) GHG emissions pricing mechanisms.
4. Revenue collection and distribution.
5. Assessment of the remaining work and indicative planning in accordance with the timelines set out in the 2023 IMO GHG Strategy (See Figure 1.1).

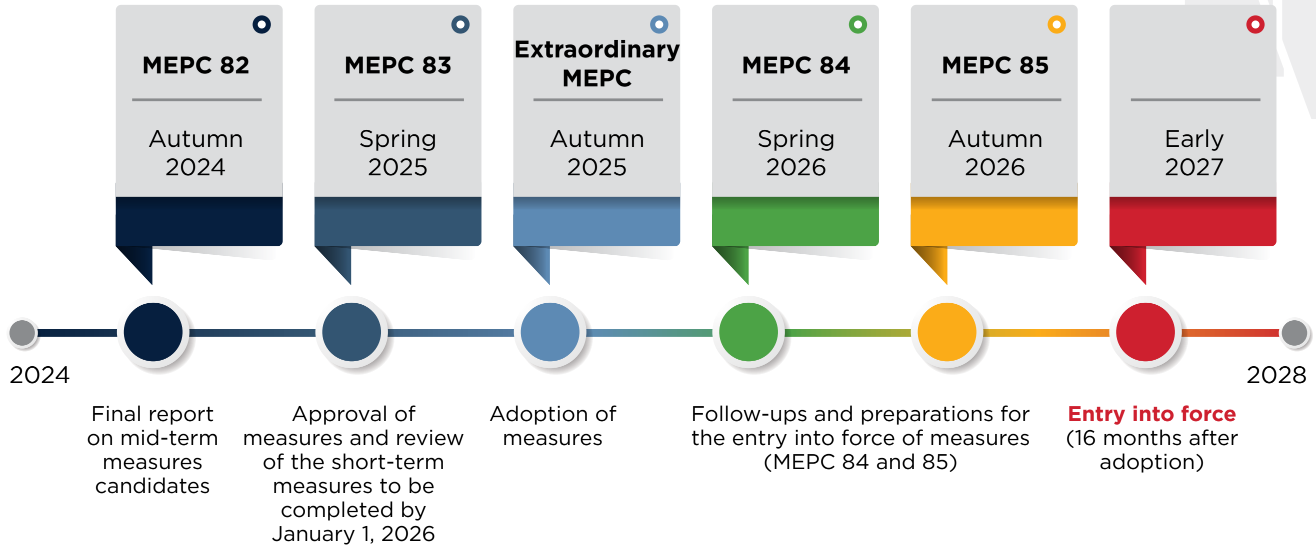


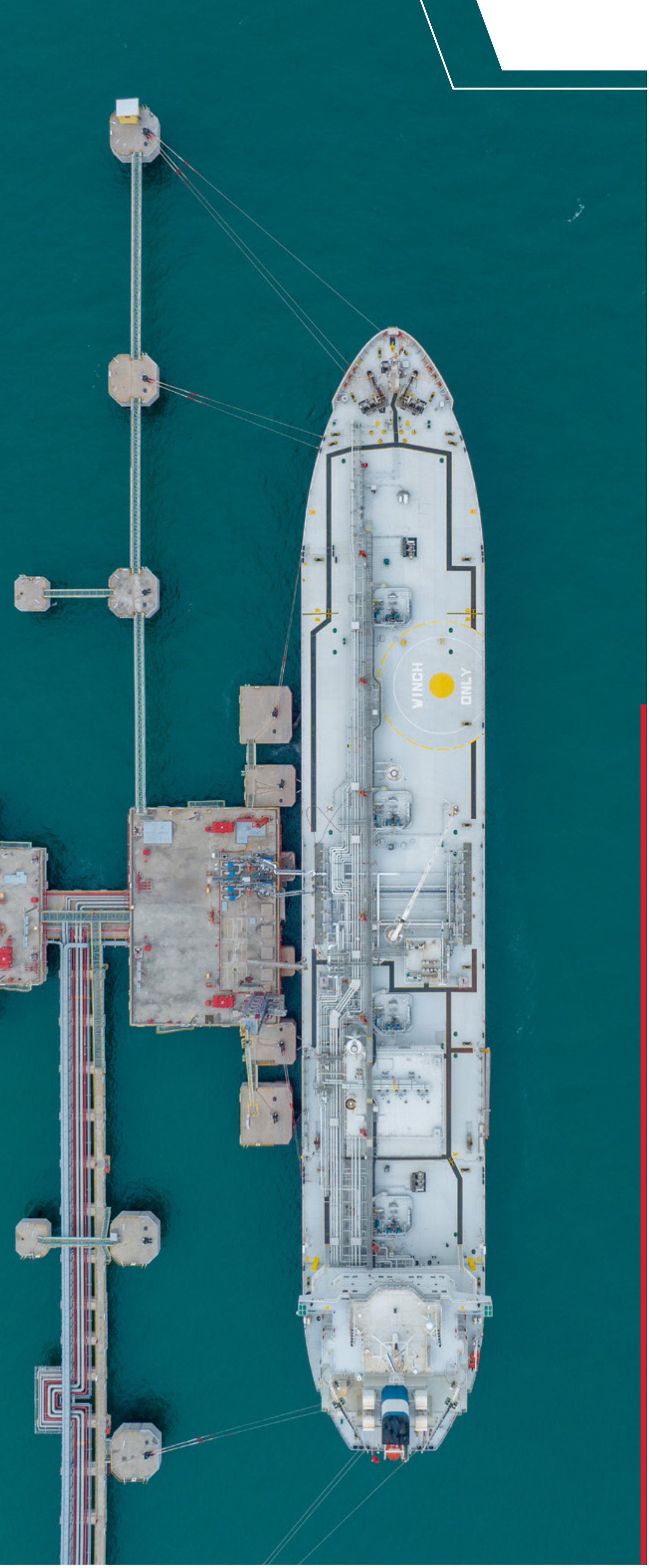
Figure 1.1: Timeline for the development of IMO mid-term measures.

Further development of the life cycle GHG assessment (LCA) framework
The Working Group recommended to the Committee the adoption of the draft MEPC resolution on the 2024 Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines).

It is clear to all stakeholders that there is still a need for continuous scientific review of the LCA Guidelines. In relation to TtW methane (CH_4) and nitrous oxide (N_2O) emission factors and slip values, the Working Group considered a plethora of proposals focusing, inter alia, on the different methodologies and their accuracy in quantifying ship-level methane slip and providing an overview of potential options for certification of TtW methane and nitrous oxide emissions and a default methane slip (C_{slip}) value from engines/energy converters. The development of a framework for the measurement and verification of TtW emissions of methane, nitrous oxide and other GHGs along with associated engine certification issues in the context of the further development of the LCA Guidelines, is widely accepted as the next step forward.

Proposals related to Onboard Carbon Capture
The Working Group considered proposals related to onboard CO_2 capture, focusing on the need for the Committee to initiate as soon as possible the study on onboard carbon capture and storage (OCCS) systems, and developing regulations covering the transportation, storage and disposal of residues and emissions these systems could produce.

Following consideration, the Group noted the broad support to further continue consideration of proposals related to onboard CO_2 capture and, in this regard, invited the Committee to instruct the Working Group of Air Pollution and Energy Efficiency to develop a work plan for the development of a regulatory framework for the use of onboard CO_2 capture with the exception of matters related to accounting of CO_2 captured and the consideration of system boundaries of the LCA Guidelines in relation to onboard CO_2 capture that should be considered in the context of further development of the LCA Guidelines.



1.1.2 IMO Mid-Term Measures: The Road Ahead

Continuing the output from ISWG-GHG 16, the Committee considered how to advance the development of the mid-term basket of measures. The Committee agreed that the possible way forward would be to identify a common structure of the legal framework for the basket of candidate measures to advance further the work of the Organization. During discussions, several delegations supported that it would be premature to rule out any of the candidate proposals without having the outcome of the comprehensive impact assessment and that the common structure should not prejudge any future changes or possible outcomes of further negotiations.

In this regard, the Committee approved the possible outline of the "IMO Net-Zero Framework" with the possible amendments to MARPOL Annex VI, which can be used as a starting point for consolidating the different proposals into a possible common structure.

The Committee agreed on establishing the Fifth GHG Expert Workshop (GHG-EW 5) on the further development of the basket of mid-term measures. During discussions, several discussions supported that the GHG-EW 5 should primarily focus on increasing understanding of the preliminary findings of the CIA for a broader group of delegates than those engaged in the Steering Committee, whereas others expressed that the GHG-EW 5 should not engage in any policy negotiations but provide relevant information to the Committee and/or Steering Committee.

Following consideration of all the views expressed, the Committee requested the Secretariat to organize a two-day GHG-EW 5 to facilitate the understanding of the preliminary findings of the CIA, including the modeling of revenue disbursement used as part of the assessment of impacts on States, taking into account the progress made within the Steering Committee and submit its outcome to MEPC 82.

1.1.3 Marine Fuel Life Cycle Guidelines

Building on the outcome of ISWG-GHG 16, the Committee adopted Resolution MEPC.391(81), 2024 Guidelines on life cycle GHG intensity of marine fuels (2024 LCA Guidelines).

The Committee agreed on the establishment of the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) Working Group on life cycle GHG intensity of marine fuels (GESAMP-LCA WG) to review scientific and technical issues.

The Committee also agreed on the establishment of the LCA Correspondence Group, to further consider "Other social and economic sustainability themes/aspects of marine fuels" as referred to in paragraph 7.1 of the 2024 LCA Guidelines for possible inclusion in the Guidelines, and submit a report to MEPC 83.

1.1.4 Carbon Capture and Storage

The ISWG-GHG 16 had invited the Committee to consider the development of a work plan on the development of a regulatory framework for the use of onboard CO_2 capture, with the exception of matters related to captured CO_2 accounting and system boundaries of the LCA Guidelines in relation to onboard CO_2 capture, which will be considered in the further development of the LCA Guidelines.

The Committee agreed on establishing a Correspondence Group that will further consider issues related to onboard carbon capture and develop a work plan on the development of a regulatory framework for the use of onboard carbon capture systems with the exception of matters related to accounting of CO_2 captured on board ships and submit a written report to MEPC 83.

1.1.5 Other IMO MEPC 81 Developments of Interest

Measurement and verification of TtW emissions of methane (CH_4), nitrous oxide (N_2O) and other GHGs.
The Committee considered the development of a framework for the measurement and verification of TtW emissions of methane and nitrous oxide and other GHGs. The Committee agreed on continuing work on this matter intersessionally, by a Correspondence Group with the following Terms of Reference (ToRs):

- Consider the development of a framework for the measurement and verification of actual TtW methane and nitrous oxide emission factors and C_{slip} value for energy converters taking into account inter alia, standardization required regarding a test cycle approach, onboard monitoring, engine load distribution and associated measurement equipment technology and procedures.
- In support of the LCA Guidelines, development of a methodological framework for associated certification issues.
- Identification of relevant gaps in existing instruments and proposed recommendations for the development of necessary regulatory or recommendatory instruments.

Guidance for the use of biofuels and biofuel blends

The Committee considered a proposal suggesting the development of interim guidelines for the use of biofuels and biofuel blends. These guidelines contained provisions on the procurement of biofuels, risk analysis and contingency measures, their proper storage and use, as also shipboard procedures, and crew familiarization. Due to insufficient support, the Committee decided to invite member States and international organizations to submit proposals relevant to the safe use of biofuels and biofuel blends to a future session of Maritime Safety Committee (MSC).

Carriage of biofuels and biofuel blends by bunker vessels

The Committee considered a proposal for the development of interim guidance on the carriage of biofuels and biofuel blends by bunker vessels, allowing for the conventional bunkering vessels certified for carriage of oil fuels under MARPOL Annex I to transport biofuel blends containing up to 30 percent of biofuel by volume while also encouraging member States to establish their own national legislation for carriage requirement of biofuel blends containing more than 30 percent of biofuel by volume up to B100.

1.1.6 Regional Regulatory Efforts: Navigating Through Diverse Waters toward Decarbonization

The pursuit of maritime decarbonization is unfolding across various regions, each with its own set of strategies, challenges, and advancements. This diversity not only illustrates the complexity of the task at hand but also the innovative pathways being explored around the globe.

European Union: Pioneering Regulatory Frameworks

The EU has been at the forefront of integrating maritime emissions into its broader climate policy frameworks. The inclusion of maritime emissions in the EU ETS marks a significant regulatory shift, aiming to incentivize emission reductions through market mechanisms. This move is complemented by the "Fit for 55" package, which seeks to reduce net GHG emissions by at least 55 percent by 2030, compared to 1990 levels.

Moreover, the EU's focus on digitalization and innovation within port operations exemplifies its holistic approach to decarbonization. Investments in onshore power supply, automated systems for efficient cargo handling, and initiatives for green port infrastructure are poised to significantly reduce emissions from maritime logistics. However, the challenge remains in balancing regulatory ambitions with practical feasibility and ensuring that the maritime sector remains competitive and resilient in the face of stringent environmental standards.

United States: Leveraging Innovation and Partnerships

In the United States, the approach to maritime decarbonization is characterized by a strong emphasis on technological innovation and public-private partnerships. The Maritime Administration (MARAD) plays a crucial role in fostering innovation through programs such as the Marine Highway Program, which aims to alleviate road congestion and reduce emissions by shifting freight transportation to navigable waterways. Additionally, the recent infrastructure and clean energy legislation have opened new avenues for investment in clean maritime technologies, including electrification, fuel cell technologies, and alternative fuels like LNG and hydrogen.

The U.S. is also witnessing a growing trend of collaborations between maritime companies, technology firms, and academic institutions to pilot and scale new decarbonization technologies. However, the fragmented nature of the U.S. regulatory landscape, with state-level initiatives such as California's stringent emissions regulations, presents both opportunities and challenges for harmonizing efforts toward national decarbonization goals.

Asia-Pacific: Balancing Growth with Green Ambitions

The Asia-Pacific region, home to some of the world's largest shipping fleets and busiest ports, is navigating its decarbonization journey amid rapid economic growth and environmental pressures. China's dual commitment to peaking emissions before 2030 and achieving carbon neutrality by 2060 extends to its maritime sector, with significant investments in port electrification, LNG-fueled vessels, and solar-powered infrastructure. Similarly, Singapore's Maritime and Port Authority (MPA) is spearheading initiatives to promote the use of cleaner fuels, enhance energy efficiency, and develop the world's first green port standards.

The region's approach is characterized by a blend of regulatory mandates and incentives for innovation, with countries like Japan and South Korea investing heavily in hydrogen fuel cell technology and ammonia as future maritime fuels. The challenge for the Asia-Pacific lies in aligning these ambitious technological and regulatory efforts with the global standards set by the IMO, ensuring that regional progress contributes to worldwide decarbonization objectives.

The Road Ahead: Toward a Unified Global Effort

As the maritime industry ventures into the uncharted waters of decarbonization, the diverse regional efforts underscore the importance of collaboration and knowledge sharing. The IMO's role as a unifying global entity is pivotal in harmonizing these regional approaches, facilitating the adoption of universally accepted standards, and ensuring a level playing field. The complexity of maritime decarbonization, coupled with the sector's intrinsic link to global trade and economic development, necessitates a coordinated effort that respects regional nuances while striving for global environmental goals.

The journey ahead is filled with challenges, from technological hurdles and financial constraints to the need for global regulatory alignment. Yet, the regional efforts underway illuminate a path forward, showcasing a collective resolve to navigate toward a sustainable and low-carbon maritime future. As these initiatives evolve and intersect, the maritime industry's commitment to decarbonization becomes increasingly evident, heralding a new era of environmental stewardship and innovation on the high seas.

1.2 Publication Overview

The principal objective of this publication is to analyze the developments, obstacles and prospects encountered by the worldwide maritime industry during this energy transition period. Moreover, as we approach the midpoint and conclusion of this decade and contemplate the integration of alternative fuels, this publication also evaluates the techno-economic viability of the primary fuel production routes.

Section 2 delves into an analysis of the substantial changes in fuel consumption patterns, the integration of alternative energy sources, and the broader ramifications that will affect the maritime industry in the run up to 2050. Recent regulatory updates from the IMO and significant geopolitical events that have altered energy strategies and trade routes have been incorporated into the revised forecasts. These alterations signify a more complex and dynamic environment in which traditional fossil fuel energy sources are increasingly being supplemented or replaced with emission-free alternatives, such as methanol, ammonia, and potentially hydrogen, in the coming years.

This section also utilizes a rigorous methodological framework that consists of the subsequent components:

- Quantitative forecasting: Involves using historical data and trend analysis to predict future changes in fuel usage and emissions.
- Qualitative insights: Leveraging ABS' expertise, the data is analyzed by technical experts who provide interpretation within the broader framework of technology and economic advancements.

Our analysis focuses on the ramifications of recent geopolitical events on our industry's decarbonization efforts. In doing so, we have revised the projected fuel blend and explored a number of net-zero scenarios to ascertain the necessary conditions for the industry to achieve the IMO's 2050 objective.

Section 3 presents a thorough analysis of the present and anticipated market conditions as well as the capabilities of the ecosystem. It touches explicitly on the orderbook's status and progress toward retrofitting to ensure regulatory compliance. Furthermore, it investigates the broader consequences for shipyards' ability to assist the industry in the energy transition initiatives.

As of April 2024, the worldwide shipping fleet has surpassed 109,000 vessels in number, approximating 1.6 billion gross tons (gt) and 2.4 billion deadweight tonnage (dwt). The substantial compositional changes occurring on this enormous fleet, which is fundamental to international commerce, result from shifting market demands and regulatory pressures to reduce maritime emissions. The orderbook, which contains comprehensive information regarding the construction of future ships, has experienced substantial variations. A significant surge in newbuilding contracts occurred after 2020, indicative of a recovery from historically low levels and the implementation of the new environmental regulations.

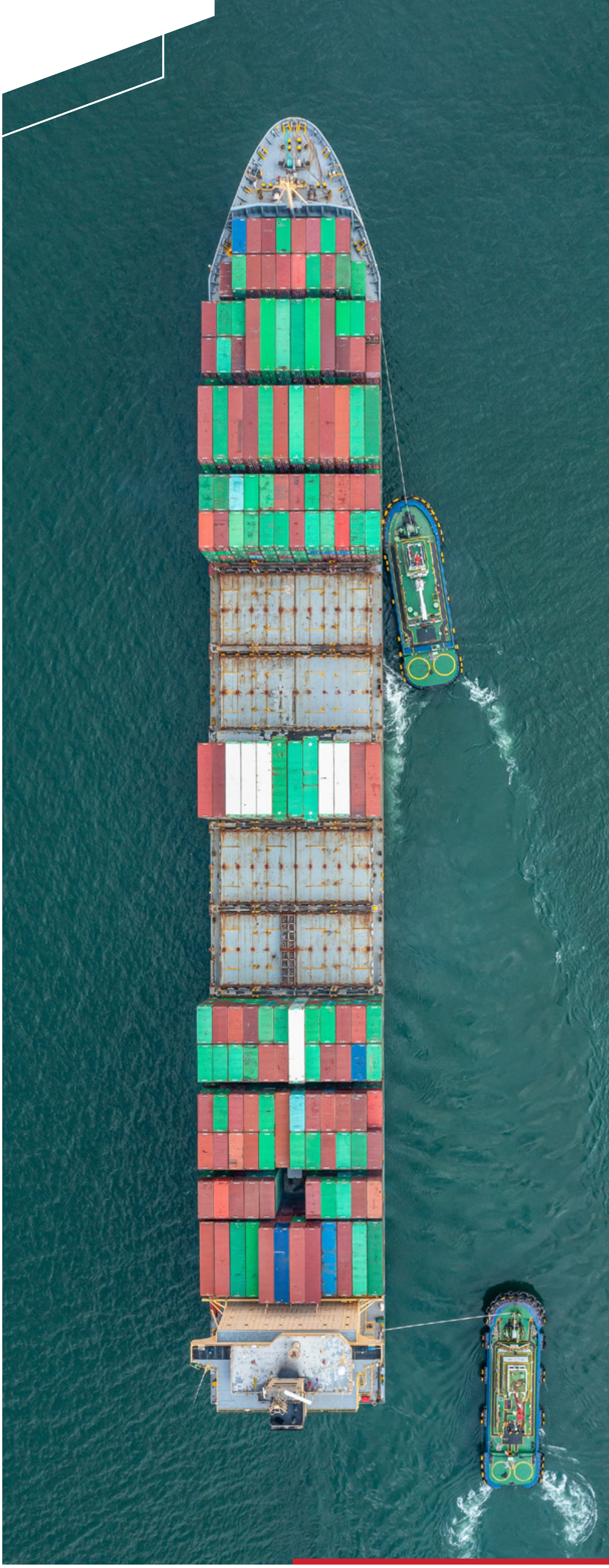
The transition to alternative fuels, which has become a significant parameter of new ship orders, is a primary focus of this section. An examination of fuel-specific contracting patterns yields valuable insights regarding the industry's strategic approach toward achieving decarbonization.

Existing vessel retrofitting is an indispensable means of compliance with new environmental regulations. Given that a mere fraction of the worldwide fleet is presently upgraded to more recent standards, the growth potential in this domain is enormous. The discourse encompasses an evaluation of the shipyards capable of carrying out these retrofits, their geographical dispersion, and the technological capacities necessary to execute such intricate alterations.

Critical for both new construction and retrofits, shipyard capacity has undergone substantial transformations. This section examines the historical contraction and recent expansions that have occurred in the industry, with a specific emphasis on the ability of shipyards to fulfill present and future requirements. This entails conducting an analysis of the roles played by global leaders in shipbuilding to determine the geographic distribution of shipyard capacity. The strategic manoeuvres of shipyards in main shipbuilding nations such as China, South Korea, and Japan and the possibility of new entrants from other regions entering the market are given particular consideration.

This segment furnishes industry stakeholders with insightful projections of forthcoming trends and current data, helping to facilitate well-informed decisions. These projections have been developed based on historical data, current market analysis, and anticipated technological and regulatory developments.

In pursuit of the critical objective of decarbonizing the maritime sector, **Section 4** analyses the present and prospective capabilities of fuels and technologies that produce zero or nearly zero carbon emissions. This section examines two main areas of emphasis: firstly, the evaluation of different marine fuel pathways, which encompass traditional hydrocarbon-based fuels as well as alternatives such as ammonia, methanol, LNG, hydrogen, and biofuels; and secondly, the investigation of Energy Efficiency Technologies (EETs).



Subsequent to examining the present condition, this section delves into a discourse concerning alternative fuel pathways and the critical significance of technology in enhancing operational efficiency and reducing emissions. It examines the WtW emissions of various fuels throughout their entire life cycle, from production to consumption. The Section examines these pathways and emphasizes the technical, economic, and environmental factors that require attention.

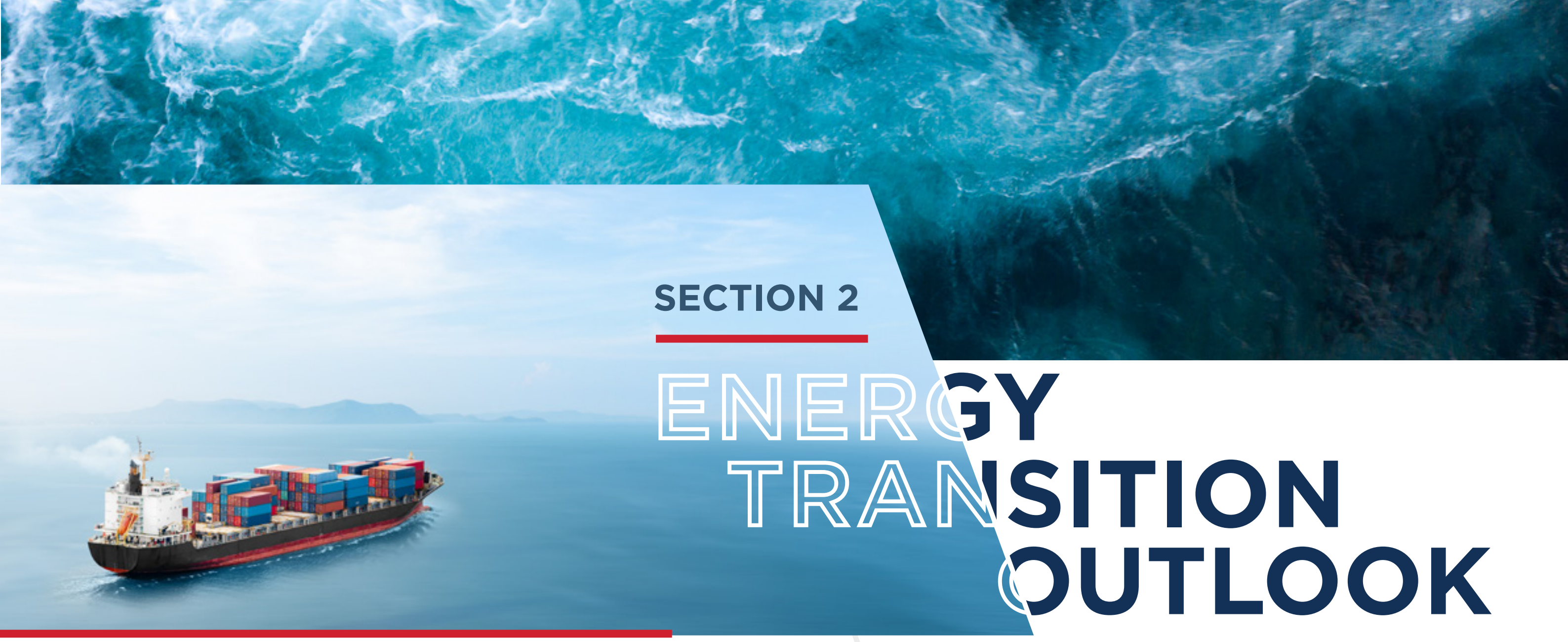
A comprehensive analysis of the primary transformative options for the maritime sector is presented in **Section 5** of this publication. The primary emphasis is on the progression and implementation of unconventional, alternative energy sources. This Section provides an in-depth analysis of five prominent technologies that are critical in attaining the decarbonization objectives of the industry:

- The investigation of OCCS technologies pertainsto the potential resolution of capturing and storing CO_2 emissions in the form of exhaust gases from ships.
- Novel EETs and the role they play in improving the performance of vessels.
- Fuel cells, emphasized as a critical technology, provide an environmentally friendly substitute for conventional internal combustion engines utilizing electrochemical energy production. A range of fuel cell types are examined, each of which possesses unique merits that are tailored to maritime contexts.
- The integration of battery energy storage systems (BESS) with internal combustion engines to produce hybrid ship propulsion systems. These configurations have the potential to substantially improve fuel efficiency, decrease operational expenses and reduce greenhouse gas emissions, rendering them well-suited for vessels that experience fluctuating power requirements.
- The section also explores the viability of utilizing nuclear power as an alternative energy source, specifically in large-scale maritime applications. Safety concerns and regulatory obstacles are among the challenges and benefits of implementing nuclear technology in the transport industry that are examined.

Section 6 provides a comprehensive examination of the present developments, obstacles and technological breakthroughs within the offshore sector, with a specific emphasis on the sector's evolving contribution to the worldwide energy composition. In light of the global shift toward sustainable energy solutions, the offshore sector finds itself at a pivotal juncture, where it must navigate the rapid integration of renewable energy technologies, including offshore wind and hydrogen production, alongside conventional oil and gas operations.

This section also addresses the exponential expansion of offshore wind energy, with its global capacity predicted to increase by a factor of 10 by 2030. Furthermore, it delves into the subject of biodiversity, which is deemed environmentally significant.

In **Section 7**, the key insights from the outlook publication for this year are concisely summarized, offering a comprehensive examination of the principal developments and obstacles that impact the worldwide maritime and offshore sectors.



SECTION 2

ENERGY TRANSITION OUTLOOK

2.1 Introduction

Significant shifts have occurred along the decarbonization trajectory, whereas broad-scale fuel mix trends have remained unchanged since ABS' 2023 Outlook. The change in emphasis toward the deliverability of targets and initiatives throughout the entire decarbonization value chain has been the most significant. While not explicitly associated with the swift decline of the worldwide geopolitical landscape in the preceding half-year, this does not appear to be unrelated.

We have fully aligned our net-zero scenario with the most recent International Maritime Organization (IMO) mandates, established during the Maritime Environmental Protection Committee (MEPC) meeting last summer, with the implementation of this update. These regulations develop explicit objectives for the shipping industry to fulfill, and a critical component of this publication involves quantifying the level of simplicity or difficulty associated with performing so. Measures aimed at attaining net zero will inherently be diverse and multifaceted, but the precise manner in which this will transpire in the present remains uncertain.

2.2 Long-Term Energy Forecasts

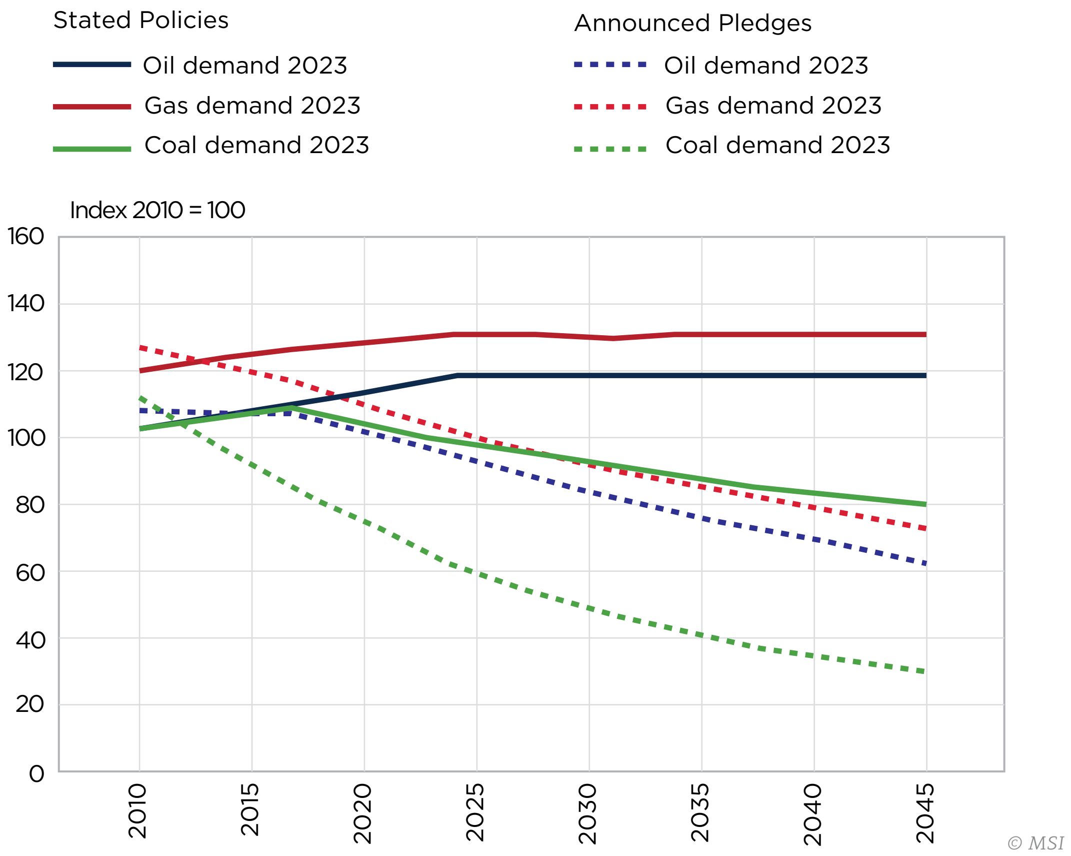
2.2.1 IEA Forecasts

The 2023 edition of the International Energy Agency's (IEA) World Energy Outlook (WEO), published in October 2023, updates the three energy transition scenarios presented in its 2022 report: the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 Scenario (NZE Scenario).

- Stated Policies (Figure 2.1), assumes today's policies remain in place and shows the associated trajectory. Under the new edition of Stated Policies, the IEA has moderately reduced its projections for fossil fuel demand relative to the 2022 scenario. This reflects a combination of policy shifts, lower economic growth expectations, and the ramifications of the 2022 energy crisis. Under the 2023 Stated Policies Scenario, and in contrast to previous editions of the WEO, each of the three main fossil fuels (oil, natural gas and coal) peaks in usage before 2030. Coal demand sees the largest proportional downgrade under this scenario update, and in 2050 sits 9.5 percent lower than under the 2022 WEO. In 2050, oil demand is 4.6 percent lower than in the 2022 WEO, and natural gas demand 4.2 percent lower.

- Announced Pledges (Figure 2.1), assumes that all aspirational targets announced by governments are met on time and in full, including their long-term net zero and energy access goals. The main change with the 2023 update is that coal demand sees an even steeper fall under the new scenario, reflecting a more accelerated reduction in coal usage in China under its 2060 net-zero emissions pledge. Changes to projected oil and natural gas demand are limited, with both continuing to see steady reductions in demand after 2030.

- The underlying assumptions for the net-zero scenario are unavailable, so ABS has not included this scenario in its analysis. Under the 2023 net-zero scenario, electrification proceeds even faster than under Announced Pledges.



© MSI

Figure 2.1: Stated policies vs. announced pledges 2023.

2.2.2 Energy Model Base Case

At a global level, it is important to recognize that over most of our projection analyses, energy demand is growing. Relative to 2023 levels, current base case sees global energy consumption increase by an additional 44 exajoules (EJ) (+7.6 percent) by 2030, 100 EJ (+17.3 percent) by 2040, and 123 EJ (+21.4 percent) by 2050 (Refer to Figure 2.2). However, beneath growth in aggregate energy demand, there are marked shifts in regional energy consumption patterns and the share of different energy carriers used to meet final demand.

Looking at the world as five regions, ABS sees three key trends with regards to the distribution of future demand:

1. Americas, Europe/Russia: stable overall demand alongside a steady decline in their global share of final energy demand.
2. China, Northeast Asia: set to stabilize overall energy demand during the 2030s, peaking above 30 percent of the global share, before seeing a long-term trend decline.
3. Africa, Middle East, South and Southeast Asia: will be the main regional drivers of long-term increases in global energy demand. These regions currently account for about 27 percent of global final energy consumption. This is forecast to rise to a combined 38 percent by 2050.

Compared to an estimated share of global energy consumption of 6.9 percent in 2023, renewables in the global energy mix rise to 12.1 percent in 2030, 21.7 percent in 2040 and 30.8 percent in 2050. Absolute consumption of oil and coal peaks before 2030 under the current base case, while natural gas peaks by the late-2030s.

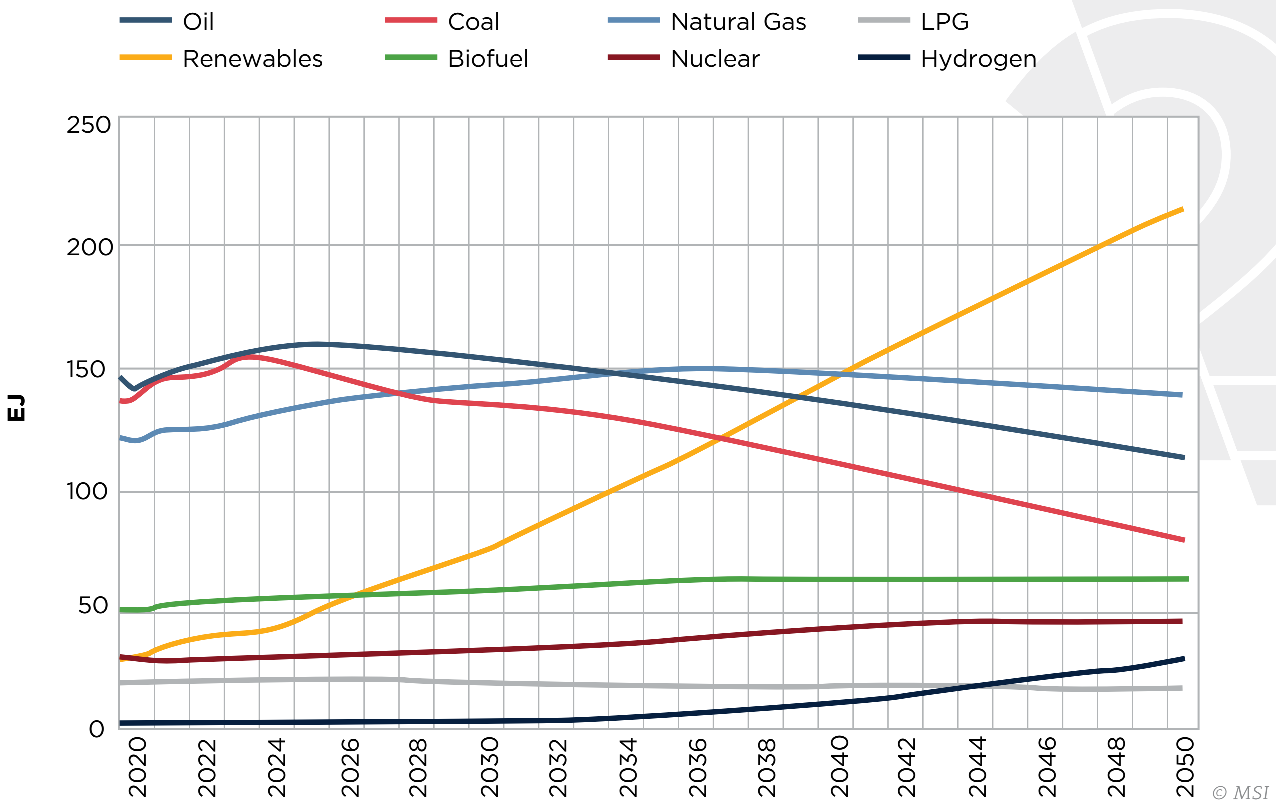


Figure 2.2: Total global consumption by energy carrier.

2.2.3 Total Final Consumption Energy Use

The transport and industry sectors are the largest "users" of final energy demand, with transport accounting for around 30 percent of global final energy consumption in 2023, and industry nearly 34 percent. The shares of final energy consumption are expected to remain relatively stable over this study's forecast horizon, with an increase in transportation energy demand offsetting a slight fall in industry energy usage between 2025 and 2050. Over this timeframe, transportation energy demand is expected to grow at a compound annual growth rate (CAGR) of 0.5 percent, while industry energy demand will contract at a CAGR of -0.1 percent.

A far more significant change will be seen in the types of energy consumed to meet the growing final energy demand (Figure 2.3).. To take transportation as an example, this sector still overwhelmingly uses oil as its energy source. However, oil's share of final transport demand has gradually dropped over the last two decades, from 95 percent in 2000 to 88 percent in 2020. Other hydrocarbons, including biofuels and liquefied natural gas (LNG)/liquefied petroleum gas (LPG), have largely substituted this.

However, ABS expects oil use for transportation to peak toward the end of the current decade. While electrification will be a key component in substituting oil, other energy sources such as hydrogen and associated products (e.g., ammonia/methanol) and other hydrocarbons such as LPG will also play a significant role.

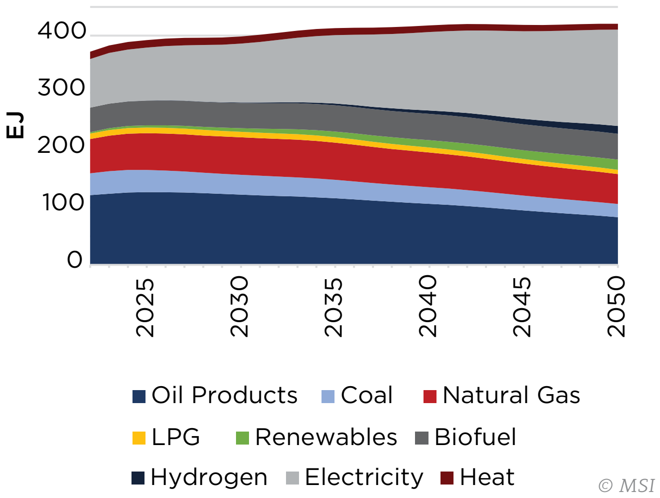


Figure 2.3: Total global final consumption by energy source.

2.2.4 Electricity Generation

Electricity demand is projected to increase over the forecast, with final demand effectively doubling from current levels by 2050 to around 160 EJ by 2050.

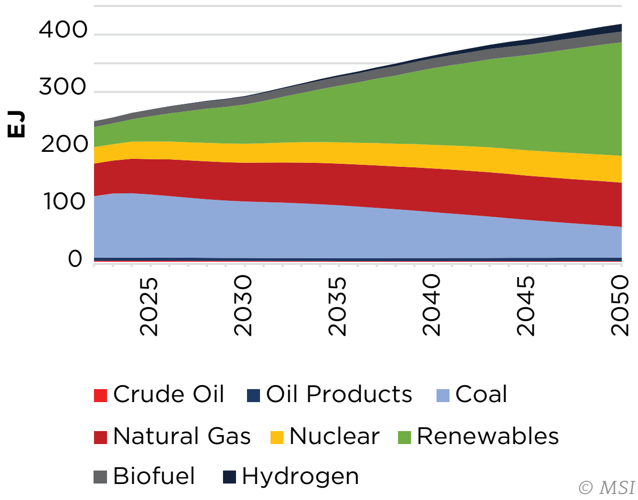
All end-use sectors will see increasing demand, notably in industry. Still, the transportation sector will be the strongest driver of incremental electricity usage by the end of the forecast horizon.

The transport demand accounts for relatively little final electricity consumption, which is dominated by industry and residential usage.

Vehicle electrification will increase transport's share of global electricity demand. By 2030, transport will account for 5 percent of global electricity demand, rising to 19 percent by 2050.

Electric vehicle (EV) sales increased by 31 percent year-on-year in 2023. Fully or battery electric vehicles (BEVs) comprised 9.5 million of the 13.6 million EVs sold, with plug-in hybrid vehicles (PHEVs) making up the remainder.

Increasing electricity demand requires growing power generation capacity. We expect renewables to drive growth, as traditional sources, particularly coal, decline (Figure 2.4).



© MSI

Figure 2.4: Electricity generation by energy source.

2.2.5 Consumption by Energy Carrier — Scenarios Compared

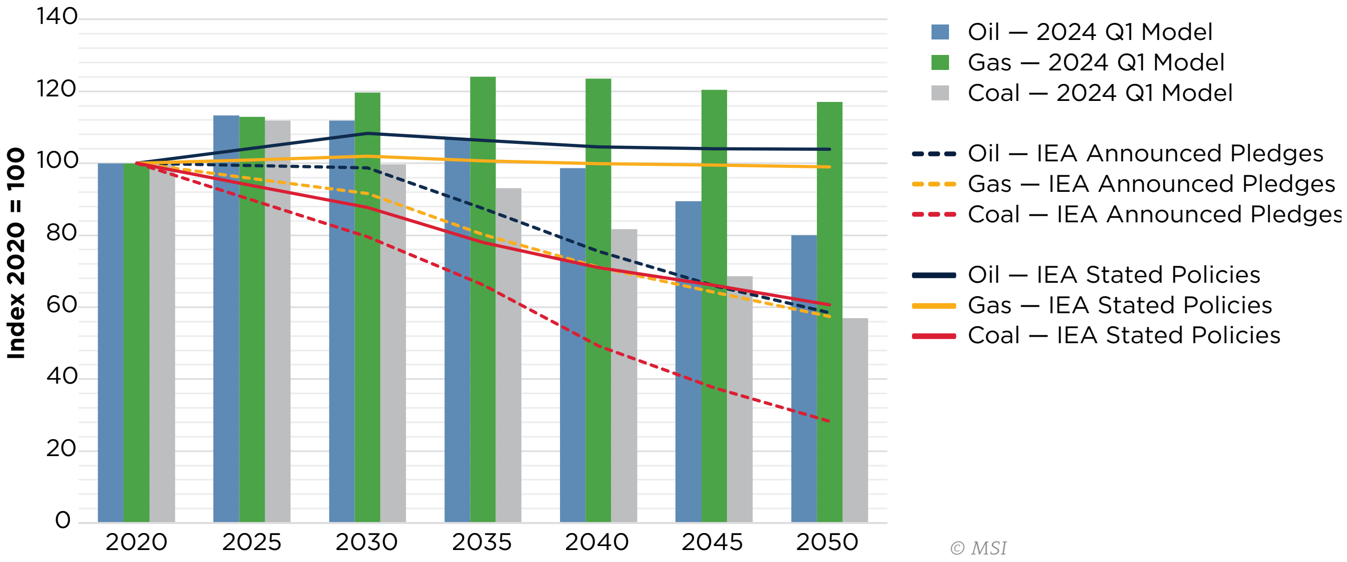
Oil consumption peaks toward the end of the 2020s under the current base case. Changes to ABS' oil demand outlook are relatively minor compared to our 2023 Outlook publication with reduced forecasted consumption in the 2020s followed by an uplift to forecasted consumption beyond the 2030s (Figure 2.5). Above all, there is clear evidence of accelerated adoption of electric vehicles in China, which will ultimately drive a steep reduction in global oil consumption. The current base case effectively plots a course between the IEA's Stated Policies and Announced Pledges scenarios beyond the 2030s.

Compared to oil, the updated scenario projects a continued increase in global demand for natural gas through the second half of the 2030s and only a steady reduction after that. Given forecasts for continued growth in overall energy consumption, a near-term reduction in natural gas demand would require a rapid uptake of electrification, or use of non-fossil fuel energy carriers, across industry and hard-to-decarbonize sectors, evidence of which is still mixed.

ABS' latest projections foresee a larger role for natural gas than under the IEA's 2023 Stated Policies scenario, which sees only limited increases in natural gas demand moving forward, and a significantly greater role than under the IEA's Announced Pledges scenario, where natural gas demand by 2030 has already fallen compared to present-day levels (Figure 2.5). Over the longer term, the uplift to our natural gas demand forecast is driven by India and, to a lesser degree, China and Southeast Asia. Throughout the forecast horizon, natural gas demand in Russia and other Commonwealth of Independent States (CIS) members is higher because of fewer export opportunities.

Energy security concerns, higher natural gas prices following the conflict in Ukraine in 2022, and weather-related disruptions to renewable energy production have boosted demand for coal in recent years. In line with ABS' 2023 Outlook publication, the current 2024 Q1 model projects a peak in global coal consumption by 2025. Total global consumption then falls by 11 percent by 2030, 27 percent by 2040, and 49 percent in 2050. This represents a slightly slower pace of reduced consumption relative to the previous study, also starting from a higher peak given the resilience of coal demand in the past several years.

This scenario update also sees an additional uplift to ABS' forecast for global coal consumption over the forecast horizon to 2050. Global coal consumption is around 6 percent higher in 2030 compared to our 2023 Outlook publication, 10 percent higher in 2040, and 19 percent higher in 2050. China and India account for most of this uplift in forecasted global coal consumption (Figure 2.5).

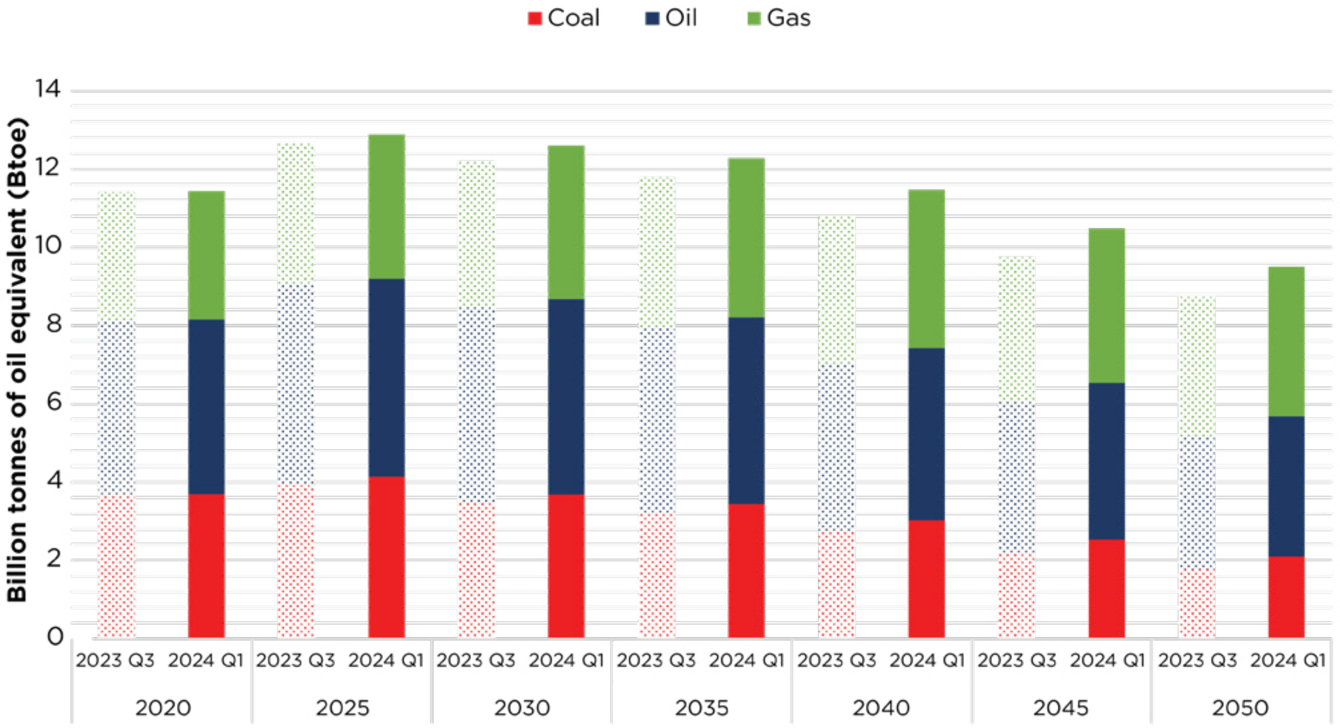


© MSI

Figure 2.5: Oil, gas and coal consumption projections.

Combined, coal, oil and natural gas will peak in consumption before 2030. However, the level of consumption of the three major carbon carriers has increased compared to our 2023 Outlook publication projection. Figure 2.6 illustrates this point.

Looking at the data at five-year intervals also exaggerates the leap in fossil fuel consumption in 2025 relative to 2020, given the fall in global energy consumption during the COVID-19 pandemic.



© MSI

Figure 2.6: Energy consumption by primary carbon carrier.

2.3 Cargo Demand and Fuel Consumption

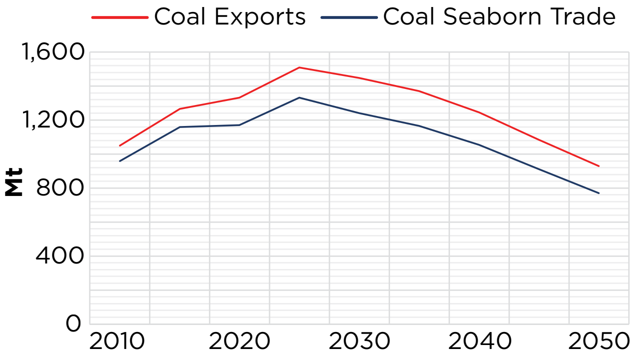
2.3.1 Bulk Carriers

With this Outlook publication, ABS has increased its long-term forecasts for seaborne coal trade compared to the 2023 study, although it is still anticipated that coal trade will soon reach a peak and then progressively decline.

The uplift in coal trade forecast partly stems from greater-than-expected resilience in recent years, where a combination of energy security concerns, higher natural gas prices and weather-related disruptions to renewable power generation have boosted reliance on coal as a low-cost energy carrier.

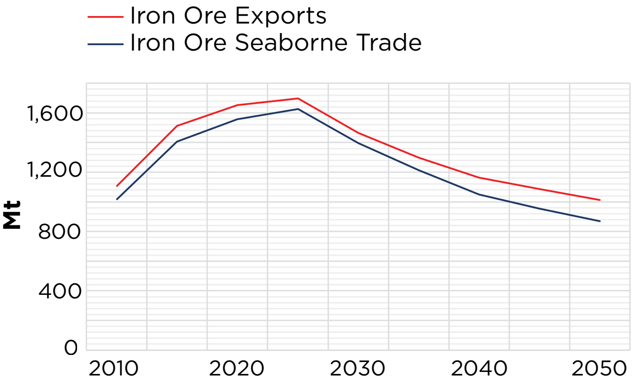
Figure 2.7 illustrates the coal trade forecast.

Beyond the coal trade, changes in the pace and steel intensity of economic growth in China drive a near-term peak in global iron ore exports, which begin to decrease in the second half of the 2020s. While other regions, particularly South Asia, see growing steel production over this period, this is insufficient to offset reduced production in China and advanced economies. Compared to ABS' 2023 Outlook publication, iron ore trade has been lowered over the longer term, in line with less optimistic economic growth forecasts for China. Figure 2.8 illustrates the ore trade forecast.



© MSI

Figure 2.7: Coal trade.



© MSI

Figure 2.8: Ore trade.

More generally, global dry bulk trade is set to become less concentrated in a handful of major commodities, with incremental dry bulk trade growth being driven increasingly by a range of minor bulk cargoes (Figure 2.9). Some of these, especially bauxite/alumina, are strongly connected to the energy transition, while others to consider are forest products, steel products, fertilizers, and minerals. By 2050, minor bulk cargoes are expected to comprise over 50 percent of totaldry bulk cargo trade, compared to around 32 percent in 2020.

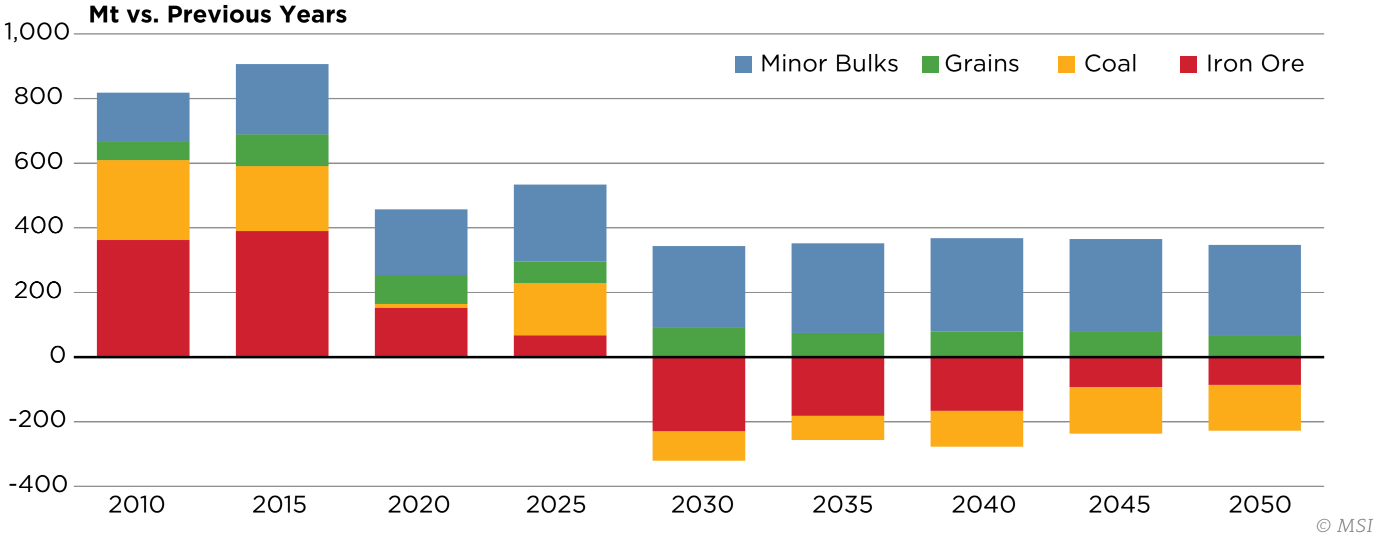


Figure 2.9: Incremental dry bulk trade.

Following a slow start compared to the containership segment, interest in alternative propulsion options for dry bulk carriers has increased, especially for large vessels.

Nevertheless, the predominant demand for dry bulk bunkers will continue to be met by fuels derived from oil until the 2040s, at which point fuels based on methanol and ammonia/hydrogen will assume larger portions. At present, the evidence is inadequate to support the notion that LNG propulsion could have a substantial impact on the dry bulk industry. In contrast to the projections from the previous year, the adoption of non-oil-based fuels is anticipated to accelerate beyond 2030. The forecasted fuel mix is illustrated in Figure 2.10.

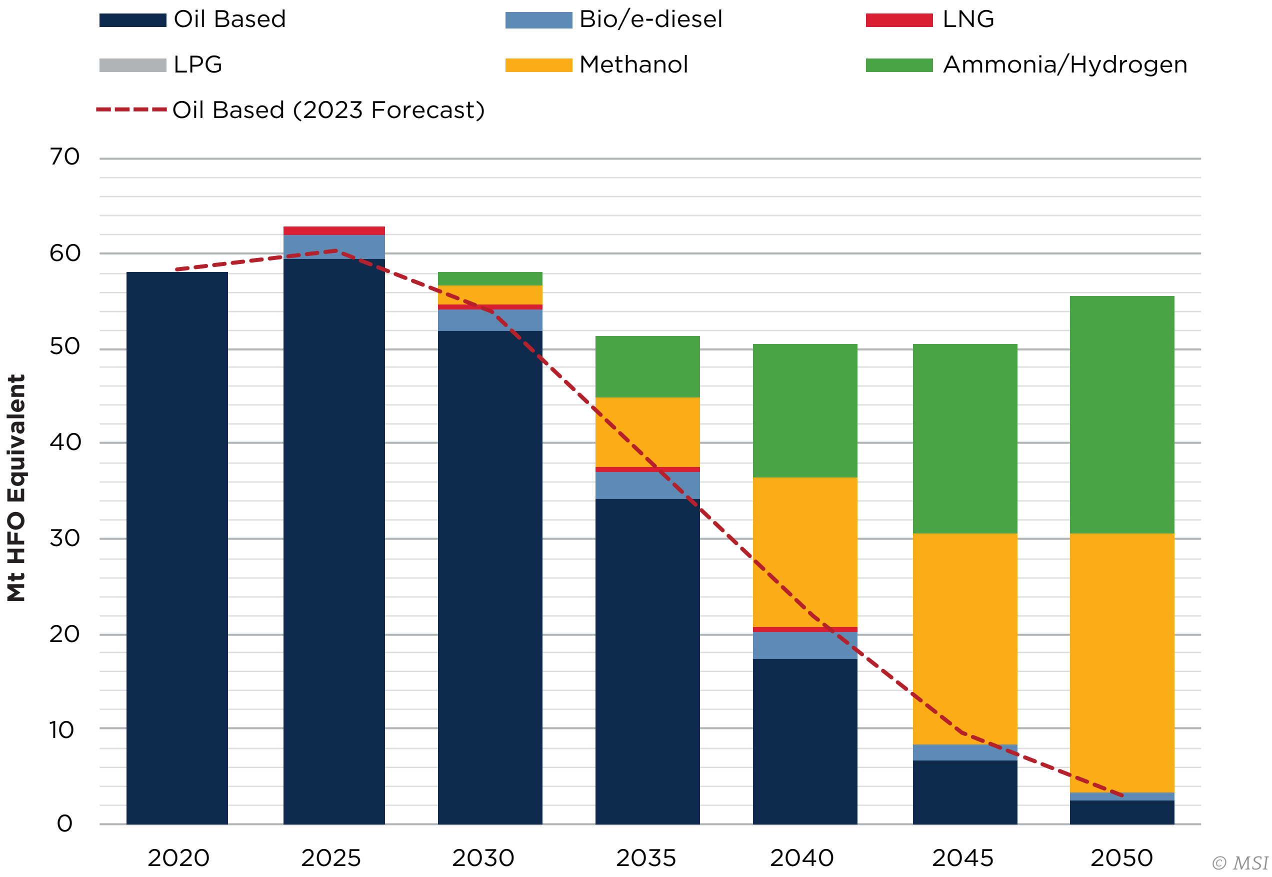


Figure 2.10: Fuel mix for dry bulk carriers.

2.3.2 Oil and Chemical Tankers

Seaborne crude oil trade is anticipated to increase compared to last year's projection. On the other hand, seaborne oil products trade is anticipated to reach its highest point in the future years, after which it will gradually decline until 2050. Oil consumption is anticipated to become more concentrated in the Asia-Pacific and Africa/Middle East regions, while Europe and North America will experience a decline in importance. This is illustrated in Figure 2.11.

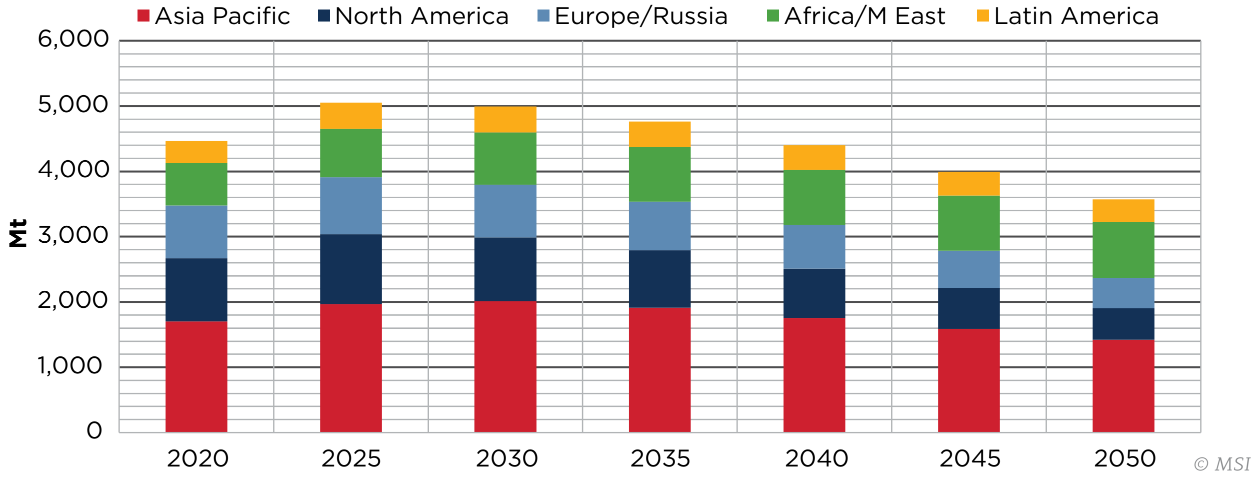


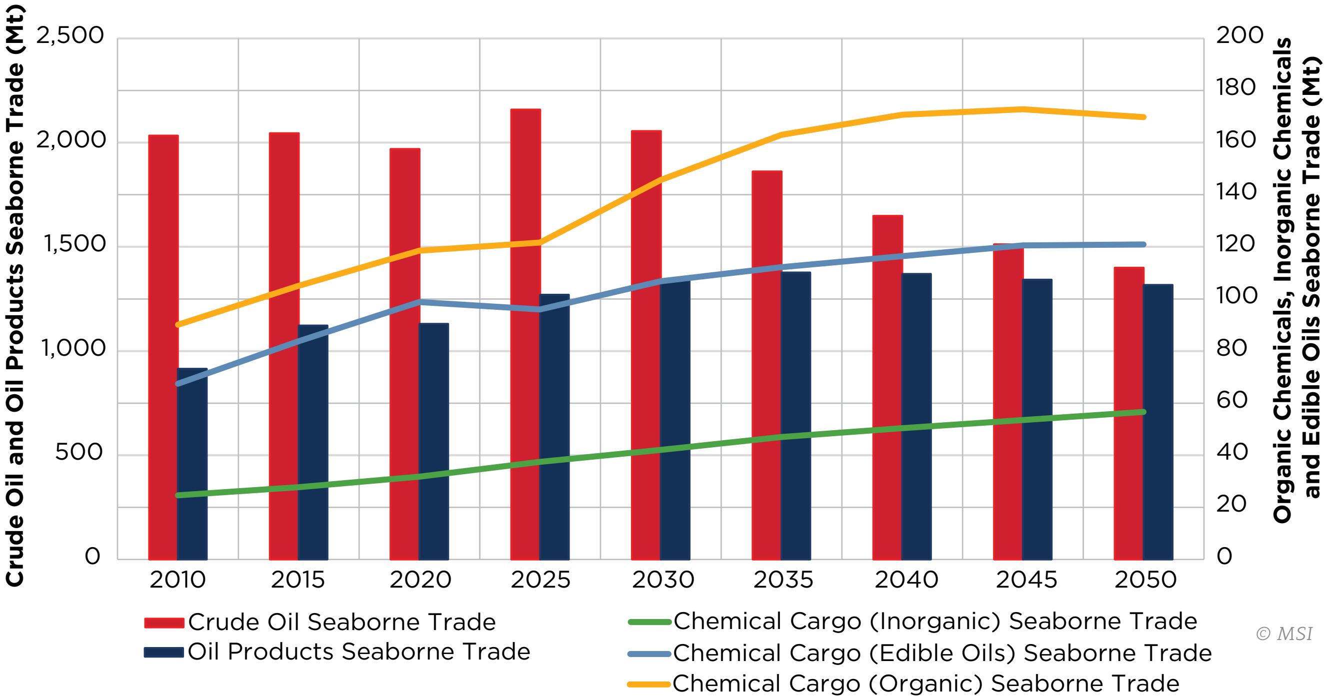
Figure 2.11: Oil consumption by region.

The distinction between crude oil and oil product trade peaks is attributed to industry trends within the oil refinery sector. Peaks in oil product seaborne trade occur subsequent to those of crude oil. Additional refineries will primarily be constructed in regions that produce crude oil (specifically, the Middle East and West Africa). Conversely, closing refineries in other areas (especially Europe) will result in a heightened reliance on imported oil products.

Changes in the global distribution of crude and oil product trade flows have had significant (and primarily positive) effects on oil tanker shipping demand since the conflict in Ukraine in 2022.

An increase in seaborne chemical trade is anticipated into the late 2040s, but trade projections have decreased since publishing last year's Outlook. The projected revision reflects less optimistic economic growth assumptions and is primarily driven by lower forecasts for the trade of organic chemicals. The dislocation between petrochemical-producing countries bolstered by cheap feedstock and rapidly developing nations that need petrochemicals to produce end products for export and domestic consumption, mining and agriculture will be the source of ongoing demand for chemical tankers. However, we anticipate that regional commerce and chemicals from cost-competitive countries will meet demand as new petrochemical manufacturing comes online in these consuming countries. Figure 2.12 illustrates the trade forecasts.

As with the dry bulk segment, the past 12 months have



© MSI

Figure 2.12: Oil trade forecasts.

seen increased interest in and ordering newbuild vessels with dual-fuel propulsion in the tanker segment. This has been seen to the greatest extent in the very large crude carrier (VLCC) segment, where, although most recent contracts have been for vessels with conventional propulsion, contracts have also been placed for LNG dual-fuel, methanol dual-fuel, and ammonia-fuel vessels. With that said, progress in adopting alternative propulsion in the tanker segment is picking up, and alternative fuels are expected to have a balanced share of the bunkering demand into the 2040s. Figure 2.13 illustrates the forecasted fuel mix.

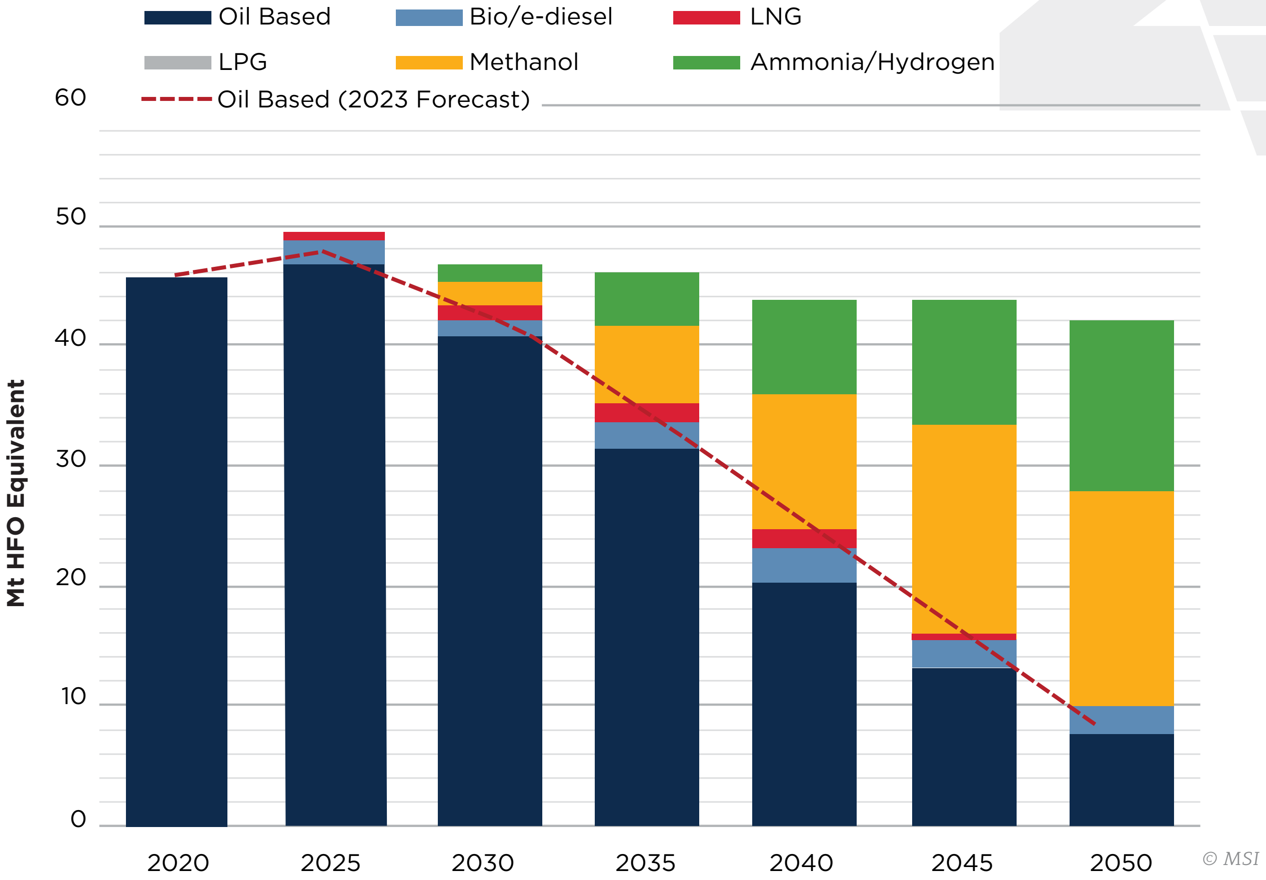


Figure 2.13: Fuel mix for oil and chemical tankers.

2.3.3 Containerships

Following the volatility of the COVID-19 pandemic years, trends in container trade have settled into a slower rhythm, with global trade volumes shrinking in both 2022 and 2023. Adjustments to long-term forecasts are generally limited with this update, with moderately downgraded projections for global macroeconomic growth feeding into a lower forecast for global container trade (Figure 2.14).

Base case continues to expect a shift in container trade geography favoring shorter-haul intra-regional trades and a more robust port handling growth in East Asia and emerging market regions relative to Europe and North America.

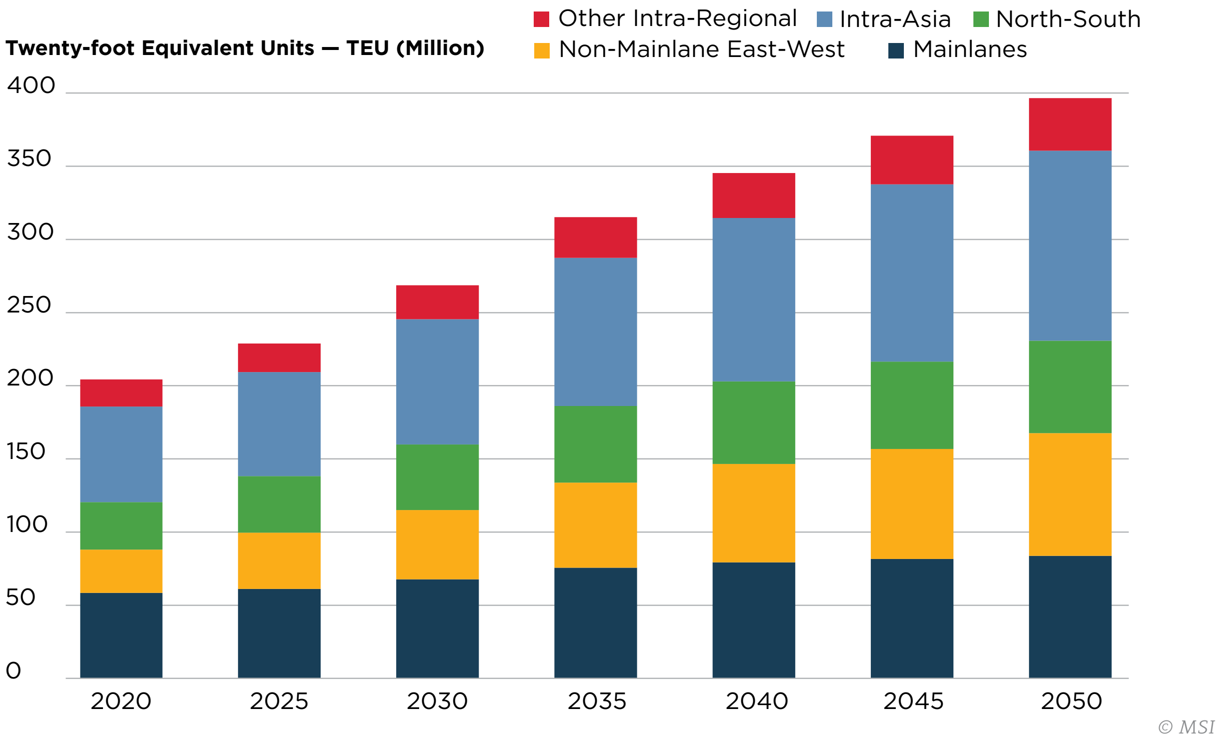


Figure 2.14: Global container trade evolution.

Over the forecast horizon, we have reduced the share of oil-based fuels in the containership bunkering mix, with methanol seeing an expanded role (Figure 2.15). A more comprehensive range of major liner operators have opted for methanol dual-fuel propulsion in orders over the past 12 months, even as the overall volume of new containership ordering has shrunk dramatically.

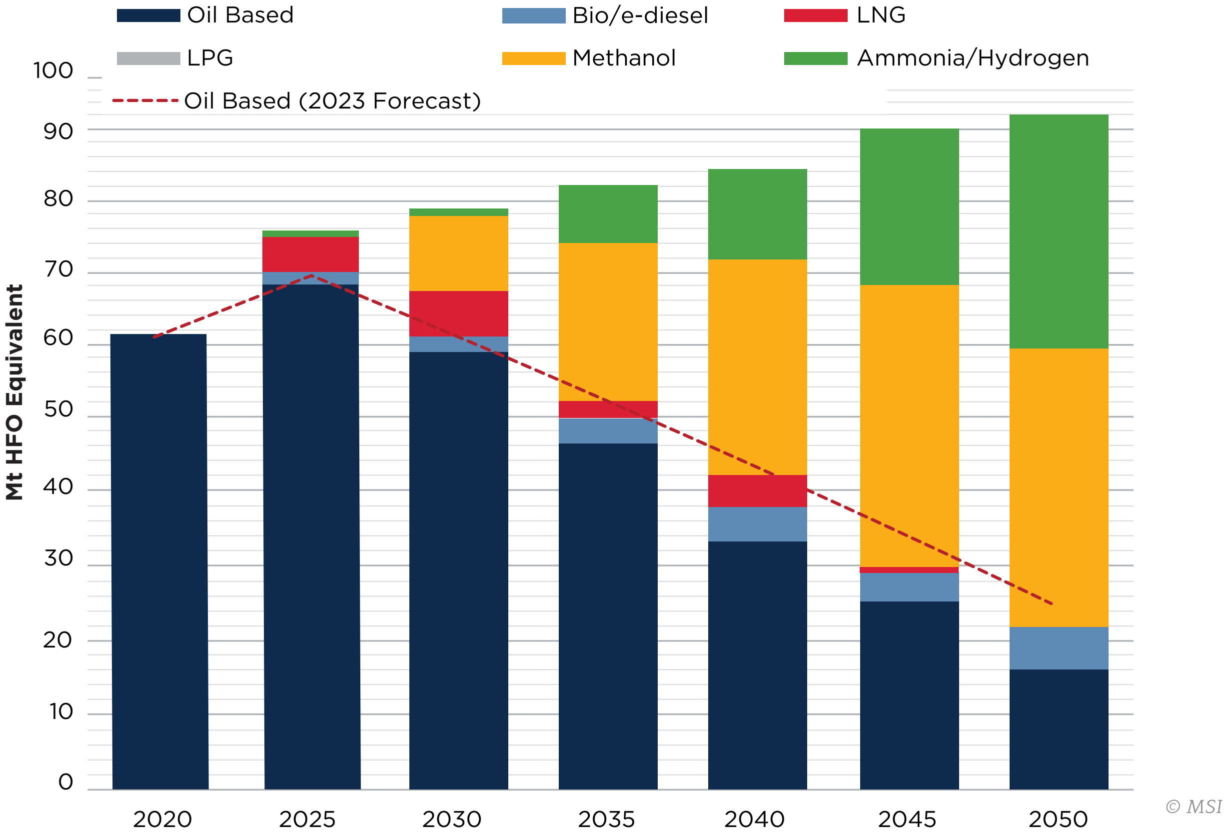
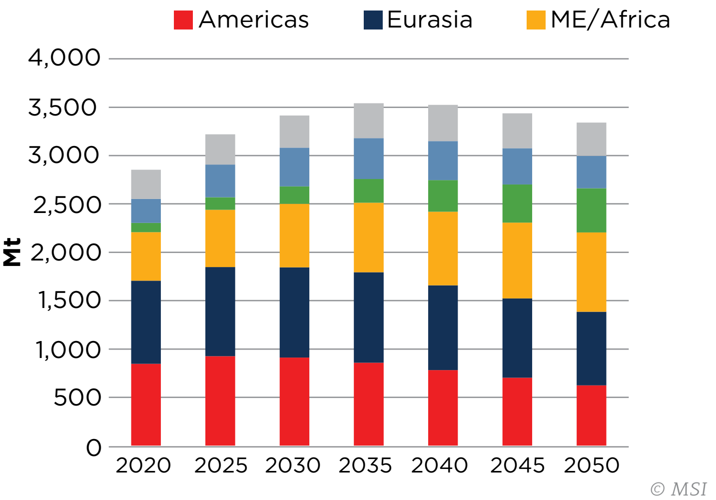


Figure 2.15: Fuel mix for containerships.

2.3.4 LNG Carriers

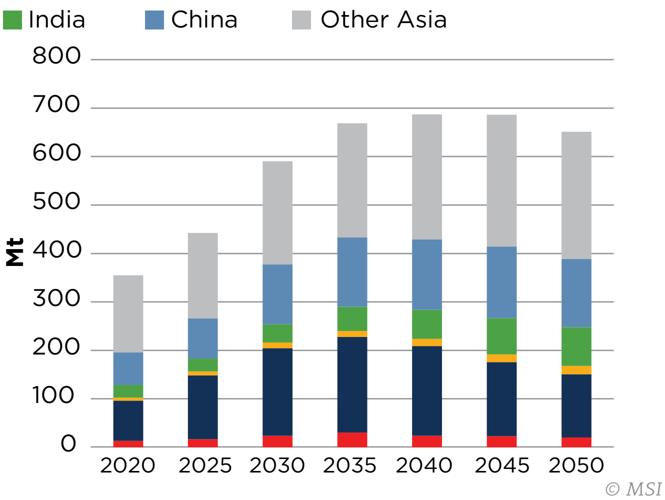
In comparison to last year's projections, the global natural gas consumption expectations have increased through 2050, while the forecasted LNG imports have been reduced. Figures 2.16 and 2.17 illustrate the revised projections for gas consumption and LNG imports by region. Above all, this has been driven by much-reduced expectations for LNG exports from Russia and a modest downgrade to forecasted exports from the Middle East and Africa.

The geography of global LNG trade will continue to change, with China and India seeing an expanded share of global LNG imports over the forecast horizon. China's share of global LNG imports is expected to rise to 22 percent in 2050, compared to 19 percent in 2020, while India's share will increase to 12 percent in 2050 from 7 percent in 2020.



© MSI

Figure 2.16: Gas consumption by region.



© MSI

Figure 2.17: LNG imports by region.

Compared to other commodity shipping sectors, revisions of our fuel mix forecasts for the LNG sector are limited with this update compared to last year's Outlook publication. There is still expected to be an increased uptake of ammonia/hydrogen as a fuel source beyond the 2030s as environmental regulations tighten. Until then, most LNG carriers will remain LNG dual-fuel (Figure 2.18).

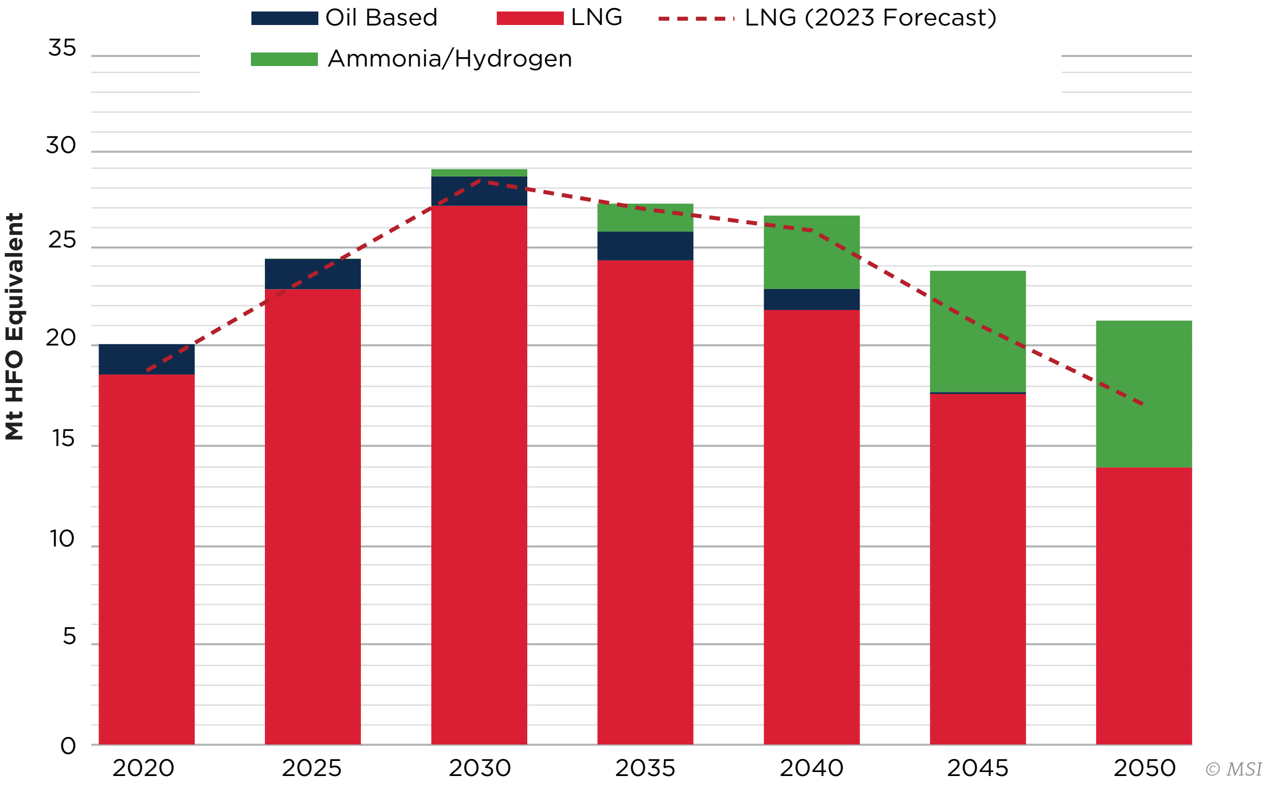
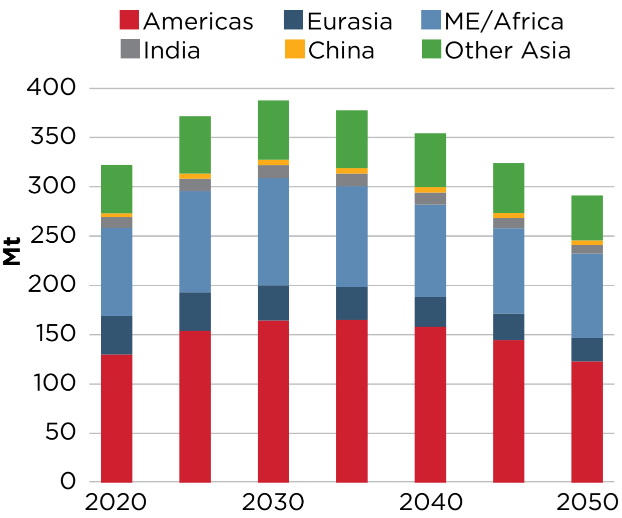


Figure 2.18: Fuel mix for LNG carriers.

2.3.5 LPG Carriers

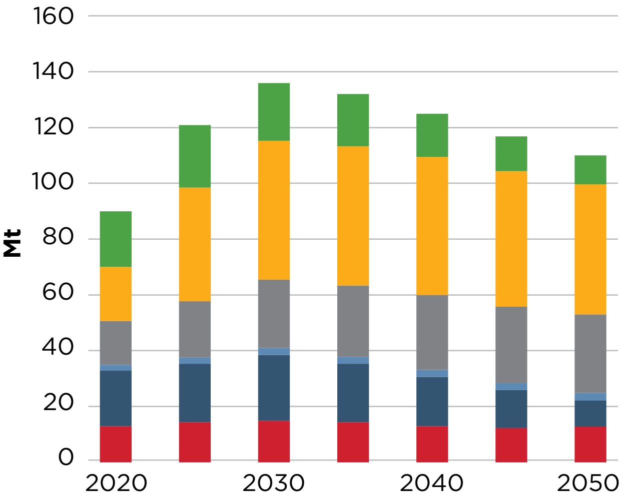
LPG is produced as a byproduct of oil and gas production and oil refining. Production and consumption of LPG are ultimately constrained by activity in the oil and gas sectors. So, the modest near-term downgrade, but longer-term modest upgrade, to forecasted global LPG production tracks the changes to oil production expectations discussed in this publication (Figure 2.19). Global LPG production is expected to peak in the first half of the 2030s.

Exports of LPG are closely aligned with regions accounting for the majority share of oil and gas production. The forecast for LPG imports (Figure 2.20) is slightly more positive than the revised forecast for LPG production, in comparison to last year's Outlook publication, with the most considerable changes to the estimates driven by increased imports into China.



© MSI

Figure 2.19: LPG production by region.



© MSI

Figure 2.20: LPG imports by region.

Newbuilding activity in the sector has focused on very large gas carriers (VLGCs) fueled by LPG, and we expect to see a significant increase in LPG usage for propulsion in the sector by 2025. Over the longer term, ammonia and hydrogen will increasingly displace fossil fuels in the fuel mix. With this update we have reduced the share of oil-based fuels within the LPG bunkering mix (Figure 2.21).

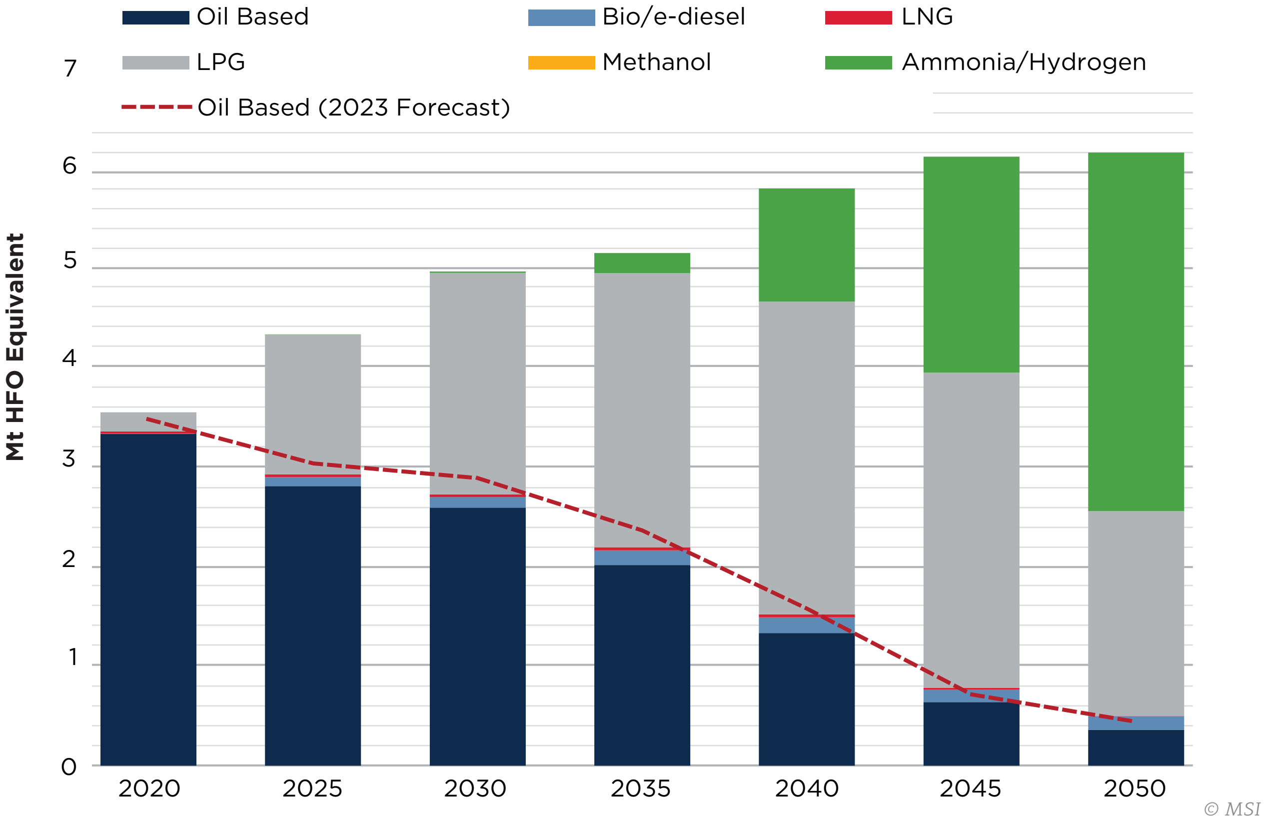
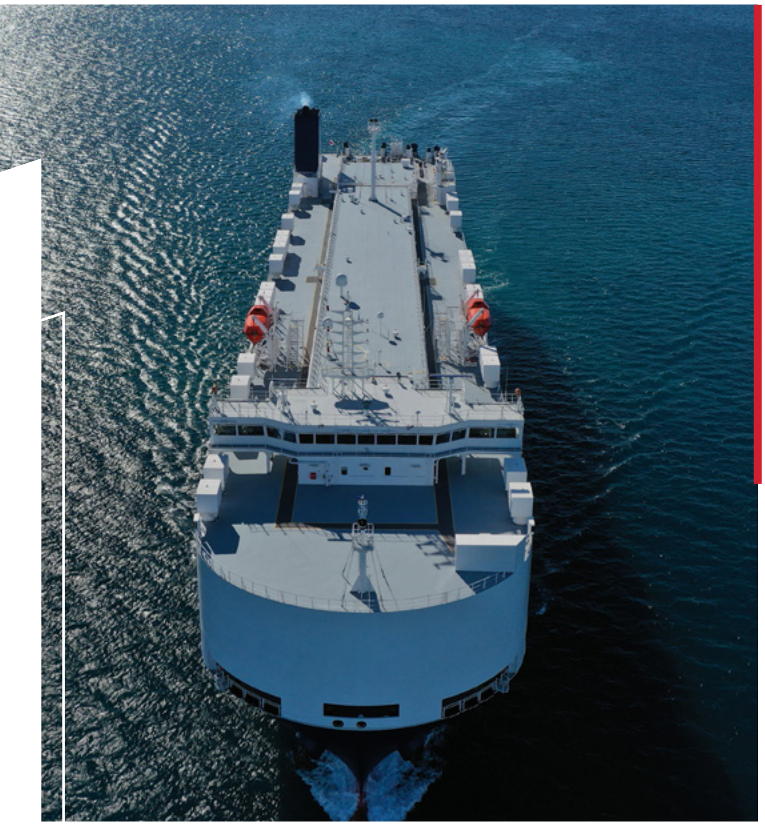


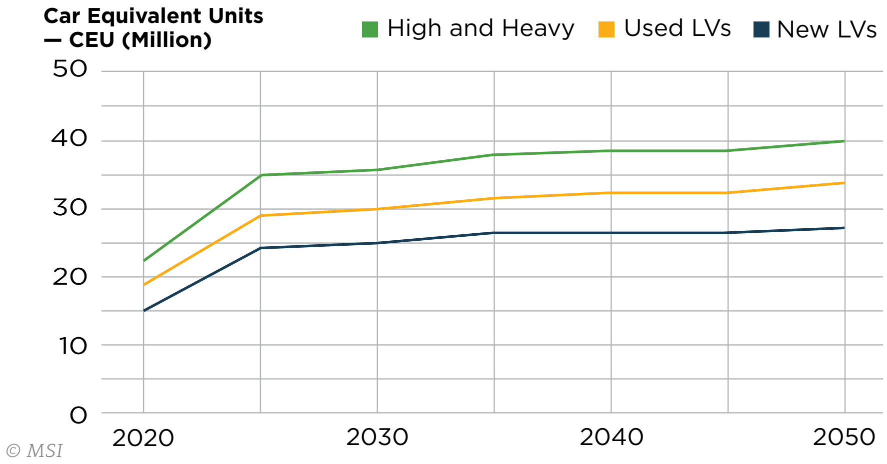
Figure 2.21: Fuel mix for LPG carriers.



2.3.6 Pure Car and Truck Carriers (PCTC)

Following extensive disruptions to vehicle production during the COVID-19 pandemic, vehicle trade has seen a strong rebound in the past year, which in part has led to exceptional strength in PCTC markets.

Revisions to the car carrier trade forecasts (compared to our previous projections) comprise of a modest downgrade to global light vehicle (LV) sale volumes, an upward revision to expected PCTC trade through the mid-2030s, and a downgrade to forecasted trade toward the end of the forecast horizon. The forecast downgrades apply specifically to trade in new and used LVs, with forecasted trade in the High and Heavy segment slightly increased relative to out last year projections. In line with the container and minor bulks segments, and contrast to most commodity shipping segments, we expect continued growth in PCTC trade over the forecast horizon to 2050 (Figure 2.22).



There has been a notable upsurge in newbuild contracting of PCTCs since the pandemic, with extensive interest in vessels with dual-fuel propulsion. We expect a comparatively rapid uptake of alternative fuels in this segment, initially driven by methanol. Figure 2.23 illustrates the forecasted fuel mix.

Figure 2.22: PCTC trade.

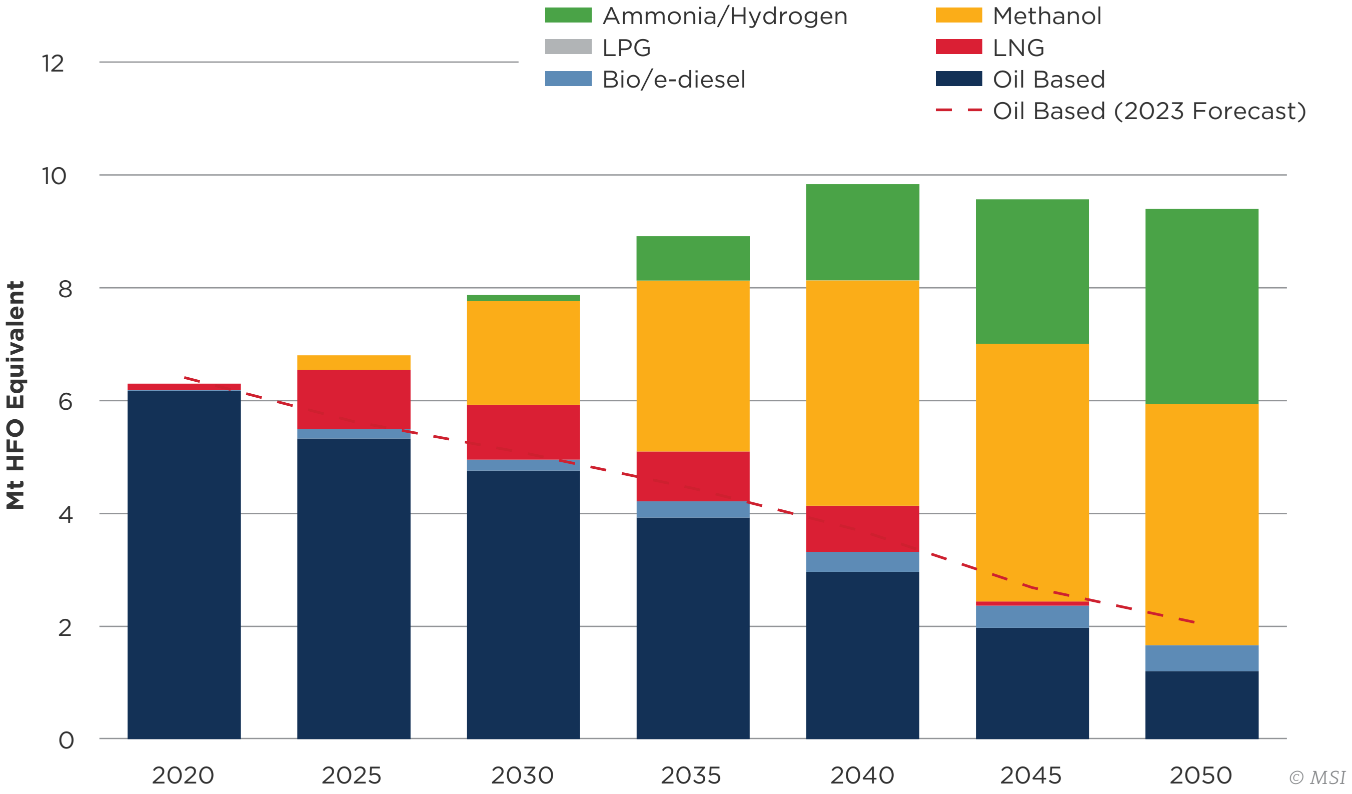
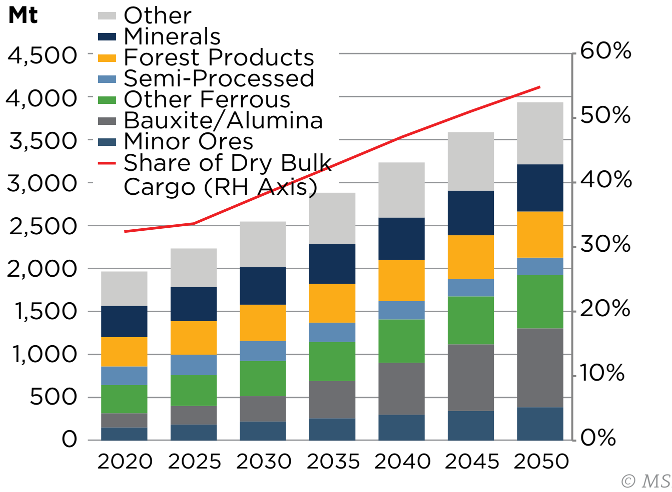


Figure 2.23: Fuel mix for PCTCs.

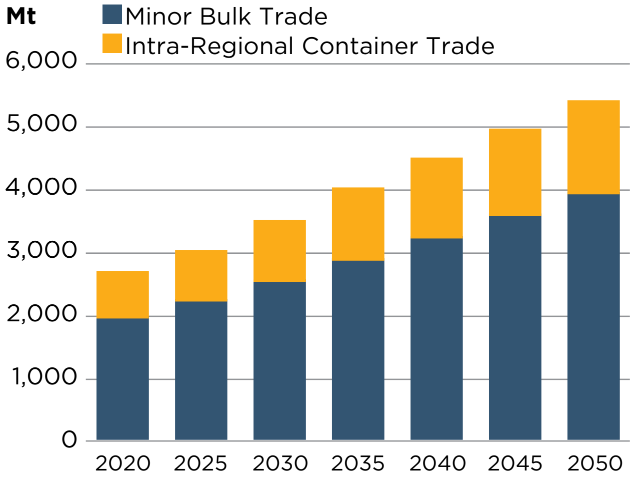
2.3.7 General Cargo/Multipurpose Vessels

Two key features of our dry bulk and container segment forecasts are expected to drive growing volumes of general cargo demand over the forecast horizon: the increased share of minor bulk cargoes within overall dry bulk cargo volumes (Figure 2.24), and the growing predominance of intra-regional volumes within global container trade (Figure 2.25). In both cases general cargo vessels are expected to retain a share of trade volumes.



© MSI

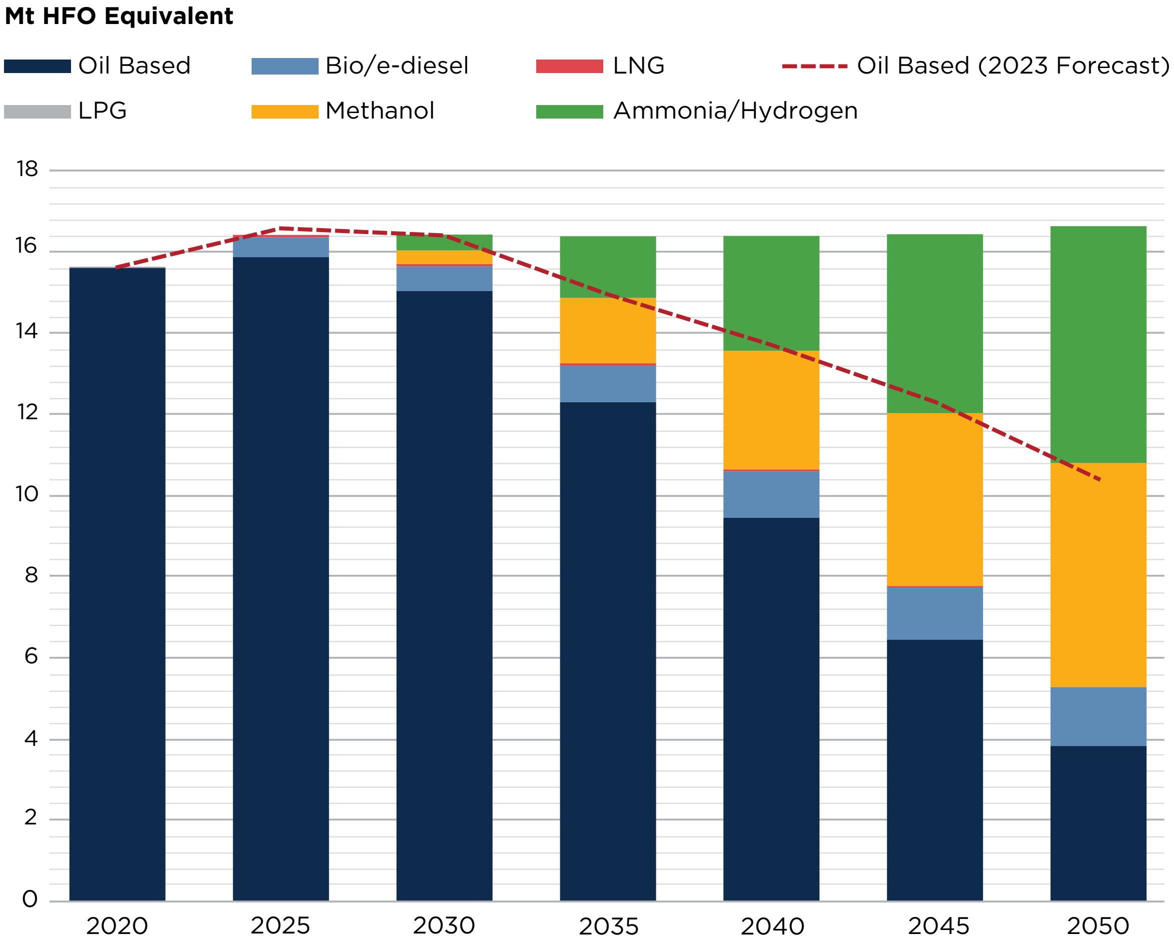
Figure 2.24: Minor bulks seaborne trade by commodity.



© MSI

Figure 2.25: Key drivers for general cargo trade.

The general cargo sees a rapidly ageing fleet age profile compared to the major shipping sectors. Despite this, newbuilding contracting volumes in this segment have been low in recent years, and in particular the general cargo segment has gotten off to a prolonged start in placing contracts for alternatively fueled vessels. As such, the bunkering mix for this segment (Figure 2.26) is set to remain dominated by oil-based fuels some way into the 2040s.



© MSI

Figure 2.26: Fuel mix for general cargo vessels.

2.3.8 Cruise Vessels

The cruise industry was hit hard by the COVID pandemic. From a record peak of 29.7 million in 2019, global passenger volumes declined by 75 percent year-on-year in 2020 and a further 50 percent year on year in 2021. After a partial recovery in 2022, global cruise passenger numbers exceeded 30 million for the first time in 2023.

Long-term prospects for the sector are positive but linked to the continued expansion of cruise holiday participation, particularly in Asia. Cruise penetration, measured as a percentage of the global population (Figure 2.27), stood at less than 0.3 percent in 2010, but reached just under 0.4 percent in 2019 and is forecast to exceed 0.6 percent by 2050.

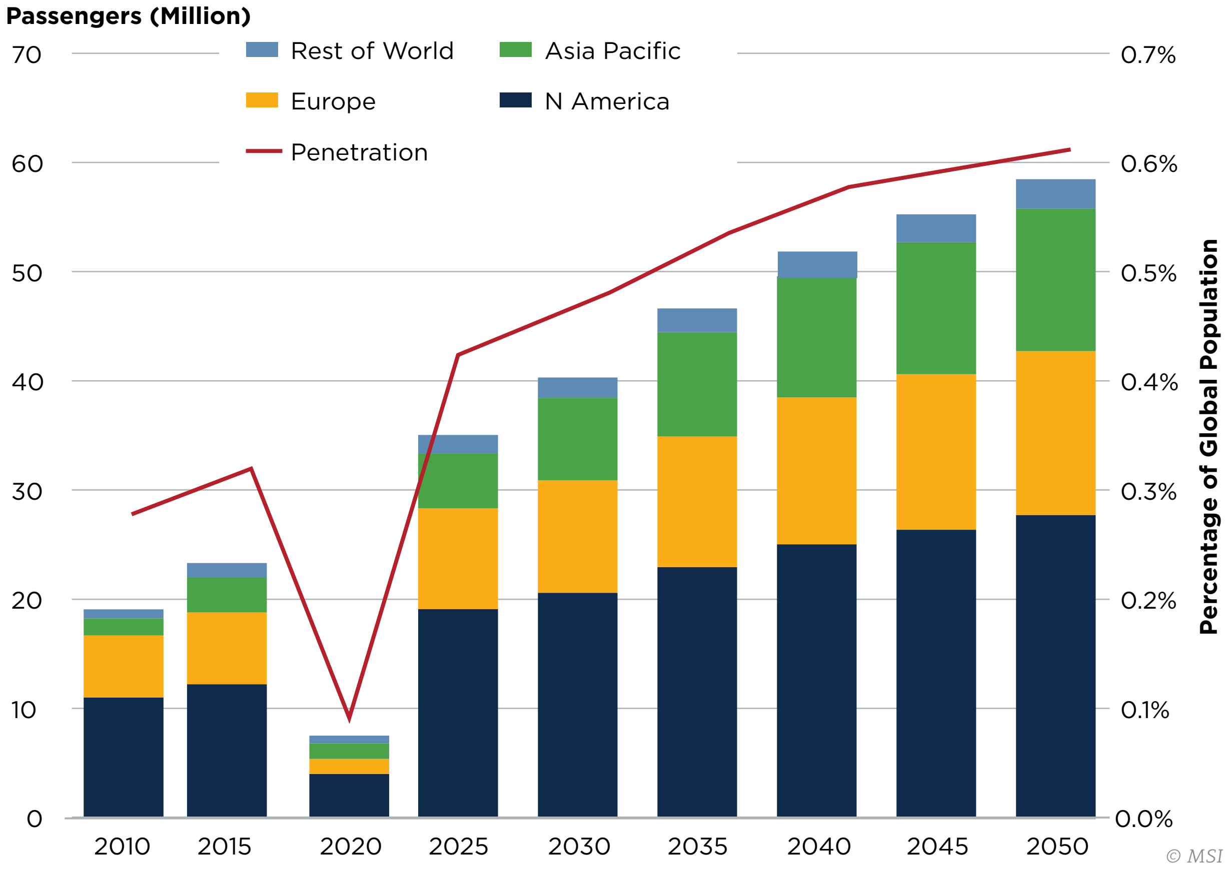


Figure 2.27: Cruise passengers by origin and global percent penetration.

The sector is dominated by four large groups, which account for approximately 80 percent of global cruise capacity, measured in lower berths. The cost of building a large cruise ship is substantial, and operating a cruise line requires significant manpower and land-based infrastructure. These two factors together represent a high barrier to entry for new players. Consequently, new entrants have typically targeted smaller niche segments, such as expedition cruises, or on budget cruising using older vessels. The four large cruise groups reported (Figure 2.28) an aggregate of 20 million tonnes (Mt) of carbon dioxide (CO_2) emissions in 2019 (Scope 1: ship fuel, refrigerants, and island fuel). The pandemic-related slump in cruising activity was mirrored in reduced emission levels from 2020 to 2021, recovering back in 2022.

The cruise sector was an early mover in LNG, with the first dual-fuel LNG vessel built in 2018. Given the frequency of port calls and the energy intensive nature of hotel operations whilst in port, shoreside power will be an essential factor in reducing emissions.

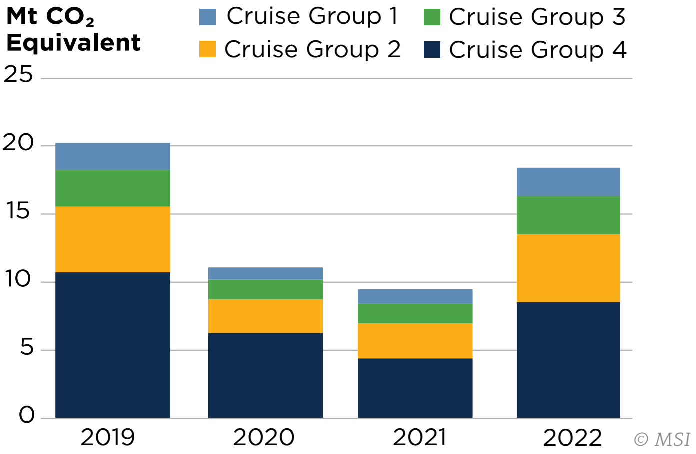


Figure 2.28: CO_2 emissions reported by leading cruise groups (Scope 1).

However, of the top 10 cruise ports (ranked by vessel calls), just three currently offer cruise lines the option of connecting to shoreside power, but cold ironing facilities are being developed in other ports. Figure 2.29 illustrates the forecasted fuel mix for the cruise industry.

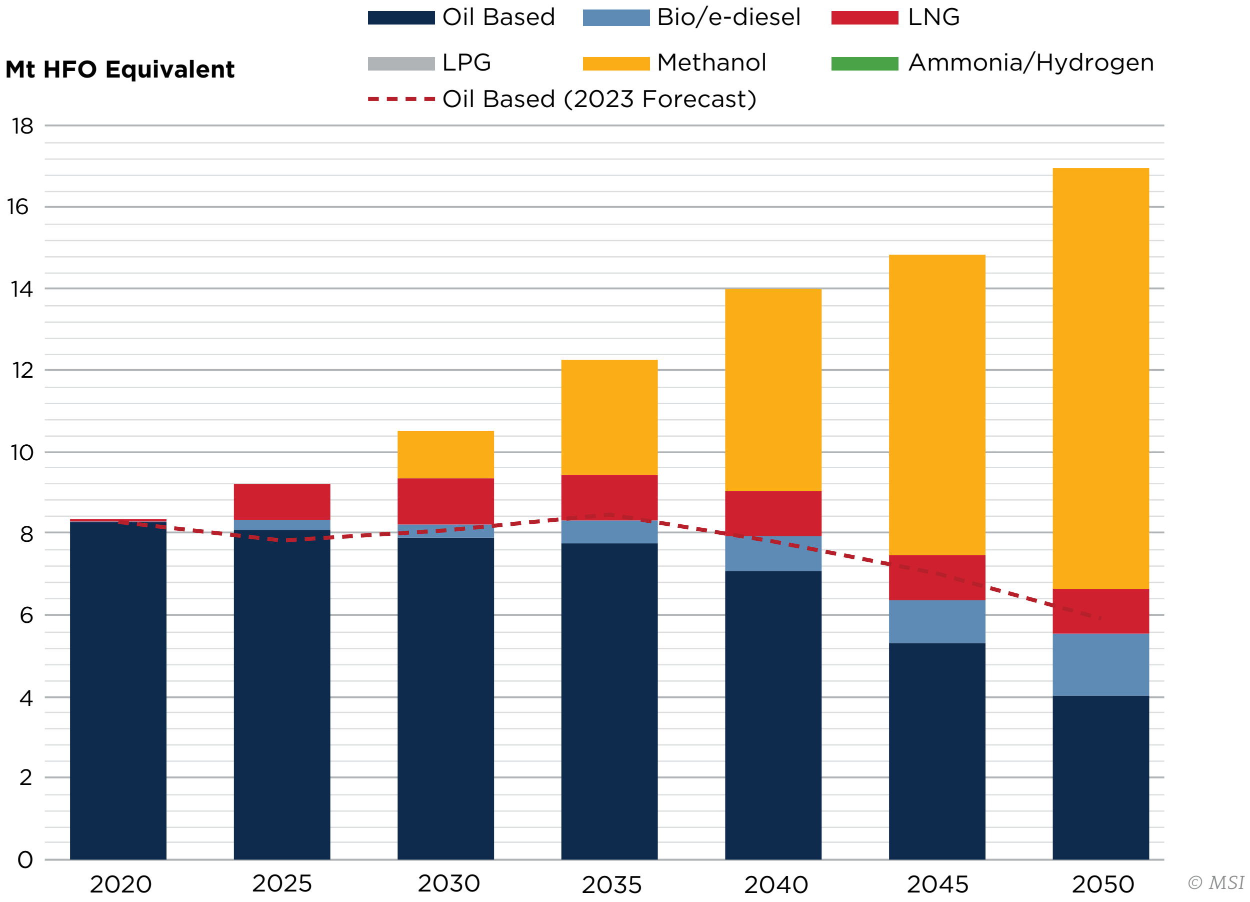


Figure 2.29: Fuel Mix for Cruise Ships

2.4 Geopolitical Impacts to Maritime Decarbonization

Beyond the conflict in Ukraine that have been going on for more than two years and its indirect impact on shipping markets, the situation has become even more complex by two additional geopolitical events expected to introduce additional challenges in the maritime industry's efforts to decarbonize.

2.4.1 Red Sea Conflict

The ongoing conflict in the Red Sea has had significant implications for global shipping trade and efforts toward maritime decarbonization. The conflict, primarily due to attacks by regional groups, has forced a major reroute of maritime traffic away from one of the world's busiest shipping lanes, the Suez Canal, to longer alternative routes such as around the Cape of Good Hope (Figure 2.30). Around 12 percent of global trade passes through the Suez Canal – Bab al-Mandab, representing 30 percent of all global container traffic. This shift has led to a variety of economic and environmental impacts.

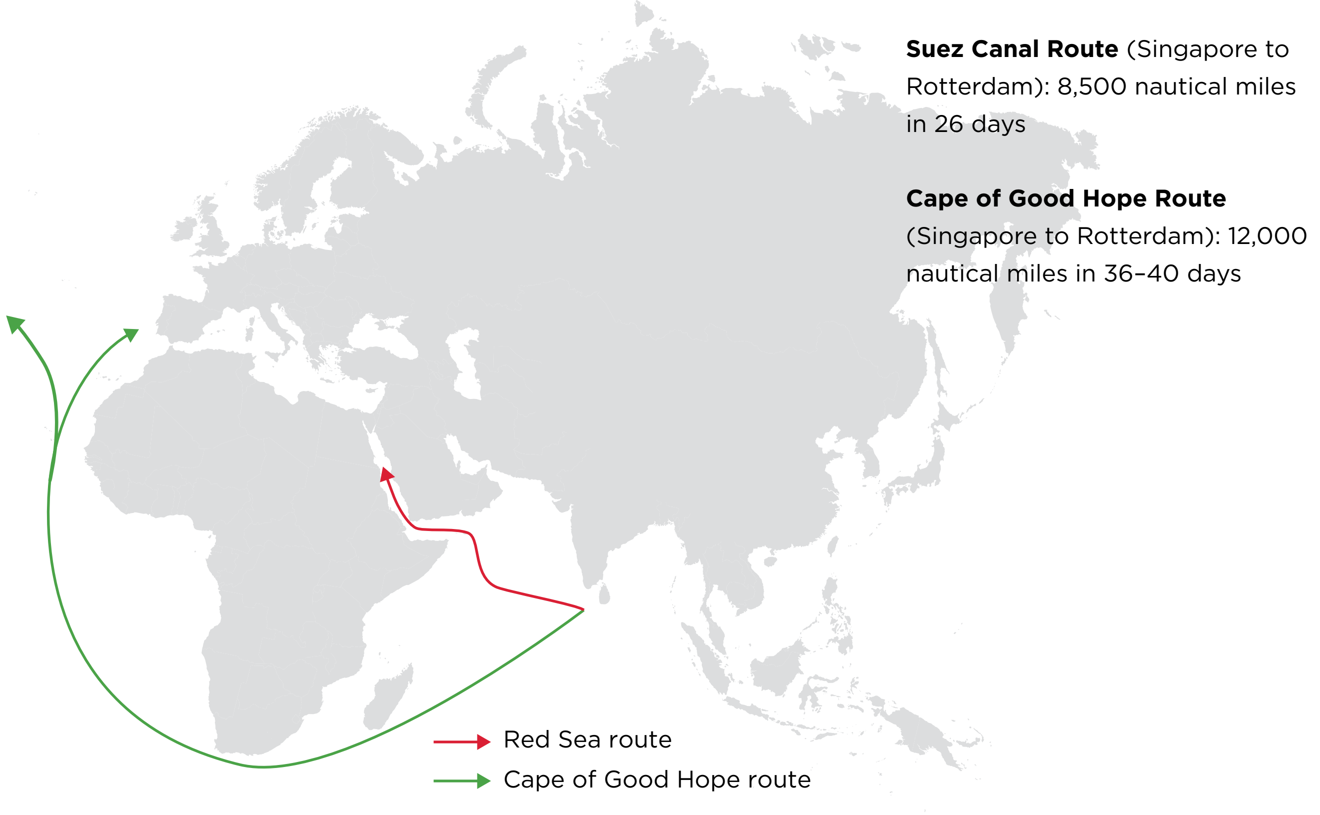


Figure 2.30: Shipping routes disruption.

A journey that typically passes through the Suez Canal takes significantly longer, increasing fuel consumption and operational costs. The latter is directly passed onto consumers through higher shipping rates, which have nearly quintupled for some routes, particularly those from Asia to Europe. The disruption has also caused a spike in shipping insurance premiums due to the heightened risks of transiting through conflict-affected areas. Marine bunker calls have surged 80 percent in South Africa.

Moreover, the rerouting has affected global trade flows, with a noticeable decline in traffic through the Suez Canal and an increase around the Cape of Good Hope. This shift is a temporary inconvenience and a substantial economic burden, as companies face delayed deliveries and the challenge of managing disrupted supply chains.

Diversion of shipping routes due to the conflict has increased transit times and costs. By checking the seven-day moving average of vessel arrival in the Gulf of Aden as illustrated in Figure 2.31, a seaborne trade disruption is apparent as vessel arrival dropped below 4 million gross tons (m gt) on Dec 28, 2023. Until now, vessel arrivals in the Gulf of Aden only accounted for two-thirds of their typical levels.

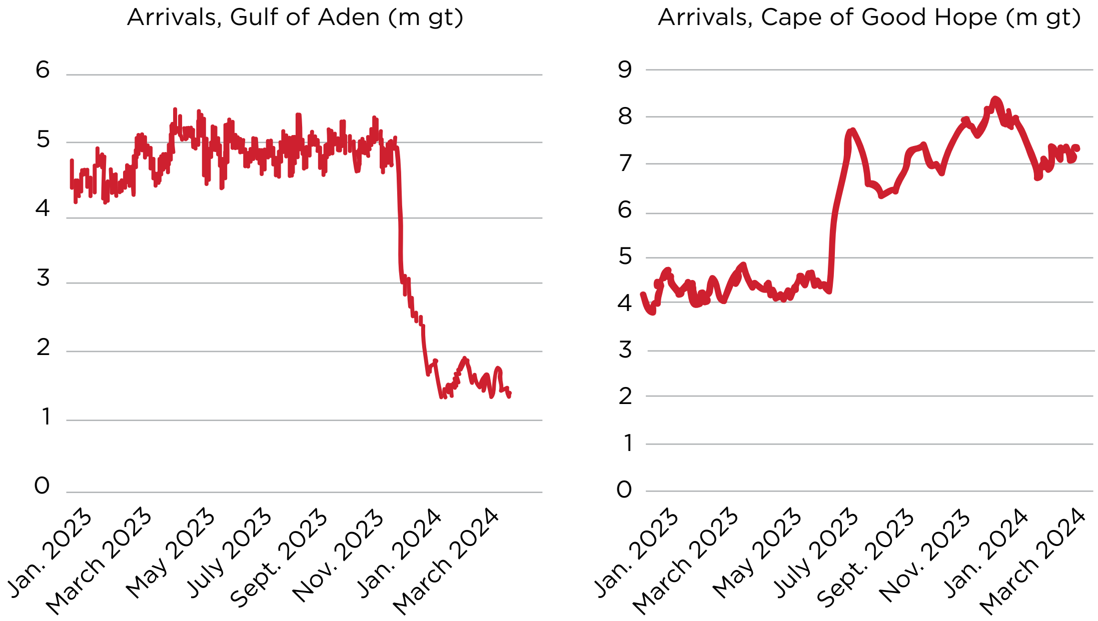


Figure 2.31: Red Sea rerouting due to vessel attacks.

The conflict also poses challenges to maritime decarbonization efforts. The longer routes significantly increase fuel consumption, which not only raises operational costs but also increases greenhouse gas (GHG) emissions. This is a cause for concern given the industry's ongoing efforts to reduce its carbon footprint.

The broader implications of these disruptions are profound, affecting everything from the cost of goods in global markets to the economic stability of shipping companies. The increased costs and operational complexities will likely persist, influencing global inflationary trends and possibly impacting consumer prices. Furthermore, the situation highlights the vulnerability of global trade to geopolitical tensions. It underscores the need for enhanced security and alternative strategies within international shipping routes to mitigate such risks in the future.

2.4.2 Panama Canal Low Water Levels

The Panama Canal, a crucial conduit for global trade, is currently facing severe operational constraints due to historic low water levels attributed to drought and exacerbated by the El Niño phenomenon. The water levels in Gatún Lake, essential for operating the canal's locks, have reached record lows, leading to significant reductions in daily ship transits. This limitation has been stepped down from the usual 36 to 38 ships per day to only 24 ships per day as of early 2024 (Figure 2.32). The reduction in transit capacity is particularly impactful on the dry bulk and LNG shipping segments, which often operate outside regular schedules and are more vulnerable to such disruptions.

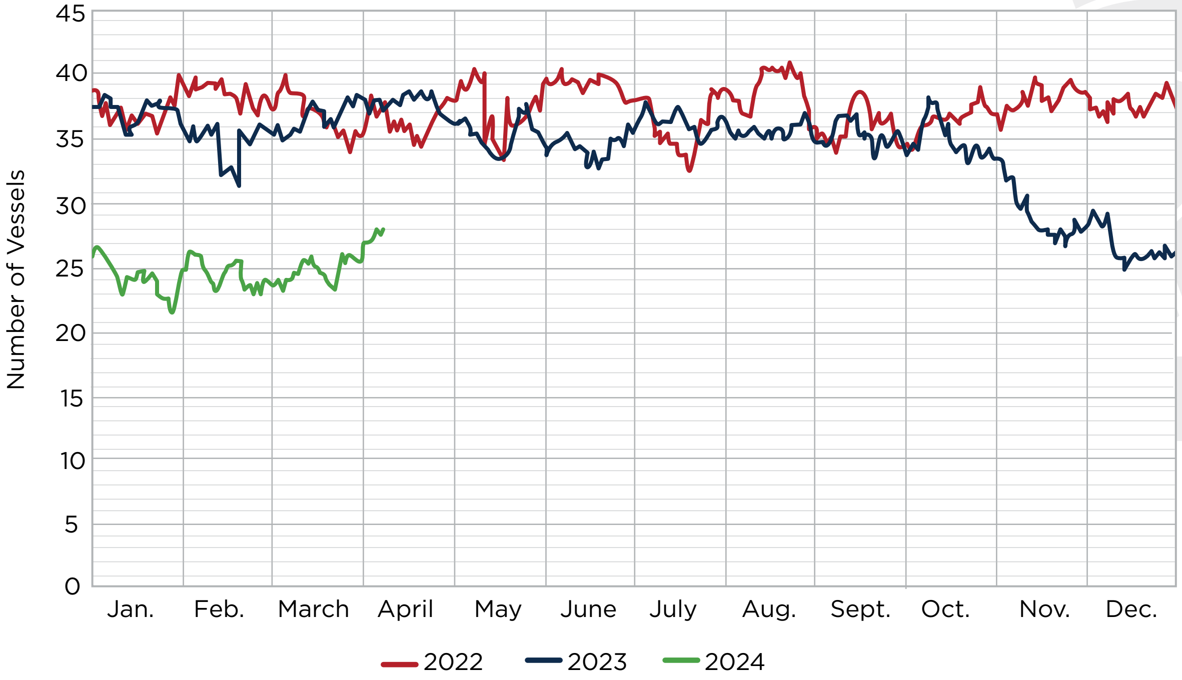


Figure 2.32: Panama Canal — daily transit calls.

Moreover, the necessity to maintain operational water levels has also reduced the allowable ship draught, decreasing from 50 feet to 44 feet. This reduction translates to a significant decrease in cargo capacity, with an average container vessel now carrying 2,400 fewer twenty-foot equivalent units (TEUs). These changes have prompted shipping companies to reroute to alternative paths, such as the longer and more costly route around Cape Horn or through the Suez Canal, despite recent instabilities in the Red Sea area.

The constraints imposed by low water levels in the Panama Canal also affect global maritime decarbonization efforts. As with the Red Sea Conflict, the need for longer routes due to canal constraints increases fuel consumption and thus GHG emissions.

The Panama Canal Authority has been exploring the reuse of water and constructing new reservoirs to mitigate water shortages. These efforts are part of a broader strategy to maintain canal operations while considering environmental sustainability. The ongoing water crisis in the Panama Canal illustrates the complex intersection of global trade logistics, environmental challenges, and efforts toward sustainable maritime operations. The situation demands significant adaptive measures from the global shipping industry and highlights the critical need for infrastructural resilience in face of climate change-induced weather patterns. Moreover, it underscores the interconnectedness of global trade infrastructure and environmental sustainability efforts, with each influencing the effectiveness and outcomes of the other

2.5 Fuel Mix Forecast

2.5.1 Trade and Fleet Growth

ABS' overriding view of the period to 2050 hasn't changed materially with this update compared to the 2023 Outlook.

There have been some near-term recalibrations due to recent geopolitical events. These generally result in supply chain disruptions leading to higher earnings in some sectors and overall higher fuel consumption in the short term due to vessel rerouting, particularly to avoid the Red Sea/Suez Canal. A major revision in this publication compared to last year's Outlook is a recalibration of the LPG carrier forecast to account for potentially soaring ammonia demand. However, this does not materially change our forecast at an aggregate level.

2.5.2 Fuel Mix Forecast — Base Case

The decarbonization of the shipping industry includes further refinements to the existing forecasting methodology. We are now including assumptions for the greening of LNG as a bunker fuel. In addition, the Well-to-Wake (WtW) emissions calculations are now aligned with the FuelEU Maritime factors to synchronize with broader industry analysis.

Notably, after consistent reductions in expectations for oil burning with ABS' previous forecasts, there is an expectation for higher than previously forecasted oil burning in the second half of this decade. This reflects lower than expected penetration of dual-fuel engines in the dry bulk and tanker sectors.

The recent disruptions to trade flows through Panama and Suez have increased fuel consumption.

Figures 2.33 and 2.34 illustrate our forecasts for the consumption and the fuel mix on heavy fuel oil (HFO) equivalent.

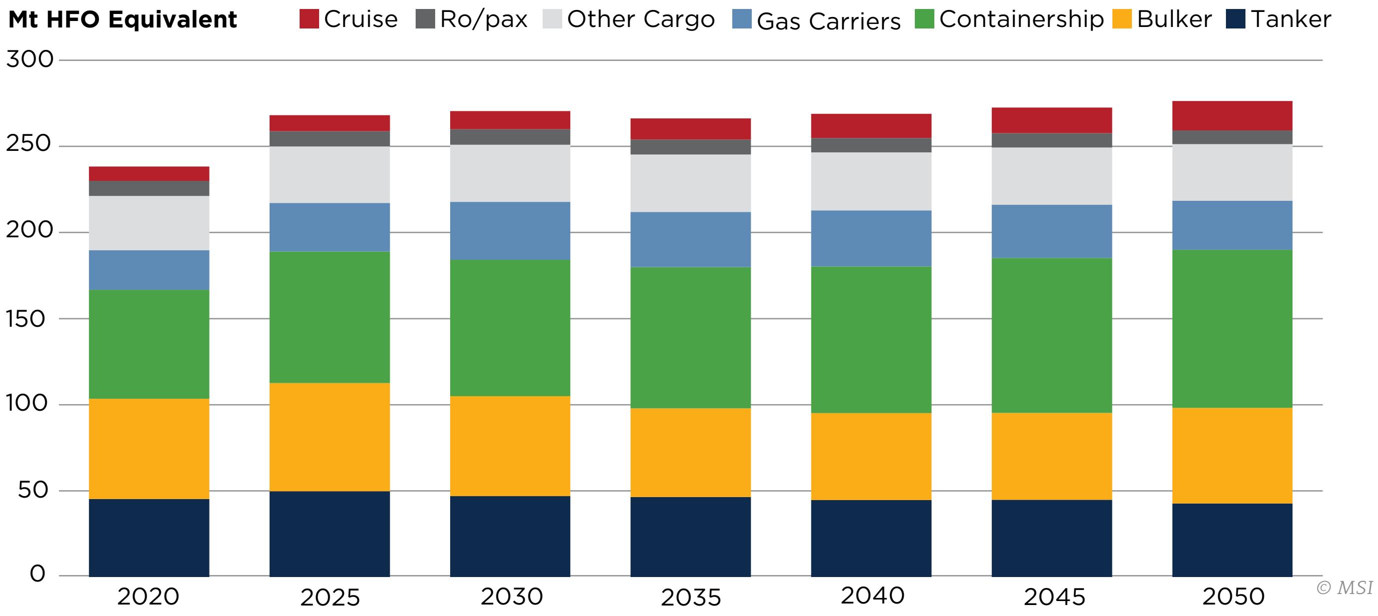
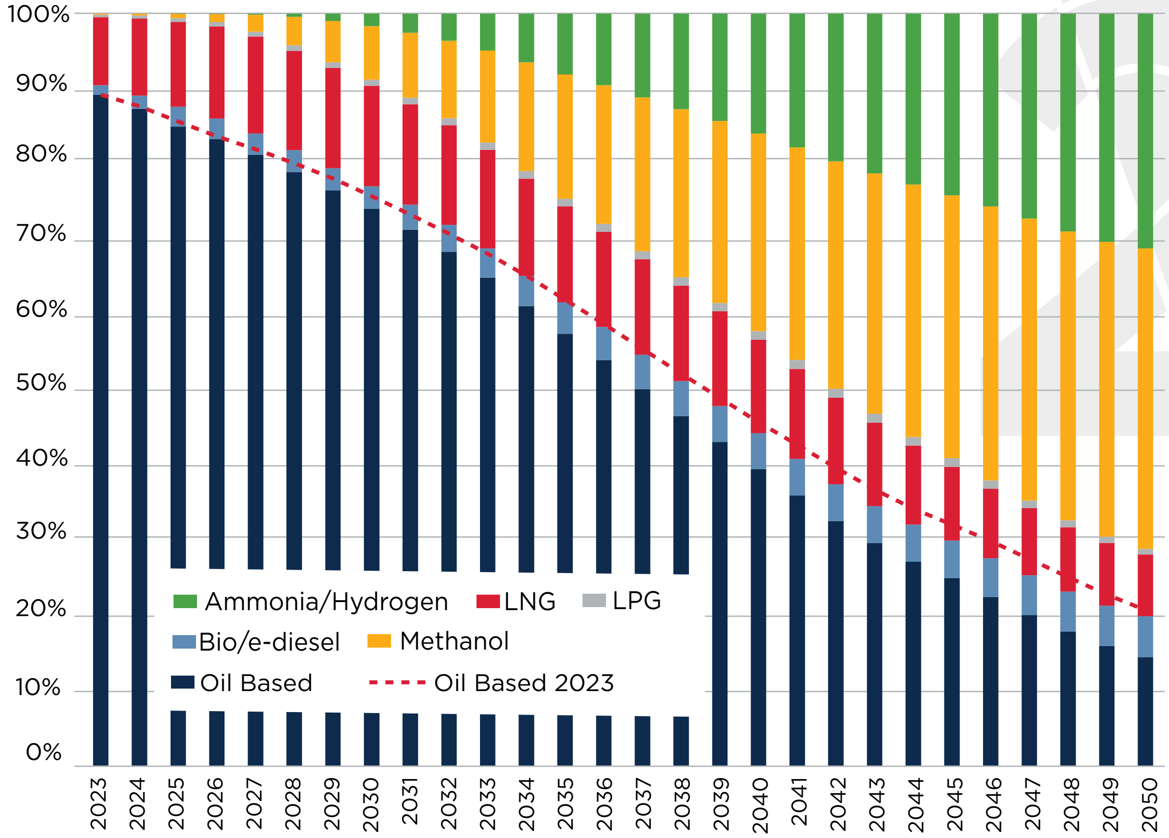


Figure 2.33: Consumption by ship type (HFO equivalent).



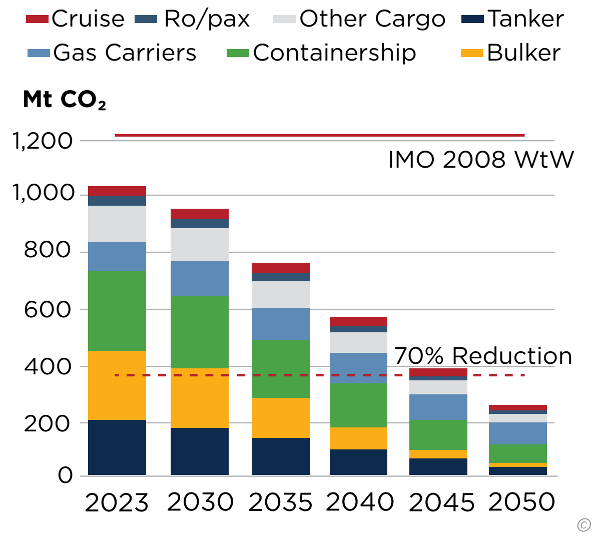
© MSI

Figure 2.34: Fuel mix (HFO equivalent).

Ship types included: oil and chemical tankers, dry bulk carriers, containerships, LPG, LNG, car carriers, general cargo, ro/ro, ro/pax and cruise.

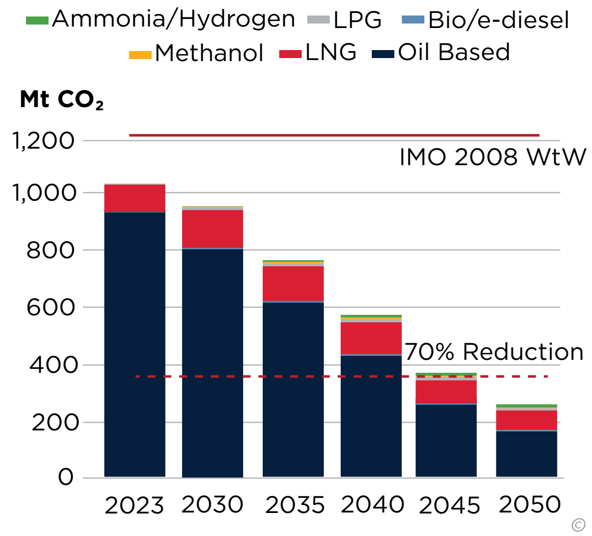
2.5.3 CO_2 Emissions Forecast — Base Case

Shipping emissions will peak in the next couple of years. This will be due to fleet growth and disruptions to trade patterns for a substantial portion of the fleet, as owners offset the implementation of fuel efficiency measures in response to the Carbon Intensity Indicator (CII) regulations from the IMO. Figures 2.35 and 2.36 illustrate the CO_2 emissions on a WtW basis.



© MSI

Figure 2.35: CO_2 Emissions by ship type — Well-to-Wake (base case scenario).



© MSI

Figure 2.36: CO_2 emissions by fuel source — Well-to-Wake (base case scenario).

Assuming that the trade patterns return to normal, we forecast emissions to further decline as we approach 2030. This will allow the efforts toward decarbonizing shipping to further increase. Based on recent history and our assumptions that penetration of dual-fuel engines accelerates in the coming years, we expect the share of the fleet capacity to be capable of burning dual fuels to reach 9 percent in 2030. The extent to which this capability is utilized depends on the development of the fuels, with the downside risk being clear. A further positive item is the growing adoption of energy efficiency technologies. In addition to many headline-grabbing additions, such as fixed sails, the adoption of simpler, less visible technologies is accelerating.

Under our base case scenario, a 20 percent reduction in CO_2 equivalent emissions in 2030 relative to 2008 is achievable on a WtW basis, but 70 percent reduction by 2040 is going to be challenging. Section 2.5.4 explores the potential routes to achieving the latter target.

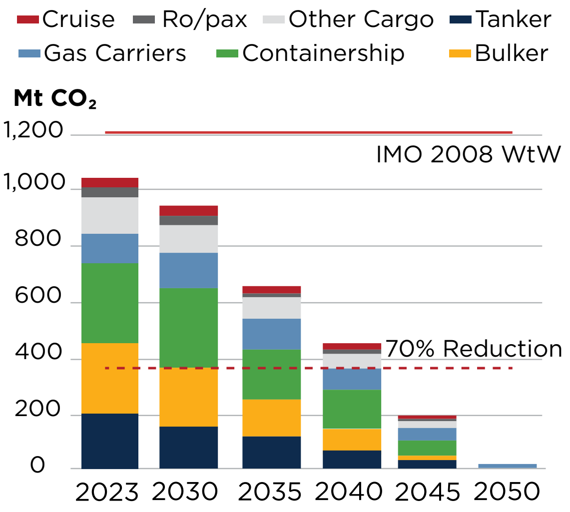
2.5.4 Net-Zero Scenarios

ABS has aligned its net-zero scenarios incorporating the latest mandates from the IMO. These set clear targets for shipping and a key component of our analysis is to quantify how easy or difficult it will be to achieve them. Measures to achieve net zero are going to be multilayered and varied. Multiple potential solutions are becoming available to the industry but what is less clear is how this will play out in real time.

2.5.4.1 Net-Zero Scenario #1 – Missing the 2040 IMO Milestone

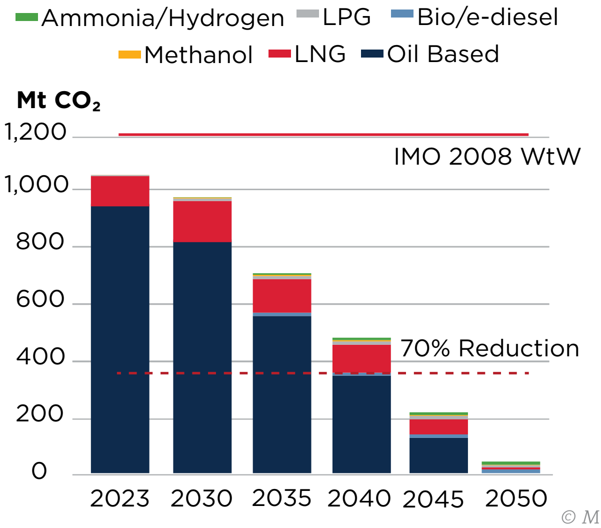
This scenario takes a similar approach to our net-zero scenario from ABS' 2023 Outlook publication. We have assumed that energy efficiency technologies (EETs) achieve a global aggregate reduction in emissions of 15 percent by 2040, after which they level out as no further gains are possible. We also assume that e-diesel replaces both oil and biodiesel in the years leading up to 2050. Ultimately the latter assumption remains necessary to achieve the final goal of zero-carbon emissions.

However, by applying a steady approach to these factors we find that the goal of a 70 percent reduction in emissions relative to 2008 would not be met by 2040. This is because the cumulative impact of many of the transitions in technology and fuel gathers pace in the later years of the forecast. Figures 2.37 and 2.38 illustrate the CO_2 emissions on a WtW basis. The radical measures needed to meet the 2040 target are explored in the next subsection.



© MSI

Figure 2.37: CO_2 emissions by ship type — Well-to-Wake (Net-Zero Scenario #1).



© MSI

Figure 2.38: CO_2 emissions by fuel source — Well-to-Wake (Net-Zero Scenario #1).

2.5.4.2 Net-Zero Scenario #2 – Achieving the 2040 IMO Milestone Through Retrofits

As outlined in net-zero scenario #1, an assumption of a steady acceleration in emissions reduction to a peak in time for 2050, does not achieve the IMO's target for a 70 percent reduction in emissions by 2040.

Based on the net-zero scenario #1, we still have around 375 Mt CO_2 equivalent (CO_2eq) emissions from oil-based fuels and 120 Mt from liquefied gases in 2040. To achieve an aggregate level of 360 Mt CO_2eq (the 70 percent target) would, therefore, mean a hugely accelerated reduction in the use of oil and gas, which would mean a significantly more rapid renewal of the fleet to replace oil-fueled vessels or a high degree of retrofitting suitable engines.

In line with ABS' studies, it is estimated that in 2040, around 733m gt of vessels will still have oil based fuel engines, though a small proportion of these will be burning biodiesel and e-diesel. However, if one-third of these (or half the vessel candidate pool for engine retrofit identified in Section 3.2.1) were converted to ammonia or methanol by 2040 and could also access zero-carbon fuels, then the 70 percent reduction from the 2008 baseline would be achieved. Figures 2.39 and 2.40 illustrate the CO_2 emissions on a WtW basis under this scenario.

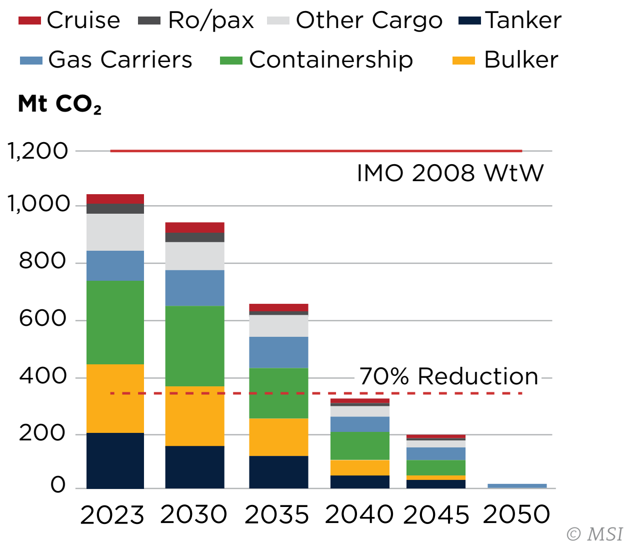


Figure 2.39: CO_2 emissions by ship type — Well-to-Wake (Net-Zero Scenario #2).

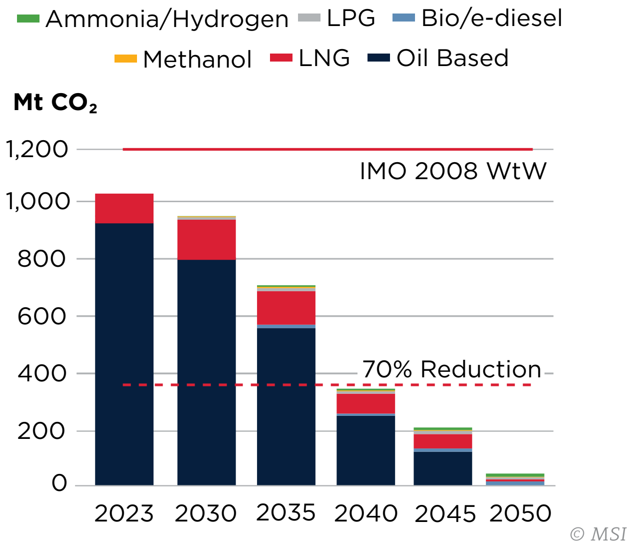


Figure 2.40: CO_2 emissions by fuel source — Well-to-Wake (Net-Zero Scenario #2).

SECTION 3

MARKET OUTLOOK AND ECOSYSTEM CAPACITY

3.1. Orderbook Status

3.1.1. World Shipping Fleet

The current world shipping fleet as of April 2024 , in gross tons and number of vessels is shown in Figures 3.1 and 3.2 (world fleet totals shown based on vessels >2000 dwt). In total, there are over 109,000 ships in operation with a total deadweight of around 2.4 billion deadweight tonnage (dwt) and 1.6 billion gross tons (gt).

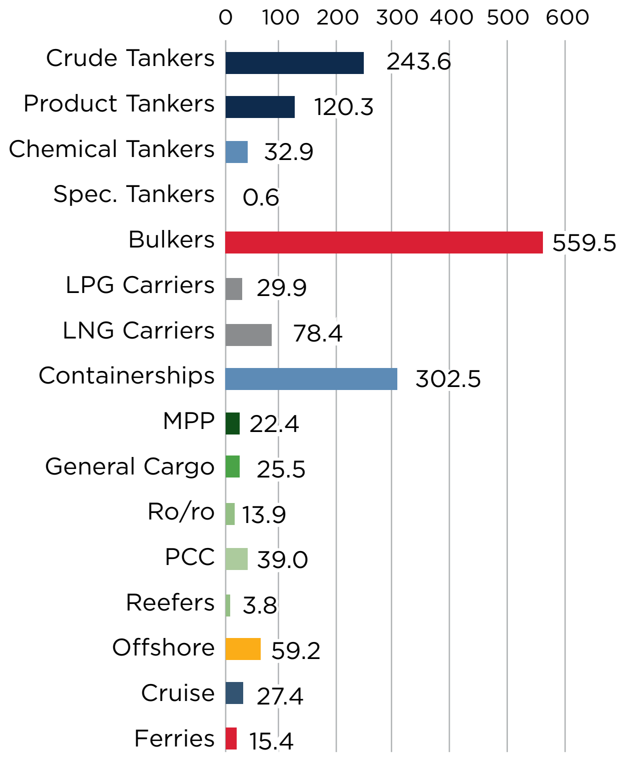


Figure 3.1: World fleet, million gross tons.

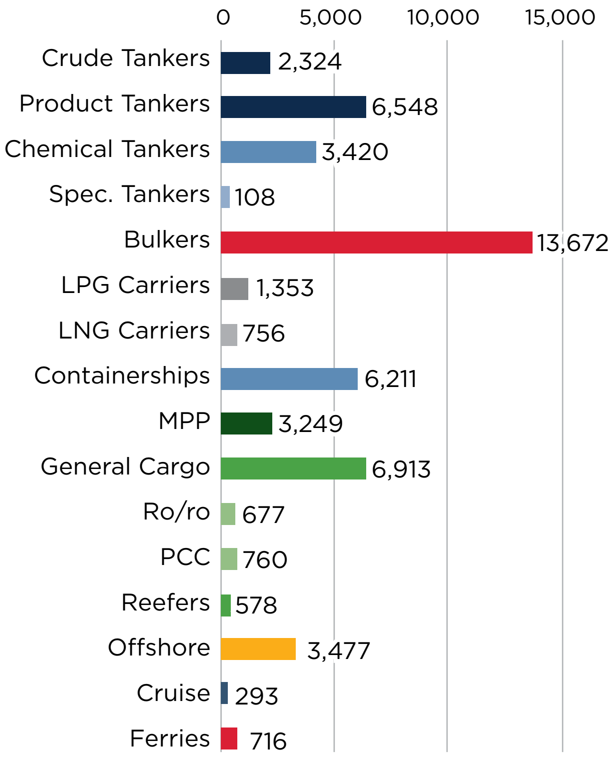


Figure 3.2: World fleet, number of vessels.

(Source: Clarksons Research, World Fleet Register, April 2024)

3.1.2. Status of Global Orderbook

The evolution of the orderbook closely follows developments relating to newbuilding contracting and the delivery of ships into the world fleet. Between the onset of the global financial crisis in 2008 and 2020, the supply side was characterized by two broad trends:

1. A general reduction in newbuilding contracting
2. Except in the period 2013-2015, deliveries typically outpaced contracting.

The net result of this is a significant contraction in the size of the global orderbook for >5,000 gt commercial ships from a peak of over 360 million (m) gt at the end of 2008 to a nadir of around 121m gt at the end of 2020. The orderbook-to-fleet ratio equated to just 9.2 percent at the end of 2020, compared to 50 percent at the end of 2008. As a percentage of the fleet, this was the lowest level recorded since the mid-1990s (Figure 3.3).

Following the recent spike in newbuilding contracting from the end of 2020 onward, the global orderbook has increased from this nadir, reaching 208m gt by the end of 2023. This is equivalent to 14.3 percent of the world fleet. In line with the concentration of newbuilding contracting in a handful of markets in recent years, the composition of the global orderbook has been drastically altered. The orderbook is now remarkably lopsided with sizeable orderbooks for some ship types and historically small orderbooks for others.

As detailed in Figure 3.4, the orderbook for gas carriers is large as a percentage of the current fleet, as are the orderbook for liner vessels, namely containerships and car carriers. However, the orderbooks for crude and product tankers and dry bulk carriers remain relatively modest. We have also seen a notable contraction in the orderbook for cruise ships since 2020, which is unsurprising given the extremely adverse impact the global pandemic had on this market.

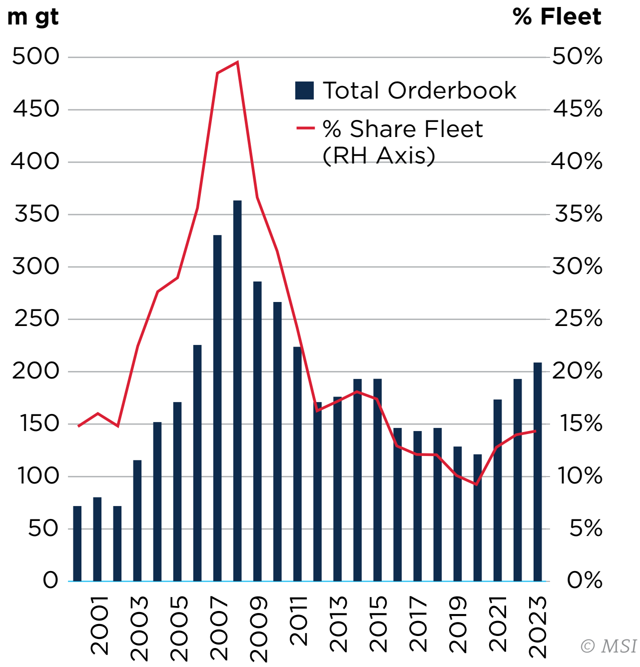


Figure 3.3: Global >5,000 gt orderbook 2000–2023.

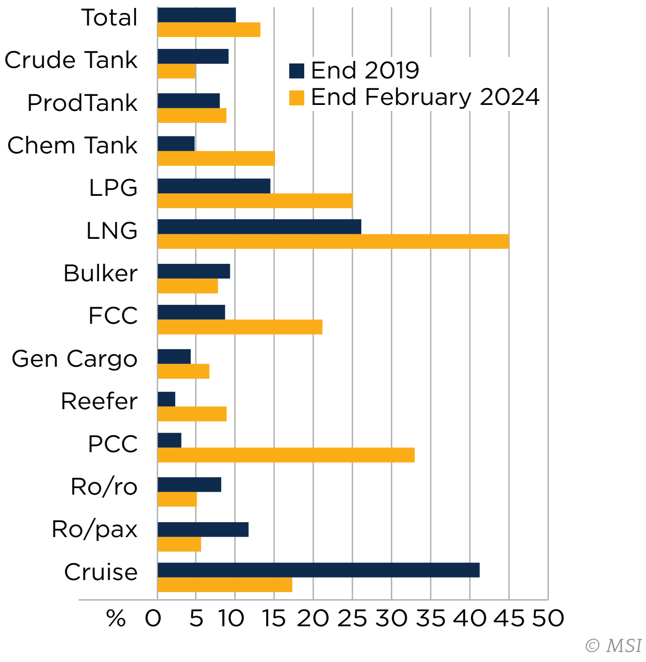
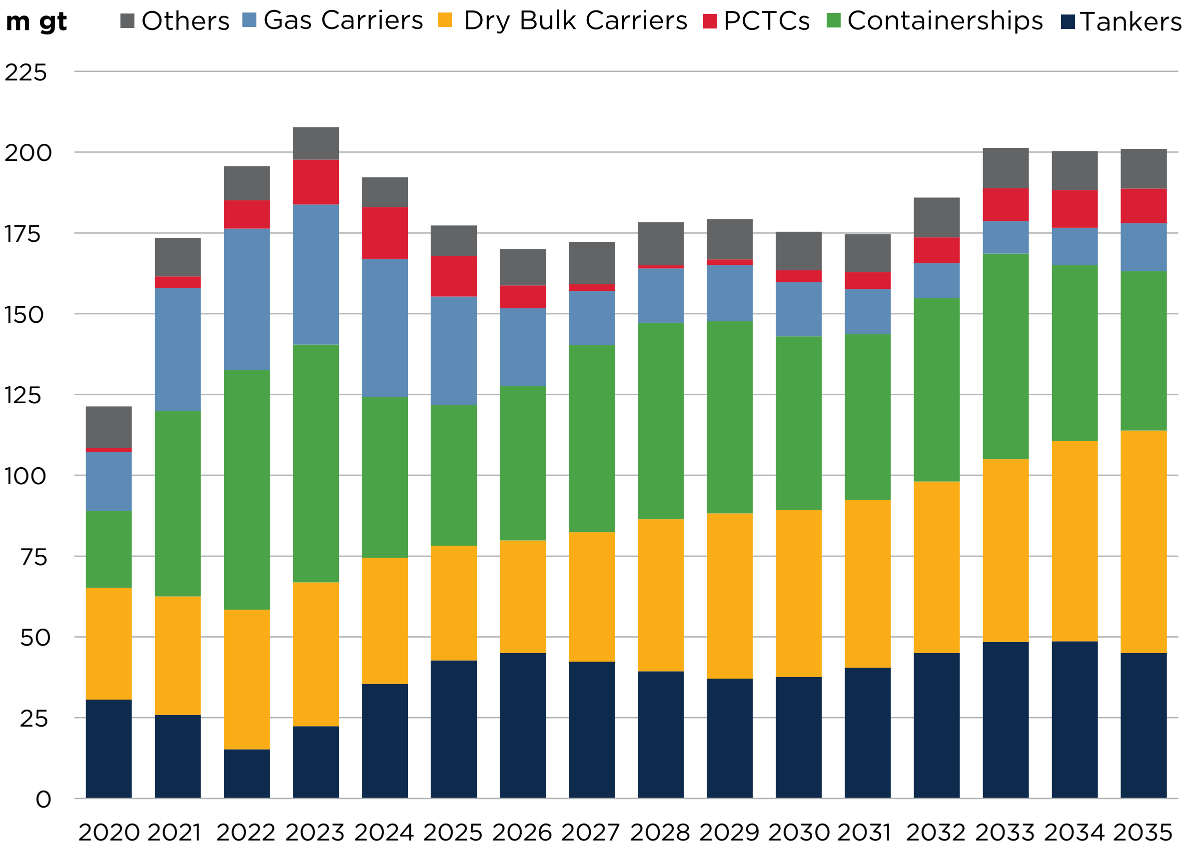


Figure 3.4: Global >5,000 gt orderbook as percent of fleet by ship type.

After the robust newbuild contracting volumes recorded in recent years, the newbuilding market has cooled rapidly since Q4 2023. While there continues to be notable interest in the tanker and gas carrier markets, fresh newbuild contracting for dry bulk carrier and containership has been limited in recent months.

Faced with a multitude of headwinds, ranging from economic uncertainty and softening freight markets to elevated newbuilding prices and long lead times at shipyards, it is expected that ship owners will take a step-back from the newbuilding market this year.

The current forecasts suggest that aggregate contracting volumes will reach around 55m gt in 2024, down 31 percent year-on-year and 45 percent below 2021's recent high of 99.8m gt. A comparable level of activity is expected next year before volumes recover in the second half of the decade in response to the twin drivers of replacement demand and tightening environmental regulations. However, the recovery will be gradual, and volumes are not expected to recover to levels close to recent highs until the middle of the next decade (Figure 3.5).



© MSI

Figure 3.5: Global >5,000 gt fleet supply-side developments by ship type.

After the surge of contracting in recent years, the global orderbook reached 208m gt by the end of 2023. This is its highest level since 2011 and 71 percent higher than at the end of 2020. Moving forward, we expect the orderbook to shrink, as the ships ordered in the last few years start being delivered and newbuild contracting activity remains subdued.

The orderbook is forecast to fall to a nadir of around 170m gt in 2026. While this is 18 percent below its peak in 2023, it is notably larger than at any point in the second half of the 2010s. Thereafter, we expect the orderbook to remain stable before trending upwards in the first half of the next decade (Figure 3.6).

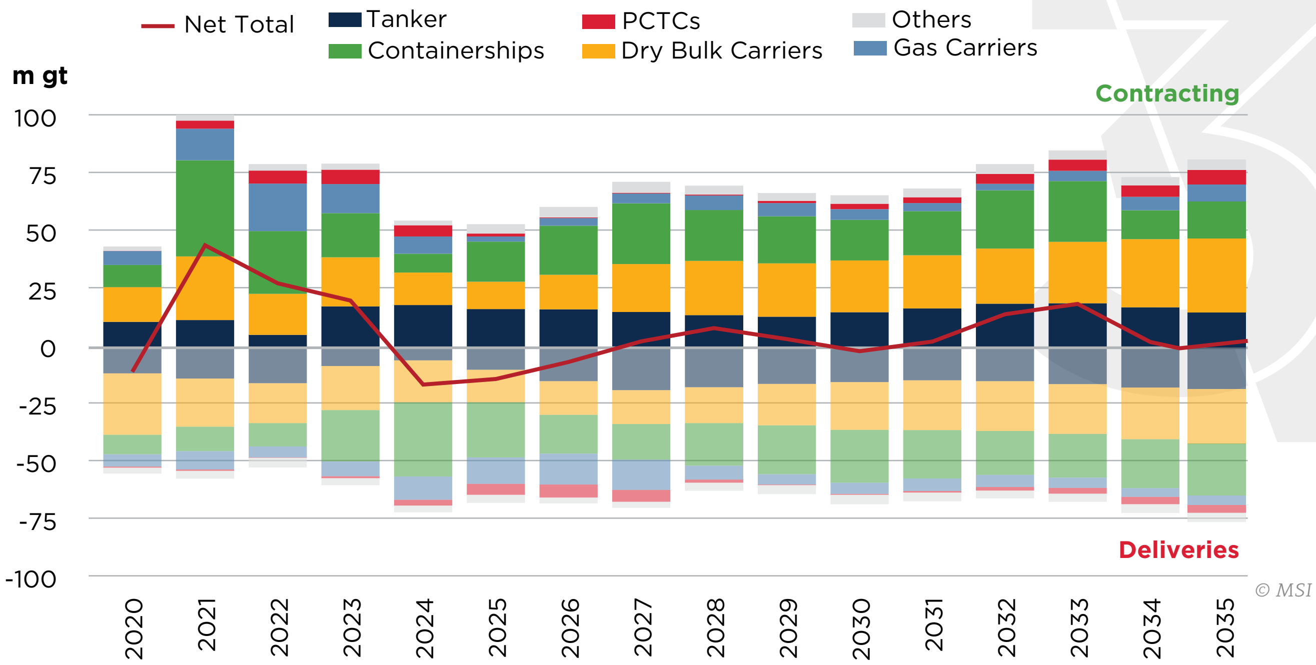


Figure 3.6: Global >5,000 gt orderbook dynamics by ship type.

3.1.2.1. Oil Tanker Orderbook

Tankers comprise one of the highest world fleets in terms of numbers and gross tonnage. There has been a steady increase in ordering since 2023. The breakdown of all tanker contracts by year and by sector are shown in Figure 3.7 and Table 3.1.

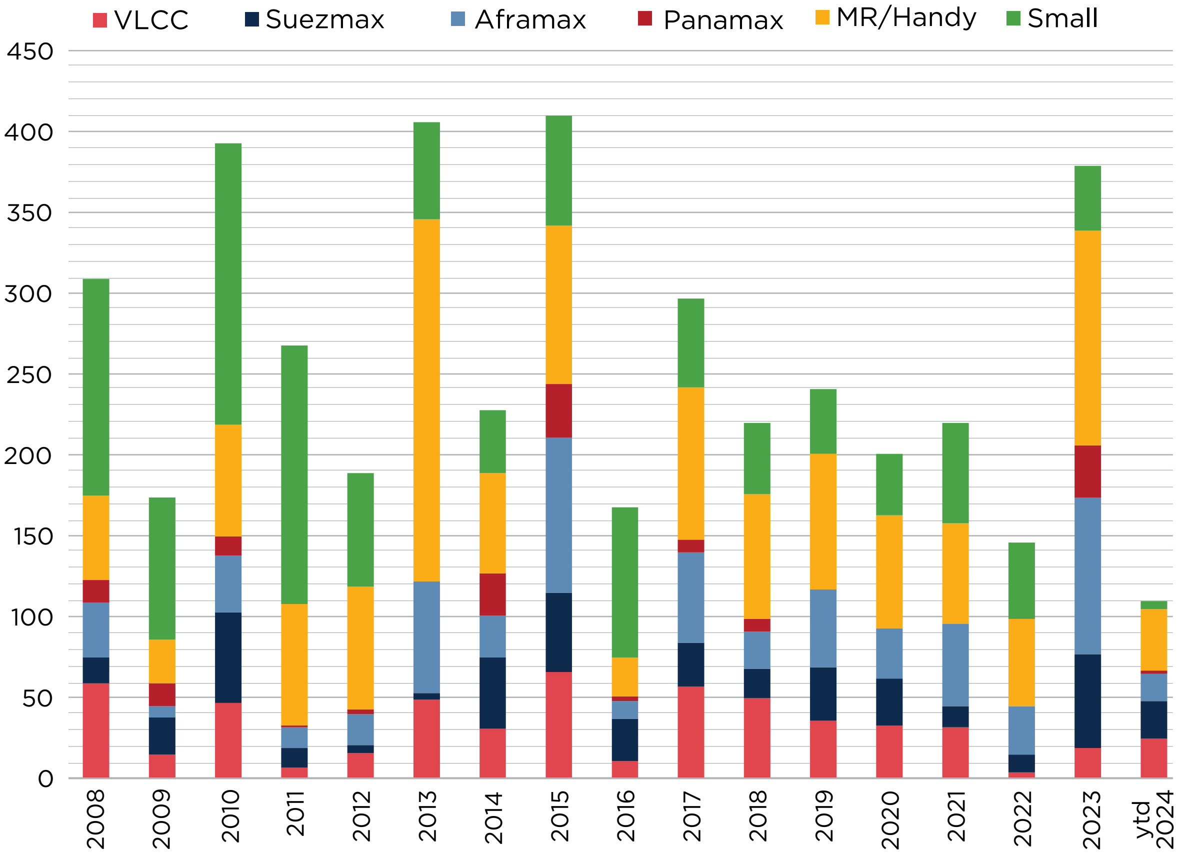


Figure 3.7: Annual tanker contracting by sector and number.

(Source: Clarksons Research, World Fleet Register, April 2024)

Sector	10 Year average	2022	2023	YTD 2024
VLCC	33	3	18	24
Suezmax	31	11	58	23
Aframax	47	30	97	17
Panamax	11	-	32	2
MR/Handy	76	54	133	38
Small	53	47	40	5
Total	**250**	**145**	**378**	**109**

Table 3.1: Tanker contracting by sector and number.

(Source: Clarksons Research, World Fleet Register, April 2024)

3.1.2.2. Battery-Fitted Vessels Orderbook

There has been a significant increase in battery-fitted vessels in the last three years with the momentum expected to continue. Figure 3.8 shows the number of orders placed for battery-fitted ships including battery-hybrid ships based on vessel type.

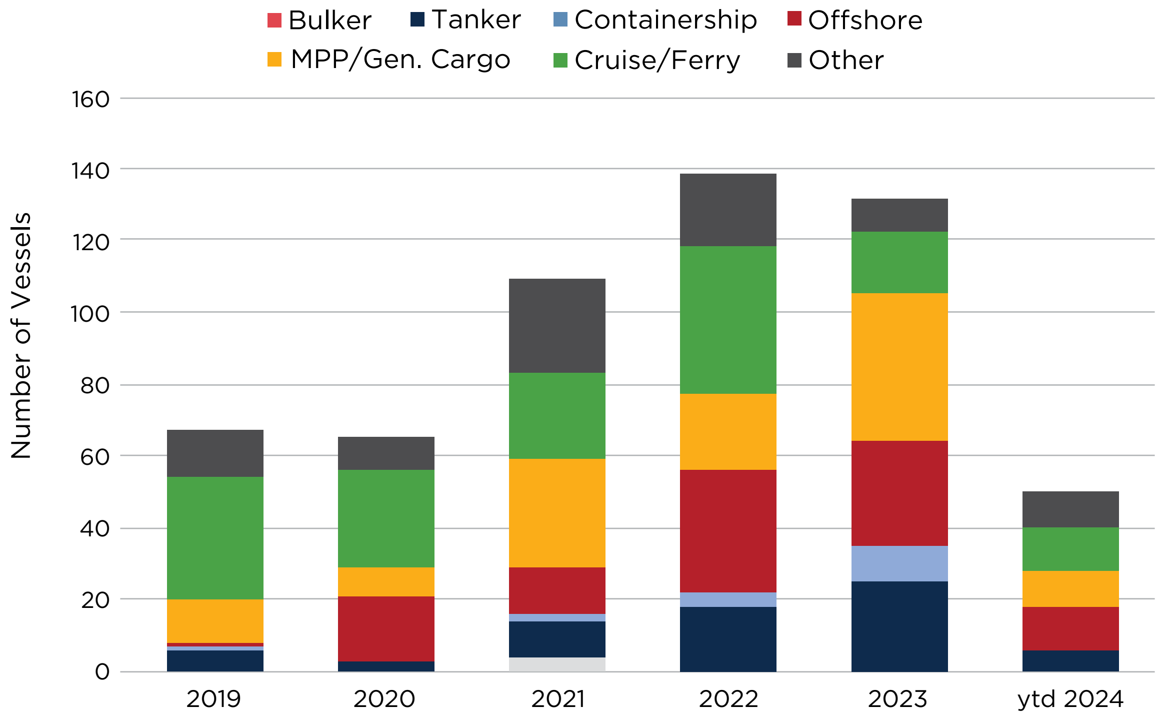


Figure 3.8: Orderbook of battery fitted ships (including battery-hybrid).

(Source: Clarksons Research, World Fleet Register, April 2024)

3.1.2.3. Alternative Fuels Uptake

Section 2.5.2 addressed the fleet evolution and the investment in alternative fuels. It can be clearly observed that in the latest decade there has been a significant surge in ordering of alternative fuel capable ships, with demand being steady in 2024 (Figure 3.9).

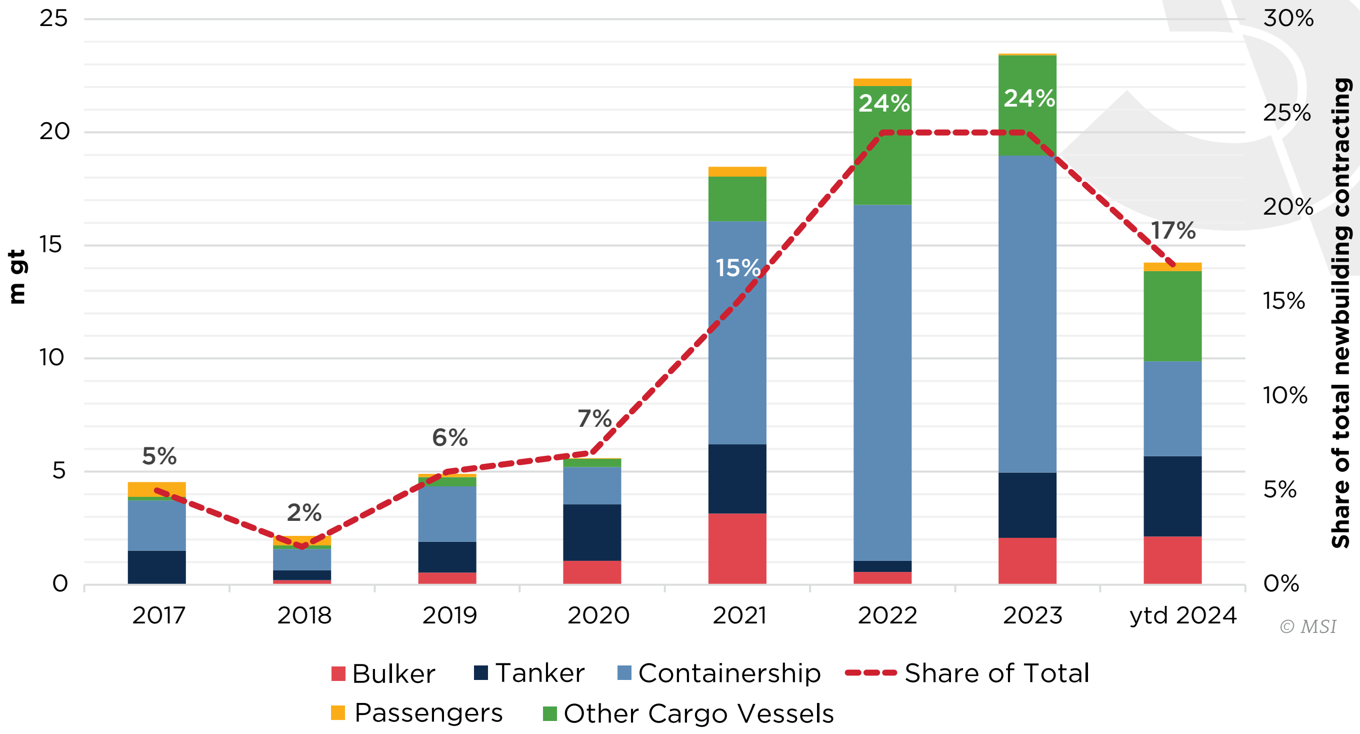
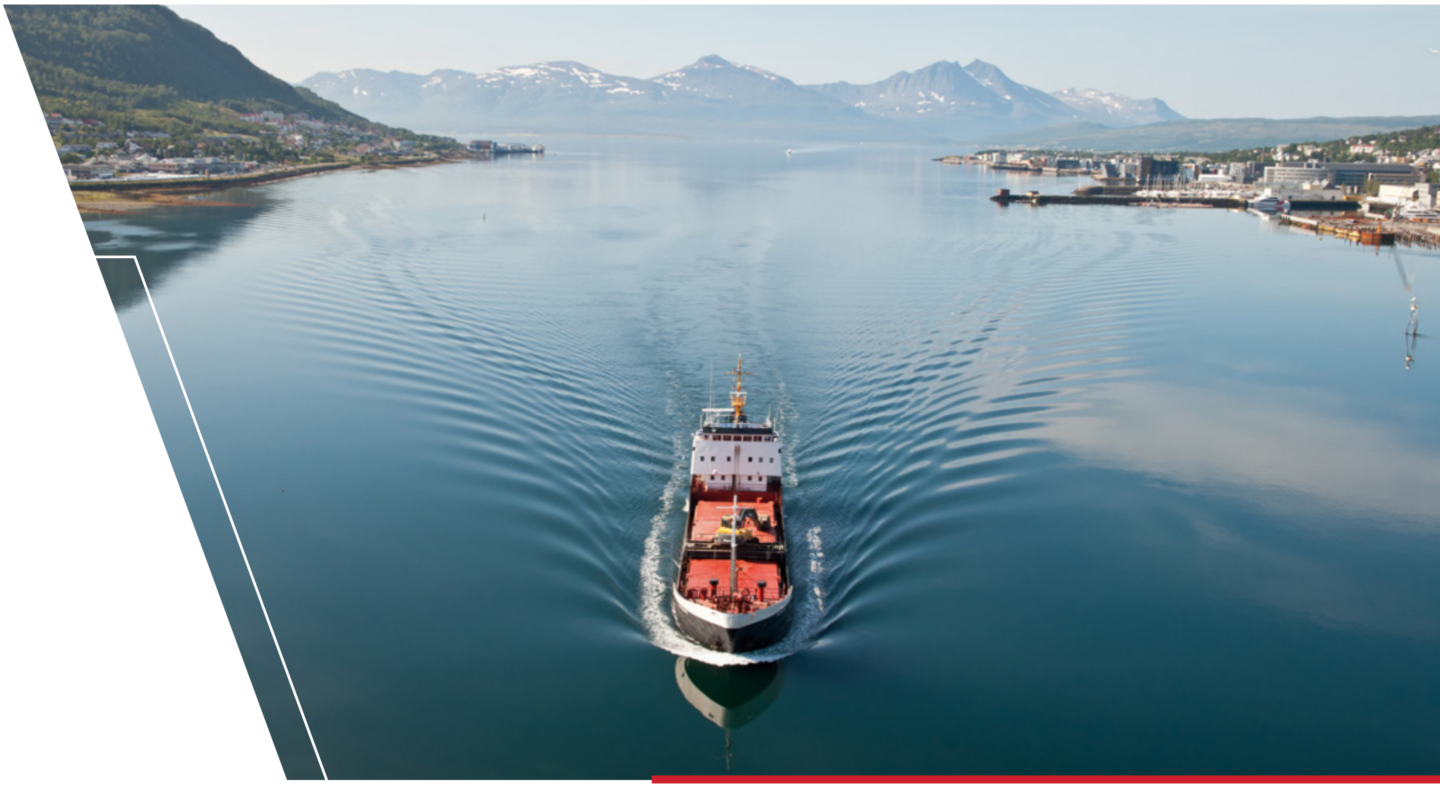


Figure 3.9: Number of owners ordering alternative fuel capable ships.

Figures 3.10 and 3.11 illustrate the increase in the ordering of vessels capable of using alternative fuels. Liquefied natural gas (LNG) and methanol are the top two alternative fuels currently on the orderbook.



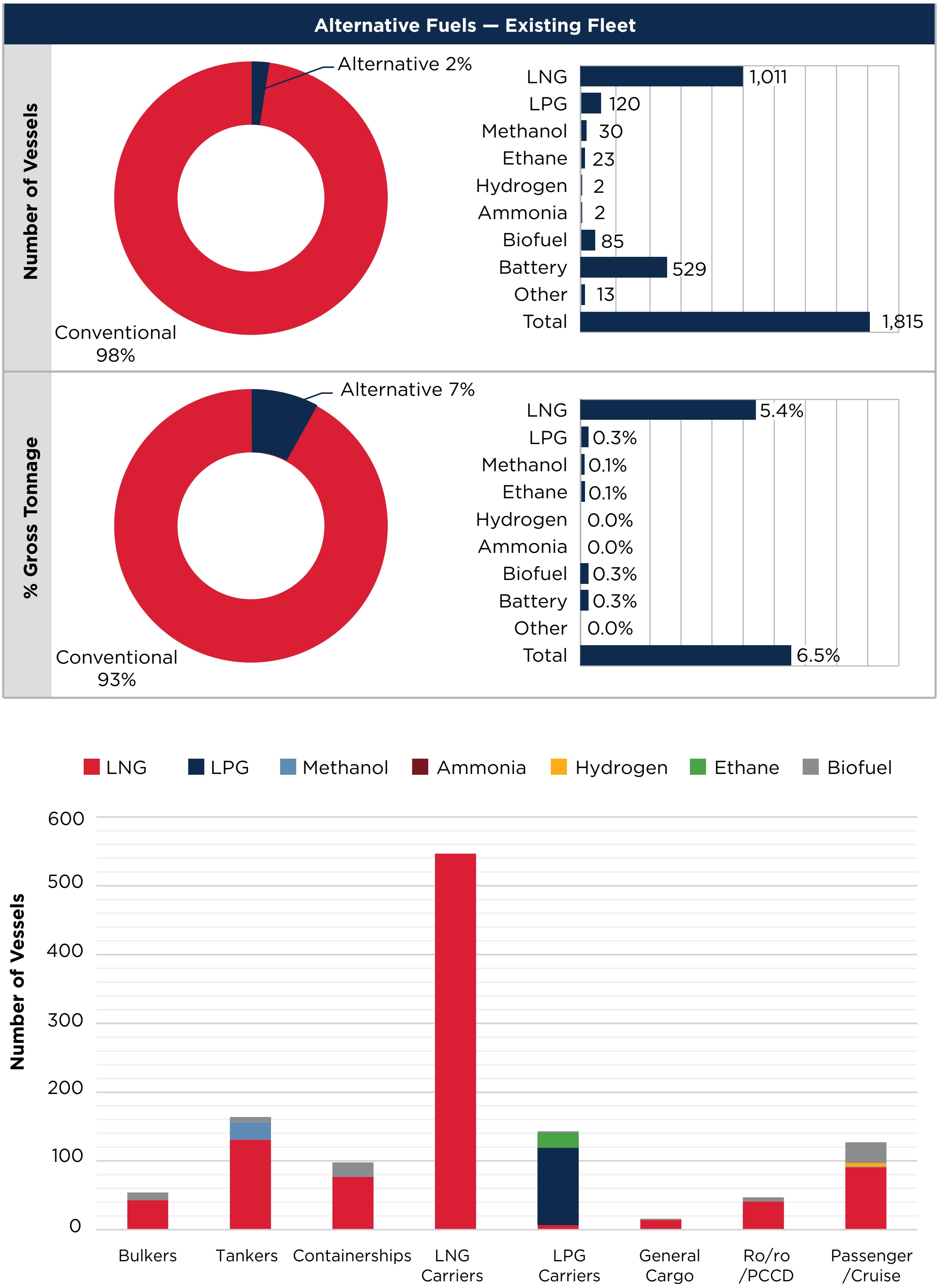


Figure 3.10: Existing fleet by fuel type.

(Source: Clarksons Research, World Fleet Register, April 2024)

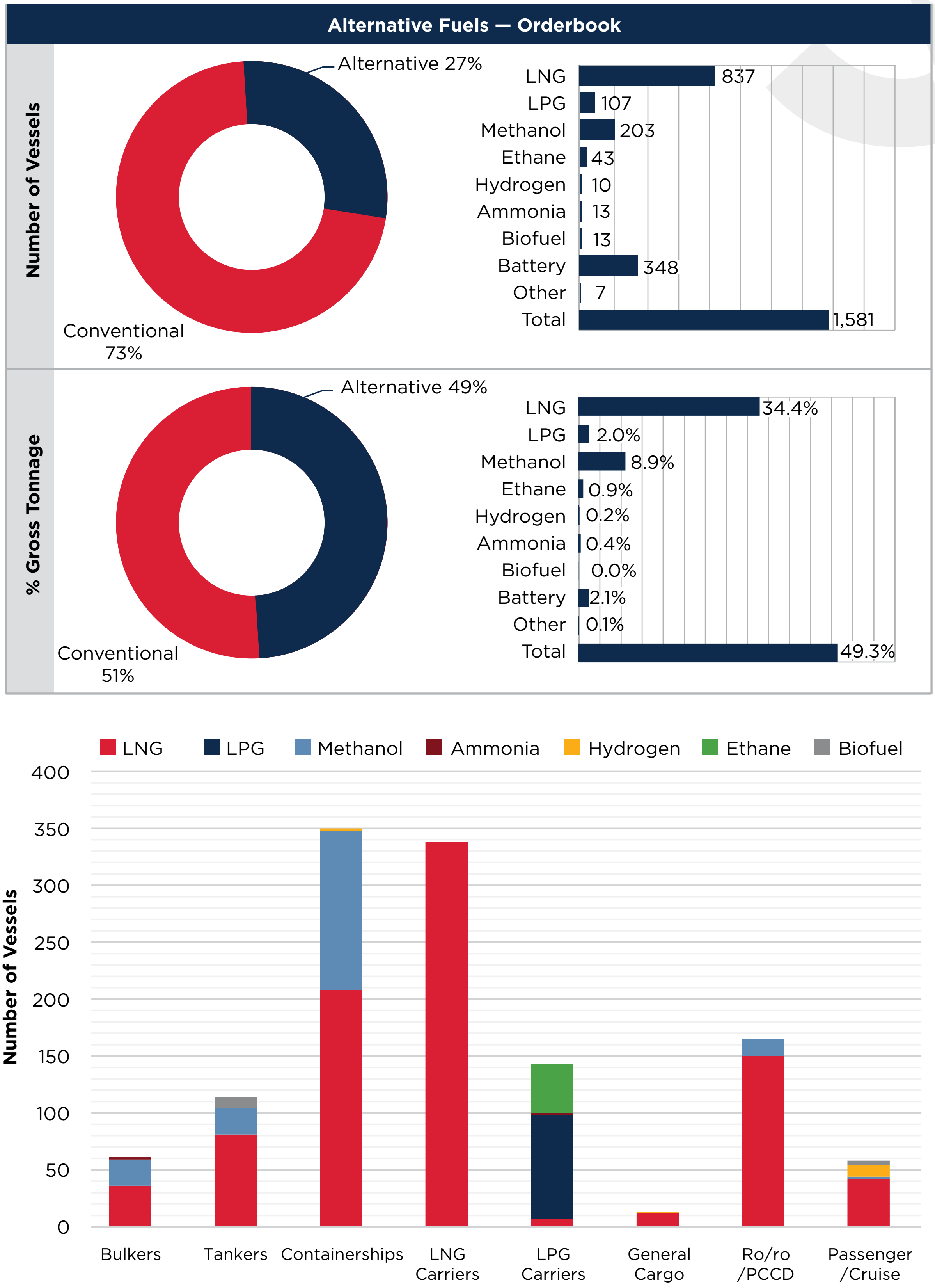


Figure 3.11: Orderbook by fuel type.

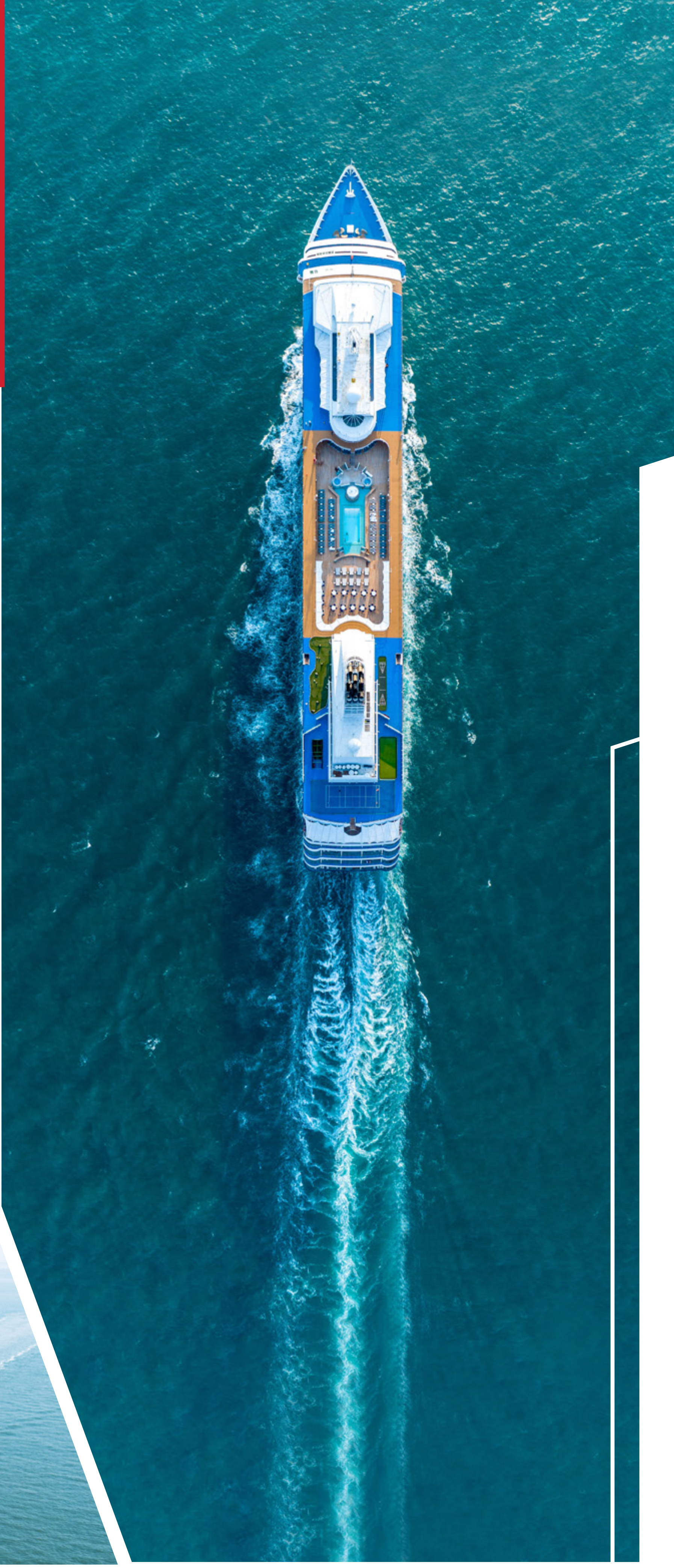
(Source: Clarksons Research, World Fleet Register, April 2024)

3.1.3. Status of Energy Efficiency Technologies — Existing Fleet

The energy efficiency technologies (EETs) adoption rate for the current fleet is relatively low, but as shipping continues toward 2030 and beyond, the adoption rate is expected to grow. As seen in Table 3.2, there are certain takeaways from the current EET profile across the existing fleet.

- The highest EET uptake ship type for the existing fleet is bulk carriers, followed by containerships, LNG carriers, and liquefied petroleum gas (LPG) carriers.
- EETs with the highest adoption rates in the current fleet benefit from their relative ease of implementation (e.g., propeller ducts, rudder bulb, etc.).
- Wind-assisted propulsion systems have some of the lowest levels of adoption in the current fleet.
- However, some vessel types are more suitable for renewable options. One such example is the Flettner rotor, a cylindrical structure that utilizes the Magnus effect to generate propulsion power, which is much more practical for a bulker than a containership.

It is important to note that each technology's effectiveness in reducing greenhouse gas (GHG) emissions depends on various factors such as vessel type and operational profile. A comprehensive approach that combines multiple EETs tailored to specific ship characteristics is often the most effective way to achieve significant emissions reductions.



Energy Efficient Technology	Bulkers	Tankers	Container-ships	LNG	LPG	General Cargo	Ro/Ro or PCC	Passenger/ Cruise	All Ship Types
Air Lubrication System	0.1%	0.06%	0.8%	6.4%	0.1%	0.02%	1.1%	0.5%	**0.3%**
Hull Fin	4.0%	0.6%	0.9%	-	0.2%	0.03%	0.5%	0.07%	**1.1%**
Twin Fin	0.01%	-	-	-	-	-	-	-	**0.001%**
Bow Enhancement	7.0%	0.9%	5.3%	1.4%	5.6%	0.2%	2.1%	0.2%	**2.4%**
Bow Foil, Retractable	-	-	-	-	-	-	-	0.02%	**0.003%**
Hull Skating System	0.01%	-	0.1%	-	-	-	-	-	**0.01%**
PBCF — Propeller Boss Cap Fin	5.4%	1.6%	7.8%	2.9%	1.5%	0.08%	3.3%	0.1%	**2.4%**
Propeller Duct	10.0%	5.8%	0.9%	2.0%	5.9%	0.04%	0.1%	-	**3.7%**
Wake Equalizing Duct	0.9%	0.7%	1.2%	0.9%	-	0.2%	0.1%	-	**0.5%**
Stator Fin/Pre-Swirl	8.6%	2.0%	8.9%	-	2.4%	0.06%	1.2%	-	**3.1%**
Stator Fin/Post-Swirl	0.1%	-	-	-	0.6%	-	0.6%	-	**0.04%**
Rudder Bulb	7.8%	2.9%	12.4%	12.8%	4.7%	0.2%	7.2%	0.6%	**4.0%**
Rudder Fin	1.7%	0.2%	0.02%	-	-	0.02%	-	0.01%	**0.4%**
Gate Rudder	0.0%	-	0.08%	-	-	0.02%	-	-	**0.013%**
Solar Panel	0.01%	0.01%	-	-	-	-	1.9%	0.2%	**0.1%**
Wind, Flettner Rotor	0.07%	0.02%	-	-	0.1%	0.01%	0.2%	0.03%	**0.03%**
Wind, Kite	0.01%	-	-	-	-	-	-	-	**0.003%**
Wind, Rigid Sail	0.02%	0.01%	-	-	-	-	0.1%	0.01%	**0.01%**
Wind, Suction Wing	0.01%	0.01%	0.02%	-	-	0.02%	0.2%	-	**0.02%**
Wind, Inflatable Sail	-	-	-	-	-	-	0.1%	-	**0.001%**
Waste Heat Recover System (WHRS)	0.09%	0.02%	0.26%	-	-	0.01%	-	0.2%	**0.08%**
All EETs	**26.0%**	**11.2%**	**25.0%**	**21.3%**	**14.0%**	**0.7%**	**12.5%**	**2.4%**	**11.7%**

Table 3.2: EETs uptake — existing fleet.

(Source: Clarksons Research, World Fleet Register, April 2024)

3.1.4. Status of Energy Efficiency Technologies — Orderbook

EETs offer a promising pathway toward a more sustainable and environmentally friendly maritime industry. The International Maritime Organization (IMO) proposed the penetration rate for EETs in the fourth GHG study report, adopting this parameter to define the percentages of the ships that will implement each technology. The orderbook adoption rate for EETs can be seen in Table 3.3, with key insights provided below:

- More shipowners invest in EETs for new ships. Compared to last year's EET uptake, the latest rate for the global fleet orderbook jumps from 28 percent to 37.4 percent.
- The highest EET uptake ship type is roll on/roll off (ro/ro)/pure car carrier (PCC), followed by containerships, LNG carriers, and bulk carriers.
- Design considerations, such as bow enhancement and rudder bulbs have a much higher adoption rate on new vessels than the previous EETuptake rate.
- Air lubrication systems have a lower adoption rate for the overall global fleet orderbook, but containerships and gas carriers show an increasing trend.

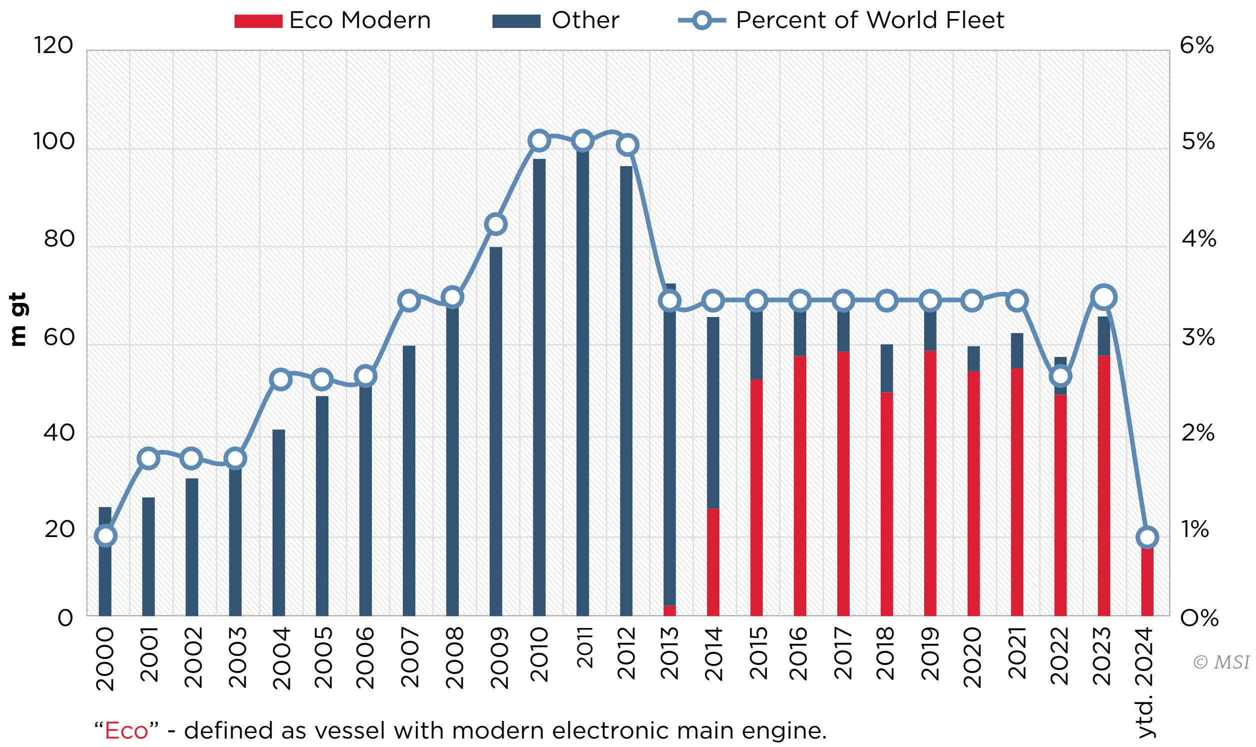
Energy Efficient Technology	**Bulkers**	**Tankers**	**Container-ships**	**LNG**	**LPG**	**General Cargo**	**Ro/Ro or PCC**	**Passenger/ Cruise**	**All Ship Types**
Air Lubrication System	0.3%	0.4%	12.6%	39.8%	1.9%	-	14.2%	1.9%	**6.4%**
Hull Fin	8.9%	1.2%	1.6%	-	-	-	-	-	**3.0%**
Twin Fin	-	-	-	-	-	-	-	-	**-**
Bow Enhancement	15.3%	7.5%	26.6%	2.6%	26.9%	18.4%	44.9%	1.6%	**15.9%**
Bow Foil, Retractable	-	-	-	-	-	0.2%	-	-	**0.02%**
Hull Skating System	-	-	-	-	-	-	-	-	**-**
PBCF — Propeller Boss Cap Fin	7.8%	4.5%	1.9%	3.8%	-	1.5%	34.2%	0.6%	**5.6%**
Propeller Duct	7.8%	4.5%	6.6%	-	7.1%	0.7%	-	-	**4.6%**
Wake Equalizing Duct	-	0.2%	-	-	-	-	-	-	**0.05%**
Stator Fin/Pre-Swirl	20.9%	7.5%	17.2%	-	1.4%	-	29.8%	-	**11.8%**
Stator Fin/Post-Swirl	-	-	-	-	-	-	-	-	**-**
Rudder Bulb	11.8%	12.9%	40.2%	20.8%	6.1%	1.9%	19.6%	5.3%	**16.3%**
Rudder Fin	4.7%	0.2%	-	-	-	-	-	-	**1.3%**
Gate Rudder	-	-	-	-	-	-	4.4%	-	**0.2%**
Solar Panel	0.8%	-	0.8%	-	-	-	16.9%	2.5%	**1.4%**
Wind, Flettner Rotor	0.6%	-	-	-	1.9%	-	1.3%	-	**0.3%**
Wind, Kite	0.1%	-	-	-	-	-	-	-	**0.02%**
Wind, Rigid Sail	0.1%	0.2%	0.7%	-	-	-	0.4%	0.6%	**0.3%**
Wind, Suction Wing	-	-	-	-	-	6.1%	-	0.3%	**0.6%**
Wind, Inflatable Sail	-	-	-	-	-	-	-	-	**-**
Waste Heat Recover System (WHRS)	-	1.1%	3.0%	-	-	-	0.9%	4.0%	**1.1%**
All EETs	**38.4%**	**25.6%**	**54.4%**	**51.8%**	**31.6%**	**21.3%**	**70.7%**	**14.3%**	**37.4%**

Table 3.3: EETs uptake — orderbook.

(Source: Clarksons Research, World Fleet Register, April 2024)

3.1.5. Future Fleet Renewal

Figure 3.12 shows the world fleet by delivery year. This provides an estimate of future replacement requirements for the world fleet as fleet age is a good indicator of fleet retirement, shipbreaking, and retrofit potential. Further, Figure 3.13 illustrates the advanced age of a large portion of the fleet (about a third of the fleet is over 15 years old) and the average fleet age is 12.5 years. These are indications that there will be the need for a significant fleet renewal in the near future especially considering the IMO decarbonization strategy and targets (as well as other regional requirements) that make it even more challenging for older tonnage to remain compliant.



"Eco" - defined as vessel with modern electronic main engine.

Figure 3.12: World fleet by delivery year.

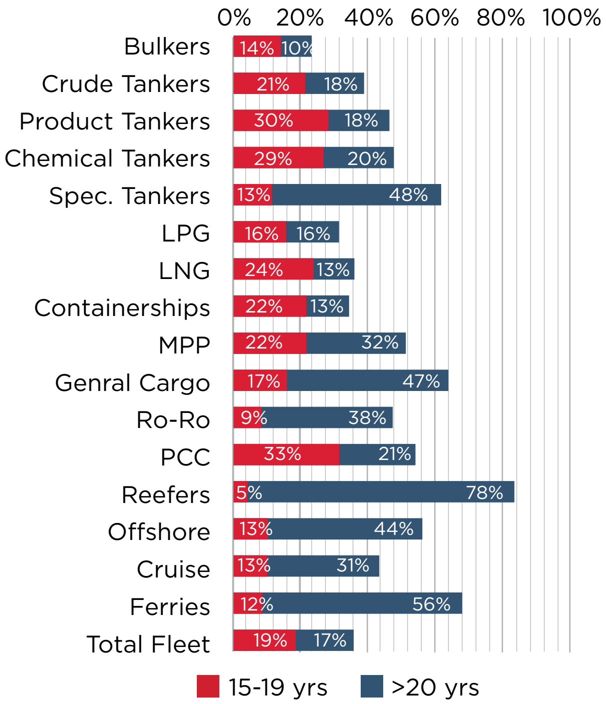


Figure 3.13: Portion of fleet >15 years old.

(Source: Clarksons Research, World Fleet Register, April 2024)

3.2. Retrofit Status and Outlook

3.2.1. Alternative Fuel Retrofits

Addressing the status of ships currently in service that run on conventional fuels is a crucial element of decarbonizing the maritime industry. Amongst the many solutions currently under consideration, one of the most prominent is retrofitting the engines onboard ships to use carbon-neutral or zero-carbon fuels.

The decision to retrofit a ship is a complex one, involving a range of technological, financial, and operational barriers. As a means of compliance, it is at nascent stages of development and to date, only a small number of ships have undergone a fuel retrofit. As of March 2024, the number of retrofitted ships in the >5,000 gt world fleet totaled just 49 of an aggregate 1.8m gt. A further 43 ships of 5.1m gt, primarily large containerships, are pending retrofit. This brings the total completed and pending retrofits to 92 ships, equivalent to 0.15 percent of the world fleet in terms of numbers. Figure 3.14 and Table 3.4 provide an overview of the fuel retrofits status.

Excluding LPG which is typically deployed on a "cargo-as-fuel" basis on LPG carriers, the most popular fuel for retrofitting has historically been LNG. However, the number of LNG fuel retrofits has remained modest due to many challenges. These include technical challenges around retrofits, the rising cost of LNG in recent years, and mounting uncertainty around the emissions profile of LNG as a fuel when measured on a Well-to-Wake (WtW) basis and the attendant problem of methane slip.

Looking at the short-term, data demonstrates an increase in methanol dual-fuel retrofits. However, this may be due to the containership market's current preference for this fuel. The majority of pending retrofits are owned by a small number of the major containership lines. As such, the preferred fuel for retrofits remains far from certain.

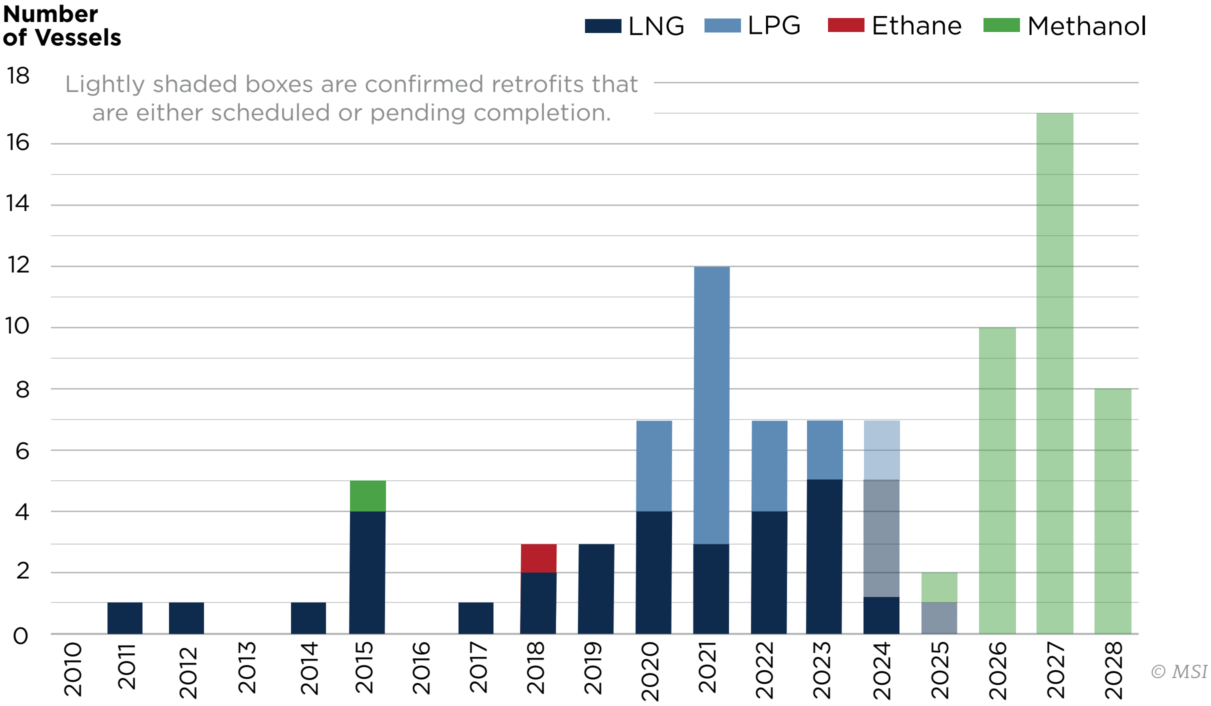


Figure 3.14: Historical retrofit of >5,000 gt world fleet by year of retrofit/fuel type.

Ship Type	Completed Retrofit			Pending Retrofit		
	Number	k gt	% of Fleet	Number	k gt	% of Fleet
Crude and Product Tankers	-	-	-	-	-	-
Chemical Tankers	3	33	0.07%	4	29	0.09%
Dry Bulk Carriers	-	-	-	-	-	-
LPG Carriers	18	848	1.06%	2	96	0.12%
LNG Carriers	2	170	0.26%	-	-	-
Containerships	5	281	0.08%	37	4,967	0.62%
RoRo/RoPax	20	484	0.93%	-	-	-
Cruise Ship	1	12	0.14%	-	-	-
Others	-	-	-	-	-	-
Total	**49**	**1,828**	**0.08%**	**43**	**5,092**	**0.07%**

Table 3.4: Completed and pending fuel retrofits by ship type; data as of April 1, 2024.

Given the nascent nature of the fuel retrofit market, not all ships in service are suitable candidates at present. ABS conducted an analysis around the issue to determine the characteristics typically cited as being key determinants in a ship's suitability. These are detailed in Table 3.5. They fall into two broad categories:

1. Technical: Specifically, the type of engine installed onboard the ship and whether it is electronically controlled.
2. Financial: Namely, the ship's year of build and age, and its type and size.

Applying these criteria to the >5,000 gt world fleet of conventionally fueled ships currently in service, we identified a potential pool of 3,300 ships that are broadly suitable candidates for fuel retrofit (Figure 3.15). When considering the forecast for future supply-side developments – specifically the ships currently under construction or yet to be ordered that will be delivered with conventionally fueled engines – this pool of candidates expands to close to 5,000 ships of an aggregate 500m gt.

It is important to note that as the technology and experience around fuel retrofitting develops, the retrofit option will potentially become available to ship types excluded from the current analysis, older ships, and smaller ships. However, this is largely dependent on a range of other factors, which will be discussed in Section 3.2.2.

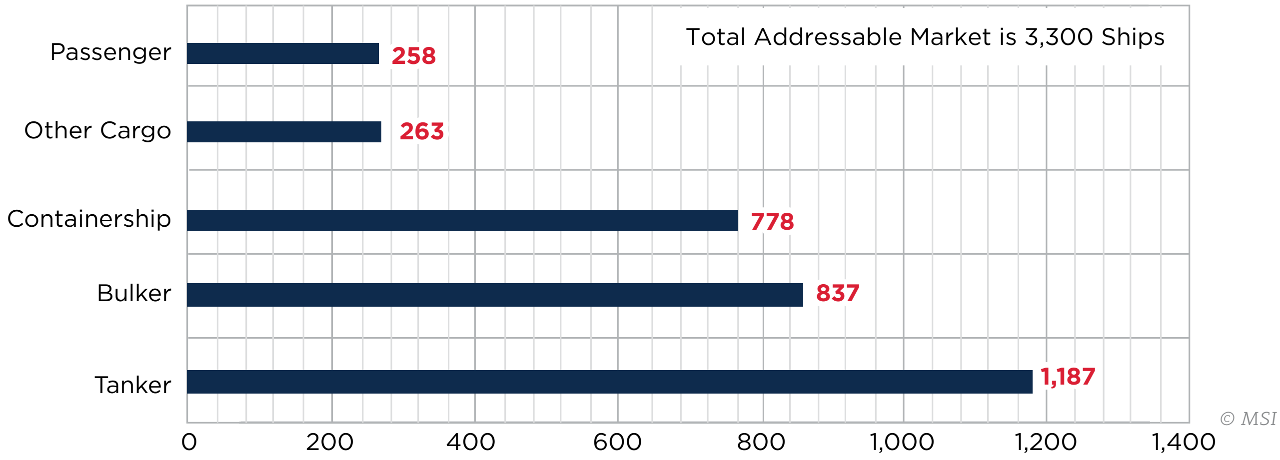


Figure 3.15: Retrofit candidates by sector.

Type	Criteria	Details
Technical	Engine Type	Electronically controlled engines
Financial	Year of Build	Modern "Eco" ships delivered in 2013/2014 or later
	Vessel Age	Up to 10 years old
	Vessel Type/Size	Tankers: >70k dwt Bulkers: >150k dwt LNG Carriers: N/A LPG Carriers: N/A Container: >7.6k TEU General Cargo/MPP: N/A Ro/ro: N/A Ro/pax: Included Cruise: No restrictions Car Carriers: >6k CEU
	Timing	Next special survey is likely to be date of retrofit

Table 3.5: Criteria and assumptions for fuel retrofit suitability/timing.

3.2.2. Engine Retrofits Demand — Forecasting the Timing

To effectively forecast potential future fuel retrofits, the pool of candidates must be considered in conjunction with other assumptions. These include: the legislative landscape for the decarbonization of shipping, the speed at which industry support for alternative fuels ramps up, the commercial availability of fuel retrofit options and developments around its associated capital expenditure (capex), and finally, developments around the widespread availability of low- to zero-carbon fuels. It is also important to keep in view the maturation and adoption of "competing" technologies such as "drop-in" fuels and carbon capture.

In modeling the potential development of fuel retrofit, we have assumed that:

1. Shipping adheres to its goal of net zero by 2050.
2. Ammonia dual-fuel engines become commercially available from 2027 to join methanol engines in the marketplace.
3. The availability of low- and zero-carbon marine fuels tracks demand and they become widely available over the next decade.

Another assumption is the timing of the retrofit. From feasibility study to adoption, the retrofit process generally takes around 13 to 20 months. The physical retrofit itself takes an average of around 60 to 80 days; although this can vary depending on the size of the vessel, the scope of the changes required and the level of preparation. It can be assumed that to minimize off-hire time and therefore, lost income, owners will undertake fuel retrofits at the same time as the next scheduled Special Survey.

The results of this analysis are presented in Figures 3.16 and 3.17. Given lead times, retrofits are assessed from 2025.

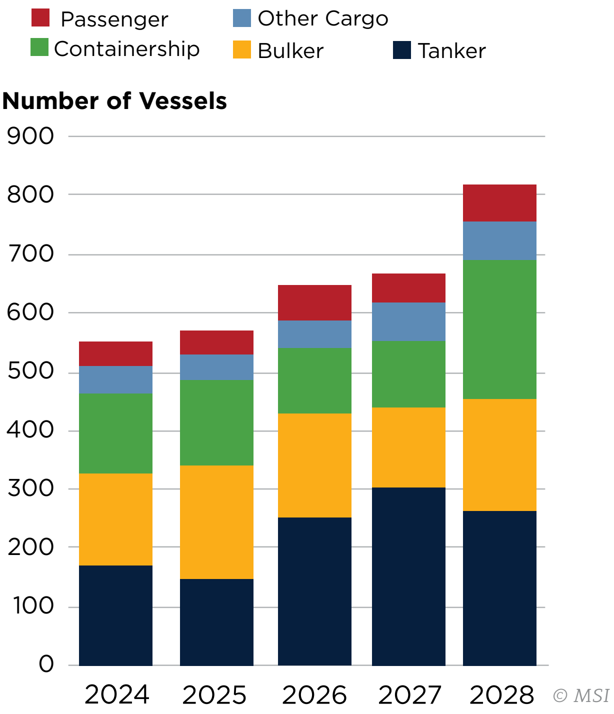


Figure 3.16: Estimated dry docking schedules (large vessels).

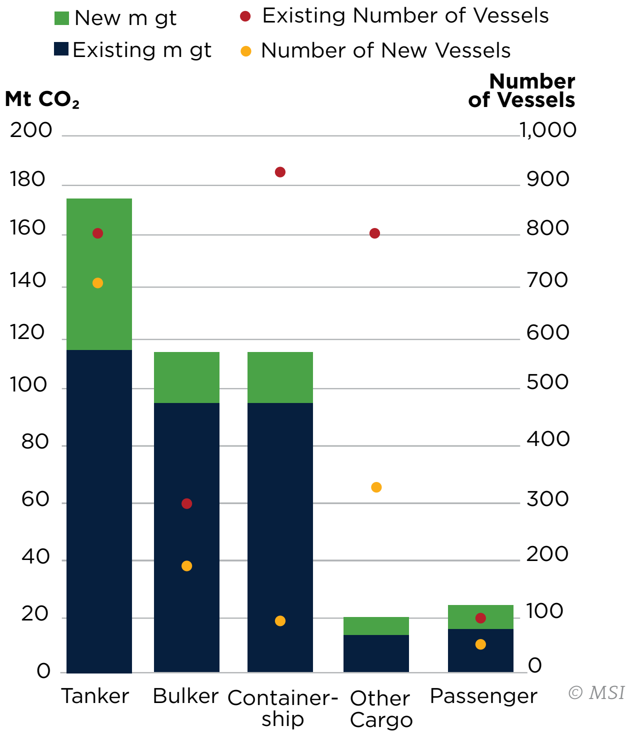


Figure 3.17: Theoretical addressable market for retrofits.

3.2.3. Cruise Vessel Retrofits and Energy Efficiency Technologies

Cruise vessels are discussed in detail in Section 2.3.8. In relation to the topics of vessel retrofits and EETs, the cruise industry is currently focusing on the following options that can provide the necessary short-term improvements until a selection for a different energy source is made.

1. Installation of waste heat recovery (WHR) systems to recover and reuse heat from engine cooling.
2. Installation of air lubrication systems and low-friction hull coatings to reduce drag and improve fuel efficiency.
3. According to some cruise operators, heating, ventilation, and air conditioning (HVAC) systems typically use around 15 percent of a vessel's total electricity load. All major cruise lines are gradually upgrading to more energy efficient HVAC systems onboard existing vessels.
4. Retrofitting of vessels with more energy efficient LED lighting.
5. Upgrading to more efficient laundry and galley equipment. Encourage guests to reuse towels to reduce laundry energy load.
6. Installation of battery storage and fuel cell systems to meet hotel power load.
7. A few of the major operators have run trials using biofuels derived from used cooking oil and animal fat and are working with suppliers to secure a reliable biofuel supply infrastructure.
8. In addition to optimizing itineraries and voyage planning to reduce sailing times, cruise lines are also evaluating greater use of open jaw voyages in place of the more common closed-loop sailings. Open jaw voyages are those where the origin and destination differ. This eliminates the return leg and allows cruise lines to start a new voyage from the point of disembarkation. It only works, however, if the cruise does not originate in the passengers' home country.

3.3. Shipyard Capacity

3.3.1. Shipyard Capacity — Newbuilds

The major difficulty in assessing the balance between supply and demand in the shipbuilding industry derives not from the demand but the supply side. When trying to assess the level of existing demand, there may be minor discrepancies in terms of units, timing, and definition. However, there is little ambiguity about the quantity of tonnage on order.

By contrast, the capacity of newbuilding facilities to supply ships is extremely difficult to measure or quantify. In the global shipbuilding industry, capacity refers to the potential output of shipyards, using their labor force, workers, equipment and resources to their fullest extent.

The capacity of newbuilding facilities has been assessed using a combination of approaches as set out in the schematic in Table 3.6. For the levels of capacity from 2020 onward, an approach suggested by the Organisation for Economic Co-operation and Development (OECD) has been adopted, which looks at an adjusted average of recent output percentile rolling average for output from each yard, aggregated to give a country/regional capability. The chosen measure of output is gross tonnage, which means there can be a high degree of volatility year-by-year. Accordingly, output can appear to reach 100 percent of capacity in some years.

	Pre-2004:Official Data	2004–2011: Expansion Phase	2011–2020: Contraction Phase
Methodology	• National and regional shipbuilding associations: Association of West European Shipbuilders, JETRO and Koshipa. • Historical data was compiled and shared by the OECD WP6. • Data typically no longer compiled from the early 2000s.	• Official data is no longer consistently available. • Output is assumed to match capacity.	• Monitoring shipyard status/visbility. • Measuring retrenchment at surviving shipyards. • Monitoring labor force reducation and cuts to shift patterns/working hours. • Tracking public announcements from major shipyards. • Monitoring government strategies
	2020–Present		
	• In a relatively stable period for output, we have moved to a system based on monitoring production at each yard. • Reactivations are being closely followed as the actual capacity deployed will be much lower than when yards were previously operating. • A key constraints on capacity remains the shortage of skilled labor. In that context, we are monitoring efforts by yards to recruit, including from abroad. • Further productivity gains are being made. For example, a shipyard has a new welding robot that can half the time to weld tanks for LNG carriers.		

Table 3.6: Approaches for assessing capacity of newbuilding facilities.

Shipbuilding supply, or capacity, is relatively elastic. The fixed assets in the shipbuilding industry are highly specialized and their usage outside of the industry is limited to other heavy industry projects or naval construction. The market value of fixed assets, such as cranes, is far less than the investment value. Because of this, shipyards generally respond to changes in the market by means of price adjustment in the short term, rather than output adjustment.

After increasing dramatically over the 2000s as the newbuilding contracting super-boom gathered pace and China expanded its shipyard capacity at an unprecedented rate, the watchword for global shipyard capacity throughout the 2010s was rationalization. Global capacity fell 41 percent from a peak of around 107m gt in 2011 to 63.4m gt in 2021.

While the process of retrenchment was global, it was markedly pronounced in Asia. China, in particular, bore the brunt of shipyard closures, with capacity in the country falling 43 percent from 43.3m gt in 2011 to around 24 to 25m gt in 2021-22. A significant proportion of the reduction in capacity, particularly in China, was due to the smaller, recently built shipyards (widely known as "Greenfield" yards) exiting the shipbuilding industry. Some shipyards reorientated their business to other heavy industry projects, such as the offshore oil and gas sector, wind farms, power plants and civil engineering. In addition, many of the larger, established shipyards also scaled back their operations. They mothballed certain berths and reduced their workforce and/or altered their shift patterns from a 3 x 8-hour schedule to a 2 x 8-hour schedule to reduce effective capacity, for example.

Shipyard capacity levelled out and started to increase in the last few years as capacity – predominantly in China – has been reactivated. It is estimated that global shipyard capacity totaled 64m gt in 2023. The "Big 3" shipbuilding nations of Japan, South Korea, and China account for 90 percent of all capacity. China has the largest market share (40 percent), followed by South Korea (29 percent) and Japan (21 percent). Figures 3.18 and 3.19 illustrate these points.

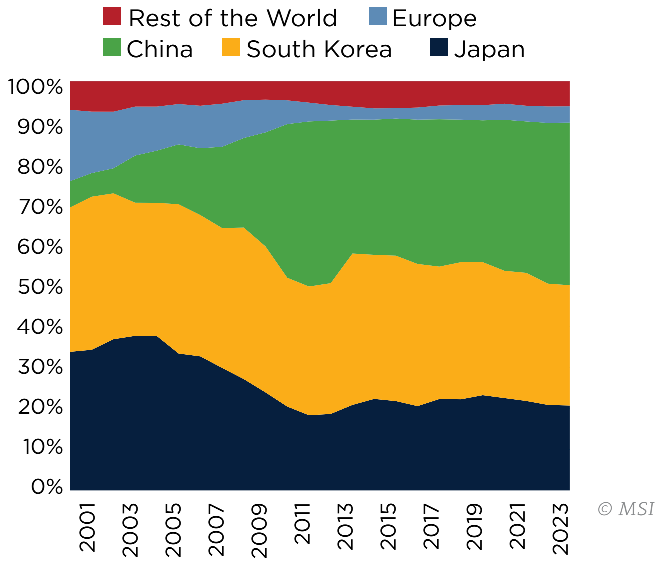


Figure 3.18: Share of global shipyard capacity by builder country/region.

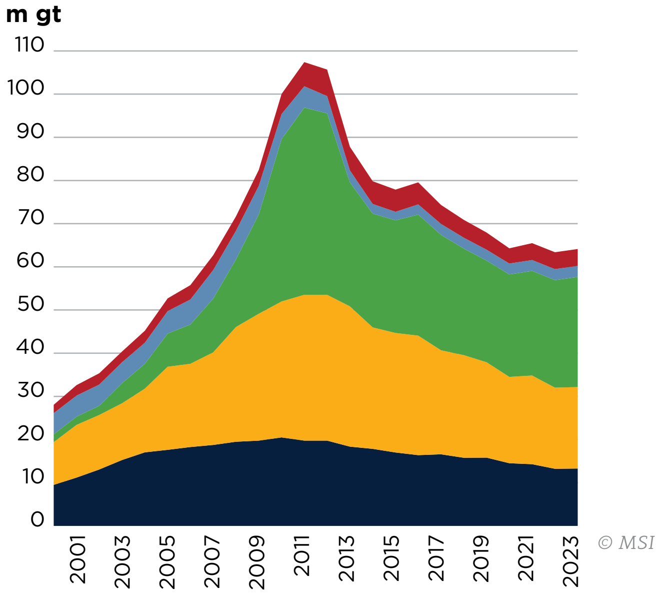


Figure 3.19: Global shipyard capacity by builder country/region.

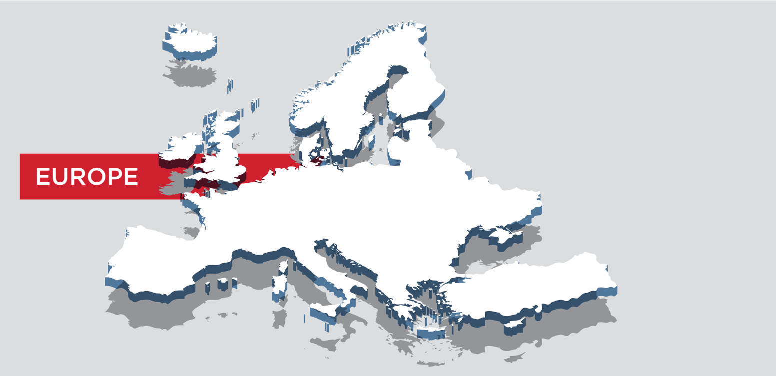
The Japanese shipbuilding industry was not immune from the processes of retrenchment and rationalization over the last 10 years or so. It is estimated that between 2011 and 2022, Japanese shipyard capacity fell 33 percent to 13.2m gt. This is reflected in the graph on Figure 3.26, which details Japanese newbuilding deliveries as a percentage of capacity. Between 2015 and 2023, output from Japanese shipyards has averaged around 82 percent of the total capacity per year, albeit with some significant fluctuations on a year-to-year basis.

Since 2021, output has stabilized at around three-quarters of total capacity.

▲ **Figures 3.20 through 3.23 illustrate the vessel deliveries as a percentage of capacity.**

Although China's output has remained relatively stable at around 23m gt per year between 2013 and 2022, there were significant developments in shipyard capacity over the same time period. The process of retrenchment and rationalization that characterized global shipyard capacity in the 2010s was particularly severe in China. Since 2016, we have seen aggregate Chinese shipyard utilization levels rise. As a percentage of total capacity, newbuilding deliveries fell to a low of 78 percent in 2016. Since 2018, this figure has consistently been above 90 percent. Chinese shipyards have been the primary beneficiaries of the recent newbuild contracting boom that started in Q4 2020. These ships started to enter service in 2023 and as a result, output from Chinese shipyards increased notably to around 30m gt last year. This resulted in aggregate Chinese shipyard capacity utilization maxing out.

The process of capacity retrenchment and rationalization during the 2010s in South Korea disproportionately impacted small- and medium-sized shipyards in terms of closures and aggregate shipbuilding capacity has increasingly become consolidated. Our modeling suggests that after a prolonged period of retrenchment over the 2010s, South Korean shipyard capacity has remained relatively static at around 20 to 21m gt from 2020 onwards. As such, fluctuations in shipyard capacity utilization closely track output volumes in recent years, averaging around 85 to 90 percent.



Aggregate European shipyard capacity has more than halved since its peak in 2007 and 2008 and was around 2.5m gt in 2023, with the majority based in Western Europe. Despite this fall, shipbuilding capacity there remains underutilized. Based on our latest modeling, ABS estimates that on an annual average basis, newbuilding deliveries from European shipyards have accounted for around 70 percent of their total capacity since 2010.

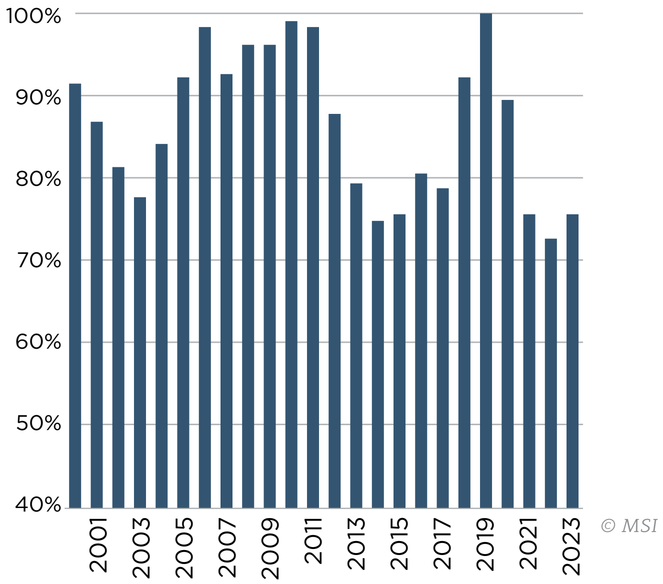


Figure 3.20: Japan newbuild deliveries as a percentage of capacity.

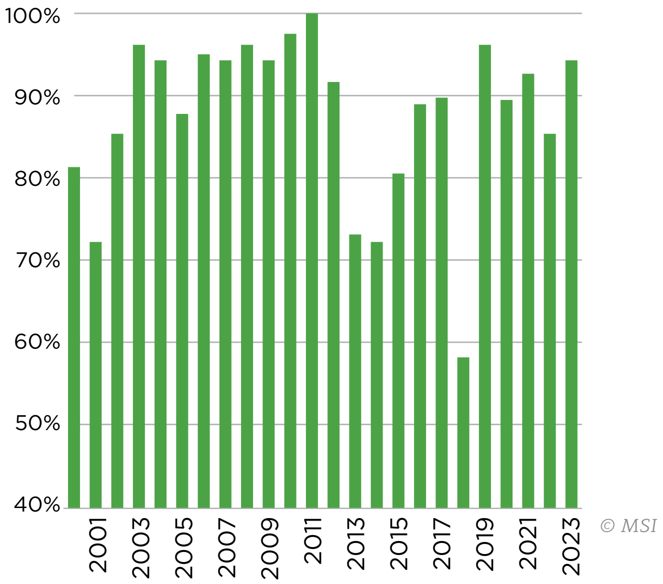


Figure 3.21: South Korea newbuild deliveries as a percentage of capacity.

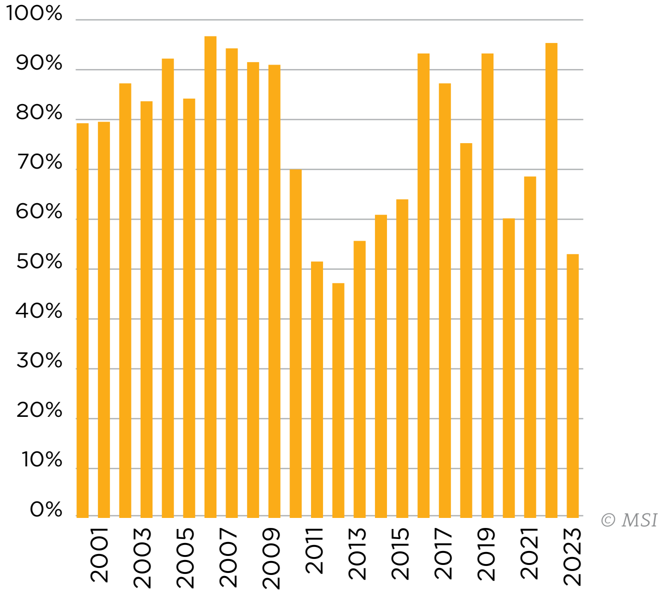


Figure 3.22: China newbuild deliveries as a percentage of capacity.

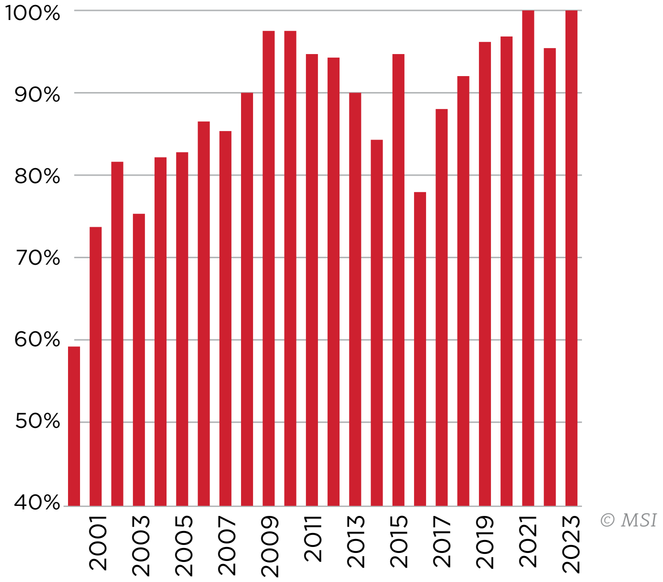
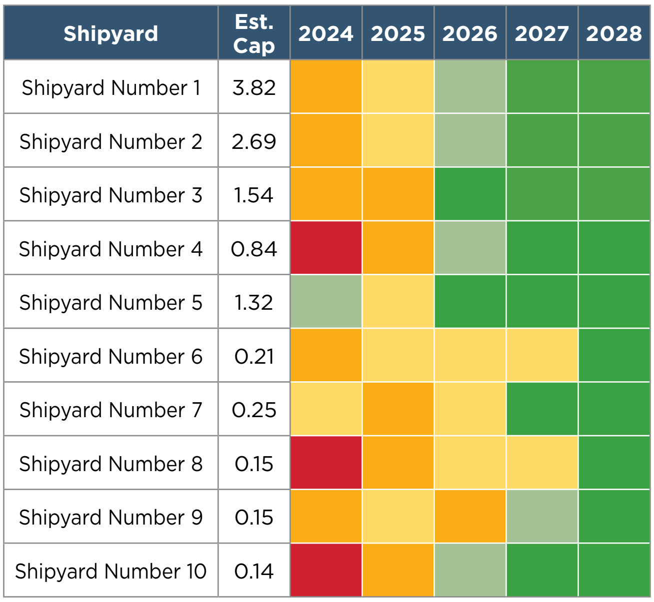


Figure 3.23: Europe newbuild deliveries as a percentage of capacity.

3.3.1.1. Major Shipyards Current Orderbook Size

As indicated previously, the estimated capacity is based on the 75th percentile of the annual delivery volume in the period 2019 through 2023. Based on this, the following figures (Figure 3.24 through 3.27) illustrate the orderbook size of the top 10 shipyards in the "Big 3" shipbuilding countries as well as the rest of the world.

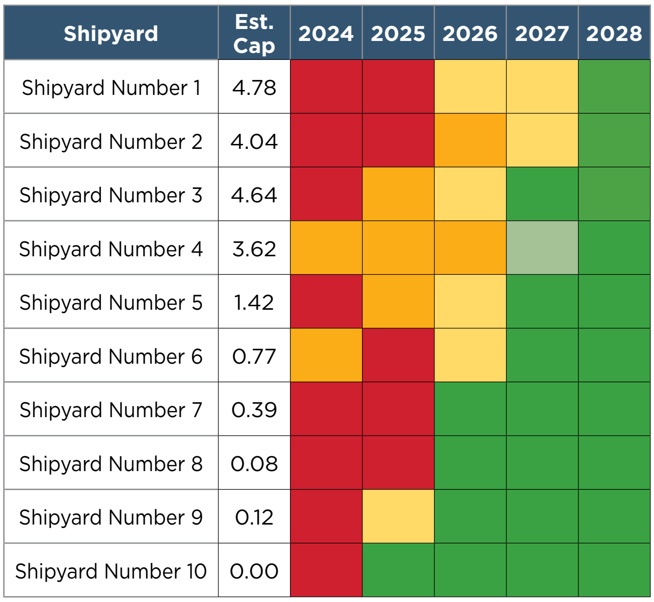
Legend				
Colored squares are the orderbook size for a given year versus estimated capacity.				
🟥	🟧	🟨	▧	🟩
100%	**75-99%**	**50-74%**	**25-49%**	**0-24%**



Shipyard	Est. Cap	2024	2025	2026	2027	2028
Shipyard Number 1	3.82	🟧	🟨	▧	🟩	🟩
Shipyard Number 2	2.69	🟧	🟨	▧	🟩	🟩
Shipyard Number 3	1.54	🟧	🟧	🟩	🟩	🟩
Shipyard Number 4	0.84	🟥	🟧	▧	🟩	🟩
Shipyard Number 5	1.32	▧	🟨	🟩	🟩	🟩
Shipyard Number 6	0.21	🟧	🟨	🟨	🟨	🟩
Shipyard Number 7	0.25	🟨	🟧	🟨	🟩	🟩
Shipyard Number 8	0.15	🟥	🟧	🟨	🟨	🟩
Shipyard Number 9	0.15	🟧	🟨	🟧	▧	🟩
Shipyard Number 10	0.14	🟥	🟧	▧	🟩	🟩

© MSI

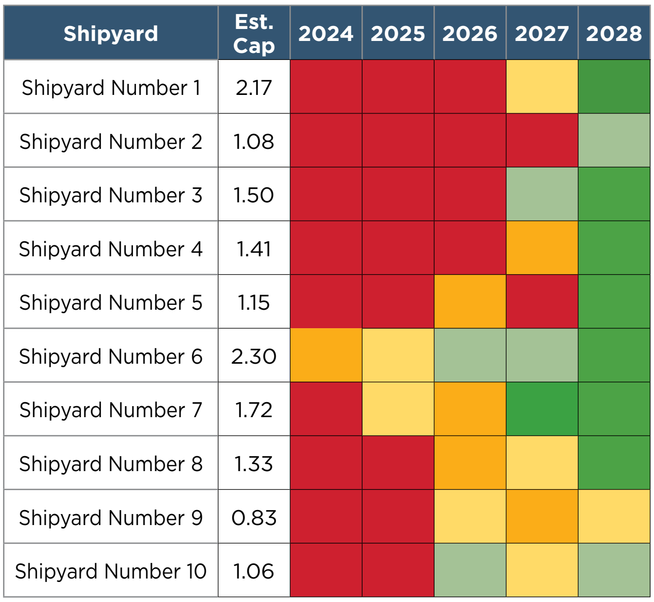
Figure 3.24: Top 10 Japanese shipyards by orderbook size (gt).



Shipyard	Est. Cap	2024	2025	2026	2027	2028
Shipyard Number 1	4.78	🟥	🟥	🟨	🟨	🟩
Shipyard Number 2	4.04	🟥	🟥	🟧	🟨	🟩
Shipyard Number 3	4.64	🟥	🟧	🟨	🟩	🟩
Shipyard Number 4	3.62	🟧	🟧	🟧	▧	🟩
Shipyard Number 5	1.42	🟥	🟧	🟨	🟩	🟩
Shipyard Number 6	0.77	🟧	🟥	🟨	🟩	🟩
Shipyard Number 7	0.39	🟥	🟥	🟩	🟩	🟩
Shipyard Number 8	0.08	🟥	🟥	🟩	🟩	🟩
Shipyard Number 9	0.12	🟥	🟨	🟩	🟩	🟩
Shipyard Number 10	0.00	🟥	🟩	🟩	🟩	🟩

© MSI

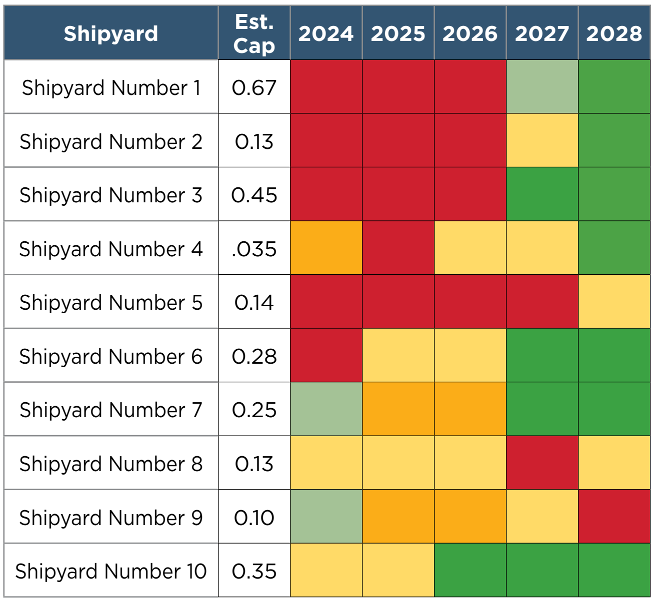
Figure 3.25: Top 10 South Korean shipyards by orderbook size (gt).



Shipyard	Est. Cap	2024	2025	2026	2027	2028
Shipyard Number 1	2.17	🟥	🟥	🟥	🟨	🟩
Shipyard Number 2	1.08	🟥	🟥	🟥	🟥	▧
Shipyard Number 3	1.50	🟥	🟥	🟥	▧	🟩
Shipyard Number 4	1.41	🟥	🟥	🟥	🟧	🟩
Shipyard Number 5	1.15	🟥	🟥	🟧	🟥	🟩
Shipyard Number 6	2.30	🟧	🟨	▧	▧	🟩
Shipyard Number 7	1.72	🟥	🟨	🟧	🟩	🟩
Shipyard Number 8	1.33	🟥	🟥	🟧	🟨	🟩
Shipyard Number 9	0.83	🟥	🟥	🟨	🟧	🟨
Shipyard Number 10	1.06	🟥	🟥	▧	🟨	▧

© MSI

Figure 3.26: Top 10 Chinese shipyards by orderbook size (gt).



Shipyard	Est. Cap	2024	2025	2026	2027	2028
Shipyard Number 1	0.67	🟥	🟥	🟥	▧	🟩
Shipyard Number 2	0.13	🟥	🟥	🟥	🟨	🟩
Shipyard Number 3	0.45	🟥	🟥	🟥	🟩	🟩
Shipyard Number 4	.035	🟧	🟥	🟨	🟨	🟩
Shipyard Number 5	0.14	🟥	🟥	🟥	🟥	🟨
Shipyard Number 6	0.28	🟥	🟨	🟨	🟩	🟩
Shipyard Number 7	0.25	▧	🟧	🟧	🟩	🟩
Shipyard Number 8	0.13	🟨	🟨	🟨	🟥	🟨
Shipyard Number 9	0.10	▧	🟧	🟧	🟨	🟥
Shipyard Number 10	0.35	🟨	🟨	🟩	🟩	🟩

© MSI

Figure 3.27: Top 10 shipyards in Rest of World by orderbook size (gt).

3.3.1.2. Forecasting Shipyard Capacity

Forecasting future shipbuilding capacity is a blend of qualitative and quantitative inputs. For the short term, it is necessary to track the activities of existing and emerging shipyards to assess the potential for expansion or contraction. This allows for an assessment of how the balance of capacity between key building regions may change over the next two to five years.

Beyond that horizon, ABS' forecasts for the shipbuilding capacity are primarily driven by medium- to long-term views of requirements for new ships. These are driven by ABS' forecast for cargo trade, ship demand, and renewal of ageing fleets. It is assumed that, as in any market, an increase in demand (and prices) will drive an increase in supply. Given the relative inelasticity of shipbuilding capacity it is assumed that any changes will be relatively gradual both in periods of expansion and contraction. But overall, it is assumed that there is sufficient capacity to meet demand over the long term. This represents the quantitative aspect of the forecast.

The next stage is to forecast the composition of shipbuilding capacity by country or region. This is a function of both the composition of future shipbuilding demand but also an assessment of long-term trends competitiveness of each building country or region. This is, by its nature, a qualitative task.

In summary, it is assumed that based on historical trends, shipbuilding will reduce in the current centers of production over time and new builders will emerge. These are likely to be in India and the Middle East. There is also potential for recovery in Vietnam and Philippines. Neither of these countries remain long-term prospects. At the same time, we do not expect production in the key Asian countries to collapse and residual production is anticipated in Europe and other existing shipbuilding regions.

As indicated earlier, after a prolonged period of rationalization throughout the 2010s, global shipyard capacity fell to a nadir of 63.4m gt in 2022. Since then, capacity has started to increase once again, driven in large part by the spate of reactivations in recent years. However, thus far, these increases have been relatively modest, with the latest estimates suggesting that capacity only grew by a net 0.75m gt in 2023 to 64.1m gt. Figure 3.28 illustrates this point.

Similarly, despite the headline figures around shipyard reactivations, capacity will continue to take time to come online. Based on our current modeling, we only expect global capacity to increase to 66.5m gt by the end of this year. Ultimately, global capacity will only be 5 percent higher by the middle of this decade than at its nadir in 2022. As we approach the end of the decade, we expect to see a more substantial ramp-up in global capacity in response to elevated contracting volumes. By 2030, we are forecasting that global shipyard capacity will exceed 71m gt. While this is 12 percent higher than capacity in 2022, it remains 33 percent below the historical peak of 107.4m gt in 2011.

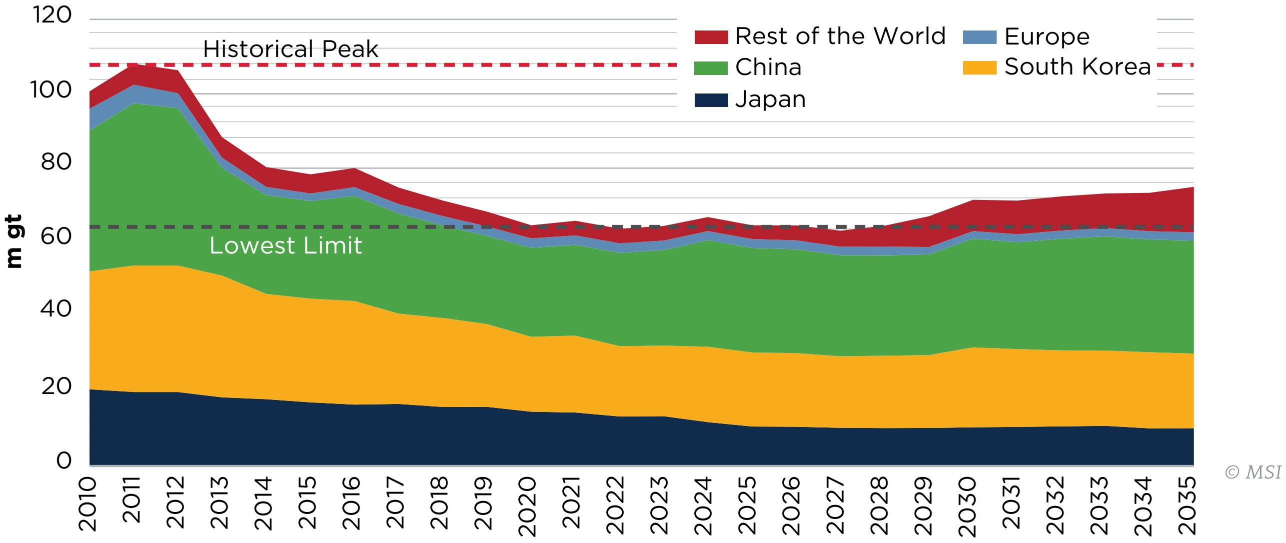


Figure 3.28: Global shipyard capacity by builder country/region.

In terms of market share by country, we expect China's to increase marginally over the remainder of this decade, rising from 40 percent in 2023 to around 42 to 43 percent in the second half of the decade. South Korea will maintain its current market share and Japan's will continue to decline from around 21 percent currently to 15 percent by the end of the decade.

The outlook for developments around shipyard capacity becomes increasingly opaque beyond the end of this decade. However, there are several potential trends we consider are worth highlighting.

1. The global capacity will remain at consistently elevated levels of 70–76m gt through to the middle of the century.
2. The "Big 3" Asian shipbuilding nations will collectively continue to dominate the industry.
3. We do expect other nations to begin entering commercial shipbuilding in a significant way (included in "Others" in the summary table below – Table 3.7). Potential candidates include Vietnam, the Philippines and India. However, there are significant downside risks to this aspect of our forecast.

Year	Japan	South Korea	China	Europe	Others	Total
2010	20.5	31.5	37.6	5.8	4.6	100.0
2015	17.0	27.7	26.1	2.0	5.1	77.9
2020	14.5	20.0	23.7	2.5	3.5	64.3
2025	10.6	19.8	27.9	2.4	3.7	64.3
2030	10.3	21.4	29.0	2.0	8.3	71.1
2035	10.1	20.0	30.1	2.2	12.1	74.5
2040	9.7	17.9	25.4	2.1	16.1	71.3
2045	9.3	17.2	21.9	2.1	16.1	66.6
2050	9.5	19.2	23.3	2.1	21.0	75.1

Table 3.7: Global shipyard capacity (m gt) by builder country/region.

3.3.2. Shipyard Capacity — Retrofits

According to some market estimates, there are around 1,250 active shipyards and ship repair yards. These range from small, privately-owned individual enterprises to large groups that operate multiple yards.

Despite this apparent surplus of potential capacity, the pool of yards capable of carrying out fuel retrofits is significantly smaller. Turnkey fuel retrofits are complex projects, requiring capabilities that are not available at all yards. A yard's ability to design and execute a holistic fuel retrofit is dictated by a range of factors. Arguably, the two most important are the fact that it requires a highly skilled workforce, including naval architects and experienced electrical engineers, and the ability to safely handle and deploy alternative fuels.

Due to these requirements, we estimate that only a small number of shipyards can undertake fuel retrofits. In total, 18 yards globally accommodated two-thirds of all demand for the vessel types and sizes. These are assumed to be those most likely to be able to carry out retrofits at present. However, in our analysis we included the capacity from around 50 yards in total. The historical data is derived from actual yards visits over the last five years. To analyze the demand for ship repair, we use the measure of "gt yard days", which is each individual vessel's gross tonnage multiplied by the time spent in the yard.This metric captures the difference in demand for repair between vessels of different sizes.

The additional forecast demand is due to retrofitting vessels already in the fleet and oil-fueled vessels that are yet to be delivered. It is important to note that if the fuel retrofit option gains traction, the number of yards capable of completing fuel retrofits is likely to increase. However, in all probability, the larger yards in Northeast Asia and the Middle East and the more specialist yards in Europe will capture most of the business. Figure 3.29 illustrates the retrofits constraints by limited shipyard spare capacity.

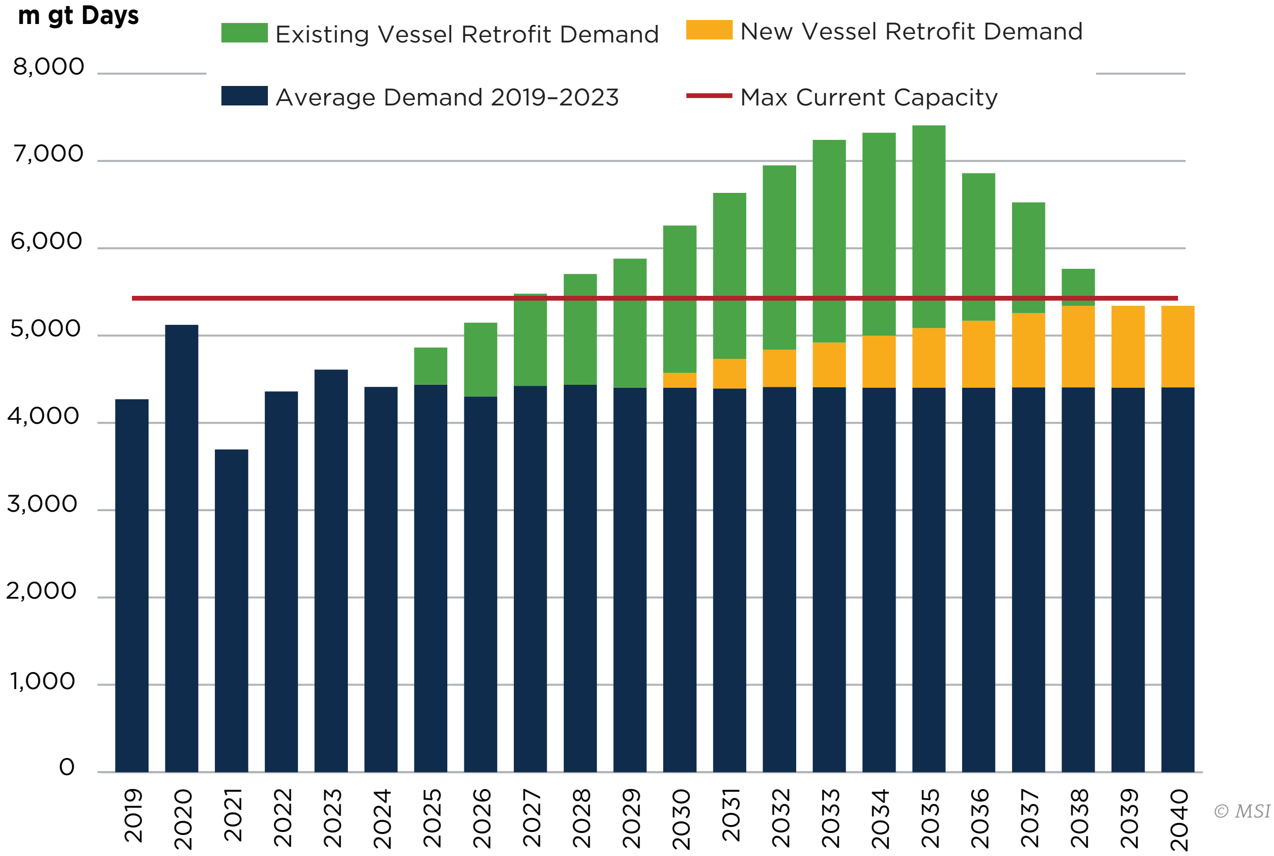


Figure 3.29: Retrofits constrained by limited spare capacity.

SECTION 4

FUEL PATHWAYS AND TECHNOLOGIES

4.1. Introduction

The International Maritime Organization (IMO) modified its greenhouse gas (GHG) strategy in July 2023. Expanding upon this, the pursuit of net-zero or nearly net-zero GHG emission technologies, alternative fuels and renewable energy sources will constitute the next phase of maritime decarbonization. This section will examine the current state and future prospects of these fuels and technologies with respect to these two pillars.

Marine fuels consist of hydrocarbons and are utilized for combustion on board vessels. At present, the preponderance of marine fuels, including heavy fuel oil (HFO), very low sulfur fuel oil (VLSFO)/ultra-low sulfur fuel oil (ULSFO), marine gas oil (MGO) and marine diesel oil (MDO), are derived primarily from petroleum sources.

Hydrocarbons, which can be utilized as alternative fuels, can be manufactured using renewable energy sources, thereby contributing to the long-term decarbonization goals. Prominent alternative fuels that find application in the marine environment comprise ammonia, methanol, liquefied natural gas (LNG), hydrogen and biofuels. This section will examine their primary critical production pathways and analyze the fundamental criteria that must be considered when making their selection.

The current orderbook indicates a wave of change, with 27 percent of the number of vessels (49 percent of gross tonnage (gt)) being able to use alternative fuels. The energy efficiency technologies (EETs) constitute a fundamental element of the decarbonization strategy. By increasing vessels' fuel efficiency and operational efficacy, these technologies can help reduce their emissions. Propulsion-improving devices, air lubrication systems, wind-assisted propulsion, residual heat recovery systems and digital optimization tools are all examples of EETs. The compatibility and practicability of these technologies determine whether they can be implemented on new or pre-existing vessels. Potential solutions for managing emissions compliance for the extant fleet as opposed to the new fleet are frequently dichotomous. Retrofitting the current fleet with EETs results in a gradual reduction in emissions, ensuring compliance within a moderate to brief timeframe.

4.2. Alternative Fuel Pathways

The necessity of a collection of alternative marine fuels to meet the IMO's long-term decarbonization objectives is prevalent knowledge. Amid this intricate environment, each stakeholder must meticulously evaluate a number of variables in order to choose a viable candidate fuel for their vessels. Initial consideration should be given to ensuring regulatory compliance and offering competitive prices that offset any potential penalties imposed on high-carbon fuels. Subsequently, the necessary infrastructure for shipping application of these alternative fuel options should be in place. Regarding onboard combustion, the aforementioned fuel alternatives possess the capability to be integrated with alternative fuels while maintaining optimal propulsion performance. To summarize, the assessment matrix for the potential alternative fuels ought to encompass the following dimensions: infrastructure readiness, technology, safety, sustainability, affordability, scalability and availability. Biofuels, ammonia, methanol, LNG and hydrogen are the five alternative fuels that exhibit the greatest potential for maritime decarbonization, taking into account all relevant factors.

4.2.1. Pathways for Alternative Fuels: Well-to-Wake

The IMO adopted the Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines) at MEPC 80, opting in that the evaluation of GHG intensity for all fuels and energy carriers (e.g., electricity) utilized aboard a vessel be conducted using a full life-cycle approach, specifically through Well-to-Wake (WtW) emission analysis.

The life cycle or value chain of a commercial product generally commences with the extraction and processing of its raw materials (referred to as the "cradle"). It subsequently progresses via the product's manufacturing, distribution and utilization phases, culminating in the recycling or final disposal of the constituent materials (called the "grave").

Two processes comprise the standard marine fuel value chain called WtW: Well-to-Tank (WtT) and Tank-to-Wake (TtW). The value chain is illustrated in Figure 4.1. Similarities exist between these two processes and the cradle-to-grave process. The GHG footprint associated with the TtW process pertains to the carbon dioxide (CO_2) equivalent (eq) emissions generated by the vessel. In contrast, the WtT process commences with the exploration and processing of feedstocks and proceeds with refining and transportation to storage facilities situated in port regions.

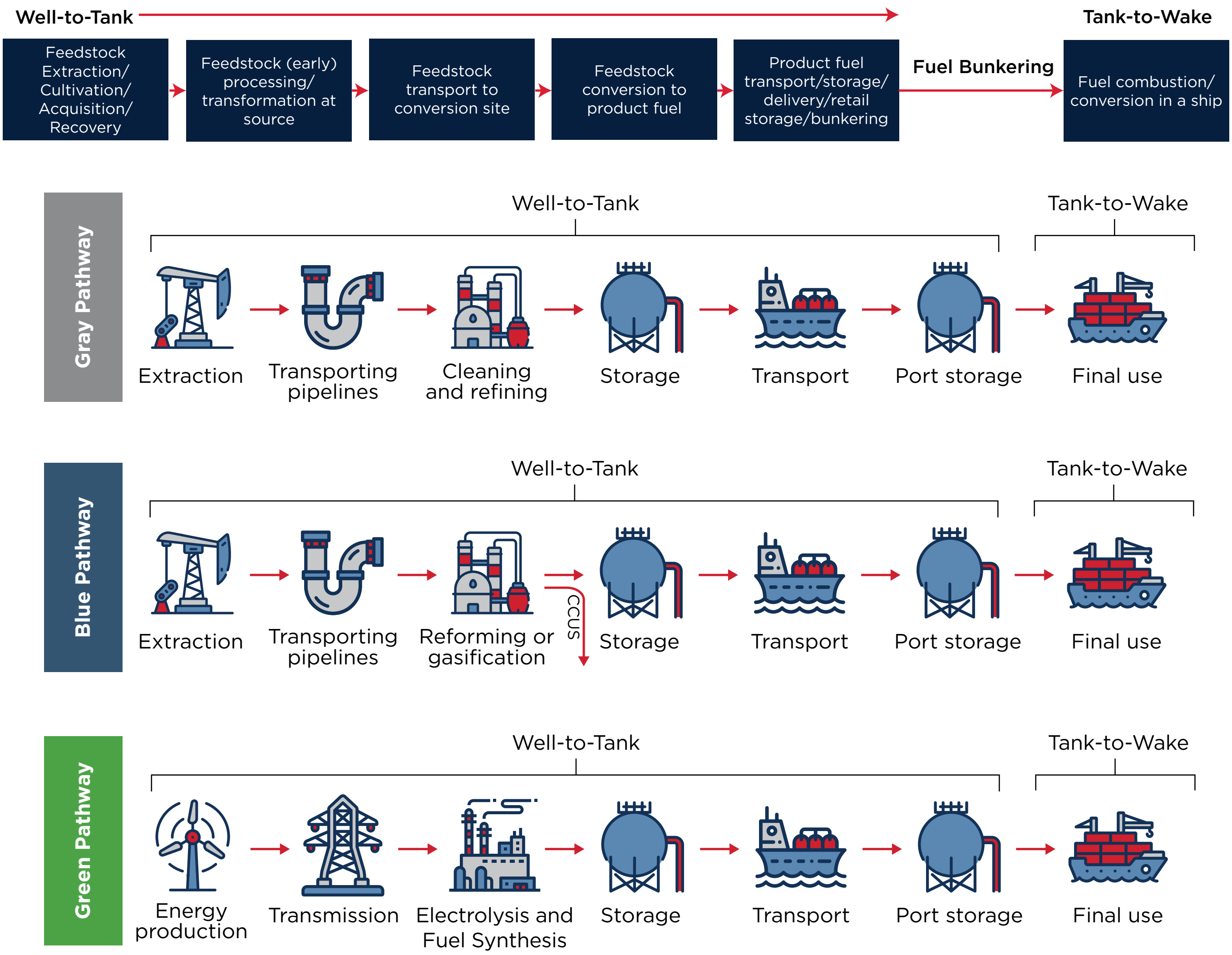


Figure 4.1: Alternative fuel pathways — Well-to-Wake.

Along the marine fuel value chain, three color coded pathways have been typically identified to research safety, emissions and cost-effectiveness of the WtT process of the promising alternative fuels:

- Gray pathway: Fossil fuel based marine fuel value chain without carbon capture and storage (CCS).
- Blue pathway: Fossil fuel based marine fuel value chain with CCS.
- Green pathway: Renewable energy (e.g., wind, solar PV, geothermal, etc.) based marine fuel value chain.

4.2.2. Gray Fuel Pathways

Globally, more blue and green pathway initiatives are emerging in response to the urgent need to reduce GHG emissions from a WtW perspective. However, the gray pathway continues to dominate marine fuel production thus far.

In the conventional process for producing marine fuel, multiple fuel pathways are utilized. ABS performed a comparative analysis of the WtW emissions resulting from various marine fuel pathways. The WtW emissions of methanol, hydrogen, and ammonia are 14 percent, 47 percent and 64 percent higher than those of VLSFO, respectively. As depicted in Figure 4.2, the inability of any of the gray pathways to achieve the IMO's 2030 decarbonization targets underscores the maritime industry's critical need for an energy transition.

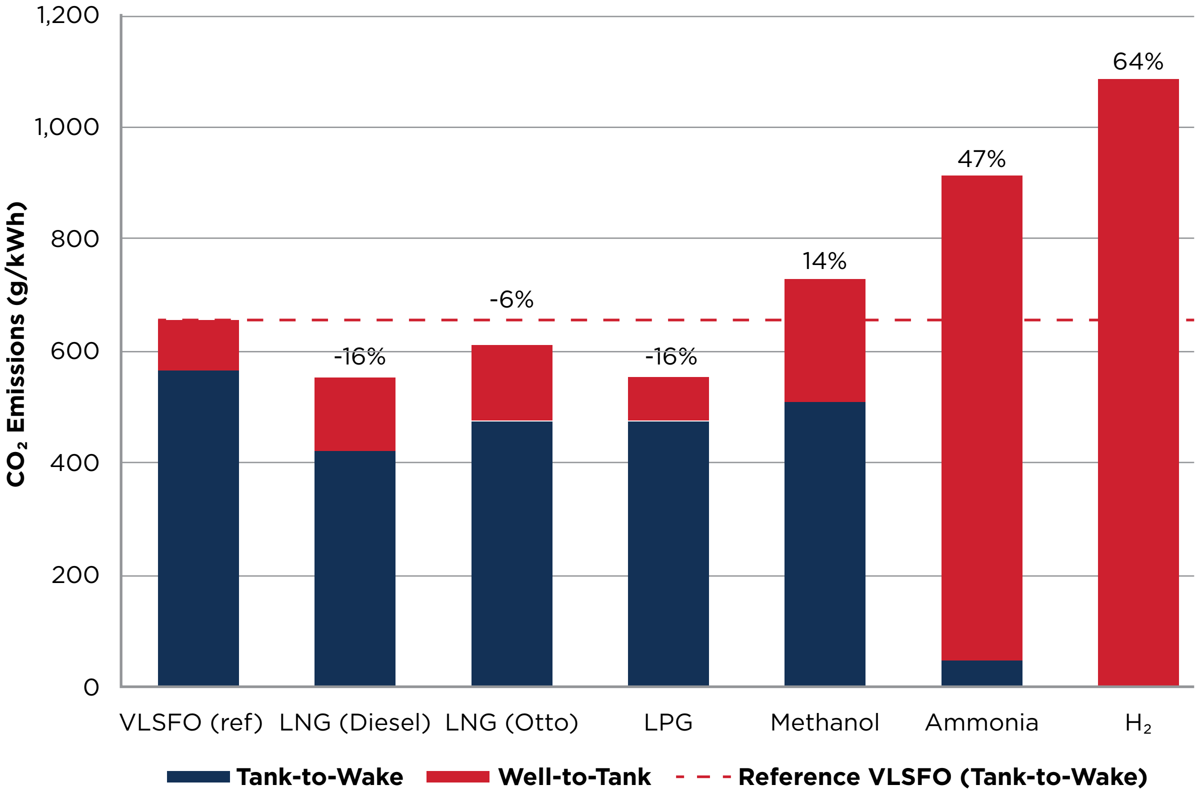


Figure 4.2: CO_2 emission comparison of gray fuel pathways.

The conventional fuel percentage may drop below 80 percent as soon as 2030, while by 2050, it is projected that around half of the global fleet in m gt may still employ conventional diesel fuels. In order to achieve carbon net zero emissions in 2050, drop-in fuels such as e-diesel and biodiesel could contribute to lower the GHG emissions from international shipping, and other effective solutions may involve increasing the penetration rate of onboard carbon capture and storage (OCCS) systems and EETs for conventional fuel driven vessels.

4.2.3. Blue Fuel Pathways

Three decarbonization pathways – blue fuels, e-fuels and biofuels – show promise in achieving the long-term WtW GHG emissions targets. Blue fuels are classified as gray fuels whose upstream emissions have been subjected to carbon capture, as per their definition (Figure 4.3). In theory, the implementation of land-based carbon capture systems has the potential to convert each conventional gray pathway into a blue one. In light of the financial implications linked to carbon capture units, three blue decarbonization pathways – blue hydrogen, blue methanol and blue ammonia – have been recognized among the potential effective alternatives.

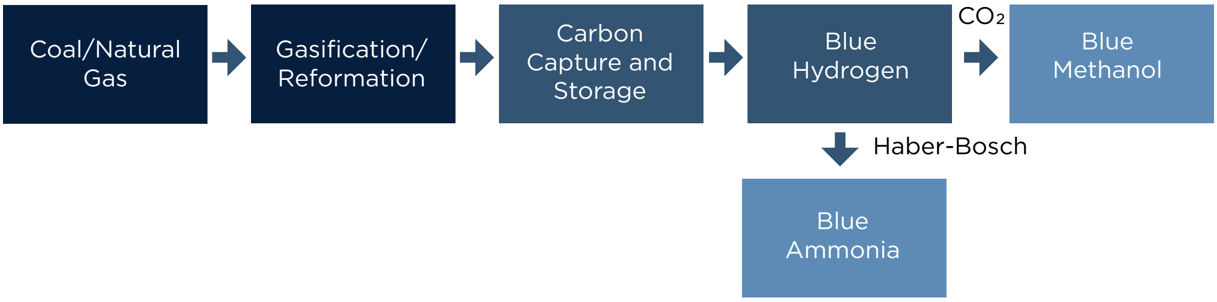


Figure 4.3: Blue fuel pathways.

By utilizing the VLSFO WtW GHG emission intensity of 96kg CO_2e/GJ as the reference line, it is observed that blue methanol has the capacity to reduce GHG emissions by 27 percent. In contrast, blue ammonia and blue hydrogen exhibit potential savings of 57 percent and 74 percent, respectively (Figure 4.4).

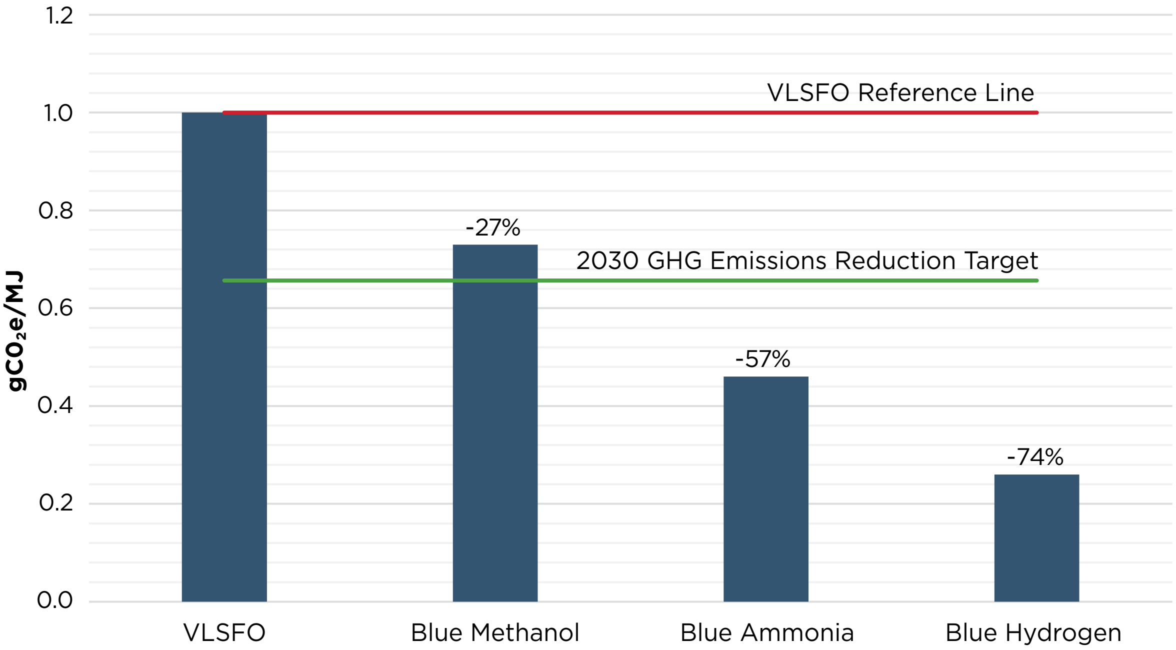


Figure 4.4: Normalized WtW GHG emission intensity for blue fuel pathways.

Blue methanol, in comparison to the other two carbon-free blue fuels, poses a greater obstacle to achieving the IMO's short-term decarbonization objective. Furthermore, the utilization of WtW carbon offsetting for blue methanol introduces certain uncertainties, which diminish the appeal of this pathway in comparison to blue hydrogen and blue ammonia. The pathway information is depicted in Figure 4.5.

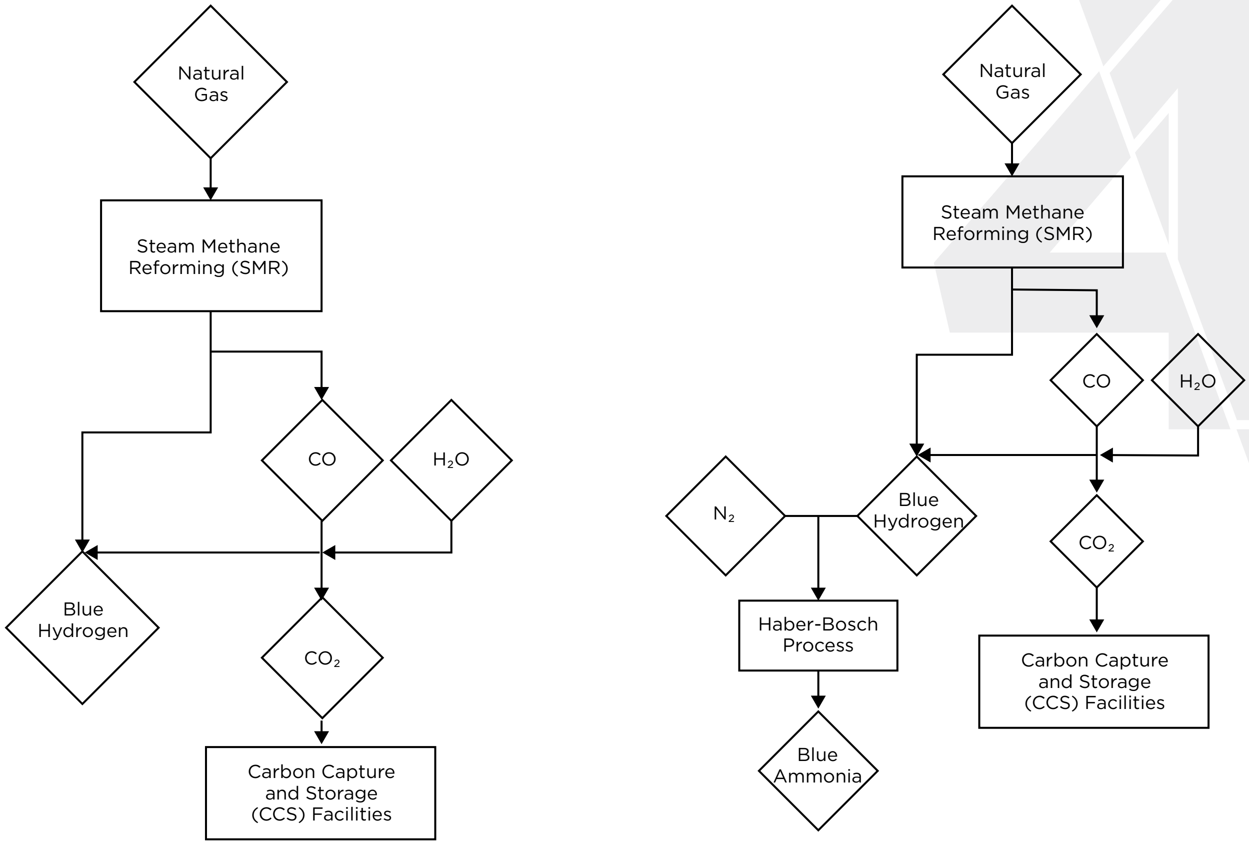


Figure 4.5: Blue hydrogen pathway (left), blue ammonia pathway (right).

Blue hydrogen is derived from natural gas through the process of steam methane reforming (SMR). SMR produces hydrogen by reacting natural gas with steam, creating hydrogen and carbon monoxide. Adding more water converts the carbon monoxide into CO_2 and generates additional hydrogen. Blue ammonia follows SMR at high temperatures and pressure, and the byproduct CO_2 is captured and stored. By introducing nitrogen as a reactant, blue ammonia can be produced via the Haber-Bosch approach from the blue hydrogen.

4.2.4. Green Fuel Pathways

4.2.4.1 E-Fuel Pathways

Marine e-fuels (also known as electrofuels), which are classified as renewable fuels of non-biological origin (RFNBOs), are produced through fuel pathways that rely primarily on electrolysis powered by renewable energy. Energy carriers for marine applications can be produced from renewable electric energy using various electrolysis processes. Examples of such carriers include e-diesel, e-methanol, e-methane and e-methanol, and are regarded as the most promising among these substances for use in shipping applications. The pathways of e-fuel are depicted in Figure 4.6.

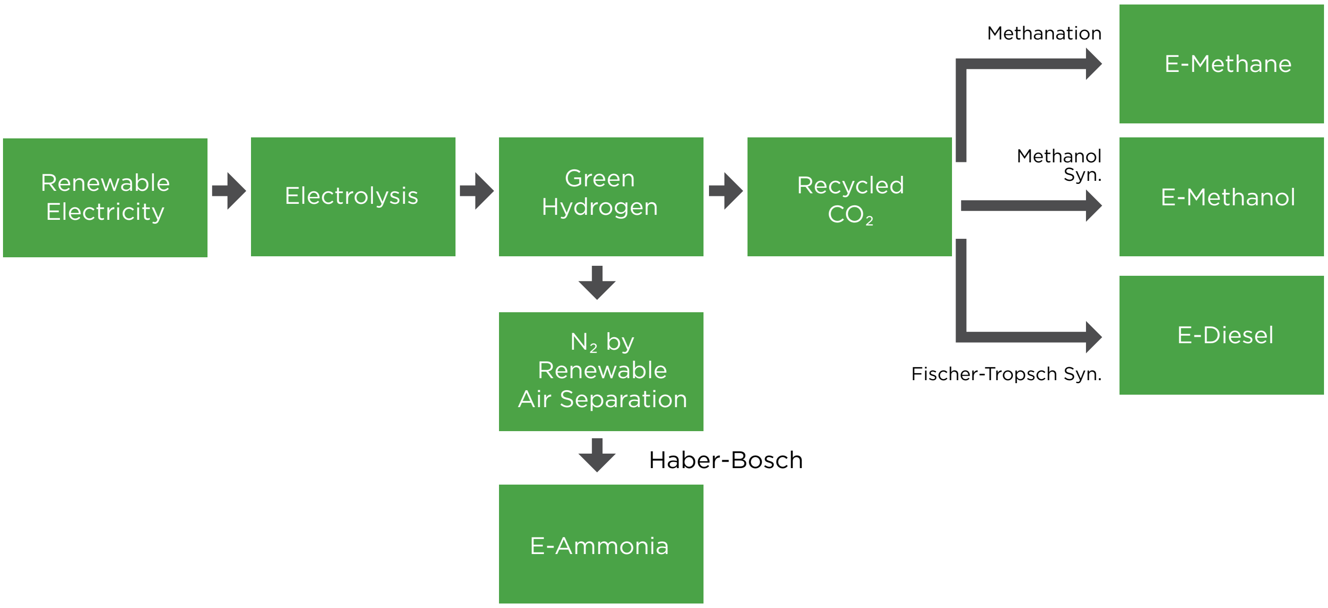


Figure 4.6: E-Fuel pathways.

Besides the major e-fuel pathways identified in Figure 4.6, ABS specifies multiple e-fuel pathways with different production processes. Figure 4.7 illustrates the e-hydrogen and e-ammonia pathways utilizing renewable-based electrolysis to split water into hydrogen (e-hydrogen) and oxygen and adopting the Haber-Bosch method to produce e-ammonia.

For non-carbon-free fuel production pathways, the viable pathways are defined as reaching carbon negative during the fuel production stage and offsetting the carbon emissions by the TtW process. To get more carbon credits at WtT process, direct air capture (DAC) and oceanwater capture may play key roles. Considering technology readiness levels, DAC is recommended for our identified non-carbon-free fuel production pathways.

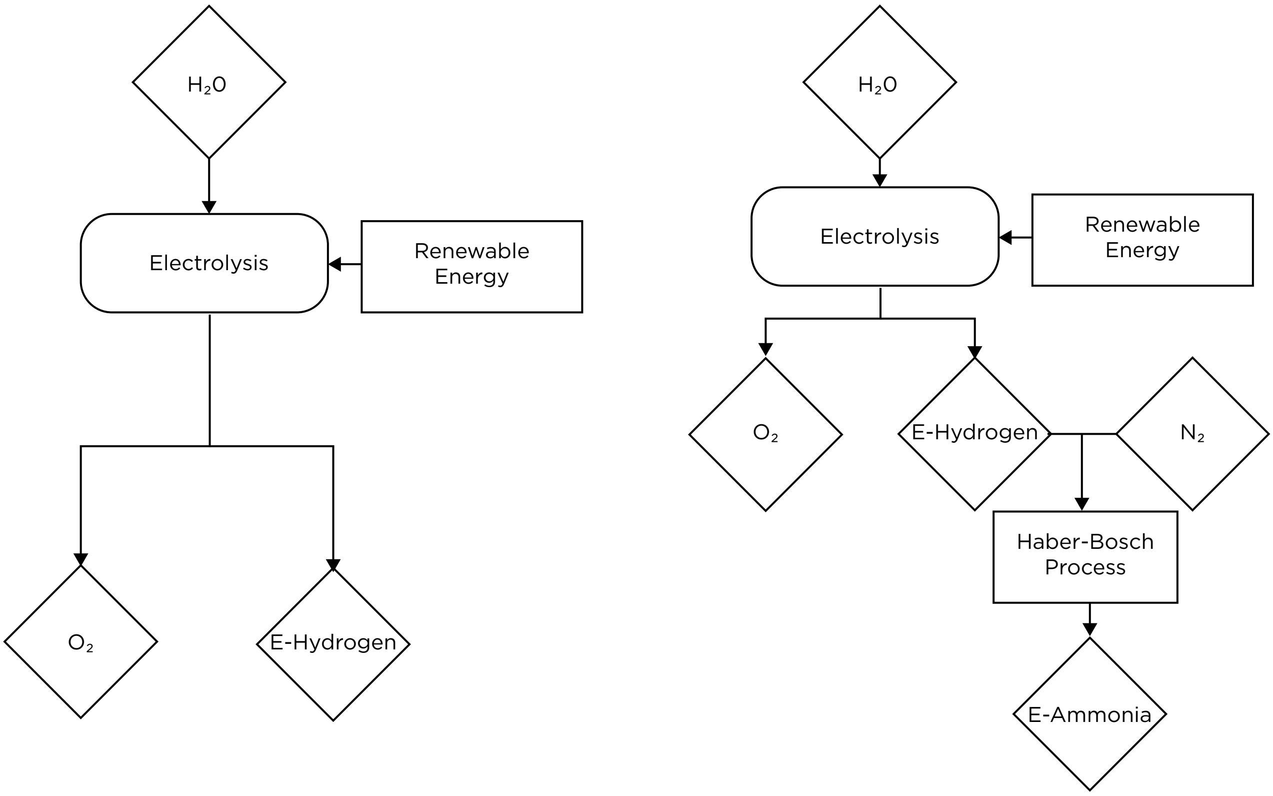


Figure 4.7: E-hydrogen and E-ammonia production pathways.

As shown in Figure 4.8, four pathways are identified for e-methanol production and each with its unique process and scientific principles.

The electrolysis and syngas conversion pathway starts with the electrolysis of water, utilizing renewable electricity to split water into hydrogen and oxygen. This hydrogen, alongside captured CO_2, is then converted into syngas through the reverse water-gas shift reaction. The syngas, a mixture rich in hydrogen and carbon monoxide, undergoes methanol synthesis. Despite its potential, the scalability of this method has been limited to small-scale implementations.

The second pathway simplifies the process through direct synthesis, combining hydrogen from water electrolysis with CO_2 to produce methanol in a single step. This method not only boosts a higher yield and purity of methanol but also exhibits greater thermodynamic efficiency due to lower operating temperatures. Although more hydrogen-intensive, it represents a proven technology with small industrial applications.

The electrochemical conversion pathway involves the direct electrochemical conversion of CO_2 and water to methanol. Operated in fixed-bed catalytic reactors under specific temperature and pressure conditions, this method currently faces challenges in energy efficiency and yield, remaining within the confines of laboratory-scale experiments.

Lastly, the co-electrolysis and syngas conversion pathway leverages high-temperature co-electrolysis of water and CO_2 to produce syngas, subsequently converted to methanol. Although it holds the promise of higher conversion efficiency, its development is still nascent, with most experiments conducted at the kilowatt scale.

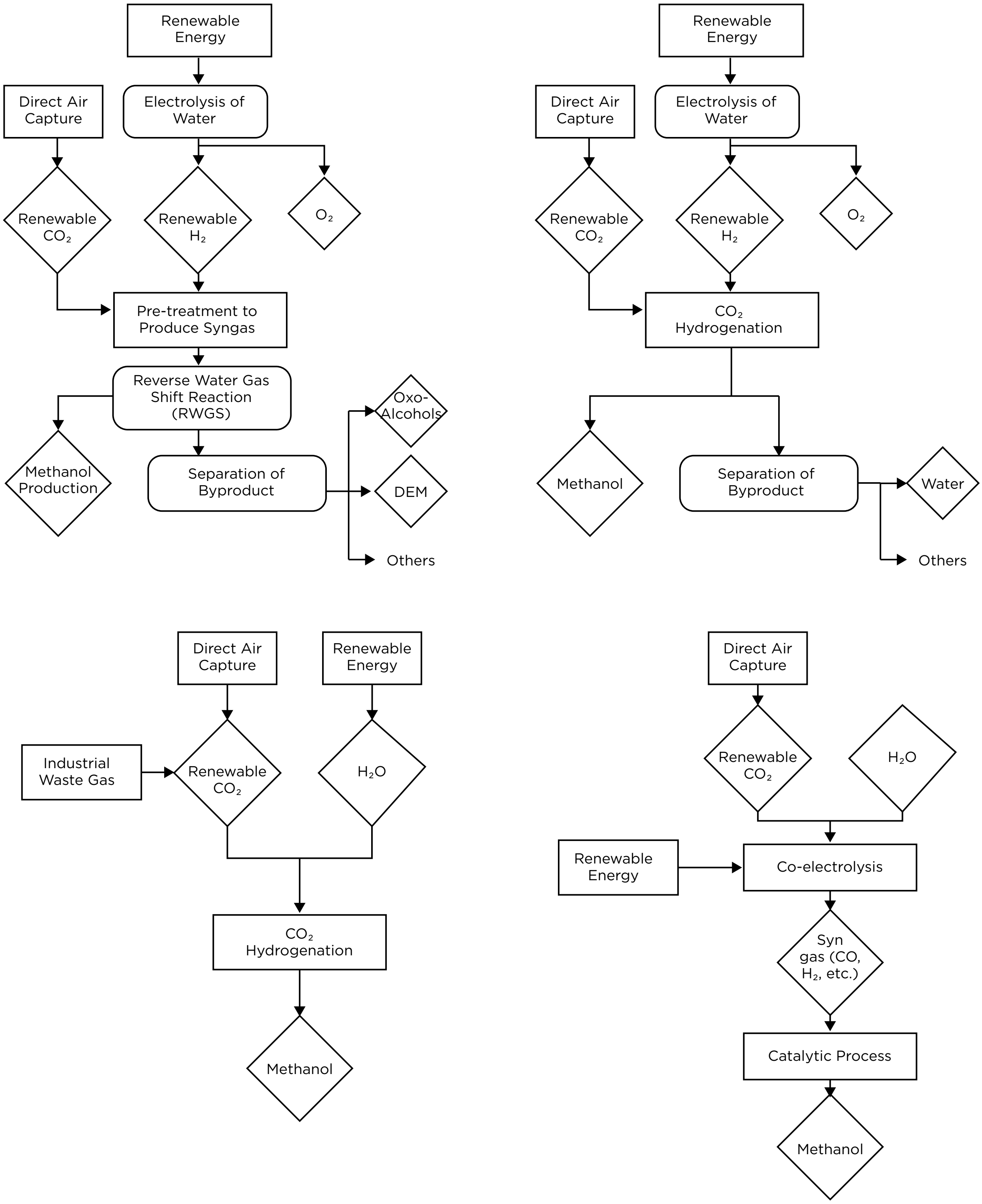


Figure 4.8: E-methanol production pathways.

(Top left: electrolysis and syngas conversion; top right: direct synthesis from CO_2 *and* H_2*; bottom left: electrochemical conversion; bottom right: co-electrolysis and syngas conversion)*

As shown in Figure 4.9, two pathways have been identified for the e-methane production process. The major pathway is based on direct methanation via Sabatier reaction, where hydrogen and CO_2 combine in the presence of a catalyst to form methane and water. This exothermic process, capable of operating at a MW scale, has yet to see widespread industrial application. A notable aspect of this method is the potential for utilizing the released waste heat in DAC processes, enhancing overall efficiency.

The alternative e-methane production pathway is based on the approach of syngas-based methane synthesis. It is the co-electrolysis of water and CO_2 in high-temperature solid oxide electrolysis cells (SOECs) to produce syngas, which is then synthesized into methane. This offers a glimpse into more efficient methane yields and energy utilization, although it requires further investigation into reaction mechanisms and materials under varying conditions.

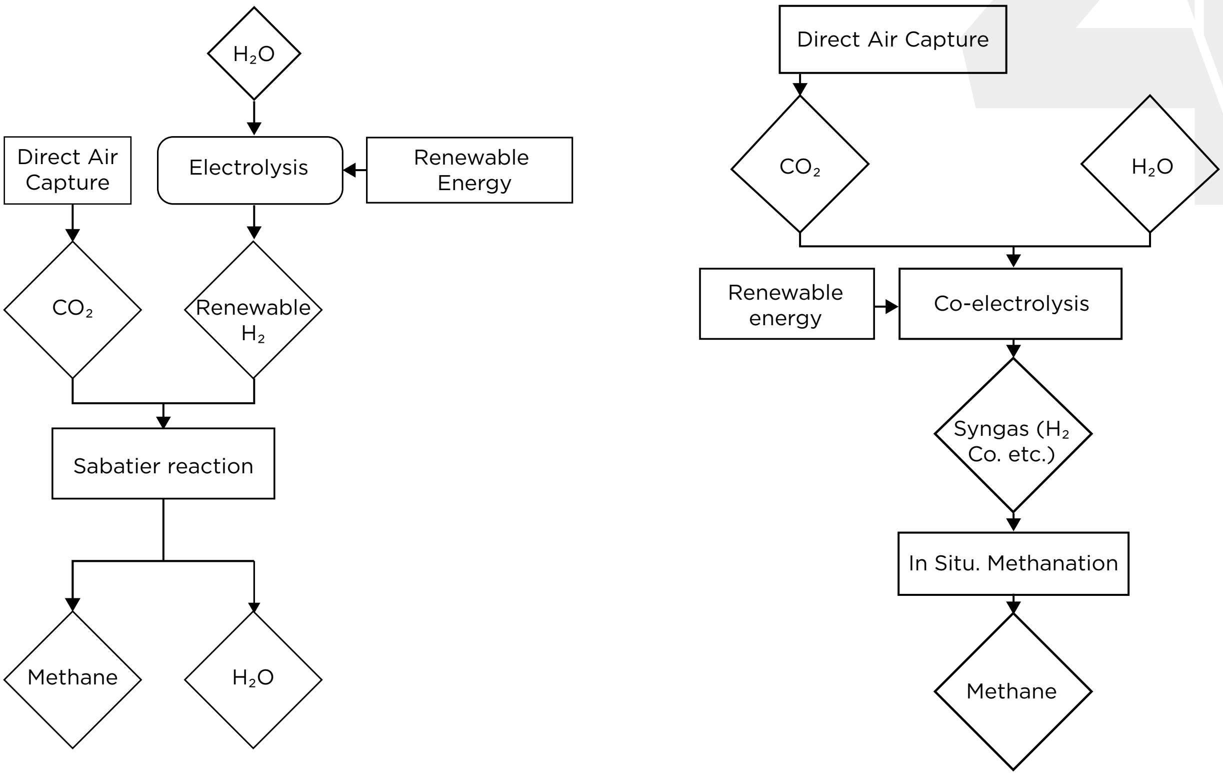
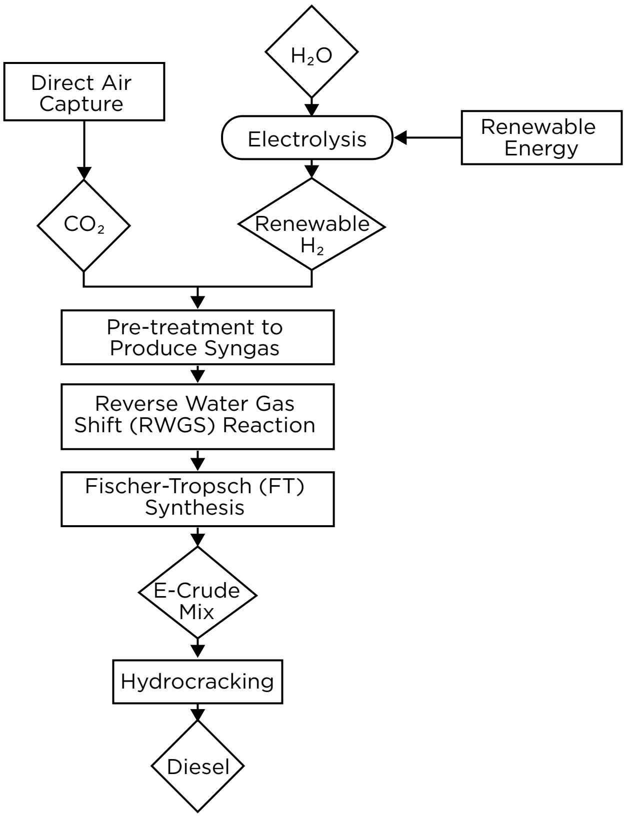


Figure 4.9: E-methane production pathways.

(Left: direct methanation via sabatier reaction pathway; right: methane synthesis from syngas pathway)

Illustrated in Figure 4.10, the e-diesel pathway is also considered a promising avenue toward decarbonizing the marine sector, offering a sustainable and cleaner alternative to traditional marine fuels. The technological challenge lies in scaling up these processes from small-scale demonstrations to industrial applications, ensuring that e-diesel can be a viable and widely available fuel for marine transportation.

Figure 4.10: E-diesel production pathway.



Multiple sources of WtW emission factors have been collected for each one of the e-fuel pathways. At present, there are significant variances on the range of emission factors, and it is noted that e-ammonia, e-methanol, and e-diesel have larger variances than other options. Based on ABS' WtW emission factor database, all five identified e-fuel pathways (e-methane, e-diesel, e-methanol, e-ammonia and e-hydrogen) can meet the IMO's 2030 decarbonization goal. This is illustrated in Figure 4.11.

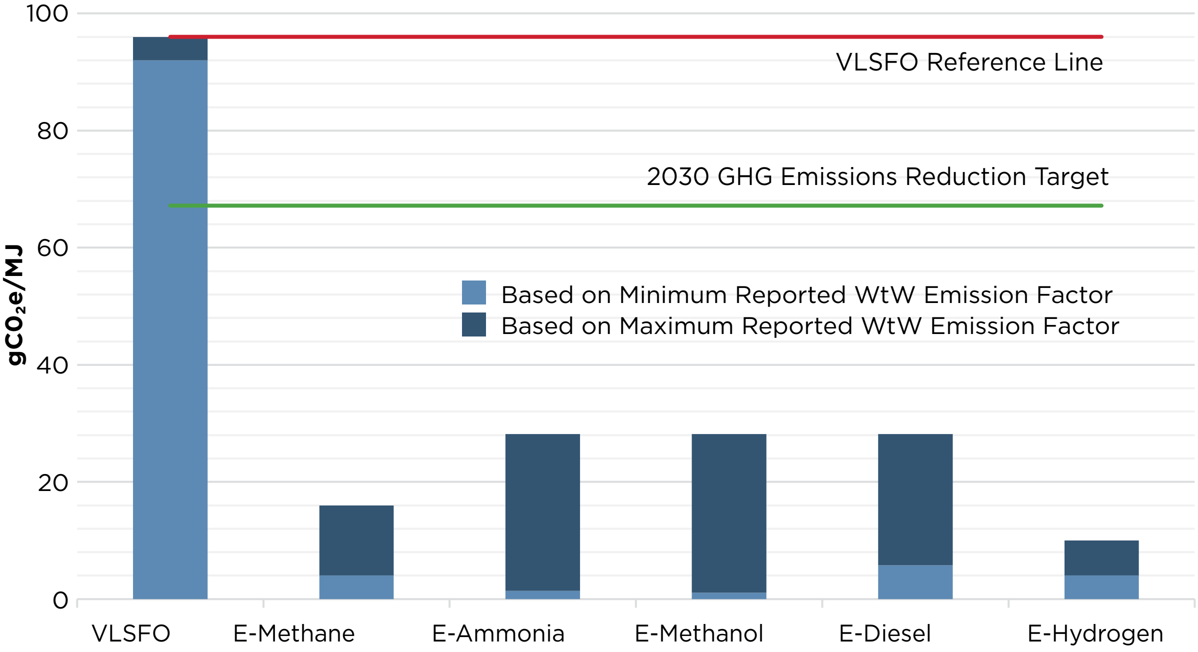


Figure 4.11: WtW GHG emission intensity for e-fuel pathways.

These e-fuel WtW GHG emission intensity values are to be viewed as being dynamic rather than fixed since more green technologies and well-established e-fuel networks may keep benefiting GHG emission savings along the marine fuel value chain.

4.2.4.2. Biofuel Pathways

Bio-pathways that are sustainable for marine application have been identified, such as biomethanol, bioethanol, hydrotreated vegetable oil (HVO), liquefied biomethane and biodiesel (Figure 4.12). Considering the fact that biofuel pathways are recognized as viable alternatives for decarbonizing the maritime sector with minimal retrofit costs and substantial potential for WtW GHG emission reduction, stakeholders in the shipping industry may perceive them as advantageous.

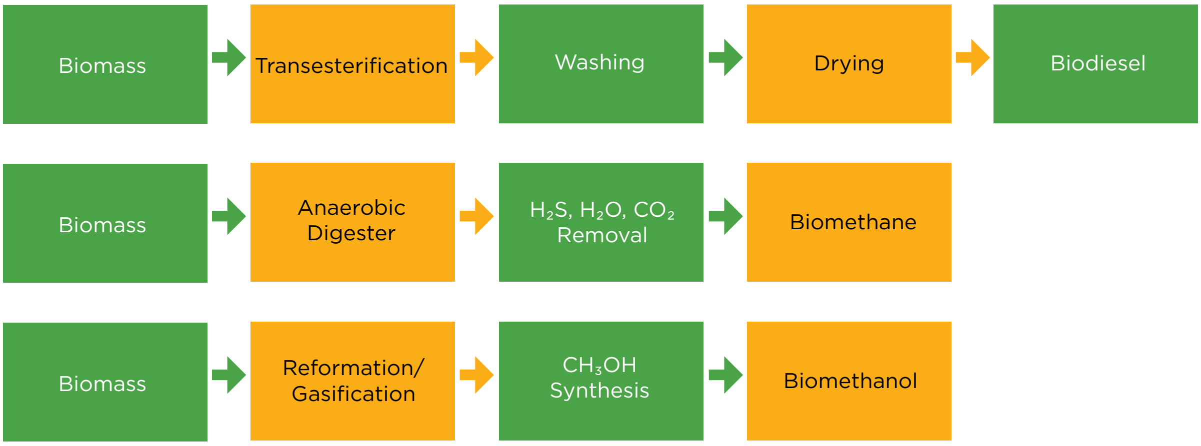


Figure 4.12: Biomass-based biofuel pathways.

Besides the pathways identified in Figure 4.12, the algae-based biomethanol production process is also considered sustainable. The three primary steps of the entire process are gasification, oxidation and pyrolysis. The fuel is dried algae that is fed into the gasifier. The water gas shift reactor is used to modify the syngas ratio to fulfill the requirements for methanol synthesis after the syngas exit the gasifier. After that, the syngas is heated and compressed before being injected into the methanol synthesis process. Figure 4.13 illustrates this pathway.

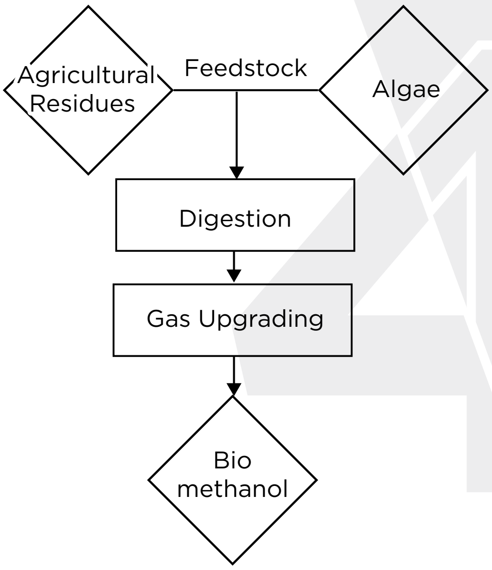
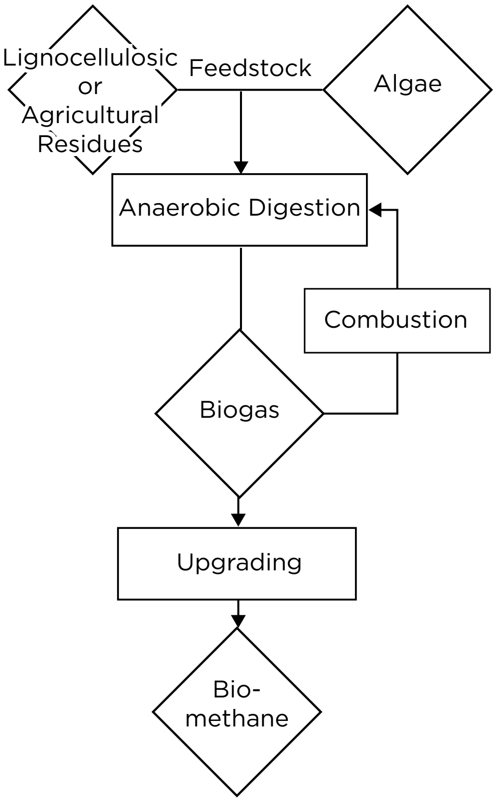


Figure 4.13: Algae biomass gasification based biomethanol production pathway.

Biomethane can be generated using two main methods: anaerobic digestion and gasification, as shown in Figure 4.14. Anaerobic digestion employs microorganisms to decompose organic substances, such as energy crops, agricultural leftovers and algae, in an environment lacking oxygen. This method produces biogas, consisting mainly of methane and CO_2. By employing a series of subsequent procedures aimed at eliminating CO_2 and other constituents, the end product obtained is biomethane.

Gasification provides an alternate method for producing biomethane by using both dry biomass and algae. Gasification, in contrast to anaerobic digestion, utilizes elevated temperatures to transform these raw materials into syngas, which is a blend of hydrogen, carbon monoxide and CO_2. The syngas is subjected to a methanation process, in which the various components chemically combine to produce biomethane. Gasification, although still being developed, has a greater conversion efficiency compared to anaerobic digestion. This makes it a promising method for future sustainable fuel production.



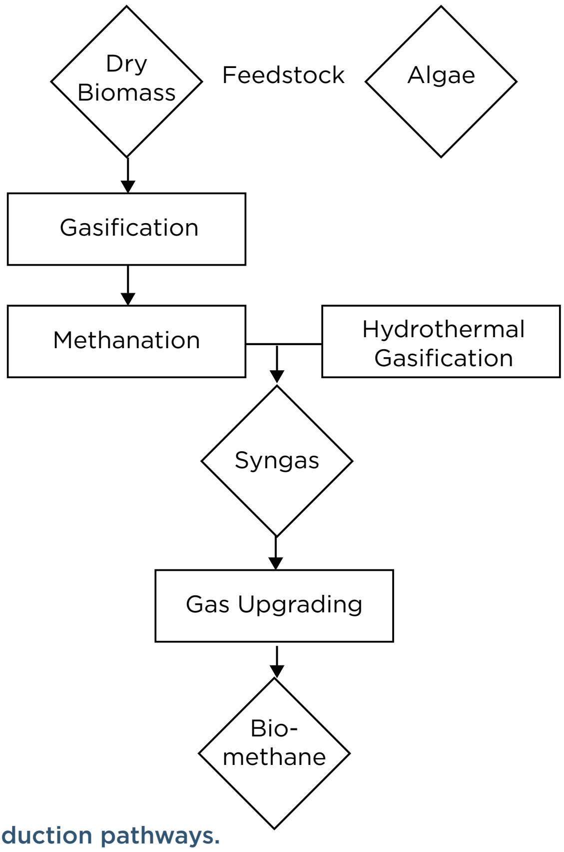


Figure 4.14: Biomethane production pathways.
(Left: anaerobic digestion-based pathway; right: gasification-based pathway)

Biodiesel, a sustainable substitute for petroleum diesel, provides a more environmentally friendly fuel choice that has the capacity to greatly decrease greenhouse gas emissions.

The manufacture of this fuel might vary depending on the chosen feedstock and production process, which directly affects its environmental advantages. Waste residues and oil crops are the main sources for the manufacturing of biodiesel. Waste leftovers, such as spent cooking oil and animal fats, offer a sustainable alternative by reusing materials that would otherwise be thrown away. Oil crops such as soybean, canola and sunflower provide a renewable supply of vegetable oil that may be converted into biodiesel.

Biodiesel can be produced using a standard production process and can be directly used as a substitute for regularly used distillates such as marine gasoil. Figure 4.15 illustrates this pathway.

The majority of a ship's internal combustion engines are powered by conventional fuel oils, with LNG and methanol-driven engines being the next most common options. Hence, biodiesel, biomethane and biomethanol could potentially offer greater prospects for sustainable maritime decarbonization in the long run.

Like e-fuels, the GHG intensity values of biofuel pathways will decrease over time, namely toward the year 2050. At present, there are significant disparities in the availability and production methods of biomethane and biodiesel, which can be attributed to regional supply conditions and diverse biofuel manufacturing technology, resulting in large variances in WtW emission factors for bio-methane and bio-diesel, as illustrated in Figure 4.16. The GHG emission intensities of all biofuel paths reported are significantly lower than the 2030 target for reducing GHG emissions, as depicted in Figure 4.16.

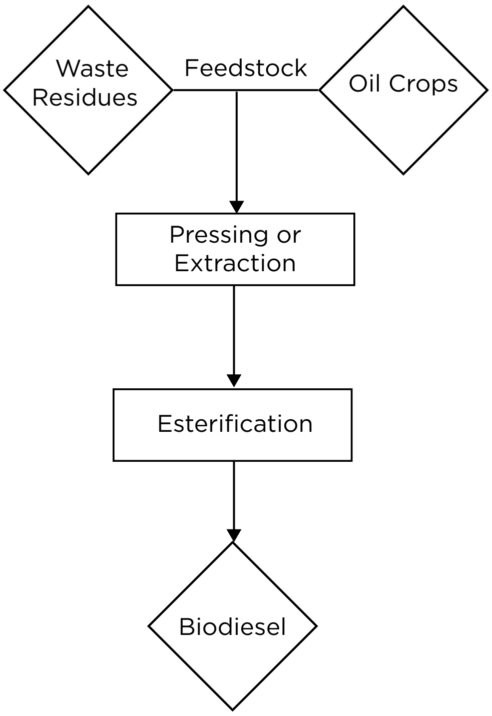


Figure 4.15: Biodiesel production pathway.

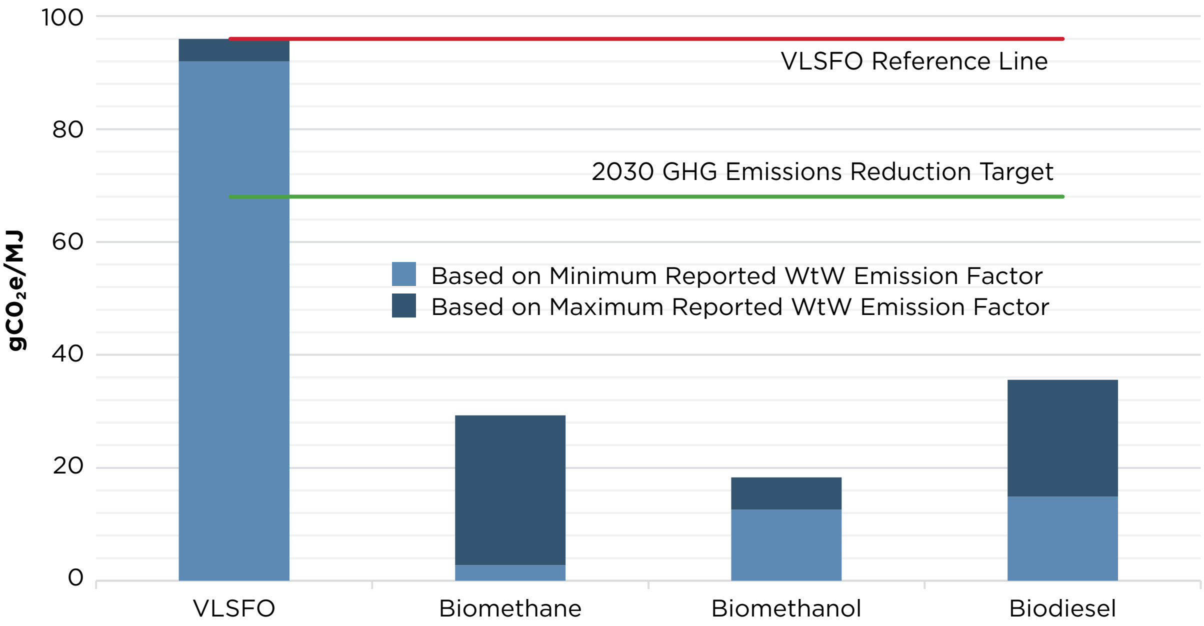


Figure 4.16: WtW GHG emission intensity for biofuel pathways.

4.3. Fuel Pathways Performance

Net zero means that carbon emissions are offset, or virtually canceled out, by the equivalent quantity being removed from the atmosphere. Due to the possibility that marine fuel production and combustion require the use of hydrocarbon fuels, there will still be fossil fuel residue in use in 2040 somewhere in the production, distribution and storage of these fuels.

So far, the WtW emissions factors are in the developing stage, while it is well accepted that dynamic emissions factors other than fixed values will be the solution for WtW emission factor database since their values will be different as technology improves in different regions. ABS has developed the emissions factor database to consider the evolving WtW GHG emissions intensities of marine alternative fuels, which is shown in Figure 4.17.

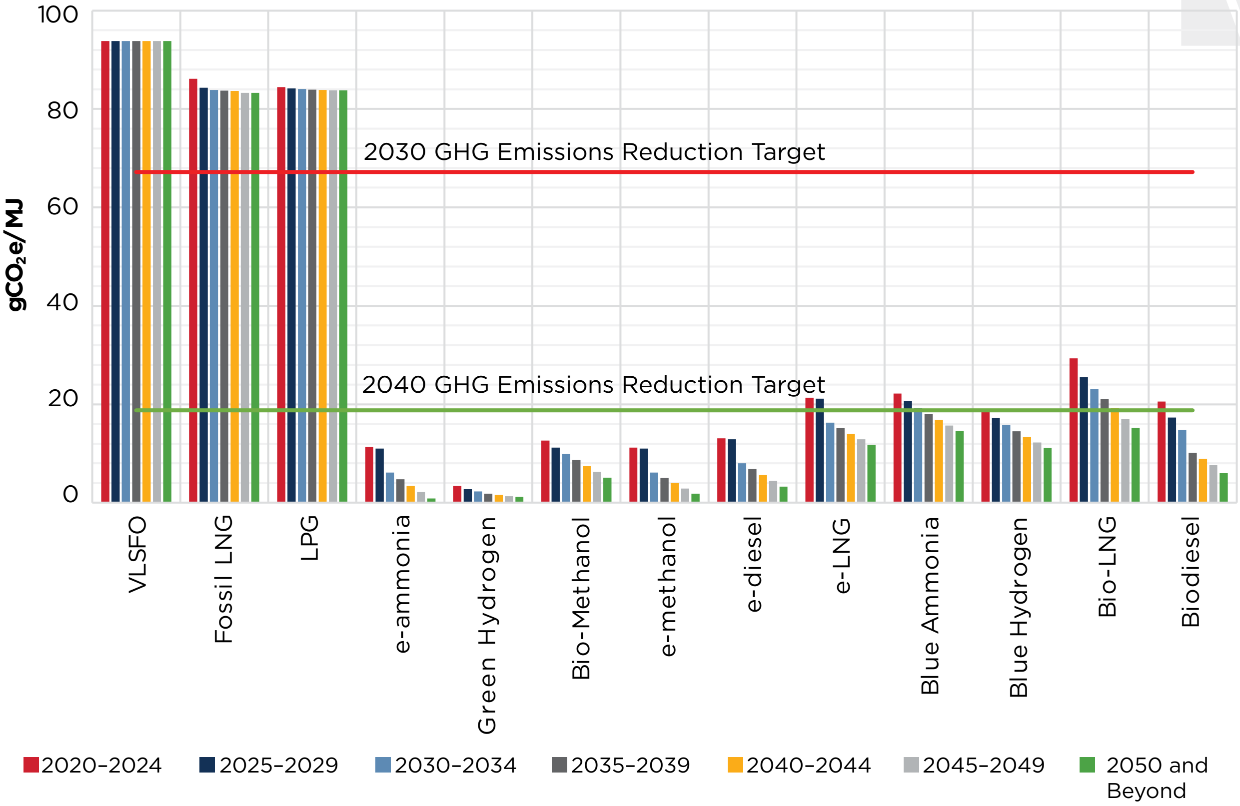
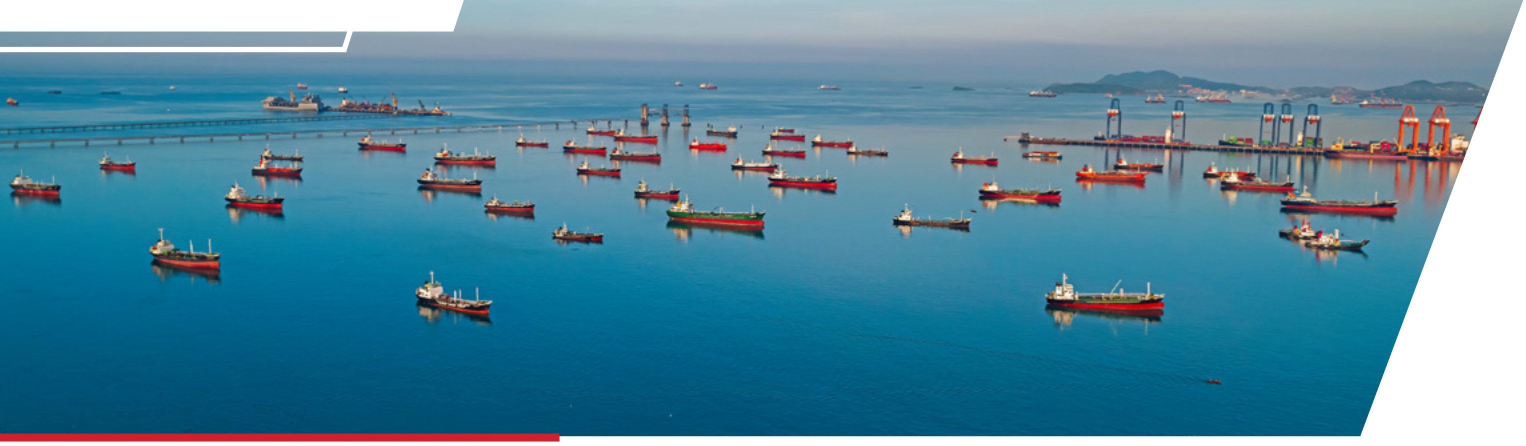


Figure 4.17: WtW emission factor for marine fuel pathways.



In terms of WtW emissions performance, the carbon neutral pathways for 2050 should aim to decrease GHG to reach net zero in comparison to the emission levels in 2008. Hence, the e-fuel paths (e-methane, e-diesel, e-methanol, e-ammonia and e-hydrogen) as well as the biofuel pathways (biodiesel, biomethanol and biomethane) have the potential to be sustainable carbon-neutral options by 2050.

Furthermore, it is important to take into account the expense and preparedness of the paths. Figure 4.18 depicts the lower calorific values and fuel prices in 2024 and 2030 for the pathways.

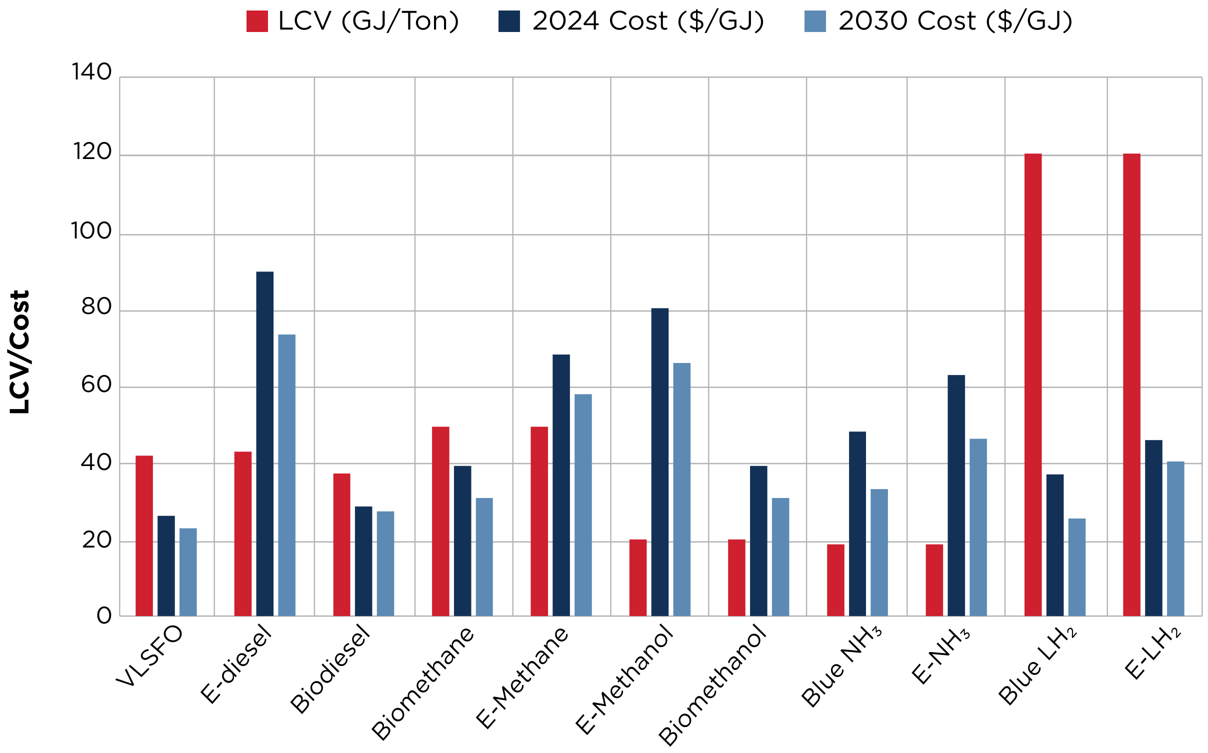


Figure 4.18: LCV and fuel cost for marine fuel pathways.

ABS has created a new index called GHG Abatement Cost (GAC) to demonstrate the suggested fuel routes for achieving the long-term IMO decarbonization goal. This index statistically assesses the trade-offs between cost and GHG emissions savings, specifically focusing on the WtW process. The GAC values for the WtW IMO sustainable/carbon-neutral fuel alternatives are determined by utilizing Equation 4.1.

$$GAC\left(\frac{\$}{tonne\ CO_{2e}\ reduced}\right) = \frac{Cost\ of\ Sustainable\ Fuel\left(\frac{\$}{GJ}\right) - Cost\ of\ VLSFO\left(\frac{\$}{GJ}\right)}{\frac{tonne\ CO_{2e}\ VLSFO}{GJ} - \frac{tonne\ CO_{2e}\ Sustainable\ Fuel}{GJ}}$$

Equation 4.1: GAC calculation.

By referring to the latest fuel price data, the GAC values for the carbon-neutral pathways are calculated and illustrated in Figure 4.19.

In the WtW emissions cost-effectiveness analysis, biodiesel, blue LH_2, biomethanol, and biomethane rank highest among alternative pathways, as determined by the calculated GAC outputs. The significant potential of e-fuels to reduce greenhouse gas emissions is hindered by the considerable expenses associated with the e-LH_2, e-NH_3, and e-Methanol pathways pathways, which could restrict their widespread adoption.

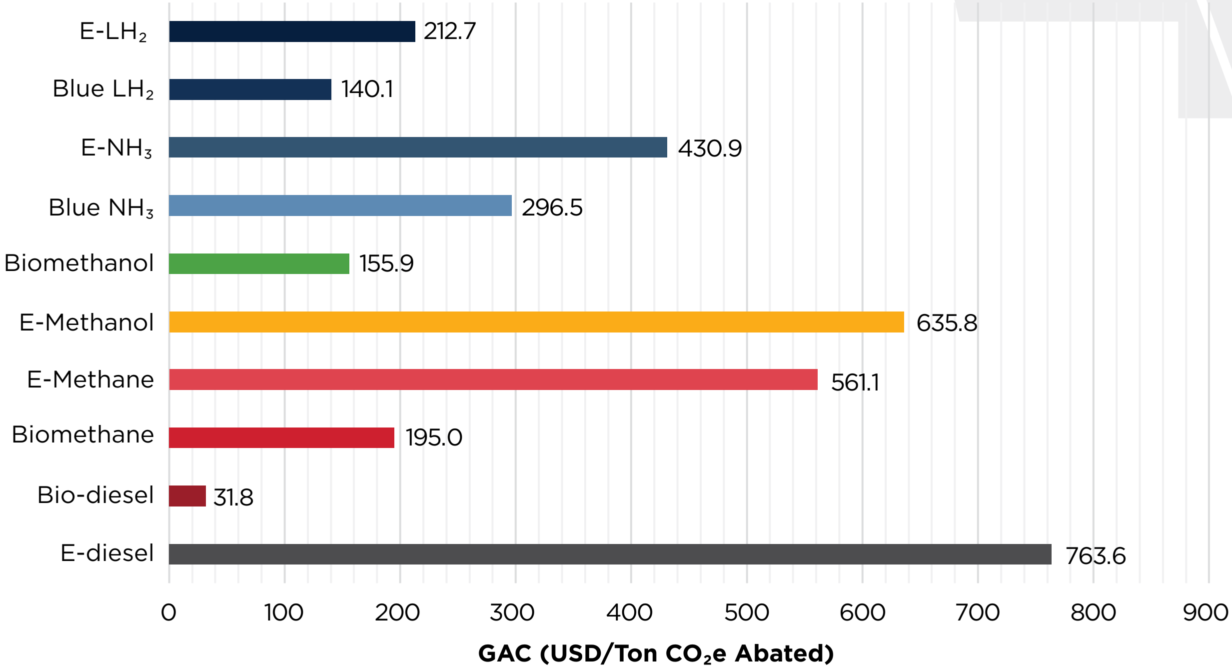


Figure 4.19: GAC performance for potential carbon neutral pathways — GAC (2024).

In addition, ABS has formulated three hypotheses in an effort to identify the most economical means of achieving the 2050 objectives. E-fuel high uptake scenario is defined as the e-fuel pathways that have the highest infrastructure readiness and fuel availability levels, resulting in great cost savings. Biofuel high uptake scenario and blue-fuel high uptake scenario are defined in the same way. Therefore, the scenarios and cost estimation assumptions for 2050 are listed below:

Scenario 1 (E-fuel High Uptake)

$Price_{e\text{-}fuel} = Multiplier_{1\text{-}e} \cdot Base\ Fuel\ Price$

$Price_{bio\text{-}fuel} = Multiplier_{1\text{-}bio} \cdot Base\ Fuel\ Price$

$Price_{blue\text{-}fuel} = Multiplier_{1\text{-}blue} \cdot Base\ Fuel\ Price$

$Price_{vlsfo} = Multiplier_{1\text{-}vlsfo} \cdot Base\ Fuel\ Price$

Scenario 2 (Biofuel High Uptake)

$Price_{e\text{-}fuel} = Multiplier_{2\text{-}e} \cdot Base\ Fuel\ Price$

$Price_{biofuel} = Multiplier_{2\text{-}bio} \cdot Base\ Fuel\ Price$

$Price_{blue\text{-}fuel} = Multiplier_{2\text{-}blue} \cdot Base\ Fuel\ Price$

$Price_{vlsfo} = Multiplier_{2\text{-}vlsfo} \cdot Base\ Fuel\ Price$

Scenario 3 (Blue-fuel High Uptake)

$Price_{e\text{-}fuel} = Multiplier_{3\text{-}e} \cdot Base\ Fuel\ Price$

$Price_{biofuel} = Multiplier_{3\text{-}bio} \cdot Base\ Fuel\ Price$

$Price_{blue\text{-}fuel} = Multiplier_{3\text{-}blue} \cdot Base\ Fuel\ Price$

$Price_{vlsfo} = Multiplier_{3\text{-}vlsfo} \cdot Base\ Fuel\ Price$

The details can be accessed in the Appendix, and the estimated fuel prices in 2050 under three scenarios are illustrated in Figure 4.20.

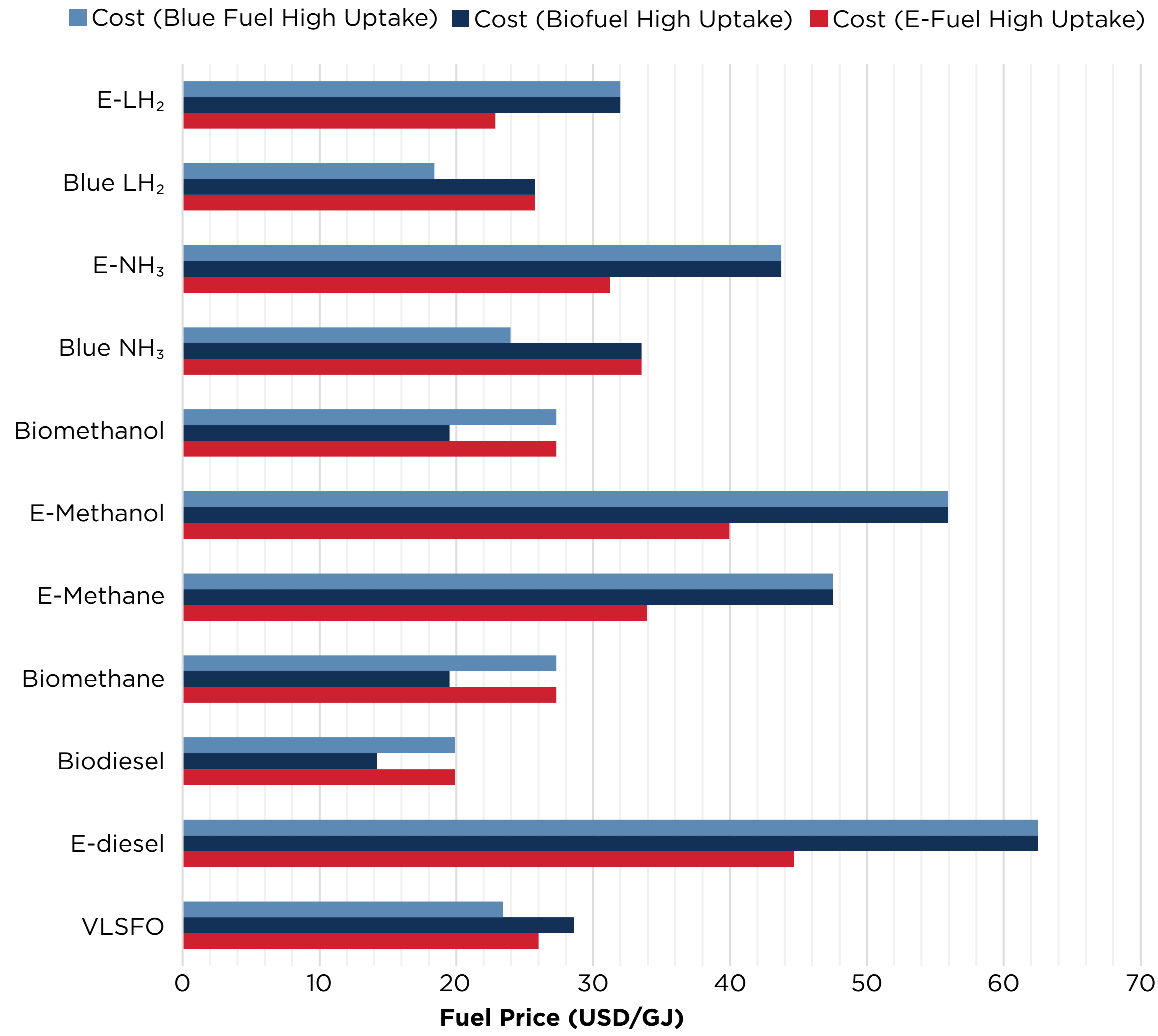


Figure 4.20: Estimated fuel prices in 2050 per scenario.

**Note: Annual Percentage Rate (APR) is excluded.*

Based on the three developed scenarios, the GAC for 2050 can be calculated accordingly and the results can be accessed in A-3 of Appendix. Overall, 10 fuel pathways have been identified for analysis to showcase the decarbonization journey of the IMO's GHG strategy. As shown in Figure 4.21, the costs of the three pathways have been projected to be lower than that of the benchmark fuel, resulting in negative GAC values. Except for e-methanol and e-diesel, all the identified pathways are projected to achieve good cost-effective performance (GAC < $100/Ton CO_2e Abated) under the e-fuel high uptake scenario.

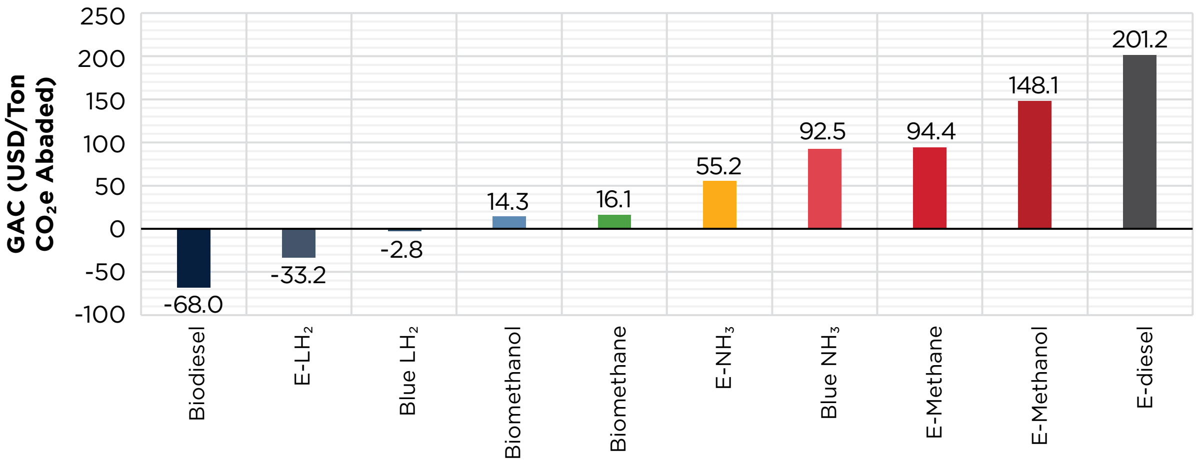


Figure 4.21: Pathway rankings in 2050 under e-fuels high uptake scenario.

Without accounting for the annual interest rate, four pathways are anticipated to reduce their fuel cost below VLSFO under the biofuel high adoption scenario, resulting in negative GAC values. Biodiesel, biomethane, biomethanol, blue hydrogen, e-hydrogen and blue ammonia are identified as the most cost-effective pathways in this scenario. For further details, see Figure 4.22.

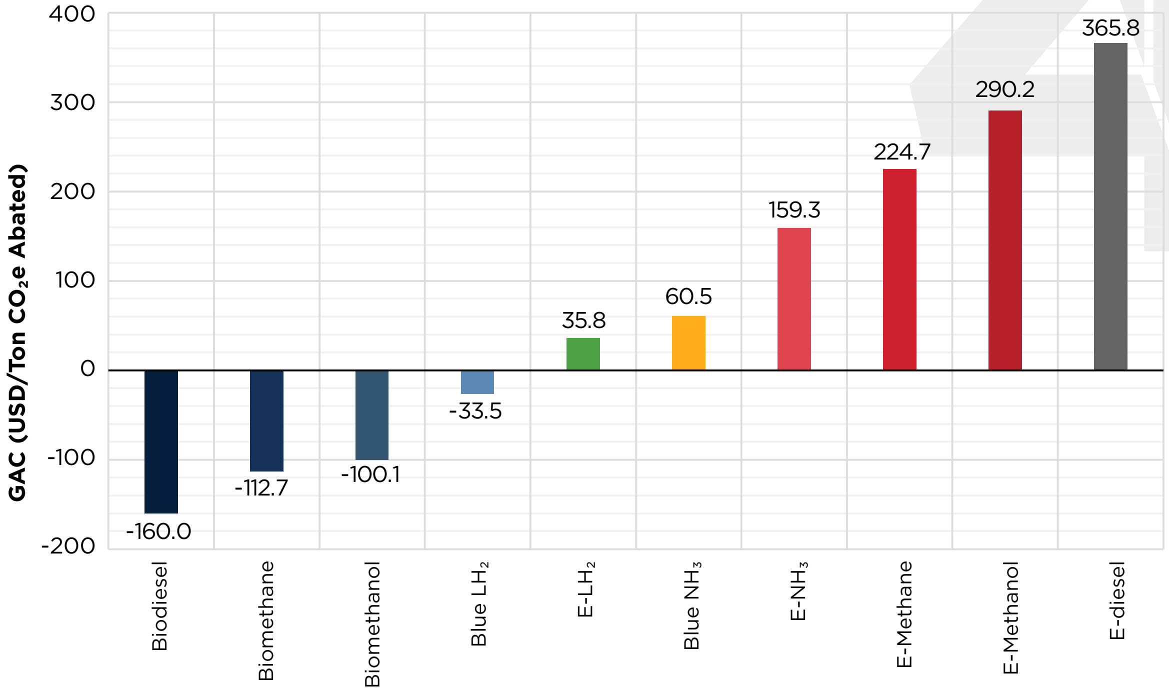


Figure 4.22: Pathway rankings in 2050 under biofuels high uptake scenario.

Similarly, in the blue-fuels high uptake scenario, the practical pathways have been identified as blue hydrogen, biodiesel, blue ammonia, biomethanol, biomethane, and e-hydrogen. Refer to Figure 4.23.

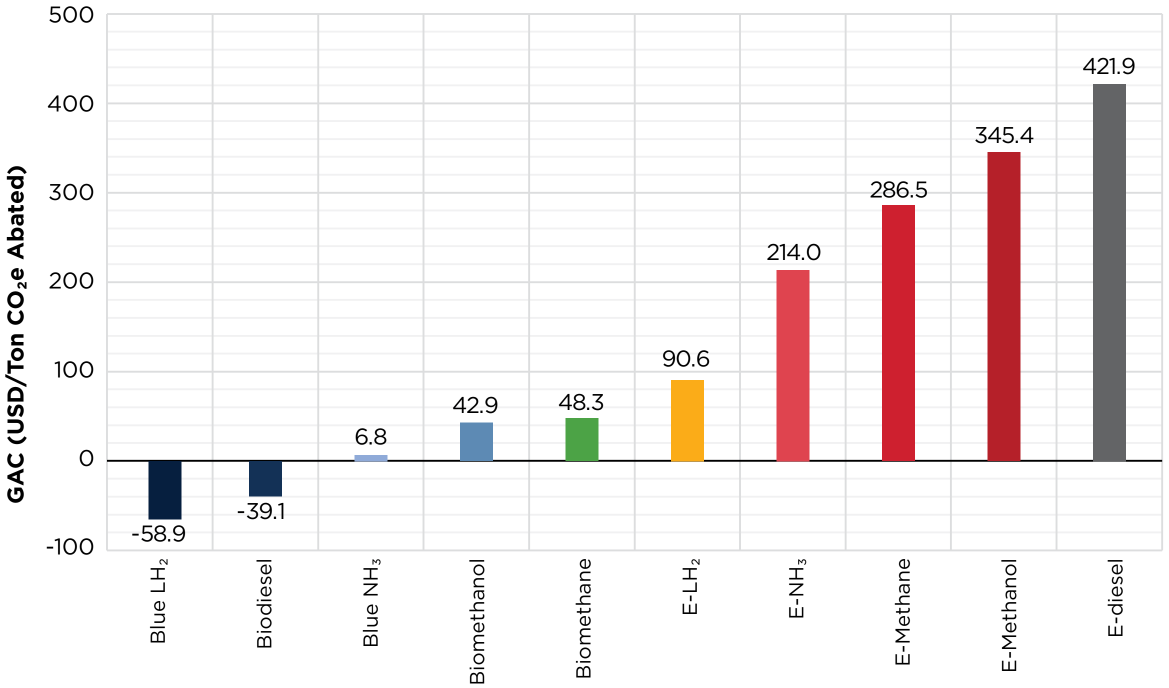


Figure 4.23: Pathway rankings in 2050 under blue-fuels high uptake scenario.

The negative GAC values indicates that the potential cost is below our benchmark fuel price, while the GHG emission is positive, making it the lower, the better. Based on the calculated GAC outputs of three developed scenarios, Table 4.1 provides a viable pathway pool of the fuel pathway's cost-effectiveness in 2050 based on three defined scenarios (e-fuels high uptake, biofuels high uptake and blue fuels high uptake).

Number	E-fuel PathwaysHigh Uptake Scenario	Biofuel Pathways High Uptake Scenario	Blue Fuel Pathways High Uptake Scenario
1	Biodiesel	Biodiesel	Blue LH_2
2	E-LH_2	Biomethane	Biodiesel
3	Blue LH_2	Biomethanol	Blue NH_3
4	Biomethanol	Blue LH_2	Biomethanol
5	Biomethane	E-LH_2	Biomethane
6	E-NH_3	Blue NH_3	E-LH_2
7	Blue NH_3	E-NH_3	E-NH_3
8	E-Methane	E-Methane	E-Methane
9	E-Methanol	E-Methanol	E-Methanol
10	E-diesel	E-diesel	E-diesel

Table 4.1: Cost-effective Fuel Production Pathways in 2050 based on GAC.

Based on the projected GHG abatement cost analysis, the biodiesel pathway shows a potential to top others under e-fuel and biofuel uptake scenarios, and other biofuel pathways and blue fuel pathways are projected to have good abatement cost-effectiveness performance. Under all three scenarios, e-methane, e-methanol and e-diesel may not be as competitive as other pathways by considering both projected fuel cost and GHG emission intensities in 2050.

4.4. Further Insights into Carbon Neutral Fuels

4.4.1. Renewable Hydrogen Transportation Solutions

Renewable hydrogen acts as a key reactant for multiple fuel pathways, so it is significant to identify cost-effective renewable hydrogen transportation solutions for the global fleet. The preferred or lowest-cost option for transportation will depend on the state of the hydrogen, the distance over which it is transported, the volume being transported and its ultimate end use. There are four typical ways for ship-based renewable hydrogen transportation solutions:

- Compressed hydrogen is more economical to transport smaller volumes of compressed hydrogen by truck. Bulk compressed hydrogen (cH_2) shipping currently exists at a conceptual level, but high expectations are being placed on this technology.
- Liquid hydrogen: Liquid hydrogen has different safety characteristics than compressed hydrogen. Larger volumes of liquid hydrogen are most easily moved via ship, and smaller volumes via truck.
- Ammonia: Ammonia can be transported and stored more economically as a liquid at low pressures or in cryogenic tanks. Ammonia can potentially be transported at a relatively low cost via pipelines, ships, trucks and other bulk modes.
- Liquid organic hydrogen carriers (LOHC): Like ammonia, LOHCs have the potential to be transported across the whole spectrum of options available. They require less energy to synthesize than ammonia.

The Joint Research Centre of the European Commission (JRC-EC) published an executive brief studying different hydrogen delivery solutions, to evaluate different alternatives from an economic perspective.

Illustrated in Figure 4.24, compressed hydrogen appears to be the cheapest option for short distances (<3,000 km); Liquefied hydrogen and LOHC are more cost-effective for medium distances (>3,000 km, <16,000 km); While for long distances (>16,000 km), chemical tankers (LOHC and ammonia) present better performance.

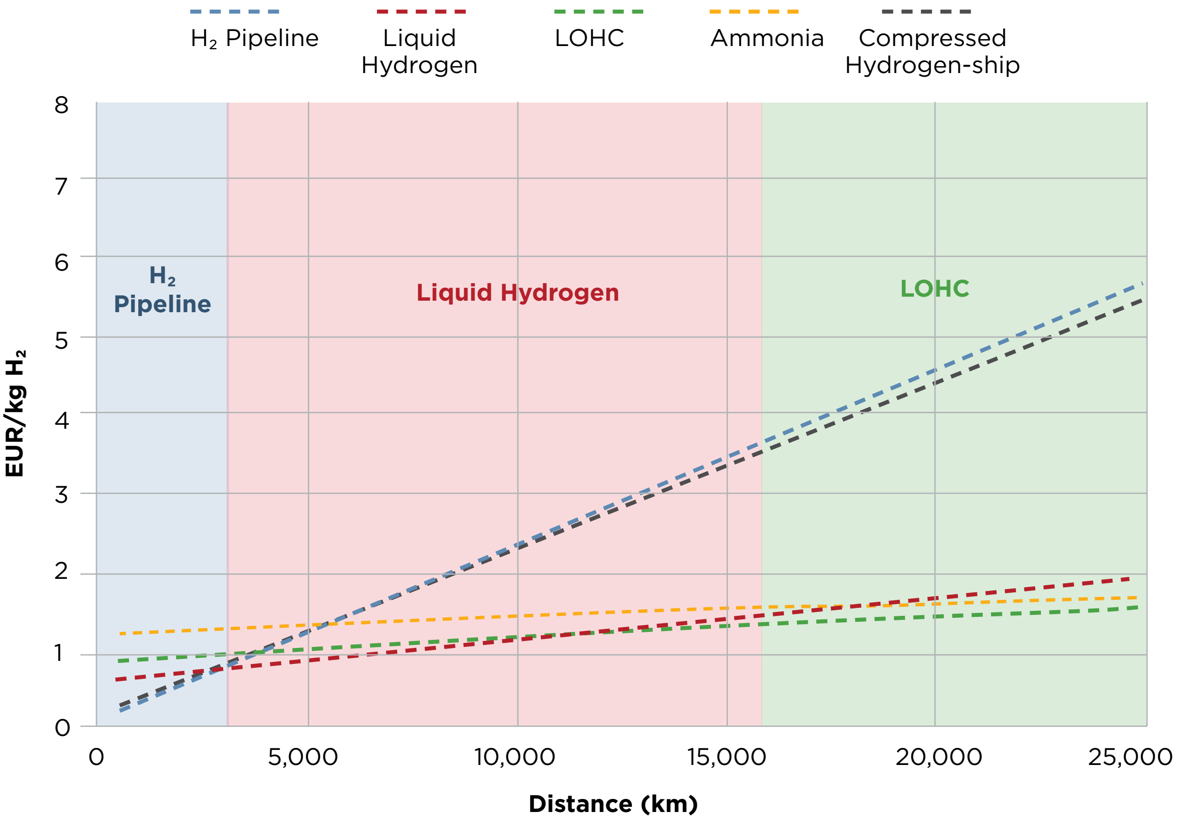


Figure 4.24 Cost of ship-based hydrogen transportation solutions (1 Mt/year H_2 scenario).

4.4.2. China's Efforts on Alternative Fuels Production

China is rapidly establishing itself as a global leader in hydrogen production and green shipping technologies, leveraging its existing industrial capacity and strategic initiatives with the intent to lead the future green energy markets.

China is currently the world's largest hydrogen producer, primarily through emissions-heavy methods involving coal and natural gas. This approach allows China to build a robust hydrogen value chain quickly, with plans to transition to green hydrogen when it becomes more financially viable. The "Medium and Long-term Plan for Hydrogen Energy Industry Development (2021–2035)" action plan reflects China's commitment to increasing hydrogen production, including green hydrogen from renewables.

China is also leading in e-methanol production, leveraging its extensive methanol industry to transition toward greener methods. By 2025, China aims to secure over 50 percent of the international market share in green-powered ships, particularly those using LNG and methanol. The country's "Action Plan for Green Development in the Shipbuilding Industry (2024–2030)" outlines targets to align maritime alternative fuels and new energy technologies with global standards, promoting methanol and ammonia-fueled vessels alongside other green technologies.

4.4.2.1. Strategic Industrial Policies and Future Trends

China's strategic policies, such as the "Made in China 2025 Plan" emphasize innovation-driven production in high-tech industries, including shipbuilding. The plan incentivizes Chinese shipyards to advance green technologies and increase their global market share. By focusing on technological advancements, China aims to surpass Western shipbuilding capabilities.

Looking forward, China's dominance in hydrogen and green methanol production is expected to grow, driven by governmental support and increasing global demand for green technologies. The acceleration in green hydrogen projects and the establishment of a comprehensive hydrogen supply chain will further solidify China's position in the global green energy market. Additionally, China's commitment to building more green ships will enhance its influence in sustainable maritime practices.

China's approach to hydrogen production and green shipping technologies highlights a strategic balance between immediate industrial growth and long-term environmental sustainability. By leading in hydrogen and e-methanol production, and investing heavily in green shipbuilding, China is positioning itself as a key player in the global transition toward cleaner energy solutions.

4.4.3. Challenges for Alternative Fuel Pathways

In addition to cost concerns, ABS has identified multiple hurdles facing carbon-neutral alternative fuel pathways.

4.4.3.1. Blue Fuel Pathway's GHG Emissions Levels

Blue fuel pathways generally encompass the utilization of natural gas to generate hydrogen and ammonia, with the integration of CCS technology throughout the production phases. Depending on the CCS process efficacy, the source of the natural gas, and the fuel combustion process, the environmental impact of these fuels can vary. Recent research suggests that the actual GHG emissions from blue fuels surpass the initial estimates. This discrepancy can be attributed primarily to fugitive emissions and indirect emissions originating from hydrogen.

A sensitivity analysis conducted by Howarth and Jacobson (Howarth and Jacobson, 2021) on WtT methane and CO_2 emissions found that blue hydrogen offers 22 percent (with a methane slip of 2.54 percent) and 34 percent (with a methane slip of 1.54 percent) reductions in GHG emissions compared to gray hydrogen, using the current technologies. Precise assessments necessitate comprehensive and precise data pertaining to the technologies employed, production processes and CCS efficiency in the context of blue fuels.

4.4.3.2. Renewable CO_2 Shortage for Green E-fuel Production

Carbon offsetting for shipping is a way to compensate for carbon emissions from transportation and operations to produce a net-zero amount of CO_2. Burning fuels that are not carbon-free leads to GHG emissions at the TtW stage. To achieve WtW carbon neutrality, it is crucial for green e-fuel pathways to secure emissions offsets during the fuel production phase. Besides green hydrogen, renewable CO_2 is another reactant to produce synthetic fuels like e-diesel, e-methane and e-methanol. Two typical ways have been identified to get renewable CO_2, one is from DAC, and the other is oceanwater capture, which exhibits a lower technology readiness level (TRL) compared to DAC.

DAC, a promising green technology, can potentially offset GHG emissions from synthetic fuels like e-diesel, e-methane, and e-methanol, offering reductions of 60 to 80 kg CO_2eq/GJ . The complete switch of the global maritime sector to e-fuels requires a large expansion of renewable electricity production capacity, electrolyzer capacity, DAC capacity, and e-fuels synthesis plant capacity. However, to date, the TRL for hydrogen production can reach up to 9 based on different electrolysis technologies, while the TRL for DAC is still in the system validation stage (5–7). The comparison of required capacity and available capacity for the different e-fuel production segments indicates that the largest bottleneck for the expansion of e-fuel production capacity is the development of DAC capacity. It is likely to take the most time before the DAC technology is technically ready for mass deployment. In addition, the high costs associated with DAC pose a significant barrier to its widespread adoption in alternative fuel production.

In summary, the low TRLs of DAC and oceanwater capture technologies present a major barrier to getting sufficient renewable CO_2, leading to lower maturity levels of e-fuel pathways..

4.4.3.3. Challenges in Carbon Offsets for Non-Carbon-Free Fuel Pathways

Non-carbon-free fuel pathways are defined as the marine fuel combustion on board TtW associated with CO_2e gases. Besides the low TRL and the high costs associated with DAC, other challenges in carbon offsetting for non-carbon-free fuel pathways are identified:

- Lack of accurate methodologies for measuring WtT and TtW emissions: There are challenges in developing accurate methodologies for measuring emissions across the entire alternative fuel value

chain to determine the appropriate amount of offsets needed. Furthermore, the GHG emission intensities from WtT processes are highly location-dependent, and the lack of comprehensive regional emission data for synthetic fuel pathways introduces further uncertainties in evaluating these non-carbon-free approaches.

- Robust methodology and verification needed for high-quality carbon offsets: Carbon offsets to be credible for non-carbon-free fuel pathways need to meet criteria like additionality, permanence, avoiding double counting, and avoiding social/environmental harm. The information of the nature of offset projects, emissions scope covered and volumes of carbon neutral are required to be shared to ensure high-quality carbon offsets.

- Potential for greenwashing: Without proper oversight and standards, there are risks of greenwashing through the use of low-quality offsets that do not reduce GHG WtW emissions. This could undermine the credibility of carbon-neutral marine fuel claims.

- Governance and regulatory gaps: There is a lack of comprehensive governance frameworks and regulations to ensure the integrity of offset markets. While initiatives like the Integrity Council for the Voluntary Carbon Market (ICVCM) and the International Sustainability Standards Board (ISSB) are working to establish standards, there is still a need for stronger oversight and enforcement mechanisms.

To secure the integrity of carbon markets and alternative fuel pathways, the challenges in carbon offsets for non-carbon-free fuel pathways can be dealt with by better measurement methodology, governance frameworks, enhanced standards, transparency and third-party verification. In the absence of such safeguards, the possibility of greenwashing could jeopardize decarbonization initiatives in sectors such as shipping.

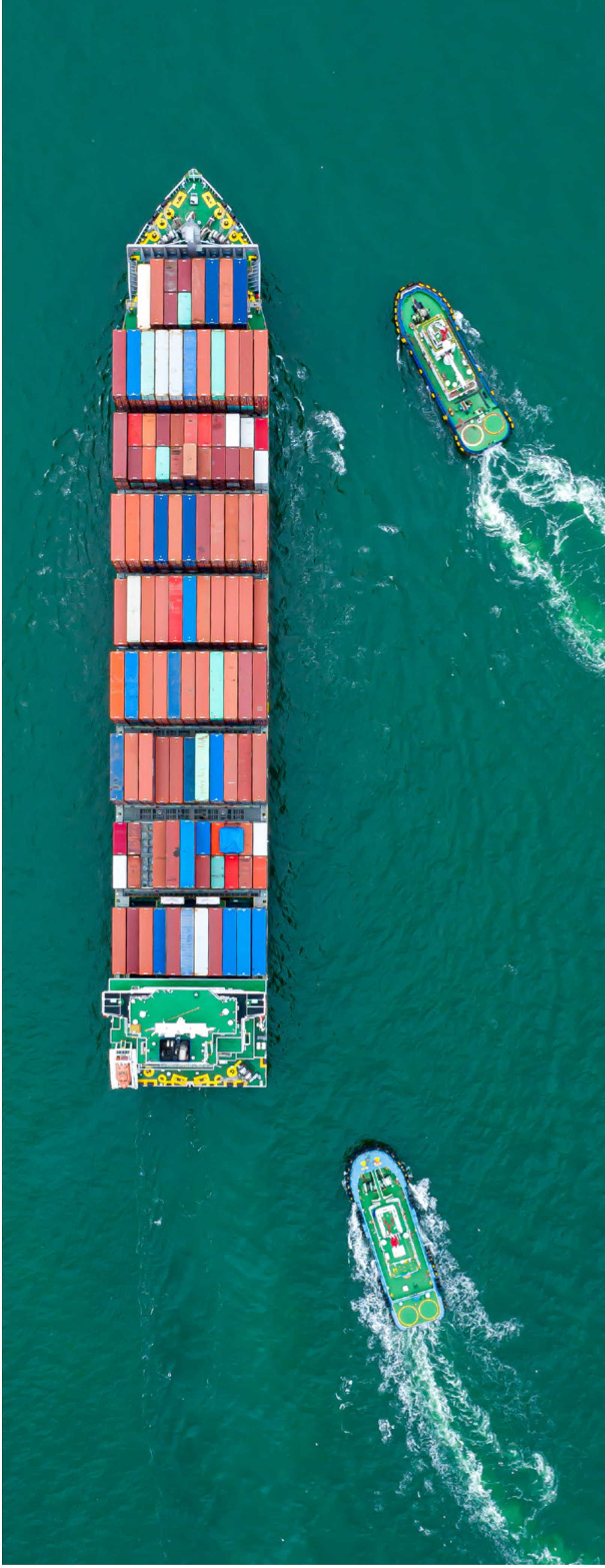
4.4.3.4. Black Carbon Emissions Effects On Global Warming Potential

Black carbon, the dark particulate matter released from gas and diesel engines, coal-fired plants, and other fossil fuel combustion processes, significantly contributes to global warming by absorbing solar

radiation. Notably, individual particles of black carbon can clump together, forming complex structures that combine with other particles. This aggregation alters the Earth's reflectivity (albedo) and intensifies the warming effect of black carbon emissions. The emission levels of black carbon vary with the blend of biodiesel used and are directly correlated with the aromatic content of the fuel.

An ICCT study (Olmer et al., 2017) pointed out that BCA is the second largest contributor to ship-induced GWP emissions, larger than methane and nitrous oxide, representing 7–21 percent of CO_2e emissions from the global shipping sector on a 100-year and 20-year timeframe. For black carbon emissions from different marine fuel options, a study conducted by Ji and El-halwagi (Ji and El-halwagi, 2020) pointed out that black carbon emissions from VLSFO burning are even worse than HFO with a scrubber and LNG-fueled vessels showed a good black carbon emissions saving performance compared to diesel-driven vessels. An MIT working group also stated that the recommended maritime shipping black carbon reduction technologies were diesel particulate filters, LNG, fuel switching, exhaust gas scrubbers, slide valves, etc. A recent study conducted by Brewer (Brewer, 2023) indicates that container ships, bulk carriers, and oil tankers are the top three black carbon emitters among all ship types, and the author urged the legal and institutional development for explicit international and regional regulations addressing black carbon emissions for the shipping industry.

The Arctic is already warming almost four times faster than the global average, at 0.73C per decade compared to the global average of 0.19C per decade between 1979 and 2021, according to a 2022 study by Rantanen' research team (Rantanen et al., 2022). Therefore, reducing the aromatic compounds in fossil-based marine fuels is essential, particularly in sensitive ecosystems like the Arctic, to mitigate the GWP of black carbon emissions.



4.5. EETs Uptake Rate

The shipping industry is actively embracing EETs to address the challenges of decarbonization and CO_2 emission reduction. Many different devices have been studied to either improve the energy performance of suboptimal ship designs, or to improve on already optimal or nearly optimal standard designs by exploiting physical phenomena usually regarded as secondary in the normal design process, or not yet completely understood.

There is a wide range of EETs, most of which concentrate on the improvement of propeller propulsion effectiveness. However, recent developments have led to a series of devices aimed at either reducing the hull frictional resistance or exploiting readily available natural resources, such as solar and wind energy. At ABS, EETs have been categorized into seven groups (Figure 4.25).

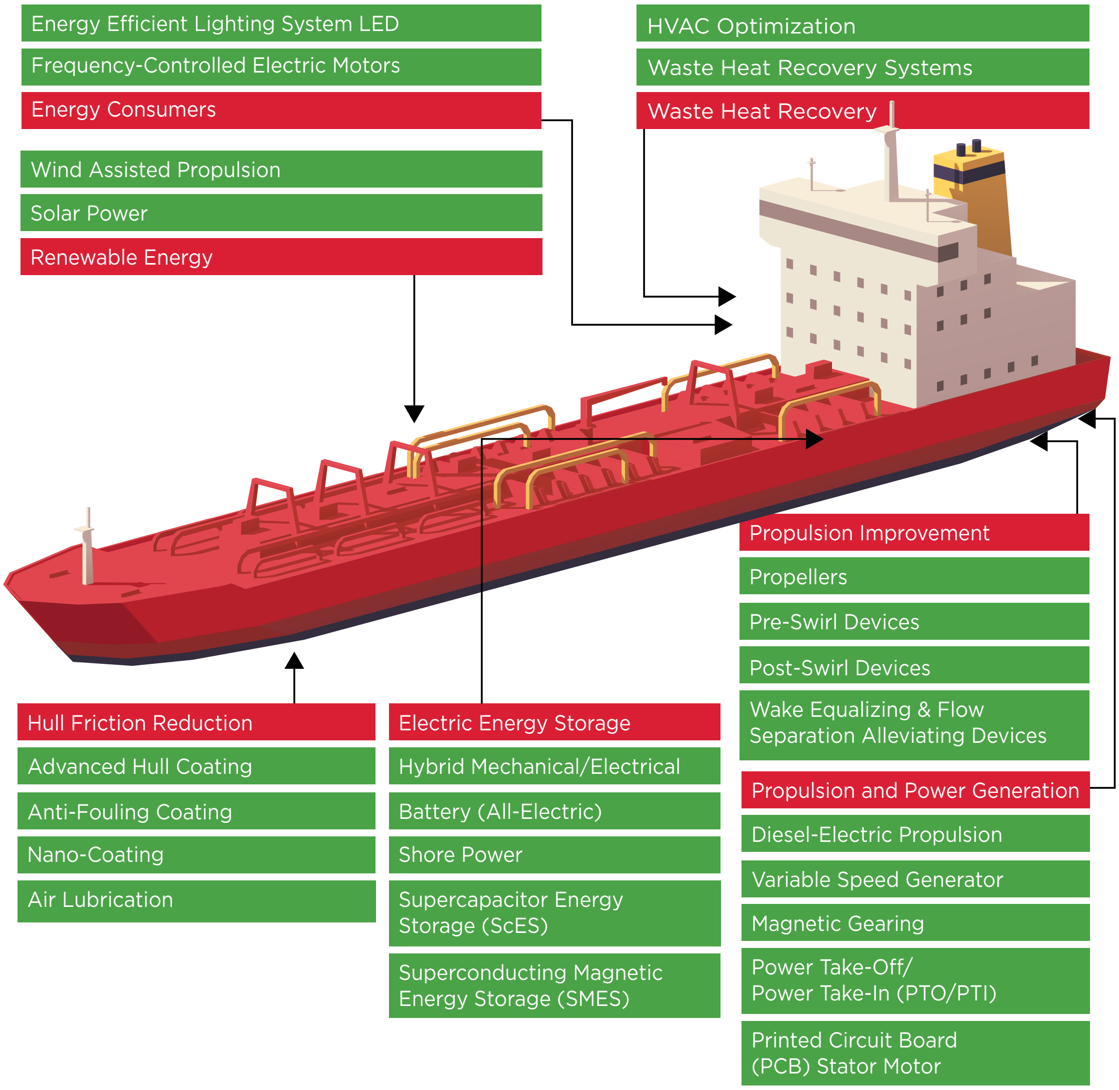


Figure 4.25: Classification of energy efficiency technologies.

An important fact to be considered relating to the application of EETs either for a newbuild or retrofit project is the compatibility of the different options with each other when considering retrofitting more than one. The benefits of two or more EET retrofit options will not provide an aggregated improvement. Further, one option may cancel the benefits obtained by another, if considered to be implemented concurrently.

To support the implementation of the IMO GHG Strategy, IMO's GreenVoyage2050 project provided cost and energy-saving potential for some of the EETs (Table 4.2). By integrating published data with the ABS EET insights database, the following table showcases the maturity level, implementation cost, efficiency rate, and penetration rates in 2030 and 2050 of different EETs.

Group	Title	Current Maturity Levels	Cost	Energy Saving (percent of ME/AE/Boiler Power)		Energy Saving Source	IMO Prediction Penetration Rates (% of ships applying a technology)	
				Min.	Max.		Min.	Max.
Group 1 Main Engine improvement	Main Engine Tuning	Semi-Mature	High	2%	10%	ME	80%	100%
	Common rail	Mature	Low	1%	4%	Overall Ship	7%	32%
	Electronic engine control	Semi-Mature	Medium	1%	4%	Overall Ship	6%	31%
Group 2 Auxiliary Systems and Boilers	Frequency converters	Mature	Low	2%	10%	AE	17.5%	42.5%
	Speed control of pumps and fans	Mature	Minimal	0.25%	0.75%	Overall Ship	55%	80%
	Steam plant operation improvements	Mature	Low	10%	30%	Boiler	80%	100%
	Reduced auxiliary power demand (low energy lighting etc.)	Semi-mature	Low	1%	5%	Overall Ship	55%	80%
Group 3 Waste heat recovery	Waste heat recovery	Semi-Mature	High	3%	8%	ME	17.5%	42.5%
	Exhaust gas boilers on auxiliary engines	Semi-Mature	Low	0.0%	5%	AE	17.5%	42.5%
Group 4 Propeller Improvements	Propeller-rudder upgrade	Mature	Medium	0.5%	5%	ME	17.5%	42.5%
	Propeller upgrade (nozzle, tip winglet)	Mature	Medium	0.5%	5%	ME	17.5%	42.5%
	Propeller boss cap fins	Mature	Medium	0.5%	5%	ME	15%	40%
	Contra-rotating propeller	Mature	Medium	0.5%	5%	ME	17.5%	42.5%
	Propeller performance monitoring	Mature	Minimal	0.25%	1.5%	ME	17.5%	42.5%
	Propeller polishing	Mature	Low	3%	4%	ME	80%	100%
Group 5 Hull Friction Reduction	Air lubrication	Semi-Mature	High	7%	10%	ME	5%	30%
	Low-friction hull coating	Mature	Low	1%	4%	ME	17.5%	42.5%
Group 6 Hull maintenance	Hull performance monitoring	Mature	Low	0.5%	3%	ME	17.5%	42.5%
	Hull brushing	Mature	Low	1%	5%	ME	17.5%	42.5%
	Hull hydro-blasting	Mature	Low	1%	5%	ME	17.5%	42.5%
	Dry-dock full blast (old ships)	Mature	Low	1%	5%	ME	55%	80%
Group 7 Renewable power	Towing kite	Not Mature	High	1%	5%	ME	5%	30%
	Wind power (fixed sails or wings)	Not Mature	High	1%	10%	ME	5%	30%
	Wind power (Flettner rotor)	Not Mature	High	3%	15%	ME	5%	30%
	Solar panels	Not Mature	High	0.5%	2%	AE	5%	30%

Table 4.2: Status, cost, energy saving and penetration rates of EETs.

Besides the mainstream energy efficiency technologies listed in Table 4.2, other EETs with low expected penetration rates in 2030 and 2050 have been summarized in Table 4.3.

Title	**Current Maturity Levels**	**Cost**	**Energy Saving (percent of ME/ AE/Boiler Power)**		**Energy Saving Source**	**ABS Prediction Penetration Rates** (% of ships applying a technology)	
			Min.	**Max.**		**2030**	**2050**
Wind turbine	Not Mature	High	1%	7%	AE	<1%	3%
Bow wind shield	Not Mature	Medium	1%	3%	ME	<1%	5%
Stern Flap	Semi-Mature	Medium	0%	10%	ME	<1%	2%
Bow Foils	Not Mature	High	0%	10%	ME	<1%	2%
Ducted propeller	Mature	High	2%	4%	ME	3%	5%
Propeller with Tip Fins	Semi-Mature	High	1%	3%	ME	<1%	3%

Table 4.3: Other EETs for shipping decarbonization.

By incorporating IMO's EET penetration rate we developed projected uptake rates for two scenarios from 2019 to 2050. As shown in Figure 4.26, EETs uptake rates for the global fleet are shown in two color codes, blue for Scenario High, and purple for Scenario Low.

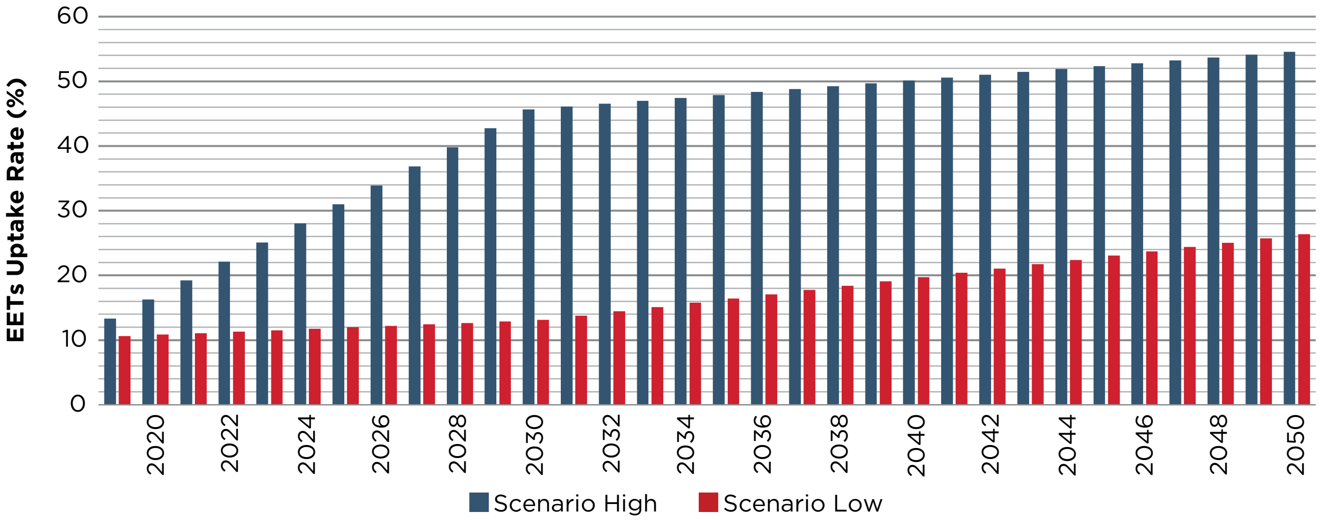


Figure 4.26: EETs uptake rates projection.

By analyzing the energy-saving potentials of EETs, it is concluded that EETs are considered short-term options since, in most cases, they cannot serve as the primary decarbonization solutions to meet long-term emission reduction targets. According to the projected EET uptake ratios and the updated EET energy saving potential, the global fleet energy consumption can be calculated, and the outputs are illustrated in Figure 4.27.

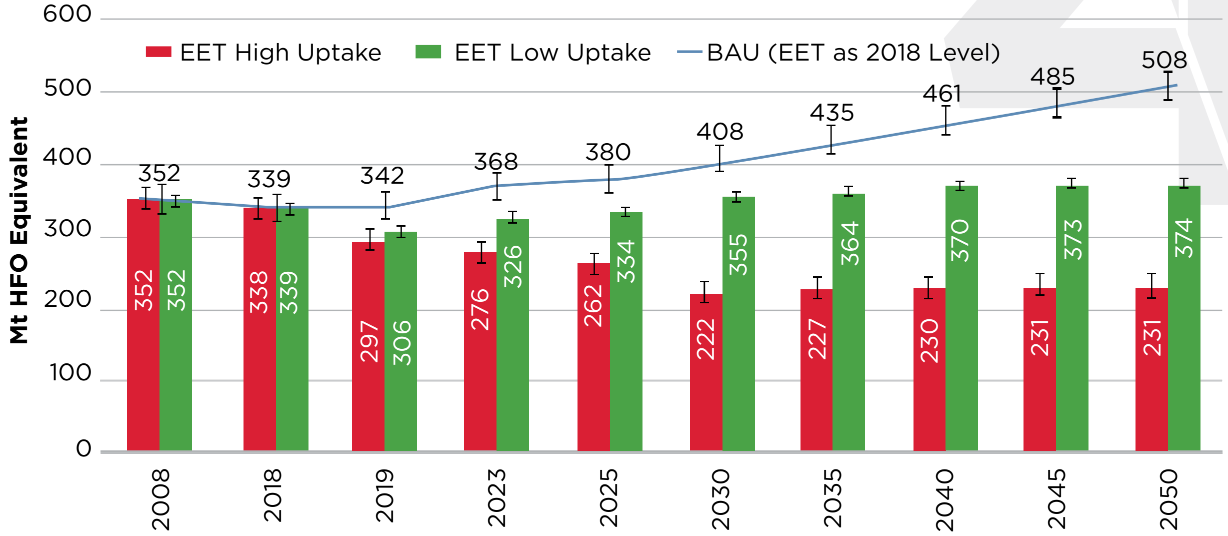


Figure 4.27: Global fleet energy consumption under two EET scenarios.

As shown in the above figure, EET High Uptake Scenario can save up to 46 percent energy consumption compared to the Business As Usual (BAU) case in 2030, and this value jumps to 55 percent in 2050 based on IMO EET high update rate.

The EET Low Uptake Scenario, which is more reasonable to achieve, may save up to 13 percent of energy consumption in 2030 and 26 percent in 2050 compared to the BAU case.

Although the projected results for EETs alone cannot individually lead the maritime industry to carbon net zero emissions, the encouraging results do suggest that EETs should play a key role in the maritime decarbonization journey. For long-term decarbonization, stakeholders in the shipping industry need to look at alternative fuel system retrofits and onboard carbon capture installations to meet the more stringent regulatory requirements that the industry will be facing in the next decade.

4.6. Alternative Fuels and the Human Element

The increasing focus on the energy transition through the adoption of alternative fuels brings both opportunities as well as challenges. Although these fuels have significant environmental advantages, their implementation presents specific safety challenges and requires a renewed understanding of operations.

Transitioning to alternative fuels is not merely a technical challenge but a significant human one. The safe and effective management of these new fuels and technologies requires a well-prepared workforce equipped with new skills and knowledge. Furthermore, regulatory frameworks need to evolve to support these changes. Understanding these human and regulatory dimensions is essential for the industry to meet its environmental targets and ensure the safety and efficiency of its operations.

Each alternative fuel offers significant benefits for reducing emissions but also introduces specific challenges:

- LNG reduces sulfur oxide and particulate matter (PM) emissions but requires additional crew training and safety measures.
- Biofuels are versatile and have a lower carbon footprint but can vary in quality and may compete with food resources.

- Methanol is easy to handle because it does not require cryogenic or pressurized tanks but is highly flammable and if not handled properly can cause eye irritation, headaches, fatigue and can destroy the optic nerve.
- Ammonia has high hydrogen content and burns cleanly but requires stringent safety measures due to its toxicity.
- Hydrogen offers high energy efficiency and zero emissions but requires advanced cryogenic storage solutions.

4.6.1. Human Element Considerations

4.6.1.1. Skills and Training Requirements

Traditional maritime training programs have been centered around conventional fuel technologies, and the new fuel types introduce complex challenges that must be addressed through specialized training:

- LNG handling: Training for LNG involves understanding the properties of gas, safety protocols for leak detection and emergency response procedures.
- Biofuel compatibility: Seafarers need to be trained on the various types of biofuels, their storage requirements and how they differ in handling from conventional fuels.
- Methanol safety: Training should include fire safety and its inherent reactivity to other chemicals, the health risks due the potential toxicity and the proper storage.
- Ammonia awareness: Training should include the health risks associated with ammonia exposure, safe handling practices and the use of protective equipment.
- Hydrogen safety: Due to its highly flammable nature, training must focus on safety measures specific to hydrogen, including the handling of leaks and fire prevention.

4.6.1.2. Workforce Adaptation

The adoption of these alternative fuels will potentially lead to the reconsideration of job roles and responsibilities:

- New technical roles may emerge, such as alternative fuel specialists and environmental compliance officers, to oversee the handling and use of these fuels.
- Existing maritime roles may require adjustments to incorporate new responsibilities related to the operation and maintenance of alternative fuel systems.
- A shift toward a culture that prioritizes sustainability and safety though continuous education.

4.6.1.3. Evolving Training Needs

- Training programs must continually evolve to keep pace with technological advancements and changing regulations. This includes virtual reality simulations for emergency response and routine operations with new fuels.
- New certification standards will need to be developed to ensure that seafarers are proficient in the technologies and safety practices specific to each type of alternative fuel.

4.6.2. Safety of Alternative Fuels

As indicated previously, the adoption of these fuels will introduce specific challenges that would need to be addressed through revised operational management and specialized training for the workforce. The main challenges and characteristics associated with each fuel, include:

- Flammability and explosion risks
- Toxicity
- Material compatibility, reactive and corrosive behaviors
- Emissions

4.6.2.1. Comparison of Fuel Properties

The properties of different fuels are summarized in Table 4.4, offering a comparison with conventional MGO and LNG.

Fuel	Boiling Point (° C) at 1 bar(a)	Liquid Density (kg/m³)	LHV (MJ/kg)	Flammable Range (% vol in air)	Energy Density (MJ/L)	Volume Comparison with MGO
MGO	360	855	45.9	1-8	39.2	1
LNG	-163	428	48.6	5-15	20.6	~1.9
Methanol	65	790	19.9	6-36	15.7	~2.5
Ammonia	-33	682	18.8	15-28	12.8	~3.1
Hydrogen	-253	71	120	4-75	8.5	~4.6

Table 4.4: Fuels comparison.

4.6.2.2. Ammonia Safety

The adoption of ammonia needs a solid understanding of the associated risks for both the ship and health and safety of people on board. Key risk is toxicity, but other notable challenges include combustion emissions, ammonia slip and stress corrosion cracking. Table 4.5 illustrates these risks.

Toxicity	Ammonia poses serious health risks at low concentrations and can be fatal at higher levels. Due to its pungent smell, ammonia can be detected well below 25 ppm which works as an early warning signal. Introduction of toxic fuel creates new challenges related to safe bunkering, storage, supply and consumption. A ship's design is affected as the release of ammonia should be mitigated in all cases. Toxic areas should be determined upon an ammonia gas dispersion analysis.
Flammability	While less likely to ignite in open air due to its highly flammable range (15–28% vol in air) and rapid diffusion, ammonia presents a significant ignition risk in confined spaces, especially in the presence of oil and other combustibles. Storage tanks may also risk explosion under high heat.
Storage	Ammonia requires refrigeration at -33° C to remain liquid at atmospheric pressure. Exposure to higher temperatures can lead to brittle fractures in containment materials and frostbite risks from evaporating ammonia.
Material Compatibility and Stress Corrosion Cracking	Ammonia's reaction with various materials can lead to significant integrity issues. It should not contact mercury, copper, copper-bearing alloys and zinc to avoid corrosion. Interaction with CO_2 can form carbamates, leading to clogs and damage in cargo systems. Oxygen presence can accelerate stress corrosion cracking in steels at high temperatures.
Environmental Impact	Ammonia is extremely toxic to aquatic life. Spills can severely impact marine ecosystems depending on the spill's concentration and duration, as well as water temperature, pH and salinity.

Table 4.5: Ammonia safety challenges.

4.6.2.3. Hydrogen Safety

Hydrogen has the potential to be a zero-carbon marine fuel when it is consumed in a fuel cell while it can significantly reduce carbon emissions when consumed in internal combustion engines. Table 4.6 illustrates these risks.

Flammability	Hydrogen's wide flammability range (4–75% vol in air) and explosive nature at low concentrations pose significant risks, especially in enclosed or semi-enclosed spaces. The gas forms flammable mixtures quickly and can ignite from minimal spark sources due to its low ignition energy. Leaks in open or contained spaces can be a serious fire hazard due to quick formation of flammable gas mixtures (low activation and ignition energy). Flow or agitation of hydrogen gas or liquid can create electrostatic charges, resulting in sparks and ignition. Hydrogen is colorless and odorless therefore leaks are difficult to detect and the same goes for the flame that is invisible. Hydrogen also burns extremely quickly compared to other fuels.
Asphyxiation	Although non-toxic, hydrogen in high concentrations can displace oxygen, leading to asphyxiation risks.
Hydrogen embrittlement	Hydrogen embrittlement occurs when hydrogen is absorbed by a metal and collects at grain boundaries, creating weak spots within the material. Hydrogen absorption can lead to brittle failure mechanics, microscopic fractures, material cracks and leakage.
Environmental Impact	While hydrogen does not pose direct environmental threats upon release, its production and combustion can result in CO_2 emissions depending on the methods used.
Storage	Storage of liquefied hydrogen on ships in atmospheric pressure is challenging due to its very low boiling temperature of -253° C. Complex containment systems will be required to store hydrogen at extreme low temperatures. Loss of containment may result to brittle fracture of adjacent steel and cause severe frostbite if it comes into contact with human skin. Due to its small molecule, leakages through welds, flanges etc. are easy to occur and therefore equipment is difficult to be leak tight.

Table 4.6: Hydrogen safety challenges.

4.6.2.4. Methanol Safety

Methanol is a colorless liquid at ambient temperature therefore storage conditions are simplified compared to ammonia and hydrogen fuels. Table 4.7 illustrates these risks.

Toxicity	Methanol is highly toxic, with potential to cause serious health issues such as blindness or death if ingested. Its toxicity is critical not only through ingestion but also via inhalation or skin contact.
Flammability	Methanol is a flammable liquid with a large flammability range (6–36% vol in air), low flashpoint (11° C) and high heat of vaporization. Methanol-water mixture with over 25% can still be flammable. Methanol flame is nearly invisible without producing smoke and can be undetected at initial stages.
Corrosion	Methanol causes corrosion therefore carbon steels need special coating to be protected or stainless steel to be used. Non-metallic materials used in fuel tanks and pipes are to consist of appropriate methanol-compatible materials, such as nylon, neoprene, or non-butyl rubber.
Environmental Impact	Although methanol is biodegradable and less harmful in marine environments than traditional hydrocarbon fuels, high concentrations can still pose risks to aquatic life. It is naturally present in the ocean, produced by phytoplankton, and consumed by bacteria.

Table 4.7: Methanol safety challenges.

4.6.3. Training and Certification — A Paradigm Shift

The shipping industry's transition to alternative fuels will require a new way of thinking as well as the development of regulatory, training and certification instructions to support:

- Design of the vessels
- Fuel handling and operational principles.
- Bunkering procedures
- Personal protection equipment (PPE) requirements, especially for toxic fuels (e.g., ammonia, methanol)
- Training requirements of marine personnel

This is the top priority in IMO's agenda as noted in the 9th session of the Sub-Committee on Carriage of Cargo and Containers (CCC 9, September 2023). The latest CCC 9 focused on crucial discussions related to the development of guidance on the use of ammonia and hydrogen as fuels. Classification societies have also in place rules and guides for alternative fuels based on the IGF Code philosophy.

The safety of alternative fuels is also raised and investigated by many organizations (e.g., EMSA, SGMF, etc.) and flag Administrations. Recently, EMSA worked with ABS to assess the potential of various alternative fuels in shipping with recent publications that assess the availability, suitability, and sustainability of these fuels along with the risk and safety and regulatory framework:

- Potential of Ammonia as Fuel in Shipping (Published in September 2023)
- Potential of Hydrogen as Fuel in Shipping (Published in November 2023)
- Update on Potential of Biofuels in Shipping (Published in September 2023)

New, ongoing EMSA studies focus on reliability analyses of systems operating in ammonia and hydrogen and the development of industry guidelines.

There are several current deficiencies that need to be immediately addressed. There is a lack of adequate training programs addressing the specific requirements of handling alternative fuels and the existing courses do not fully cover new competencies related to these fuels.

Development of model courses and incentives for training providers to include comprehensive content on alternative fuels. Collaboration between industry stakeholders to ensure these courses are adopted and implemented swiftly.

Regulatory inertia and insufficient recognition of the urgency to update training standards pose significant barriers to the development of these training programs.

The maritime industry must prioritize the development of safety protocols, training programs, and collaborative frameworks to support the transition to alternative fuels. By addressing the identified gaps and promoting a culture of innovation and safety, the industry can navigate the challenges of decarbonization effectively.

4.7 Appendix

Fuel	LCV (GJ/Ton)	2024 Cost ($/GJ)	2030 Cost ($/GJ)	WtW GHG Intensity (gCO_2e/MJ)
VLSFO	41.6	26	22.8	96
E-diesel	42.7	89.3	73	13.1
Biodiesel	37.0	28.4	27.2	20.5
Biomethane	49.1	39	30.6	29.3
E-Methane	49.1	67.9	57.6	21.3
E-Methanol	19.9	79.9	65.6	11.2
Biomethanol	19.9	39	30.6	12.6
Blue NH_3	18.6	47.9	32.9	22.2
E-NH_3	18.6	62.5	46	11.3
Blue LH_2	120.0	36.8	25.3	18.9
E-LH_2	120.0	45.7	40.1	3.4

Table A-1: Marine fuel cost, LCV for GAC calculation.

	Multiplier(e)	Multiplier(bio)	Multiplier(blue)	Multiplier(VLSFO)
Scenario 1	0.5	0.7	0.7	1.2
Scenario 2	0.7	0.5	0.7	1.1
Scenario 3	0.7	0.7	0.5	0.9

Table A-2: Multipliers for fuel price projection in 2050.

Fuel	Cost($/GJ)	WtW	WtW 2050	GAC (2024)	GAC (E-fuel High Uptake)	GAC (Biofuel High Uptake)	GAC (Blue Fuel High Uptake)
VLSFO	26.0	96.0	96.0	-	-	-	-
E-diesel	89.3	13.1	3.3	763.6	201.2	365.8	421.9
Biodiesel	28.4	20.5	6.0	31.8	-68.0	-160.0	-39.1
Biomethane	39.0	29.3	15.3	195.0	16.1	-112.7	48.3
E-Methane	67.9	21.3	11.8	561.1	94.4	224.7	286.5
E-Methanol	79.9	11.2	1.8	635.8	148.1	290.2	345.4
Biomethanol	39.0	12.6	5.1	155.9	14.3	-100.1	42.9
Blue NH_3	47.9	22.2	14.6	296.5	92.5	60.5	6.8
E-NH_3	62.5	11.3	0.9	430.9	55.2	159.3	214.0
Blue LH_2	36.8	18.9	11.2	140.1	-2.8	-33.5	-58.9
E-LH_2	45.7	3.4	1.2	212.7	-33.2	35.8	90.6

Table A-3: Calculated GAC values for fuel pathways in 2050.

SECTION 5

KEY TRANSFORMATIONAL TECHNOLOGIES

5.1. Introduction

Compared to ABS' 2023 Outlook, large-scale trends for fuel mix remain the same, but there have been some important changes in the decarbonization pathway. Along with improvements in energy efficiency and alternative fuels, the shipping industry is also looking at other potential non-traditional solutions to support its efforts to meet net-zero target.

Onboard carbon capture and storage (OCCS) – without being an alternative energy source since it does not generate or replace energy; rather – it mitigates the environmental impact of the existing fossil fuel-based systems, is one of the technologies currently examined by the industry. Instead of replacing the fuel or changing the energy source (like switching to electric or hydrogen fuel), it aims to clean up the emissions from conventional fuels.

On the other hand, advances in alternative energy sources, such as fuel cells, hybrid systems, and nuclear power, will be pivotal to the goal of complete decarbonization of the global fleet. This section investigates the most promising decarbonization solutions, covering OCCS, fuel cells, battery/hybrid ship propulsion systems and nuclear power as an alternative energy source.

5.2. Onboard Carbon Capture and Storage (OCCS) Systems

Carbon capture technology has been around for decades and has been primarily used in onshore installations. It is now being explored as a potential solution in the push toward the decarbonization of shipping as an end-of-pipe solution to reduce vessel emissions. OCCS is still in its infancy as present land-based carbon capture equipment cannot be directly used on ships due to OCCS' unique characteristics, shown in Table 5.1.

Vessel Characteristics	Key Design Factors for OCCS	Design and Operational Considerations
Limited Space	Size/height of equipment	Constraints in absorber/stripper dimension determination
Limited utilities	Supply of heat, electric power, etc.	Energy penalty/required regeneration energy
Long lasting constant movement	Fast reaction rate, equipment effectiveness and stability	Solvent selection preference: stable, fast reaction kinetics, not subject to degradation
Multiple operation modes	Integrated carbon capture strategies	Scenario based process models, variant of flue gas flow speed

Table 5.1: OCCS characteristics and specific considerations.

OCCS reduces greenhouse gas (GHG) emissions by capturing and storing the carbon dioxide (CO_2) produced on board. Depending on the technology used, this can be done either before or after the combustion process, using different methods and the captured carbon can be stored on board in different ways.

The capture of CO_2 can occur pre-combustion synthesis gas (syngas), post-combustion (end-of-pipe solutions), and by using oxyfuels as shown in Figure 5.1.

- Pre-combustion capture involves transforming the fuel into an intermediate, non-carbonaceous form called syngas, which is mostly composed of hydrogen (H_2) and CO_2. The CO_2 is captured before being combusted and the hydrogen is the fuel, which when combusted only releases water vapor.
- The post-combustion method captures the CO_2 after the fuel is combusted and produces a product that will require additional drying, purification and compression before transportation. This is the most mature technology, but the low partial pressure of the CO_2 in the flue gas is a big downside.
- Oxy-fuel combustion is when the burners are modified to burn fuel in pure oxygen (O_2) instead of air, leading to a pure CO_2 stream and increased energy efficiency. Nitrogen oxides (NO_x) are prevented in this system and there is no need for separation of nitrogen (N_2) and CO_2. The downsides are the need for large amounts of pure oxygen and high combustion chamber temperatures.

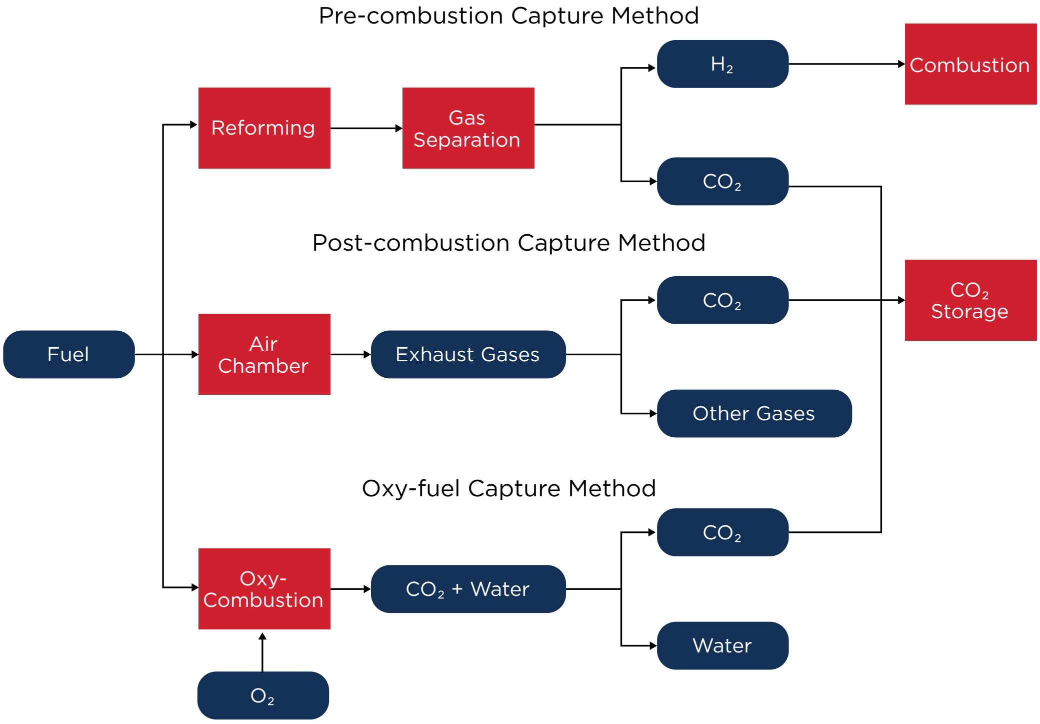


Figure 5.1: Types of carbon capture technologies.

The captured CO_2 is then stored onboard and offloaded at dedicated port facilities. Two potential onboard carbon storage methodologies are:

- Liquefaction: The CO_2 is compressed and cooled to form a liquid, which can be stored in tanks or cylinders onboard and can be transferred to shore facilities or other vessels.
- Mineralization: CO_2 is reacted with minerals to form solid carbonates, which can be stored in containers.

5.2.1. Pre-Combustion Carbon Capture Methods

Pre-combustion capture is the process of capturing CO_2 from fossil fuels before they are fully burned. Figure 5.2 illustrates the carbon capture flow chart. It is a thermocatalytic decomposition process which consists of four stages:

- The hydrocarbon fuel is converted into hydrogen and carbon monoxide (CO) to create a syngas.
- Carbon monoxide is transformed into CO_2 by a water gas shift reaction.
- CO_2 is separated from hydrogen, which can be burned cleanly.
- The captured CO_2 is delivered to a storage location in a compressed state of liquidity.

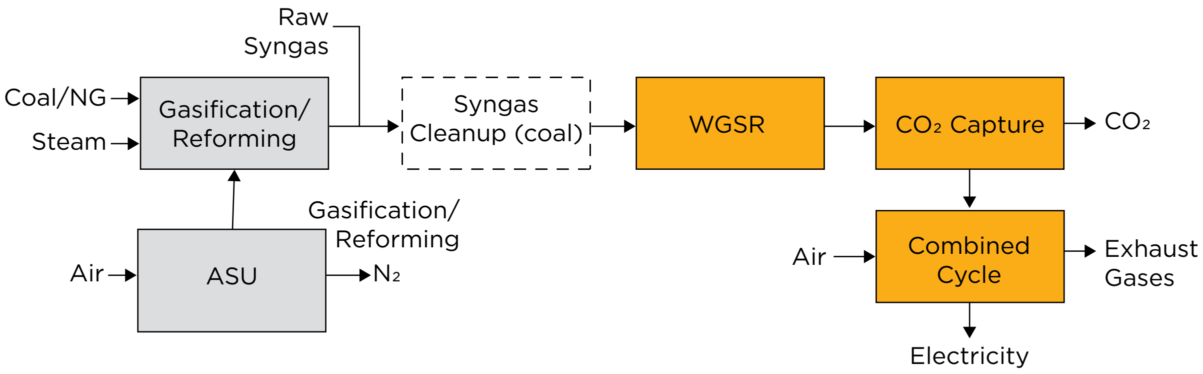


Figure 5.2: Pre-combustion carbon capture flow chart.

This technique reduces the amount of onboard storage required and allows for the endless recycling of solid carbon, which may be used to make batteries and fuel cells. This technology can accelerate the energy transition and help achieve worldwide decarbonization targets. The major technologies involve solvent-based absorption, chemical/physical sorbents-based absorption, membrane-based carbon capture, and cryogenic separation technologies.

Solvent-based CO_2 capture and hydrogen sulfide (H_2S) removal in the pre-combustion process can be achieved by various solvents (Rectisol, Selexol, Purisol, etc.). In comparison to competing solvents, the Rectisol technology offers a number of benefits, including increased loading (absorption capacity), increased thermal and chemical stability, non-foaming properties, absence of degradation, minimal corrosion, and low hydrogen loss from the system. Rectisol does have several disadvantages, though, including the following: increased solvent loss, reduced hydrogen sulfide and CO_2 selectivity, lower working temperatures, and higher energy requirements.

Based on high-tech materials, adsorption technology has offered promising perspectives on resource utilization and environmental pollution reduction. As the solid-phase adsorbent surface becomes saturated, adsorption entails the selective creation of physical or chemical links between the CO_2 (adsorbate) and the surface. The choice of an appropriate sorbent with effective regeneration for a given application is mostly influenced by temperature and pressure. Pressure swing adsorption (PSA), vacuum swing adsorption (VSA), temperature swing adsorption (TSA), or a mix of these processes are the foundations of industrial adsorption technologies.

Besides the emission reduction benefit, shipboard pre-combustion presents the following advantages:

- Compatibility with existing engines: Pre-combustion capture can be integrated with existing engines that use very low sulfur fuel oil (VLSFO) or liquefied natural gas (LNG), provided they are upgraded to handle hydrogen or hydrogen-blended fuels, unlike some other capture technologies that require complete engine redesigns.
- Scalability: The modular nature of pre-combustion systems allows for scaling the technology to different ship sizes and power requirements.
- Utilization of byproducts: The solid carbon captured can be a valuable commodity, creating potential revenue streams and incentivizing the adoption of this technology.

So far, a limited number of relevant literature has focused on pre-combustion carbon capture, partially attributed to the high capital expenditures (capex) and operating expenses (opex) associated with retrofitting existing infrastructures, and the complexity of the set-up process for shipboard pre-combustion carbon capture system.

The HyMethShip project, a European Union-funded Hydrogen-Methanol ship propulsion project, aims to separate H_2 and CO_2 from green e-methanol in a pre-combustion carbon capture process. The HyMethShip system aims to eliminate sulfur oxide (SO_x) and particulate matter emissions while reducing CO_2 emissions by up to 97 percent .

Another shipping application case in development is the adoption of the thermocatalytic decomposition process (TCD) onboard marine vessels. The technology transforms natural gas into solid carbon and hydrogen with the help of a powerful liquid catalyst. The resulting gas can be used for gas-fired boilers, combustion engines, and fuel cells. Depending on the heating method, the process can cut overall carbon emissions by up to 100 percent.

5.2.2. Oxy-Combustion Carbon Capture Methods

Instead of using air to react with the fuel for combustion, oxy-fuel combustion technology uses pure oxygen mixed with recirculated flue gas. To reduce CO_2 emissions, the oxy-fuel combustion idea has primarily been used in large-scale power plants.

As shown in Figure 5.3, an air separation unit (ASU) is necessary to separate the pure oxygen required for oxyfuel combustion from other gases present in the air to achieve combustion in pure oxygen. Currently, the cryogenic air separation unit (C-ASU), which supplies the amount and quality of oxygen necessary on a large scale, is carrying great momentum for technological improvement. However, the high energy consumption associated with C-ASU needs to be de-bottlenecked for further use. Therefore, many other oxygen separation technologies have been brought to the table, such as advanced absorption processes, oxygen transport membranes, chemical looping combustion and partial oxy-combustion. As the combustion is taking place without nitrogen being present, the oxy-fuel combustion application onboard benefits the elimination of NO_x and nitrous oxide (N_2O) emissions, which are two of the major environmental concerns for the shipping industry. Because of that, there is the potential to significantly decrease the emissions of carbon monoxide and black carbon aerosol as well.

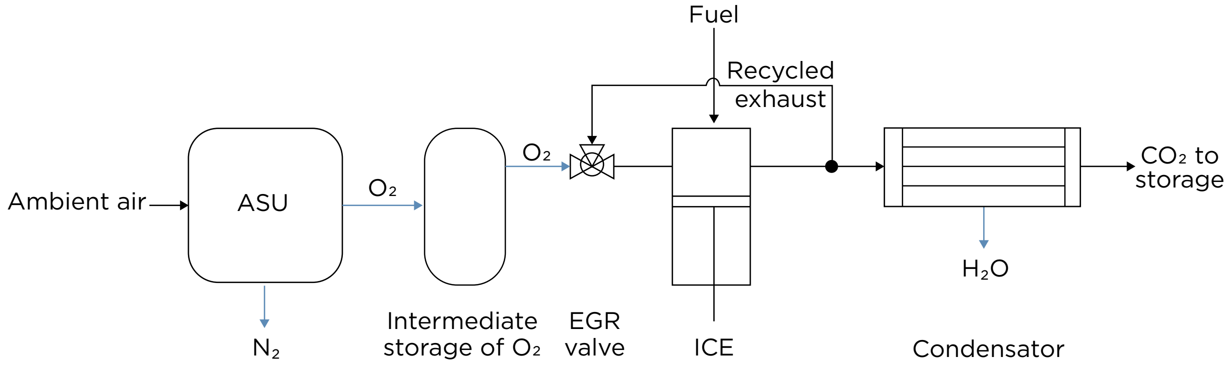


Figure 5.3: Schematic of oxy-combustion carbon capture process.

Although using CO_2 capture systems in conjunction with oxy-fuel power plants is an established technology, using such systems in ICEs designed for ship propulsion remains a significant challenge. The first challenge is to avoid high combustion temperatures in the engine due to the absence of non-reactive substances such as nitrogen. Exhaust gas recirculation (EGR), using recycled gases to dilute the oxygen-dominated combustion environment, is a major measure to lower the engine in-cylinder temperature. Water injection is another way to remove heat from the combustion chamber.

5.2.3. Post-Combustion Carbon Capture Methods

Because the pre-combustion and oxy-combustion systems must be integrated into a vessel's fuel supply and power generating system, they usually require a complete engine redesign which makes them less feasible. The most feasible method for shipboard applications is post-combustion based on either chemical absorption, membrane separation, cryogenic separation or calcium looping methods. Post-combustion technologies capture CO_2 from flue gas produced after combustion. Currently, chemical absorption is the most developed method for capturing CO_2 from combustion engines (Figure 5.4).

EXTRACTION

For post combustion systems the CO_2 is cooled in a flue gas cooling tower, then exposed in the absorption tower to an alkaline solvent, which absorbs the CO_2 in the flue gas. Solvent containing a high concentration of CO_2 is sent to the regeneration tower, where it is heated with steam to release and regenerate the CO_2. The regenerated solvent is returned to the absorption tower, where it is reused. This process can capture more than 90 percent of the CO_2 contained in the target gas.

TRANSPORTATION

Once the CO_2 has been captured, it is compressed into a liquid state. The liquid is stored on board, either in pressurized or refrigerated storage tanks or in a CO_2 battery, until the ship reaches a port with the necessary transfer infrastructure and storage infrastructure.

STORAGE

The CO_2 is transported to a suitable long-term storage solution that isolates it from the atmosphere; specific deep underground geological formations usually at depths of 1 km or more. It could also potentially be used for other purposes, such as enhanced oil recovery where it is injected into oil and gas reservoirs to increase extraction in a process known as carbon capture and utilization (CCU).

Figure 5.4: Ship-Based Chemical Absorption CCS

The typical chemical absorption-based onboard carbon capture process is illustrated in Figure 5.5. The major components are the absorber, the cross-heat exchanger, and the desorber/stripper. After the gas cooling step, the flue gas will enter the absorber column. The solvent carrying the CO_2 will pass through the heat exchanger to get into the stripper. CO_2 and the lean solvent will be separated in this desorption process. The residual solvent will go back to the first column while the captured CO_2 will be compressed into a liquid state and stored on board.

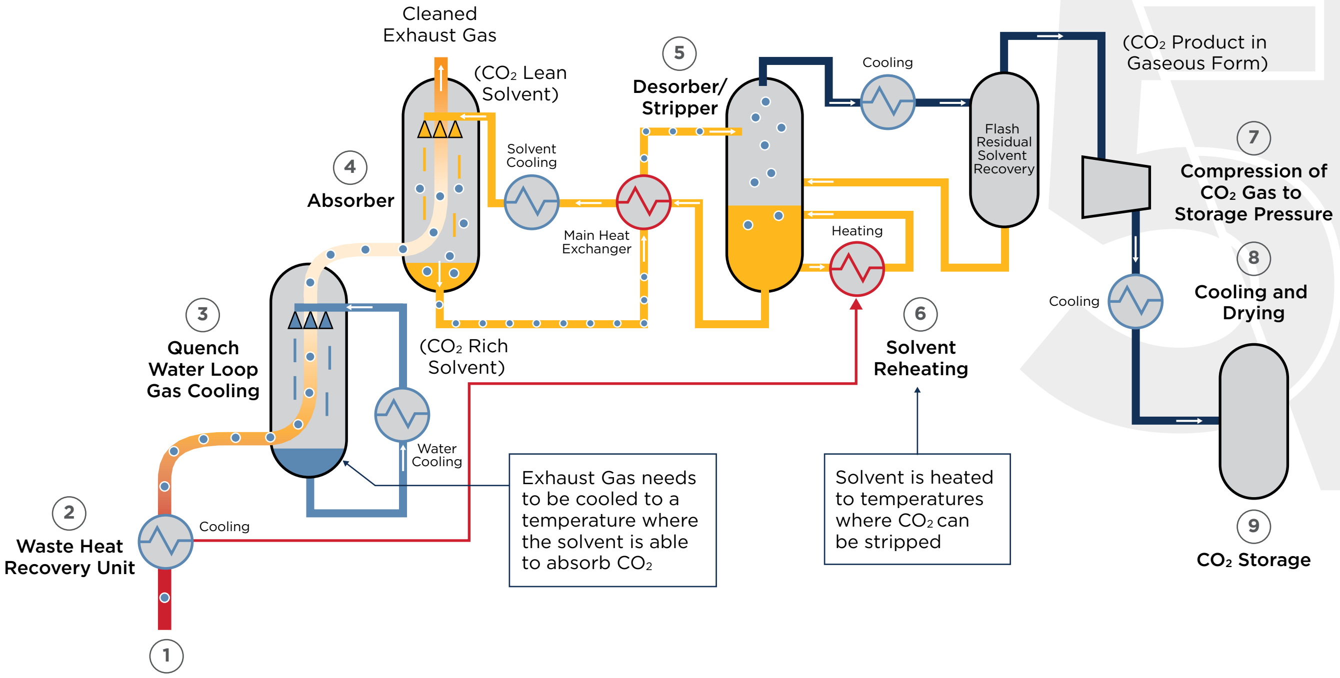


Figure 5.5: Chemical absorption-based carbon capture.

Besides chemical absorption-based onboard capture systems, calcium looping has been proven to be another candidate for OCCS. The calcium looping process is a promising post-combustion CO_2 capture technology, which is based on the cyclic calcination and carbonation of the sorbent limestone ($CaCO_3 \rightleftharpoons CaO + CO_2$). Limestone (mainly $CaCO_3$) is calcined to CaO at temperatures around 900° C and transferred to a carbonator which operates at temperatures around 650° C. In the carbonator, the calcined CaO binds CO_2 from flue gases and forms $CaCO_3$ which is transferred to the calciner to regenerate the sorbent. Figure 5.6 illustrates the concept.

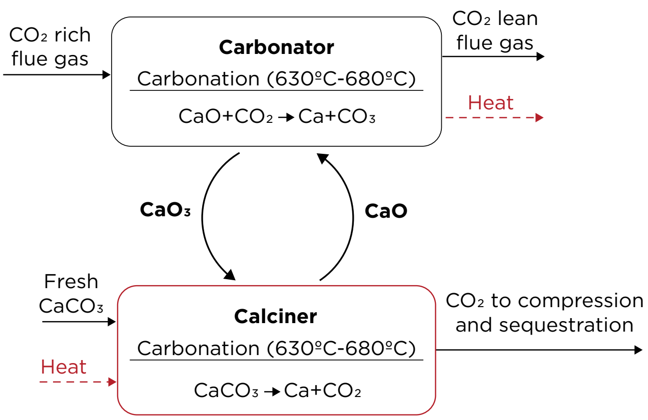


Figure 5.6: Calcium looping-based carbon capture.

Apart from these two OCCS techniques, membrane separation and cryogenic-based OCCS are the other two promising methods for capturing ship exhaust gas carbon emissions.

- In membrane separation systems, flue gases pass through membrane filters. Membrane separation is often in combination with the effects of solvents or solutes that CO_2 clings to.
- Cryogenic-based OCCS applies phase control at low temperatures, and CO_2 can be sublimated out of the exhaust gas stream (solidified) and extracted.

ABS investigated the technical performance for the most common four post-combustion onboard carbon capture technologies. It was found that chemical absorption has the highest technology readiness level. Chemical looping (CaO) performs better in energy saving. Carbon capture rates of membrane-based systems are currently lower compared to others. See Table 5.2 for details.

OCCS Method	Thermal Energy Consumption MJ/kg CO_2	Electrical Energy Consumption MJ/kg CO_2	CO_2 capture rate (%)	Purity in captured CO_2 (%)	Technology readiness level (TLR)
Chemical Absorption	-	3~5	75~98	> 97	9
Chemical Looping (calcium oxide)	2~3	-	> 88	> 95	5~7
Membrane Technology	-	3~6	> 60	> 75	3~9
Cryogenic Carbon Capture	-	-	90~99	> 99	-

Table 5.2: Post-combustion OCCS technologies parameters.

To determine which OCCS technologies are being built on board, the key performance indicators (KPI) should involve carbon capture rate, extra energy consumption, ship design integration, onboard storage, OCCS cost and operations. The detailed considerations of each KPI are summarized in Table 5.3.

Key Performance Indicators	Considerations
Capture Rate	• With current technologies, the capture rate can reach about 90% • The capture rate's validity
Extra Energy Consumption	• It consists of a series of energy-intensive processes that increase fuel consumption
Integration into the Ship Design	• Adaptation of technologies from onshore to the marine environment • Requires extra space on board vessel to accommodate capture and storage systems • Cleanup techniques for SO_x/NO_x/particulates
Onboard Storage	• Low/medium/high-pressure system
Operations	• Additional works are required for management, maintenance and handling of the systems
Capex and Opex	• Can be expensive to install and run
Permanent Storage/ Utilization	• Limited CO_2 handling infrastructure • Lack of Regulatory Framework

Table 5.3: OCCS Technologies — Key Considerations.

Among the KPIs mentioned in Table 5.2, the most important ones are carbon capture rate and extra energy consumption (energy penalty). There is always a trade-off between carbon capture efficiency and energy penalty.

For the most common chemical absorption-based carbon capture systems, ABS has compared multiple OCCS solutions. For the prevalent solvent solutions, the carbon can be captured at a rate greater than 95 percent and the energy penalty can range from 3 to 6.5 megajoules per kilogram (MJ/kg) of captured CO_2. To have an optimal carbon capture system on board, it is preferred to use a solvent with high carbon reduction performance and low energy penalty, which is depicted in the right bottom corner of Figure 5.7.

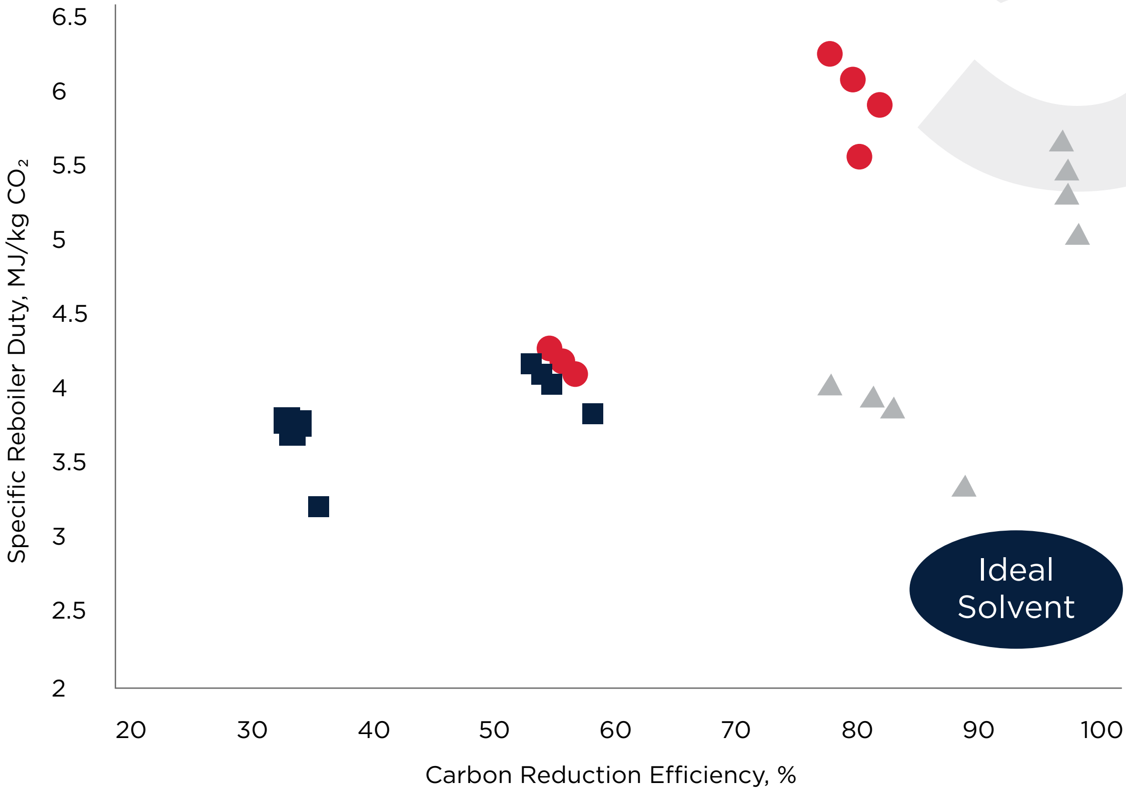


Figure 5.7: Tradeoff between carbon capture efficiency and energy penalty

In a study by Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, the extra energy use for carbon reduction was found not to vary too much by vessel type, but fuel selection did have an impact. The summarized results for the trade-off between the two KPIs of carbon capture efficiency and energy penalty are listed in Figure 5.8.

To achieve a carbon capture rate of 75 percent compared to the ship without OCCS, vessels burning low sulfur fuel oil (LSFO) required between 42 and 45 percent more energy, while the energy penalty range for methanol-fueled vessels ranges from 28 to 38 percent. Vessels using LNG as fuel require significantly less extra fuel consumption (18–20 percent). This is due to the use of the stored LNG (at minus 163° C) being used for the liquefaction of the captured carbon.

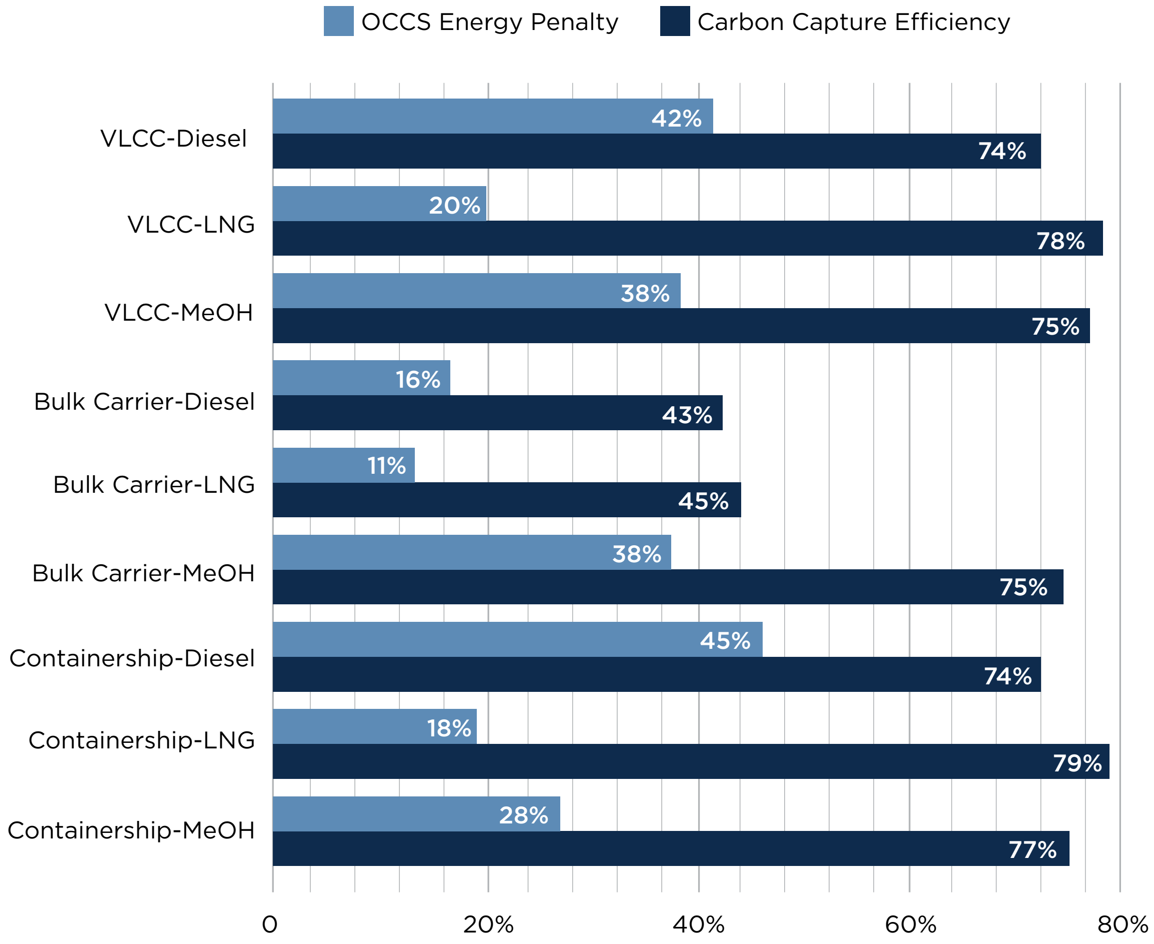


Figure 5.8: OCCS efficiency and energy penalty using chemical absorption.

Note: Carbon Capture Efficiency is based on a reduction from the ship without OCCS retrofitting; VLCCs: 300,000 dwt, bulk carriers: 205,000 dwt, containerships: 15,000 TEU.

The capex for OCCS retrofitting on different ship types presents different values compared to the newbuilding vessels. Figure 5.9 illustrates this point.

For very large crude carriers (VLCC) and containership OCCS retrofitting, the least capex case is the LNG-fueled fleet followed by the methanol-fueled fleet. The diesel-driven fleet costs the most. For bulk carriers, the methanol-fueled fleet costs the most because it is the only option to reach a carbon capture rate above 75 percent.

It is worth noting that the capex for all retrofits is well below the new ship orders. The lowest cost is 26 percent, while the most expensive one is 43 percent.

Table 5.4 summarizes the strengths and challenges of the four promising OCCS technologies.

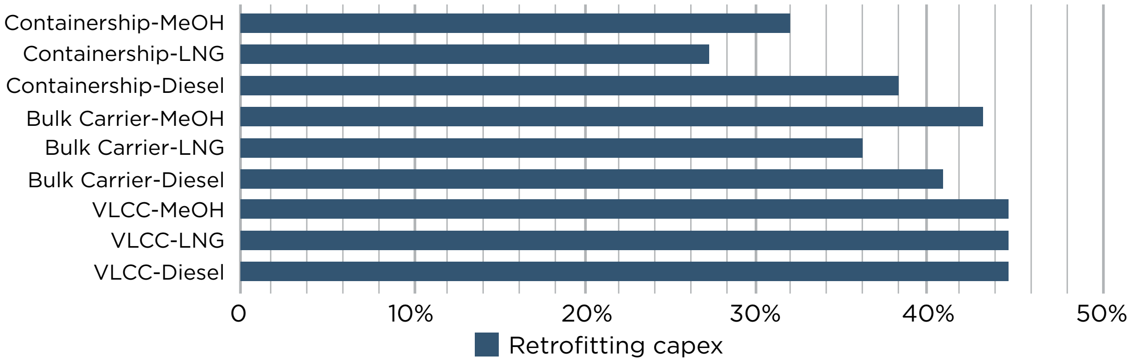


Figure 5.9: Retrofit capex compared to newbuilds.

Method	Advantages	Challenges
Chemical Absorption (Amine-based)	a. High technology readiness level (TRL); widely used in the land industry b. High capture rate potential c. High CO_2 purity d. Efficient in treating large-capacity gas through atmospheric pressure	a. Large mass flow of solvent b. Higher thermal energy consumption c. Exposure to amines/ammonia d. Complex design and plant size e. Solvent degradation/lifetime f. Harmful emissions may be formed from the degradation process of the amine
Chemical Looping	a. Smaller installation area b. Lower energy demand c. No requirement for CO_2 storage on board	a. Disposal of $CaCO_3$ b. High number of tanks c. Effectiveness depends on raw limestone hardness d. Lack of large-scale operation experience e. A high operating temperature is required for the reactor
Membrane	a. Simpler system layout b. No need for solvent solutions, regeneration units c. Smaller footprint d. Less environmental impact e. Low cost	a. Membrane unit fouling b. Less effective when CO_2 content <10% c. Difficulty to achieve desired CO_2 purity d. Purity and capture rate are linked e. Low technology maturity f. Aging and replacement costs g. Large electrical consumption h. Damage issue of barrier film by high temperature i. Low efficiency in treating large-capacity gas
Cryogenic	a. Able to remove several components in exhaust gases b. Lower opex in comparison with chemical absorption-based technologies as there are no solvents involved. c. High CO_2 purity d. High capture rate potential e. Opportunities to integrate with existing LNG systems	a. Higher onboard power consumption b. Low to medium technology maturity c. Feed composition must be stripped of water to prevent ice-plugging

Table 5.4: Comparison of OCCS post-combustion technologies.

The key takeaways are:

- Chemical absorption has the highest technology readiness level, but higher thermal energy consumption is expected.
- Chemical looping (CaO) performs better in energy-saving and has no requirement for liquefied CO_2 (LCO_2) storage on board, while the major hurdles are limestone disposals and high operating temperature.
- Carbon capture rates of membrane-based systems are currently lower compared to others, but its simpler system layout and smaller footprint are the advantages.
- Cryogenic systems are possible to integrate with existing LNG containment systems, but their feed composition must be stripped of water to prevent ice plugging.
- While onboard carbon capture percentages of 80 percent and greater are achievable, more energy and equipment may be disproportionately required, making it less economically beneficial. Therefore, a decision must be made on the percentage of carbon captured based on the trade-off between cost, storage space for onboard capture systems, energy requirements and emission reduction goals.

5.2.4. Value Chain Insights

Beyond the viability of OCCS technology for reducing CO_2 emissions in shipping, there are some broader insights and value chain connections that are equally important.

1. Systemic Impact on Global Shipping Routes and Logistics: The integration of OCCS technology might necessitate changes in global shipping routes and logistics. For example, the requirement for CO_2 offloading facilities could influence port infrastructure and the routing of ships to include stops at these facilities. This could have significant implications for global trade flow and shipping logistics.

2. Broader Environmental Life Cycle Analysis: Beyond the direct CO_2 emission reductions achievable through OCCS, there is also the environmental impact of manufacturing, maintaining, and eventually disposing of OCCS systems.

3. Impact on Maritime Labor and Training: The installation and use of OCCS on ships will likely require new skills and training for the crew. The need for specialized knowledge in handling, monitoring, and maintaining OCCS systems could necessitate a shift in maritime education and training programs.

4. Economic Implications Beyond Direct Costs: The economic analysis in this document primarily focuses on capex and opex. However, broader economic implications such as the potential for job creation in new areas (like onboard carbon capture maintenance and CO_2 handling) or job displacement due to changes in vessel operation requirements could be significant.
5. Regulatory and Policy Frameworks: Future regulatory requirements could potentially affect the adoption of OCCS and could accelerate or hinder the deployment of OCCS.
6. Alternative use of Captured Carbon: There are emerging technologies and markets for reusing CO_2 in ways that could generate additional revenue streams for shipping companies, such as converting captured CO_2 into synthetic fuels or other marketable chemicals.
7. Interplay with Other Decarbonization Technologies: The interaction between OCCS and other emissions reduction technologies (like cleaner fuel alternatives, improved vessel design, and operational efficiencies) will have synergistic effects. An integrated approach to adopting multiple technologies could provide more substantial emissions reductions than OCCS alone.

5.3. Wind Assisted Propulsion

In the past decade, the ongoing need for improving a vessel's operational efficiency and reduction of fuel consumption and emissions, has taken center stage. Wind-assisted propulsion systems (WAPS) are continuously evolving and are now considered a potential energy saving solution. These technologies harness wind power to assist traditional engines, offering both economic and environmental benefits.

The main systems currently explored by the industry are listed below:

Rotor Sails

Rotor sails, or Flettner rotors (Figure 5.10), are cylindrical towers that use the Magnus effect to create thrust from wind. Newer designs focus on collapsible or retractable rotors that can be used on routes with varying air drafts or under bridges. Rotor sails are the modernized version of the Flettner rotors and are considered mechanical sails. They are mechanically operated cylindrical sails installed vertically on the deck of a ship and rotate at a given speed range. The ship is propelled forward by the wind when the wind is perpendicular to the ship's length.

In the case of a rotor sail, the rotor sail rotates, inducing a pressure differential between its opposite sides when exposed to wind. When the rotor rotates, a small boundary layer is formed around it. This layer of air follows the rotating surface of the cylinder, which causes the boundary layer on one side to flow against the wind flow direction and be decelerated, while the opposite side of the rotor is being accelerated by the simultaneous wind flow. This then creates a pressure differential in which a force, perpendicular to the wind flow, is generated from a region of high pressure toward an area of low pressure.

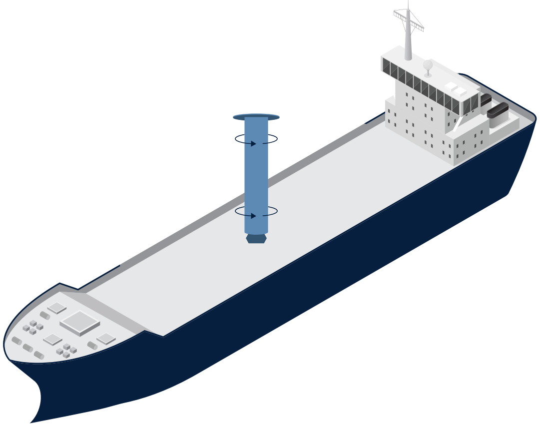


Figure 5.10: Rotor sail.

The maximum exploitation of the wind happens in beam reaching directions to the ship because the rotor sail always produces a thrust force perpendicular to the wind air flow. The thrust force magnitude is increased or reduced by the speed of rotation of the rotor sail. The maximum possible thrust is developed at straight beam reaching and with maximum rotation speed. A drag force in the same direction of the wind is also present. This force is related to the windage area of the rotor.

Wing Sails

Modern wing sails, which are rigid and aerodynamically efficient, have evolved significantly (Figure 5.11). They can be automated to adjust to wind conditions for optimal performance.

Wing sails are mounted vertically on the main deck and/or forecastle of the ship and operate under the same aerodynamic lift principles as an aircraft wing.

When they move through a fluid, it produces an aerodynamic force which consists of lift and drag. By rotating the sails to the optimum angle of attack, the lift can be maximized. As the wind flows along the wing sail, the air flows faster on one side of the sail due to the cross-sectional geometry of the sail. According to Bernoulli, if the velocity drops, then pressure rises and vice versa. Because of this, a pressure difference between the two sides of the cross-section exists, and a net force is created.

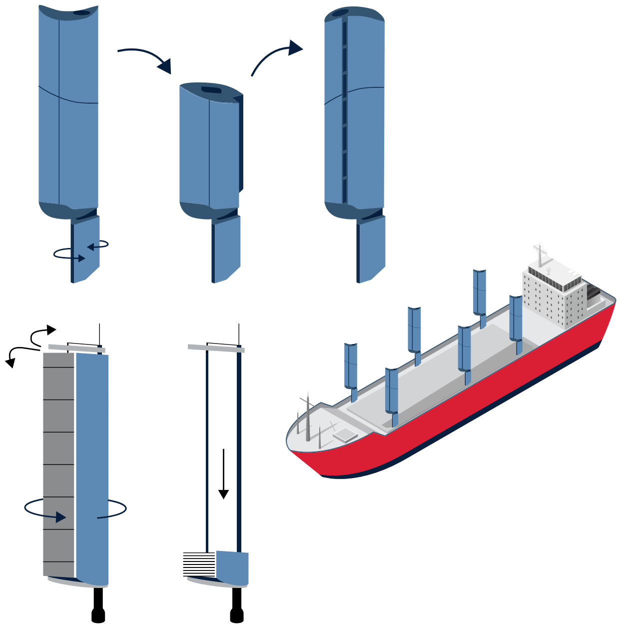


Figure 5.11: Wing sails.

Rigid wing sails are of a similar concept to the classic soft sails design. However, the sails are comprised of rigid material to make the sectional profile of the sail more stable. These sails resemble that of an aircraft wing in the cross section.

Soft wing sails are like rigid wing sails. However, they do not have a rigid wing coverage surface material, but rather a softer material. This allows furling and adjusting of the variable camber of the wing profile. These sails are asymmetric and can be equipped with trailing flaps. Like rigid wing sails, soft wing sails operation is fully automatic, and they use a wind gauge and other weather information to orientate their angle of attack and wing camber for producing the maximum lift and thrust force.

Suction Sail

The suction sail (i.e., fixed or retractable) resembles the rotor, but unlike the rotor, the sectional shape is more of an egg-shaped profile with a large thickness (Figure 5.12). The suction sail is not self-rotating and includes a built-in mechanical air suction mechanism. Suction sails can develop lift forces comparable to a rotor, but without any rotation or relevant power demand and while keeping the aspect rations lower than a similar rotor sail.

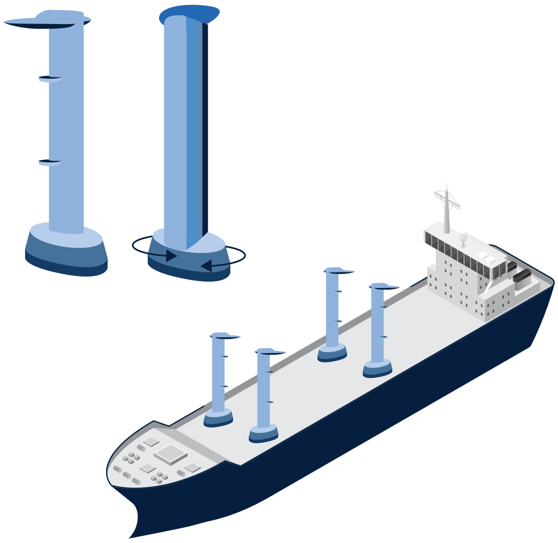


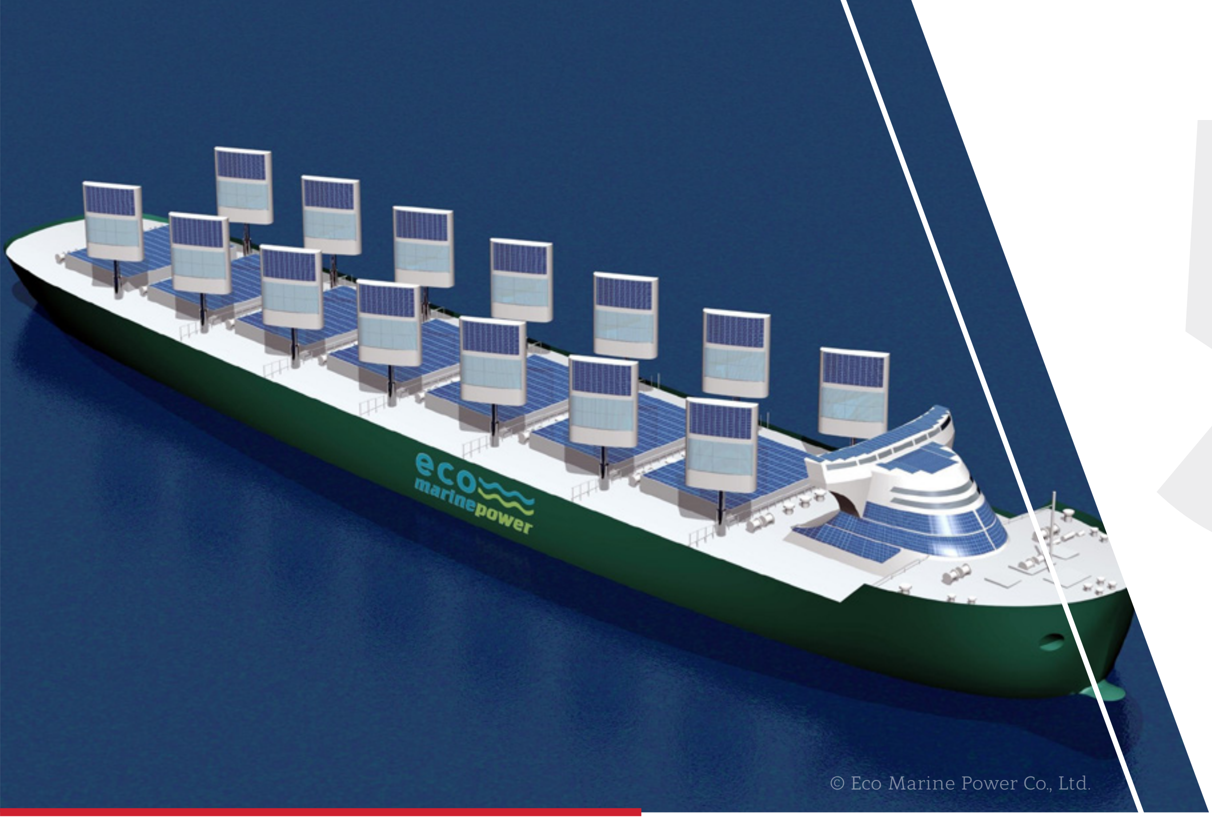
Figure 5.12: Suction sail.

The thrust force generated from the suction wing sail depends on a combination of variables such as the ventilator power (related to wind speed), effective boundary layer suction, position and size of the suction holes, shape of the profile selected, and angle of attack of the apparent wind.

The direction of the leading edge of the sail (the sharp nose of the cross section) is adjusted to an optimal angle of attack to the apparent wind each time. To control the airflow around the thick foil-shape, a boundary layer suction is applied, and a ventilator needs to be installed inside the suction wing profile. At the leading edge, the airflow is accelerated, which leads to very low pressure on the top left side of the profile and all along the suction side. This suction dramatically improves the lift coefficient and reduces the drag coefficient, which in turn counterbalances the air flow disturbances in the boundary layer after the high acceleration side. This prevents separation of the flow that occurs due to the thick profile shape, while also maintaining the advantages of high-pressure differential developed because of the thick shape.

Kite Sails

Skysails and similar systems use large kites flown ahead of the vessel to generate propulsion (Figure 5.13). Kite sails are not supported by masts and operate



© Eco Marine Power Co., Ltd.

away from the ship structure. These systems are particularly useful for open ocean travel and can be retrofitted on existing vessels. Recent advancements have improved the automation and control systems to optimize kite performance based on real-time weather data.

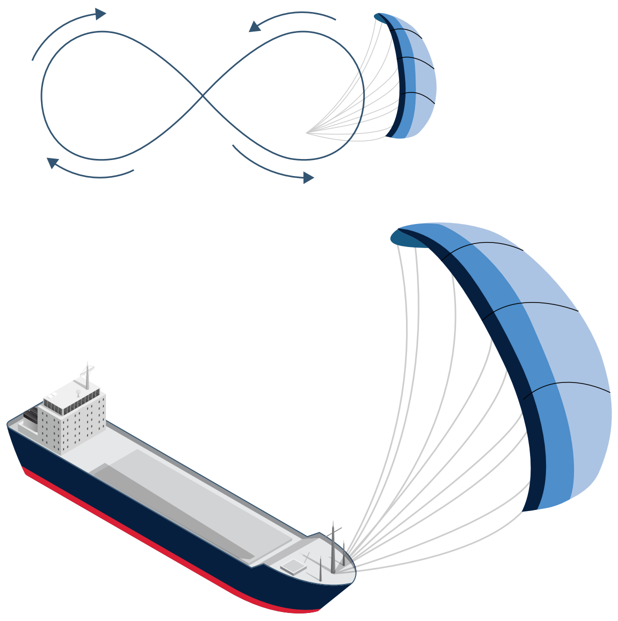


Figure 5.13: Kite sails.

Kites are installed in the forecastle in a way that it can exploit tailwinds and broad reach directions. The force that generates the kite is transmitted to the ship by a towing rope. Thus, kites work by generating a towing force or traction force rather than a propelling force or thrust. Kites need a minimum wind speed to lift-off, but then can operate at smaller than lift-off wind speeds. When the wind conditions become unfavorable (i.e., headwind), the kite comes in the neutral/parking position where no forward thrust is generated. The performance and efficiency of kites are most optimal when flying with what is known as the power zone, which has an elevation of 10–35 degrees from the sea level. Kites achieve the most optimal towing force to the ship when the wind direction is in the reaching course or side tailwind rather than in the running course or full tailwind. This is due to the benefit of apparent wind speed.

When operating in thrust generating zones and altitudes, the kite moves dynamically in a figure eight manner. During this figure eight movement, the relative velocity of the wind around the kite's geometry generates extra lift forces due to the kite's much larger apparent wind. Through this, the kite maximizes the traction force by flying fast into the incoming wind while towing the ship at the same time. Therefore, it can generate multiple times of thrust compared to other on-deck mounted wind assisted propulsors just because of the dynamic movement of the kite inside the wind and because of the stronger and more stable high-altitude winds it is operation.

Some of the newer WAPS technologies integrate multiple types of wind-assist technologies along with solar and wave energy. These hybrid systems aim to maximize the renewable energy harvested on board, pushing the limits of what is possible in emission reductions.

5.3.1. WAPS Providers Market Update

Based on information received by a number of ship owners, ship operators and WAPS providers, Table 5.5 provides an overview of the industry uptake of WAPS.

The vessel types where WAPS have been installed and are in-service include bulk carriers, tankers, general cargo, roll on/roll off (ro/ro), roll on/roll off passenger (ro/pax), fishing vessels, and small cargo vessels.

Type of system	No of WAPS providers in the market	No of Vessels with WAPS installed and in service	No of Vessels awaiting WAPS installation	No of new WAPS providers considering entering the market
Rotor Sail (i.e., Flettner)	7	12	11	2
Wing Sail (i.e., Fixed or Reefable)	12	5	9	4
Suction Sail (i.e., Fixed or Retractable)	3	5	6	1
Towing Kite	2	1	3	1
Total	**24**	**23**	**29**	**8**

Table 5.5: WAPS uptake (as of end of 2023).

5.3.2. Prediction Of Fuel Consumption Savings

Considering the intent behind installing WAPS on vessels, the main interest of a ship operator is a technically sound prediction of the fuel consumption savings. Ship operators are accustomed to other energy efficiency technologies (EETs), where the respective providers have been indicating a percentage of fuel savings. For WAPS the prediction is bespoke and parametric, (i.e., the predicted savings will vary to the assumed conditions and route).

Moreover, it should be highlighted that there are three kinds of predictions with different confidence levels:

- Low Confidence
- Medium Confidence
- High Confidence

The Low Confidence Prediction may be considered for academic purposes. Low Confidence Prediction is often available through various web-applications, some even on a gratis basis. However, these applications do not consider vessel-specific, including propeller, characteristics.

The Medium and High Confidence Predictions should always be considered by shipowners and operators before making a decision on the installation of a WAPS:

- The Medium Confidence Prediction is a desktop exercise based on naval architecture principles, thus requiring specific information to be carried out.
- The High Confidence Prediction is based on numerical analysis, such as computational fluid dynamic (CFD), where the minimum objective will be to derive either/or:
  - The aerodynamic characteristics of the WAPS in case these are neither available from dedicated wind tunnel tests nor from full scale laboratory tests, or in case the interaction effects between two or more WAPS need to be studied with higher fidelity.
  - The response of the vessel-WAPS as a system, if this needs to be studied with higher fidelity.

Since a WAPS project requires substantial resources, both funds and time by the shipowner and operator, the Low Confidence Prediction approach for commercial reasons. Instead, ship owners and operators should aim for at least a Medium Confidence Prediction, which can be relied upon to better scope the WAPS for the intended operation. Subsequently, in combination with the WAPS provider, it can better size up the potential investment versus the potential savings.

In the context of Medium Confidence Prediction, shipowners and operators will need to obtain information related to the methodology the WAPS provider is using for the prediction of the fuel savings. The methodology used for the prediction of fuel savings will need to incorporate all the following considerations, otherwise it's likely that a Low Confidence method was used.

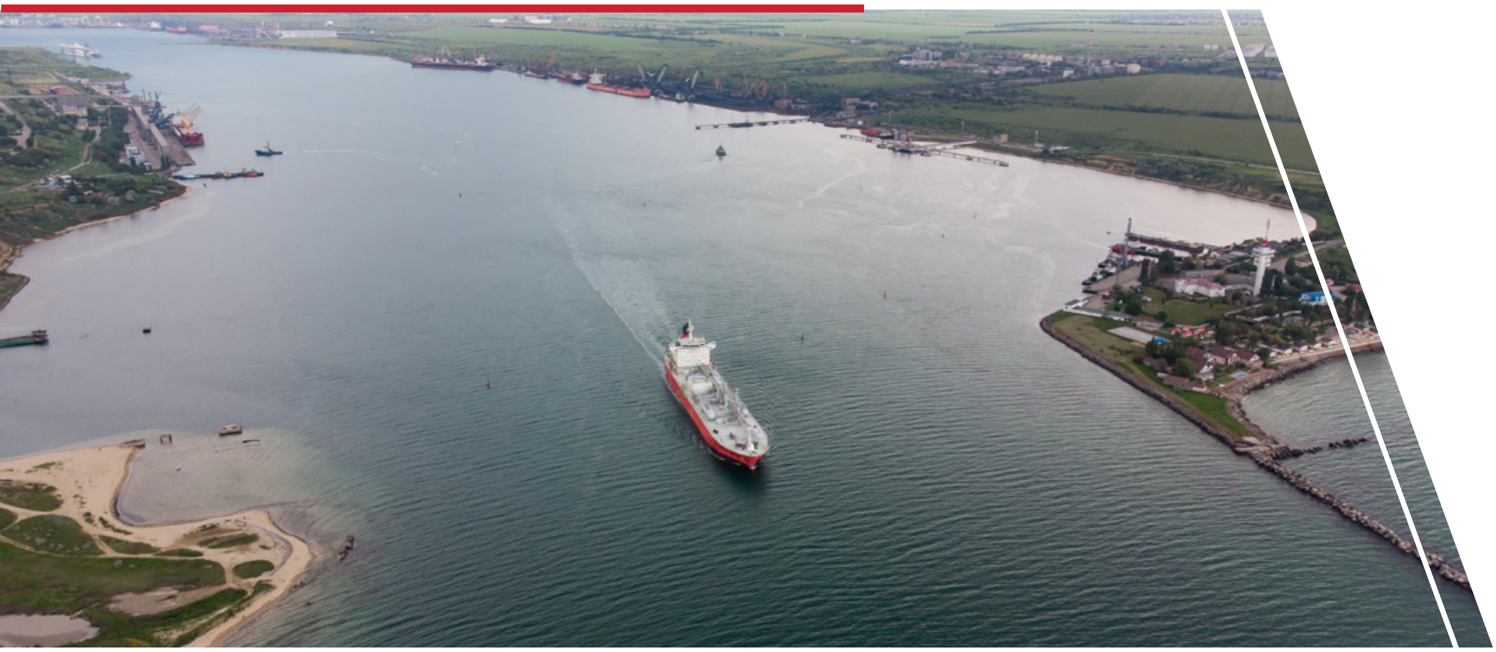
- Methodology should be consistent with naval architecture ship propulsion principles, i.e., considering the thrust due to WAPS as well as the added resistance components (wave, wind), applying hydrodynamic coefficients and solving through propeller open characteristics.
- Vessel-specific data, including sea trials, propeller open water characteristics, hydrodynamic coefficients, etc.
- WAPS-specific geometry and aerodynamic characteristics (usually in tabular format) including lift, drag, rotating speed or angle depending on the system and required WAPS power.
- Operating-specific profile in order to derive the environmental conditions (e.g., wind speed, direction, significant wave height, peak wave period) to be used in the calculation.
    - Route, i.e., Port A to Port B
    - Time Period, i.e., Month A to Month B
    - Vessel Draft
    - Vessel Speed over Ground

In the case of a retrofit project, the shipowner/operator should aim to commence with a Medium Confidence Prediction approach by carrying out relevant studies for a variety of operating profiles. The process has several loops whereby the WAPS may be resized (via WAPS provider) or the operating profile amended (via the ship operator).

5.3.3. Life-Cycle Cost Analysis

The results of the prediction of the propulsion fuel savings should then be considered by the shipowner and operator through a life-cycle cost analysis (LCCA), which will require input from the WAPS provider such as capex, additional opex and input from the operator in terms of recent actual fuel consumptions. A typical LCCA study will include any assumptions made, such as fuel savings, fuel cost increases, inflation rate and results along the lines of:

- Discounted Payback (years)
- Savings to Investment Ratio (SIR)
- Total Investment over Life
- Average Annual Savings (Net present)
- Cumulative Discounted Cash Flow



5.3.4. Retrofit Integration

The installation of a WAPS is not a common retrofit, and therefore the owner should plan such a project with close collaboration from the WAPS provider. The installation of a WAPS will need to be integrated both to the vessel structure and systems as well as to the vessel's operation.

Most owners have experience with other EETs where the off-hire time needed is, in most cases, known and manageable. In the case of WAPS, the owner will need to deal with a substantial project, requiring coordination not only with the WAPS provider but with many more parties. The project's success will depend on the integration of the technology with the vessel's operation.

In the context of integration, issues to be addressed may include:

- Installation plan and assembly, a subject often not discussed upfront
- Available deck area allowing for cargo handling and passage
- Structural reinforcement and impact on lightship
- Stability
- Course keeping and maneuverability
- Visibility
- Equipment number
- Revised plans and drawings
- Power management
- Crew access and maintenance

During the initial stages of a WAPS installation project, a hazard identification (HAZID) study/workshop would need to be performed. The objective is to identify hazardous scenarios and their effective safeguards. This process requires the engagement of the WAPS provider, ship designer, shipowner and operator.

5.3.5. In-Service Live Monitoring — Optimum Use and Safety

One of the issues that will need to be considered during the installation of a WAPS is whether there is a supporting capability for live monitoring and crew guidance regarding optimum use and safety during voyage. The shipowner/operator should confirm this with the WAPS provider.

While fuel consumption savings is the main objective of installing such a system, safety always needs to be prioritized. For instance, it's important to monitor temperature, vibration, accelerations, etc., to be within operational limits.

This topic relates to the next one since at some stage there will be a need for in-service measurements to be collected for evaluation purposes.

5.3.6. Performance Evaluation

The evaluation of the WAPS performance after installation will need to take place during service via measurements or dedicated trials. Any performance evaluation will need to be carried out by a third party.

5.4. Beyond the Engine

There are three emission-free drivers that are not talked about enough – electrification, nuclear energy, and the role of advanced digital technologies, seen in Figure 5.14. These powerful resources can be linked and offer high potential to advance decarbonization of the shipping industry.

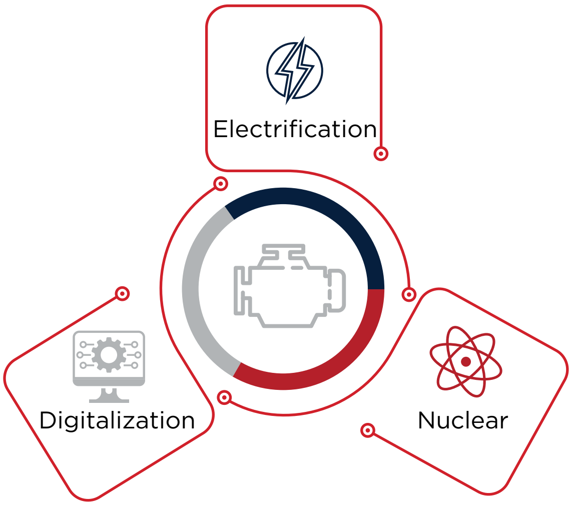


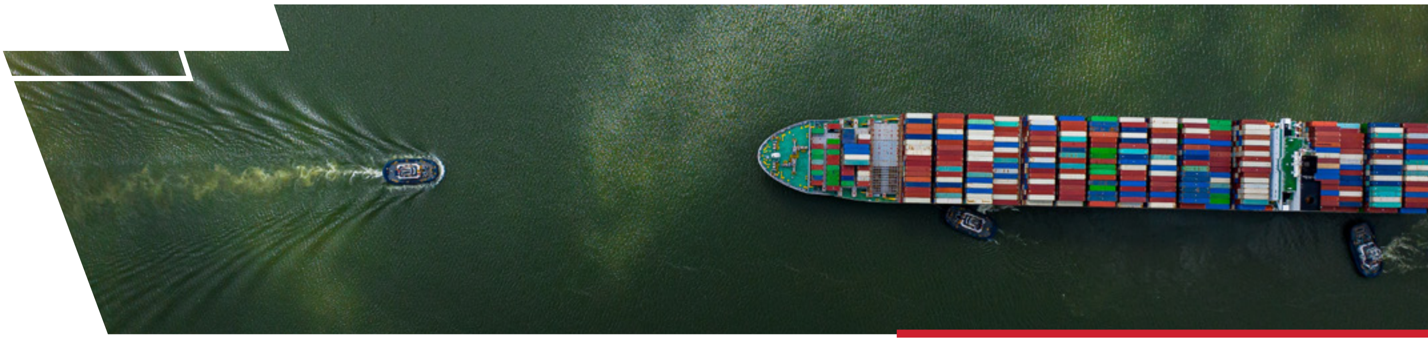
Figure 5.14: Beyond the engine — electrification, nuclear energy and digitalization.

Alternative fuels can be viewed as an essential stepping-stone to electrification – meaning the replacement of fossil fuel technologies and processes like internal combustion engines. Low-carbon fuels and carbon capture systems will lower the industry's emissions while technology develops through diesel electric to hybrid systems and ultimately, fully electric when battery technology and charging hub networks reach sufficient levels to support longer voyages with larger ships.

Lead acid batteries have been around for a while but have a low energy density. Lithium-ion batteries are readily available now as an improved battery technology. New battery technology is driving up the energy density curve with technologies such as lithium-polymer, metal halide and redox flow. Figure 5.15 illustrates the typical types of battery technology and their key parameters.

Fuel cells are another type of electrochemical device that converts fuel into electricity through chemical means. For example, in a hydrogen fuel cell, hydrogen fuel is exposed to an electrolyzer and produces an electric current with water and excess heat as byproducts. Fuel cells have better energy density than batteries and don't require recharging from land but use expensive materials and are subject to transient loads.

In addition, there are other electrical storage technologies that may play a part in the future such as photovoltaic panels or super-capacitors.



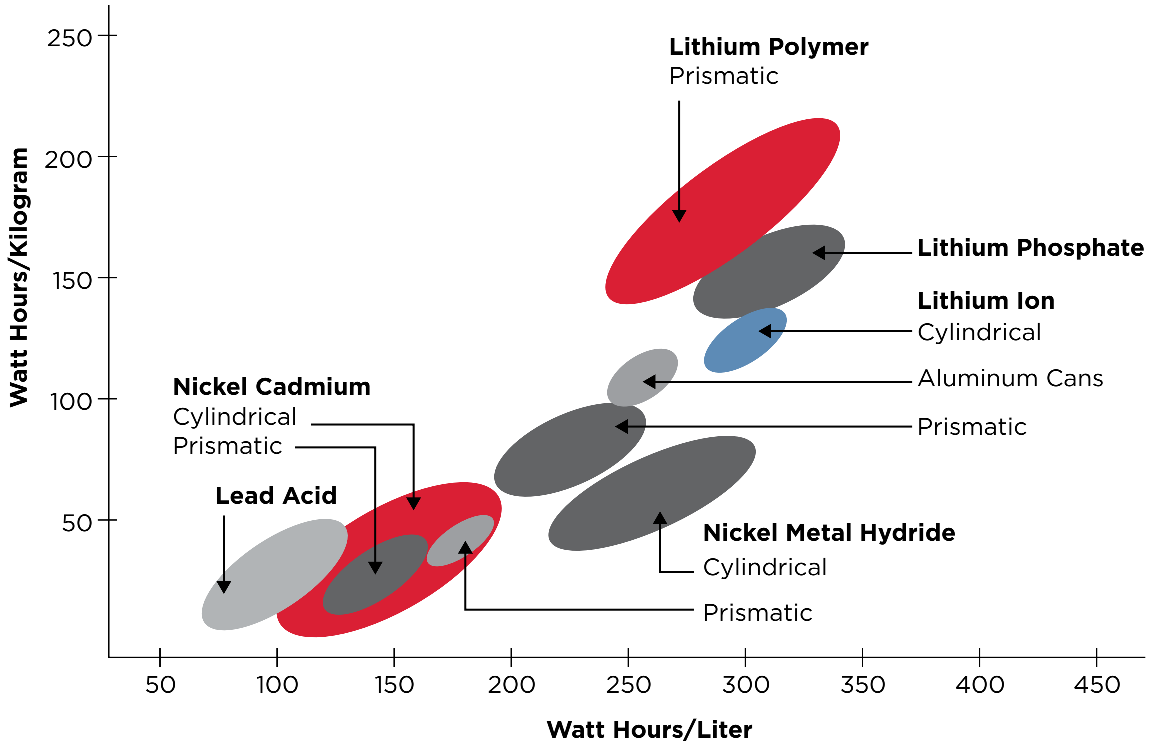


Figure 5.15: Parameters of typical types of battery technologies.

Nuclear and renewable-based energy systems extend our line of sight of solutions to achieve net zero by 2050. They can be integrated to work together rather than compete – and this is what makes nuclear power unique.

Nuclear energy is both an enabler for clean fuels, as a producer of hydrogen, and a power source for primary movers. With the small footprint and continuous power generation potential of advanced reactors, the technology offers material advantages in the production of e-fuels such as e-ammonia, e-methanol, pink hydrogen or even carbon-neutral, drop-in renewable diesel fuel.

Digitalization continues to evolve at a rapid pace and can further support the pathway to zero emission.

5.4.1. Fuel Cells

Fuel cells have emerged as a promising solution for decarbonizing marine transportation. Unlike traditional combustion engines, fuel cells generate electricity through an electrochemical process. Hydrogen serves as the primary fuel, producing only water vapor as a byproduct.

In the framework of sustainable maritime transportation, the available fuels for fuel cells – hydrogen, ammonia, renewable methane, and methanol – as well as the pre-processing technologies for them are examined.

Based on different types of electrolytes, the fuel cells for maritime applications are categorized as shown in Table 5.6. In addition, Table 5.7 provides a summary of all the technical parameters of the different fuel cell candidates.

Alkaline Fuel Cell (AFC)	AFCs use an alkaline electrolyte, usually a potassium hydroxide solution as their electrolyte. As they produce only water and heat, AFSs have good emission control benefits, and their stable operation performance makes them an FC candidate.
Proton Exchange Membrane Fuel Cell (PEMFC)	PEMFCs and HT-PEMFCs use polymer electrolyte membranes. They are lightweight and suitable for various applications. Their advantages are high energy efficiency, quick start-up, lightweight and compact design.
High-Temperature Proton Exchange Membrane (HT-PEMFC)	
Direct Methanol Fuel Cell (DMFC)	DMFCs have simple liquid fuel storage with lightweight and low volume. DMFCs can operate at low temperatures and pressures, and they do not require maintenance.
Phosphoric Acid Fuel Cell (PAFC)	PAFCs are highly efficient at converting fuel into electricity, reducing energy waste. Moreover, PAFCs can operate above the boiling point of water, unlike other acid electrolytes that require water for conductivity.
Molten Carbonate Fuel Cell (MCFC)	MCFCs operate at high temperatures (600–700° C) and use a molten carbonate electrolyte. MCFCs can use natural gas, biogas, or hydrogen as their fuels.
Solid Oxide Fuel Cell (SOFC)	SOFCs operate at around 800° C and use a solid ceramic electrolyte. They are suitable for large-scale applications. SOFCs have strengths in high energy conversion efficiency, fuel flexibility, and long-lasting lifetime.

Table 5.6: Fuel cells for maritime applications.

Fuel Cell Type	Operating Temp C	Power Range	Electric Efficiency	Typical Fuel
AFC	50–200	≤500 kW	50–60%	H_2
PEMFC	25–100	≤120 kW	40–50%	H_2
HT-PEMFC	110–220	≤1 MW	50–60%	H_2
PAFC	100–200	100–400 kW	40–45%	H_2, CH_3OCH, LNG
DMFC	75–120	≤5 kW	20–30%	H_2, CH_3OCH
MCFC	650–700	120 kW–10 MW	50–55%	H_2, CH_3OCH, Hydrocarbons
SOFC	500–1000	≤10 MW	50–65%	H_2, CH_3OCH, Hydrocarbons

Table 5.7: Parameters of typical types of fuel cells for maritime applications (continued on next page).

In summary, each type of fuel cell has its advantages and challenges. The fuel cell evaluation depends on factors such as efficiency, operating temperature, fuel availability, and vessel requirements.

So far, PEMFC and SOFC have been successfully adopted and operated on marine vessels. When energy efficiency, power capacity, and sensitivity to fuel impurities are considered, the most promising solutions are found to be the PEMFC, MCFC and MCFC types of fuel cells. As technology advances and infrastructure improves, fuel cells will play an essential role in achieving zero-emission marine propulsion.

5.4.2. Battery/Hybrid Ship Propulsion Systems

Battery energy storage systems (BESS) and hybrid systems combine energy storage (vessel batteries) with conventional engines. Ships with hybrid propulsion systems can meet their propulsion requirements in various scenarios by combining fuel-burning engines with electric motors and batteries.

These technologies can lower maintenance costs, increase fuel efficiency, and aid regulatory compliance. Hybrid systems are ideal for vessels that have flexible operation profiles and running hours with varying power demands.

The marine electric vehicle market is driven by on-water applications, which are being driven by the growing emphasis on environmental sustainability and the reduction of GHG emissions. Battery/hybrid ship propulsion systems have already been applied to power smaller vessels and port handling equipment, and transitioning to larger ships is underway. The

	Drawbacks	Electrolyte	Relative Cost	Life Span	Size
	CO_2 poisoning	Potassium hydroxide	Low	Medium	Small
	CO + S poisoning	Proton-conducting polymer membrane	Low	Medium	Small
	CO + S poisoning	Proton-conducting polymer membrane	Medium	Medium	Small
	CO + S poisoning	Liquid phosphoric acid	Medium	Good	Large
	methanol crossover	Proton exchange membrane	Medium	Medium	Small
	S poisoning, cycling effects, long start-up time	Molten carbonate salt mixture	High	Good	Large
	S poisoning, cycling effects, mechanically fragile, long start-up time	Porous ceramic material	High	Medium	Medium

Table 5.7: Parameters of typical types of fuel cells for maritime applications (continued from previous page).

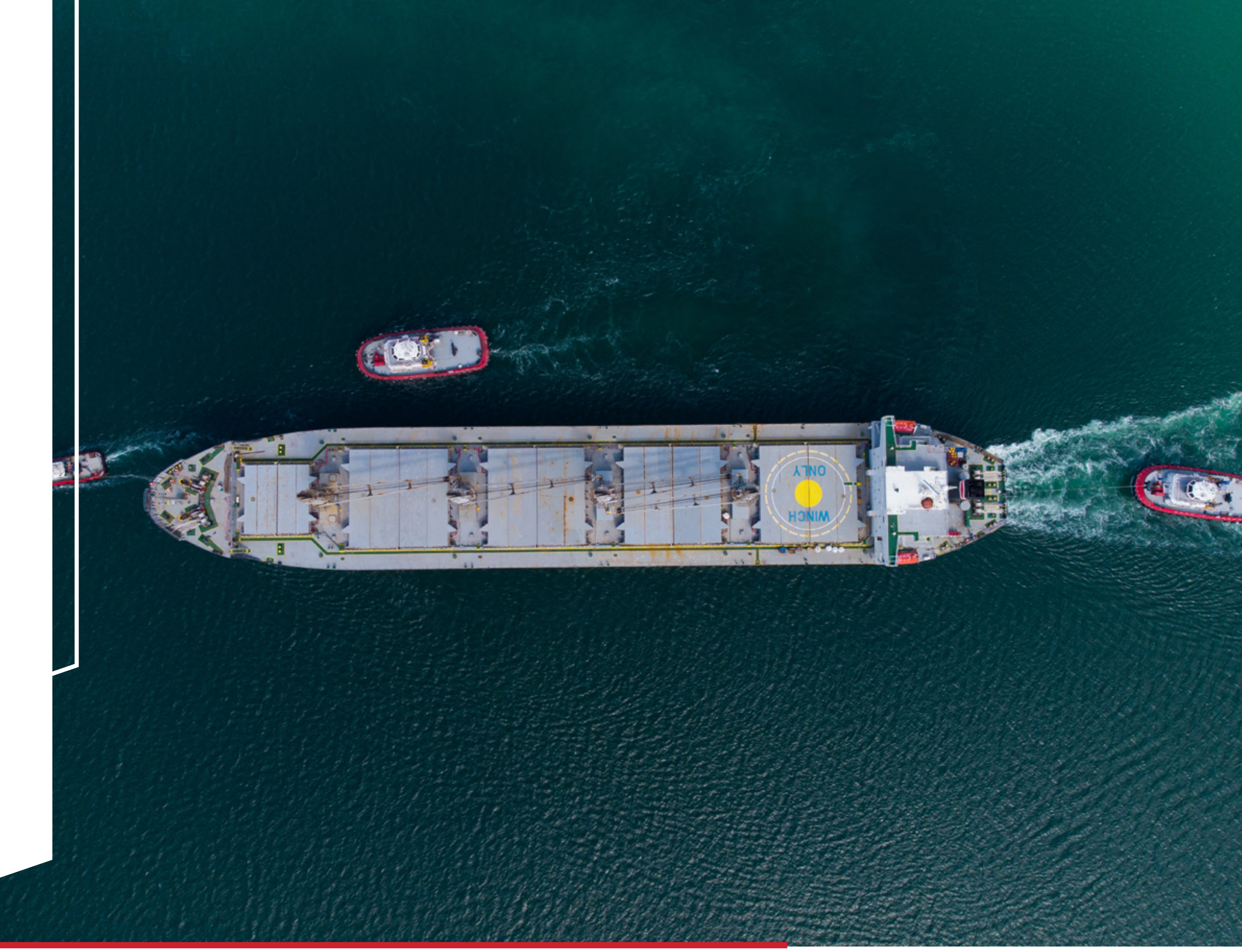
maritime industry segments that have the most interest in battery and hybrid systems include ferries, defense vessels, yachts, tugboats, hybrid boats, recreational boats and unmanned maritime vessels.

Technology benefits of battery/hybrid systems involve:

- Optimal load: Electric propulsion systems can be more economical, especially in partial propulsion power mode. Batteries absorb load fluctuations, allowing engines to run at optimal efficiency.
- Fuel savings: Battery and hybrid ships can reduce fuel costs and maintenance costs due to load balancing.
- Emission reduction: Lower GHG emissions. Hybrid ships can lower emissions compared to diesel-powered and they can help shipowners comply with emissions regulations.
- Onboard operational advantages: Electric propulsion systems can be vibration-free and low-noise. They can also have a high degree of reliability, availability and redundancy. Electric propulsion systems can offer flexible space configuration.
- Operational properties: Electric propulsion systems can offer flexible space configuration and ship mechanical operation properties.

The key considerations for adopting this maritime decarbonization solution are as follows.

- Initial cost: Hybrid systems may have higher upfront costs.
- Space and weight: Larger space requirements and weight considerations.
- Integration complexity: Integrating hybrid systems can be challenging.



- Regulatory compliance: Meeting safety and environmental regulations

ABS' Well-to-Wake (WtW) Insights on Battery/Hybrid Systems

- Battery/hybrid systems are deemed clean for Tank-to-Wake (TtW) emissions, not for Well-to-Tank (WtT). Many studies have reported GHG emissions from battery production are even worse than conventional marine fuel production.
- Energy sources utilized to generate electricity are a major component in determining the ship's WtW GHG emissions. Only highly renewable electricity has the potential for battery-driven vessels to achieve long-term decarbonization goals.
- The WtW emissions of battery/hybrid propulsion systems are highly sensitive to the locations where the hybrid ships are in service. Most of the existing value chains showed limited improvement in GHG emissions saving compared to diesel-driven vessels.

5.4.3. Nuclear Power as an Alternative Energy Source

Nuclear energy has received increased attention as a possible source of clean energy for decarbonizing the marine industry. Widespread application of advanced reactors may be a key pathway toward achieving carbon emissions reduction and producing clean alternative fuels. This section examines the nuclear energy value chain including its wide array of possible implementations.

5.4.3.1. Status, Benefits and Challenges

Currently, the civilian use of marine nuclear technology is limited to several vessels operating in the Russian Arctic, including a fleet of icebreakers and a floating power plant commissioned in 2020. Several projects are currently under various stages of development, however, the planned demonstration of several advanced nuclear reactors for maritime applications is possible in many countries over the next decade. Refer to the current list of ongoing projects in Table 5.8.

Project	Details	Timeline
Viaro Energy and Newcleo Partnership for oil and gas nuclear technology applications	The project consists of a feasibility study to be conducted for the implementation of several 200-megawatt lead-cooled fast reactors to reduce the climate footprint of operations.	Partnership announced in 2024
ULC Energy and BHP partnership for nuclear-powered cargo ships	The project consists of a study to evaluate various nuclear reactor designs as well as the many challenges in their implementation	Study completed in 2024
South Korean Small Modular Reactor Project	South Korea's HD Korea Shipbuilding & Offshore (KSOE) is undertaking joint research with Core Power, Southern Company, and Terra Power to develop a small modular Molten Chloride Fast Reactor for marine use.	After a $30 million investment in 2022, the parties have signed a memorandum of understanding in 2024
Transportable Floating Nuclear Power Plants	Canada's Prodigy Clean Energy, in partnership with Westinghouse Electric Company, plan to develop floating nuclear power plants incorporating microreactor technology	Partnership announced in 2024 with plans to be in operation by 2030
NuProShip I	NuProShip I (Nuclear Propulsion of Merchant Ships 1) is a Norwegian project headed by several organizations that aims to study the feasibility of several types of small reactors in large commercial vessels	Project announced in 2024
Nuclear Propulsion Joint Development Project	Lloyd's Register, Zodiac Maritime, HD KSOE and KEPCO E&C are undertaking a joint development project to research large nuclear-propelled ship designs.	Memorandum of understanding signed in 2023
Design of Large Nuclear Containership	China's Jiangnan Shipyard unveiled a design for a 24,000 TEU containership powered by an advanced low pressure molten salt reactor. The design has secured approval in principle from DNV.	Design unveiled in 2023
Design of a Floating Nuclear Powerplant	South Korea's HD KSOE and KEPCO received approval in principle (AIP) from ABS for the design of a floating offshore nuclear power barge. The vessel would incorporate a 240-megawatt small modular reactor along with the production of carbon-free fuel.	Approval in principle received in 2023

Table 5.8: Civilian advanced nuclear reactor projects in the marine industry (continued on next page).

Project	Details	Timeline
Nuclear Power Generation Vessel	United States shipping company Crowley has teamed with BWXT to develop a ship concept which would incorporate a microreactor on board to provide power for defense and disaster needs.	Memorandum of understanding signed in 2023
Project Pele	A United States government initiative to develop transportable microreactors for commercial and defense use. Prototype reactors will be developed by BWXT and X-Energy. BWXT is set to develop a high-temperature gas-cooled reactor utilizing tristructural-isotropic (TRISO) high-assay low enriched uranium (HALEU) fuel, while X-Energy is supporting advanced alternative options including TRISO pebbles.	Prototypes contracted in 2022 and 2023. The BWXT prototype is scheduled for completion in 2024 and operation in 2025
Feasibility Study for Nuclear Propulsion	Italy's Fincantieri and RINA have partnered with Newcleo for the completion of a feasibility study for the application of advanced nuclear reactors to the shipping industry.	Agreement signed in 2023
Nuclear Concept Ships	ABS and Herbert Engineering Corp. have partnered to model the impacts of nuclear propulsion for a container vessel and a tanker.	Study completed in 2023
CMSR Power Barge	South Korea's Samsung Heavy Industries and Denmark's Seaborg has completed the conceptual design for a floating nuclear power plant utilizing compact molten salt reactors. ABS has provided a New Technology Qualification (NTQ) Concept Feasible statement of fact for the reactor design and granted an approval in principle to the barge design. Seaborg and South Korea's Best Engineering in Energy Solutions are collaborating with Regulators to identify regulatory requirements.	Seaborg and BEES signed a memorandum of understanding in 2023
Marine-Based SMR Plant	Canada's Prodigy Clean Energy and America's NuScale have been collaborating to bring a competitive small modular reactor marine facility to market.	Memorandum of understanding signed in 2018
Thor and SIF	Norway's Ulstein has launched the design of a research vessel incorporating a Thorium Molten Salt Reactor to operate as a mobile power plant for electric vessels.	Design Launched in 2022

Table 5.8: Civilian advanced nuclear reactor projects in the marine industry (continued from previous page).

In recent years, nuclear technology has taken a new direction with the ongoing development of advanced nuclear reactors. Advanced nuclear reactors include several categories of technology in various stages of development as shown in Table 5.9. Most advanced nuclear reactors are small modular reactors which are typically those producing 300 megawatts (MW). Some are microreactors producing less than 20 MW, which may potentially be contained within a standard shipping container. Advanced nuclear reactors may potentially also be designed to be “nuclear batteries ” which are designed to be removed when spent as opposed to being refueled. Advanced nuclear reactors have many possible implementations within the maritime value chain due to their potential modularity, offering various arrangements of size and power output, as well as advanced safety systems. Other benefits can include low operating pressures and self-adjusting passive systems, potentially making the technology more applicable to widespread use in a marine setting. Other benefits of advanced reactors include their long fueling cycles, the possibility of factory fabrication and small footprints.

Reactor Type	Coolant	Moderator	Fuel
Advanced Light Water Reactors (LWR)	Water	Water, Graphite	Low enriched Uranium (LEU) – Ceramic Pellets
High Temperature Gas Reactors (HTGR)	Inert Gas	Graphite, possibly Fast Reactor (No moderator)	TRISO LEU or HALEU (Uranium Enriched up to 20%)
Heat Pipe Reactors (HPR)	Heat Pipe Passive Circulation	Graphite	TRISO LEU or HALEU
Sodium Fast Reactor (SFR)	Liquid Sodium or Sodium-Potassium	N/A	HALEU
Fluoride High-Temperature Reactor (FHR)	Liquid Fluoride Salt (FLiBe[1])	Graphite	TRISO LEU or HALEU
Lead Fast Reactor (LFR)	Liquid Lead or Lead Bismuth	N/A	HALEU
Molten Salt Reactors (MSR)	Liquid Salts	Graphite	Dissolved Uranium or Thorium, or Mixed Oxide (MOX)

Table 5.9: Types of advanced nuclear reactors.

Notes: [1] FLiBe is a blend of lithium-flouride (LiF) and beryllium-flouride (BeF_2).
MOX fuel is a low enrichment type fuel consisting of more than one oxide of fissile material.

Despite the benefits, many technical, regulatory and business barriers exist that may limit the widespread implementation of advanced reactors.

The main barriers limiting adoption are the regulatory gaps regarding mobile and non-traditional reactors, as most regulatory bodies address only traditional reactors. The Code of Safety for Nuclear Merchant Ships (Resolution A.491(XII)) for example is restricted to conventional types of vessels propelled by nuclear propulsion plants with pressurized light water type reactors. To close the gap, regulations must be amended to be technology inclusive, so that different types of reactors can be implemented into the industry.

Technical issues may also exist in the use of novel equipment or new material arrangements, including operating conditions in marine environments, arrangements for radiation shielding for a marine unit, protection from nuclear proliferation risks, and arrangements for crew certification and training. All technical solutions need to also be demonstrated and tested as satisfactorily addressing risk. To overcome some of the technical challenges, various projects have been implemented to demonstrate the maritime application of advanced reactors incorporating the unique challenges.

5.4.3.2. Nuclear Value Chain and Applications

The possible future role of the maritime industry in the nuclear value chain is extensive and diverse, as advanced reactors can support the industry in many ways, as shown in Figure 5.16.

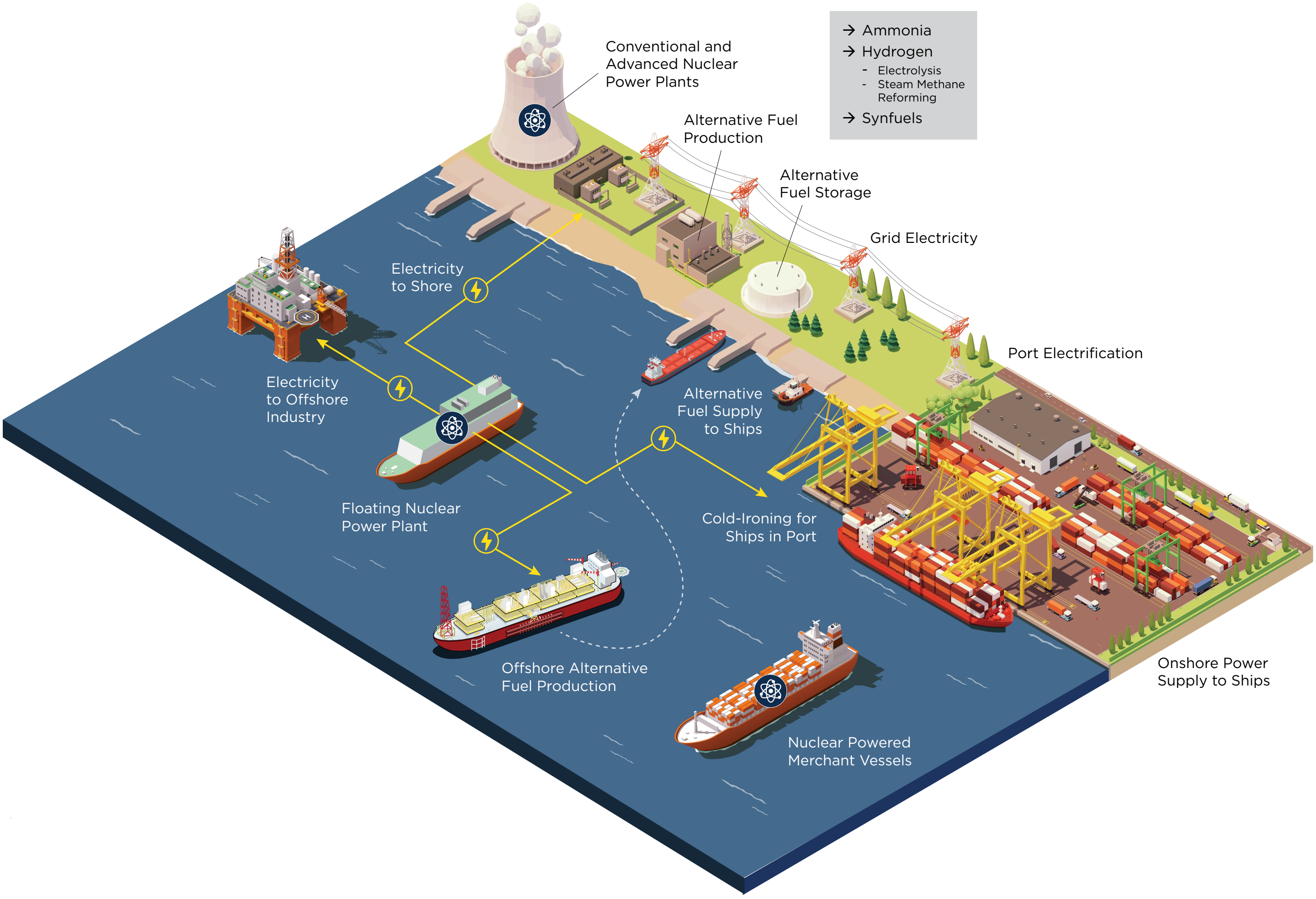


Figure 5.16: The nuclear-maritime value chain.

Land based nuclear reactors can support port infrastructure through electrification and emissions-free production of clean alternative fuels, including hydrogen and ammonia. Port electrification through clean nuclear energy would assist in the push toward decarbonization, as it would facilitate the electrification of port equipment as well as provide an onshore power supply to visiting vessels. Separate from grid electricity, nuclear energy can also provide clean energy for conventionally fueled ships' cold ironing directly while in port.

Nuclear reactors can facilitate the creation of ammonia, hydrogen and biofuels, which can then be utilized as carbon-free pink fuels for vessels. Pink fuel refers to fuels produced using nuclear energy, as opposed to green fuels (produced using renewable sources) and blue fuels (produced using carbon capture technology). Nuclear energy may offer many benefits in these applications, such as a high-density, long-term power supply.

5.4.3.3. Floating Offshore Nuclear Power Plants

Advanced offshore nuclear power plants can also be placed on board ships or barges with the benefits of being located away from population centers, being highly mobile for use in a variety of marine locations (Figure 5.17). These platforms offer versatile solutions in generating electricity not only for maritime electrification but also for broader applications such as green fuel production and supplementing terrestrial power grids. This capability is especially critical in supporting new technologies like carbon capture facilities that require significant power inputs.

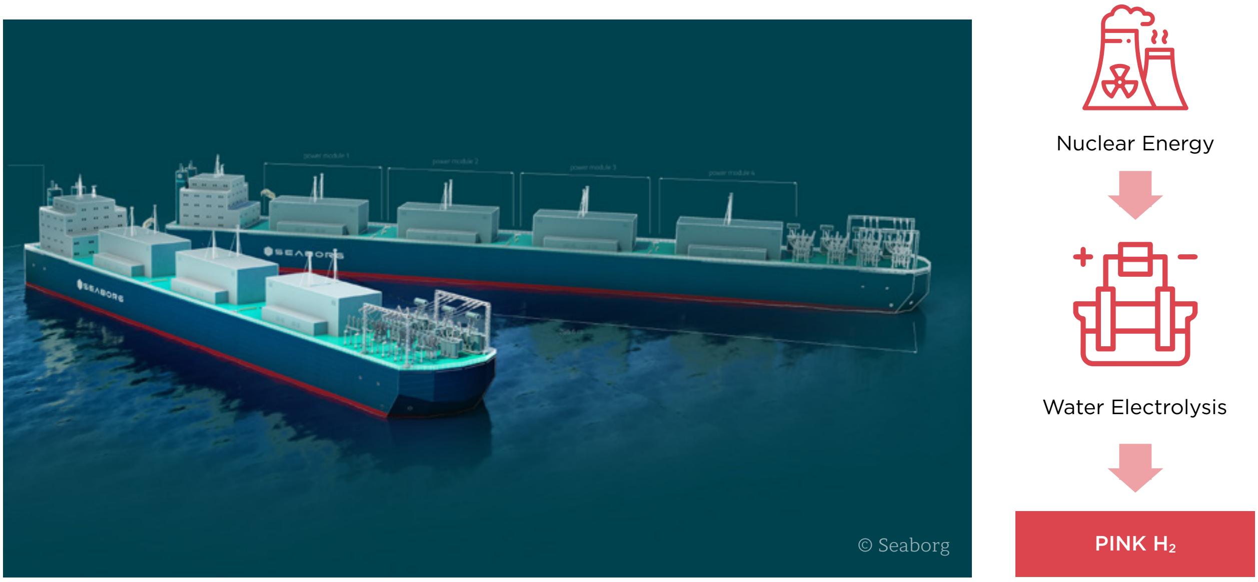


Figure 5.17: Floating offshore nuclear power plants.

5.4.3.4. Propulsion Power Source for Ships

Advanced nuclear reactors may also have the potential to play a significant role in the decarbonization of commercial vessels by providing carbon free thermal or electric energy for power and propulsion (Figure 5.18). Nuclear power has a much higher energy density than fossil fuels. This means that nuclear reactors can provide a large amount of energy from a relatively small amount of fuel and do so more consistently than wind or solar power, which are subject to weather fluctuations. For ships, this translates into the ability to travel longer distances without refueling, which is particularly beneficial for vessels on international voyages. Additionally, the higher energy output can facilitate faster vessel speeds and greater operational efficiency.

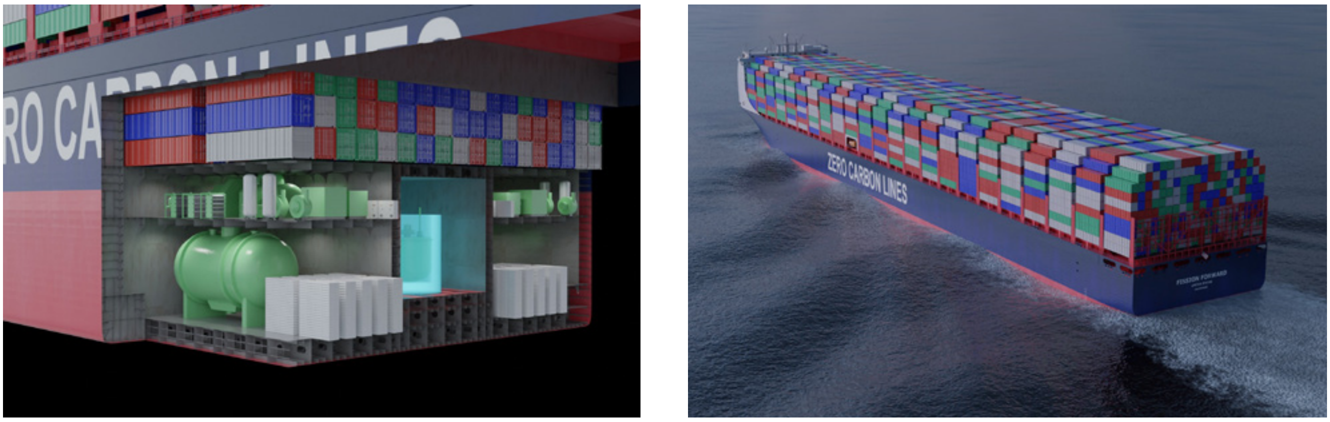


Figure 5.18: Nuclear powered vessel.

In summary, advanced nuclear reactors may be an essential key for the marine industry to meet decarbonization goals. While many barriers potentially exist, advanced reactors may hold many advantages that could assist in the journey to carbon net zero. For these challenges to be overcome, tests and demonstrations of the technology must be carried out, working with regulators to approve and adopt novel commercial applications into the marine industry, as well as to facilitate changes in regulations if necessary.

5.4.4. Digitalization

Digital technologies are transforming the maritime industry and can support the global efforts for decarbonization and safety.

Digitalization refers to technologies that fall under the categories of autonomy, artificial intelligence (AI) and digital twins.

The concept of autonomy consists of three main categories, namely, smart systems, semi-autonomous systems and fully autonomous systems. Each category establishes distinct levels of interaction between machines and humans.

- SMART systems conduct data analysis and monitoring, but the ultimate decision-making responsibility rests with the human operator. These systems aid the gathering of operational data and execute necessary analysis to support efficient operation and predict equipment failures.
- In semi-autonomous systems, certain decisions are made by the computers, but they are overseen by human operators.
- In the context of semi-autonomous operations, the system automates routine tasks, thereby reducing the workload of crew members and minimizing the reaction time in critical situations.
- Finally, fully autonomous systems operate without any form of human supervision or monitoring. By minimizing human error, these systems can contribute to safety and environmental protection.

In the maritime industry, AI may serve as a foundational element of the digital transformation. It comprises a variety of technologies that are capable of performing tasks that typically require human intelligence. AI technologies such as natural language processing, machine learning and generative pre-trained models like GPT can be of significant importance in the maritime industry. AI systems can support the analysis of large quantities of data and facilitate predictive maintenance of equipment as well as improve cargo handling and optimize routing. In any case, they can indirectly increase operational efficiency and reduce emissions.

Digital twins are an additional innovation within the maritime sector. A digital twin is a model of a physical ship that can be used to simulate and analyze different scenarios. In addition, through the use of real-time data, the model can support the reduction of fuel consumption, decrease emissions and predict the performance of vessels under various conditions.

The components of digitalization should not be considered in isolation. In order to maximize their impact, they should be used in an integrating way whereas the outputs of one system can be the data input of another. The implementation of such an interconnectivity has the potential to significantly increase operational efficiency, safety and environmental protection.

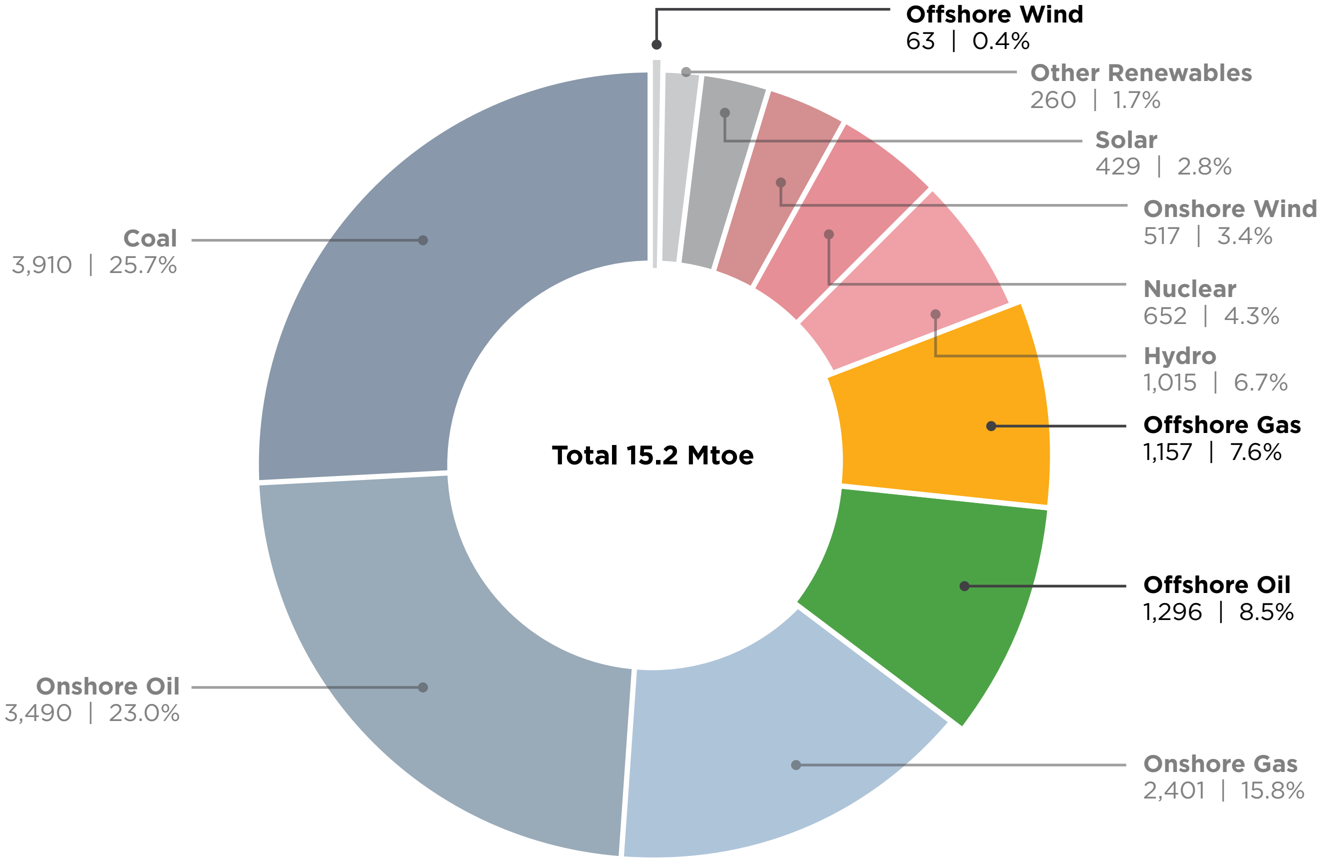
SECTION 6

OFFSHORE INDUSTRY INSIGHTS

6.1 Introduction

Offshore sustainability plays a significant role in the energy sector, involving offshore oil and gas activities and newer technologies such as offshore wind power, offshore hydrogen generation and carbon capture, utilization and storage (CCUS).

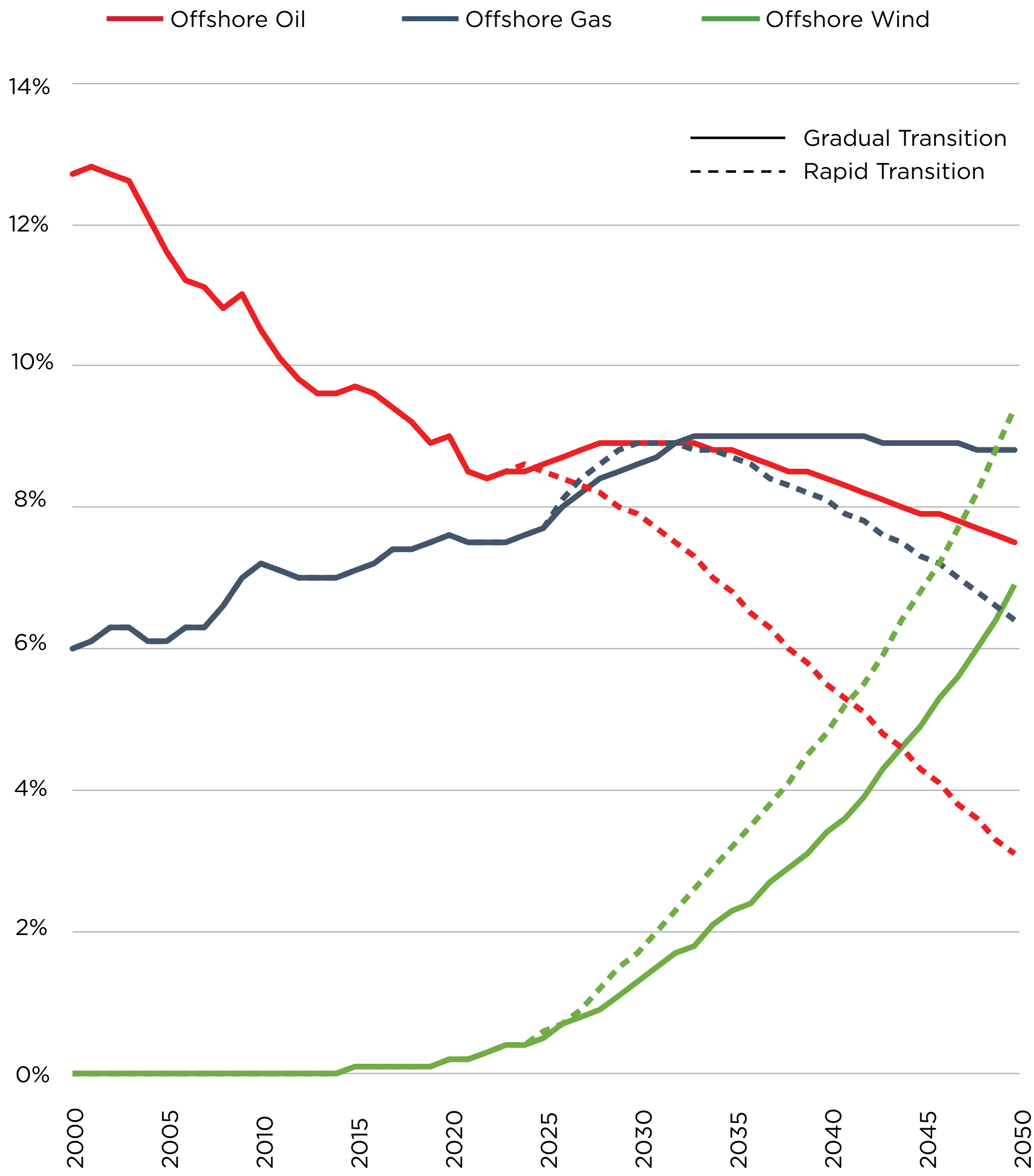
The conventional offshore oil and gas sectors account for 16 percent of the global energy mix (see Figure 6.1) and are under pressure to clarify how energy transitions will impact their operations and business models. Companies are striving for near-zero methane emissions and zero greenhouse gas (GHG) emissions.



Source: Clarksons Research, World Fleet Register, April 2024

Figure 6.1: Global energy mix.

Offshore wind power is increasingly being recognized as an alternative energy source. Figure 6.2 illustrates the comparison of energy sources and how they are expected to influence energy production in the future. The global capacity of large-scale wind farms is projected to grow tenfold to 350 gigawatts (GW) by 2030. The analysis covers oil, gas and wind as global energy sources in two scenarios: gradual transition and rapid decarbonization. The information indicates a decrease in the use of oil over time, a peak followed by a slight decline for gas, and a significant rise in wind power, specifically in the scenario with rapid decarbonization. This highlights the patterns in energy sources and the increasing importance of offshore wind in the energy evolution.



(Source: Clarksons Research, World Fleet Register, April 2024)

Figure 6.2: The rise of renewable offshore energy.

Offshore hydrogen production is also emerging as an avenue for energy generation. There are several initiatives aiming to produce hydrogen from wind sources. However, the main challenge for hydrogen projects remains the cost factor, with price estimates expected to be $7 per kilogram (kg) in 2025 and dropping to $1/kg by 2050.

The deployment of CCUS has grown in recent years, with more than 500 projects at various stages of development across the CCUS value chain. The total CO_2 captured is estimated to reach 6040 million tonnes (Mt) by 2050.

In the world of offshore sustainability, there is a growing focus on issues like the carbon market, methane emissions and biodiversity. The carbon market plays a role in efforts to reduce GHG emissions, impacting industries such as offshore oil and gas. Methane emissions pose a concern, especially within the oil and gas sector, requiring strict monitoring and control measures. Biodiversity is also a factor to consider in the planning of oil and gas, offshore wind farms and CCUS projects to ensure minimal impact on marine ecosystems.

These topics highlight the complexity of challenges faced by the offshore industry and emphasize the importance of taking a comprehensive approach to sustainable development.

6.2 Offshore Units Market Updates

6.2.1 Platforms, Rigs and Mobile Offshore Drilling Units (MODUs)

The mobile offshore drilling units (MODUs) orderbook, for both jackups and floaters, is largely made up of undelivered orders from the last upcycle in 2011–2014. The last orders made were in 2020, when three jackup orders were placed. This is unlikely to change in the short term, especially for floating units, which now cost well over $500 million to build and mobilize. This is illustrated in Figure 6.3

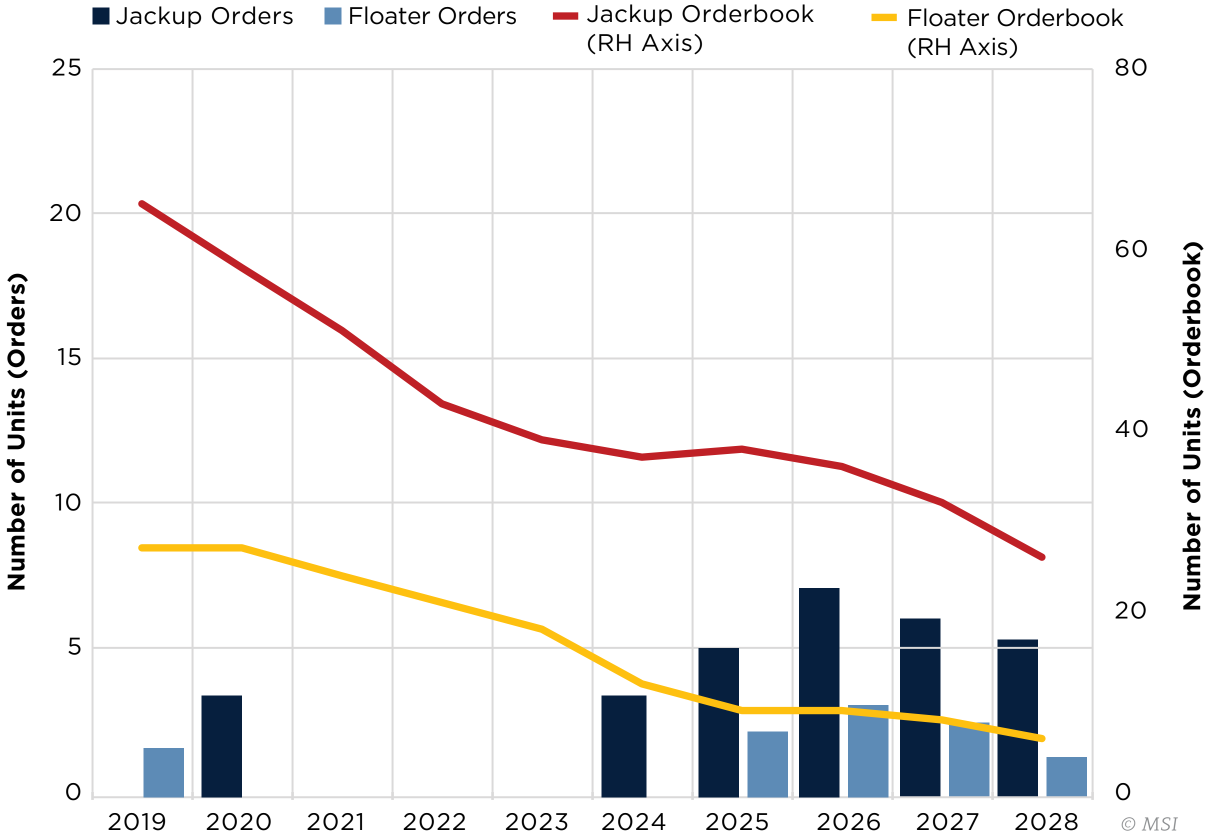


Figure 6.3: Mobile offshore drilling units — newbuild orders.

There have also been very few removals from the MODU fleet since 2022 (refer to Figure 6.4) as owners hold on to assets as supply remains tight. This, combined with the lack of new orders, has resulted in a fleet that is seeing little in the way of renewals.

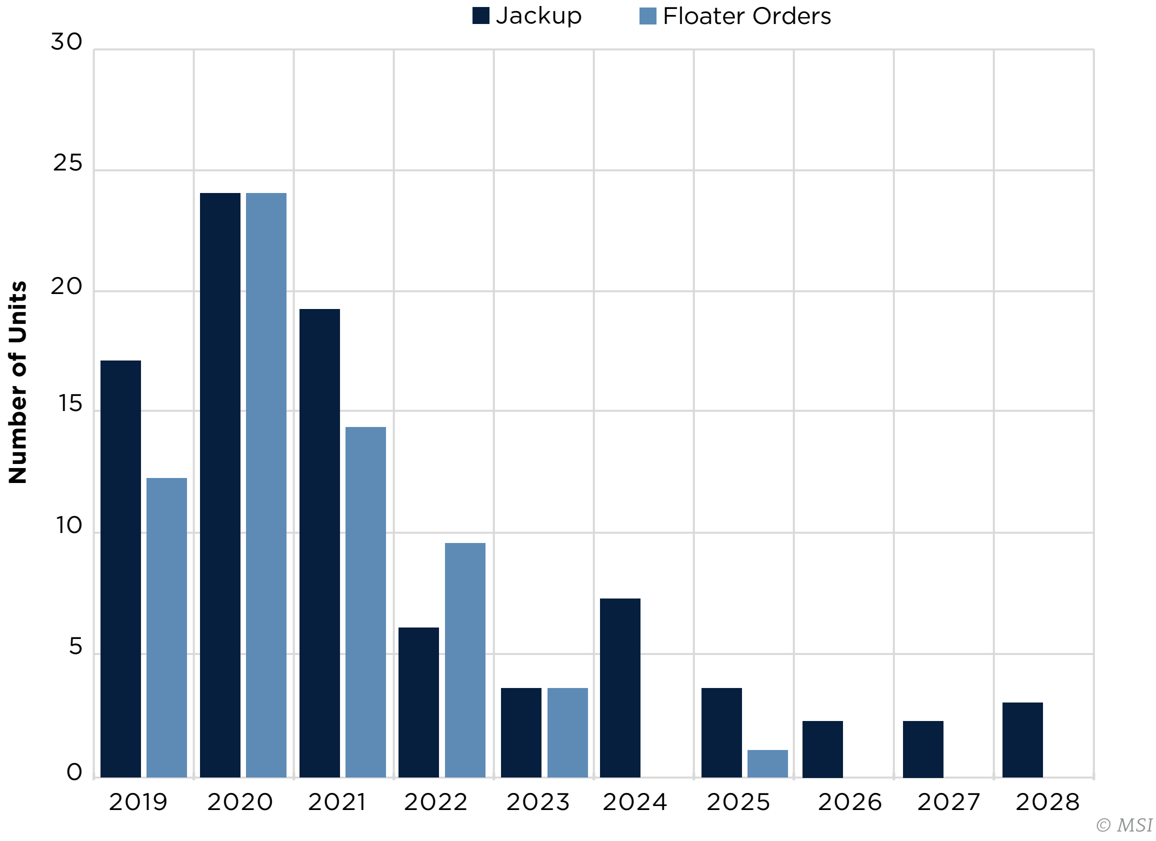


Figure 6.4: Mobile offshore drilling units — removals.

Electrification of jackup units has been happening at an increasing rate in key regions, such as Europe and the Middle East (Gulf region). Typically, this will be done via offshore oil and gas platforms which are powered by onshore power stations via subsea cables. Cables will then be laid to the jackup rig to electrify the rig and remove the requirement for diesel-powered generators, saving up to 20 kilotonnes (kT) of CO_2 emissions per rig per annum.

Electrification could also reduce the United Kingdom (U.K.) continental shelf's oil and gas power generation emissions by one-third by 2030, which will be critical to maintaining the oil and gas industry's social license to operate.

In the MODU market, several major players have been exploring options to improve fuel consumption efficiency and reduce emissions. Some operators have embarked on the rollout of digital emission-monitoring solutions to monitor and proactively reduce energy consumption. Others are exploring decarbonization options such as running biofuels pilot tests that, in certain cases, have resulted in a CO_2 reduction of up to 80 percent compared to diesel power.

The majority of low-emission retrofitted MODUs are working in the North Sea, with vessels operating in Norwegian waters leading the way due, in part, to high carbon taxes. Other retrofitted units are carrying out contracts in the United States (U.S.) Gulf of Mexico and South America, with some awaiting work in Africa, the Mediterranean and Australasia. The low-emission MODUs typically demand a premium day rate. Thus, we see the most of them utilized by major and national oil companies (NOCs).

6.2.2 Offshore Support Vessels

The levels of contracting and orderbook for offshore support vessels (OSVs) based on engine rating is shown in Figures 6.5 through 6.8. These include anchor handling tug supply (AHTS) vessels and platform supply vessels (PSV). The trends for OSVs point to a carbon-neutral future with operations fully integrated with offshore fields, port infrastructure and supply chains.

They will need to be fully digitalized, connected and highly automated to tie into their supporting ecosystems. The future OSV will be configured and connected to provide clear operational visibility and the ability to track vessels, equipment, and people around the clock.

The OSV of the future will be powered by alternative low-carbon fuels, or transition to energy-storage systems (ESS) and hybrid-propulsion solutions.

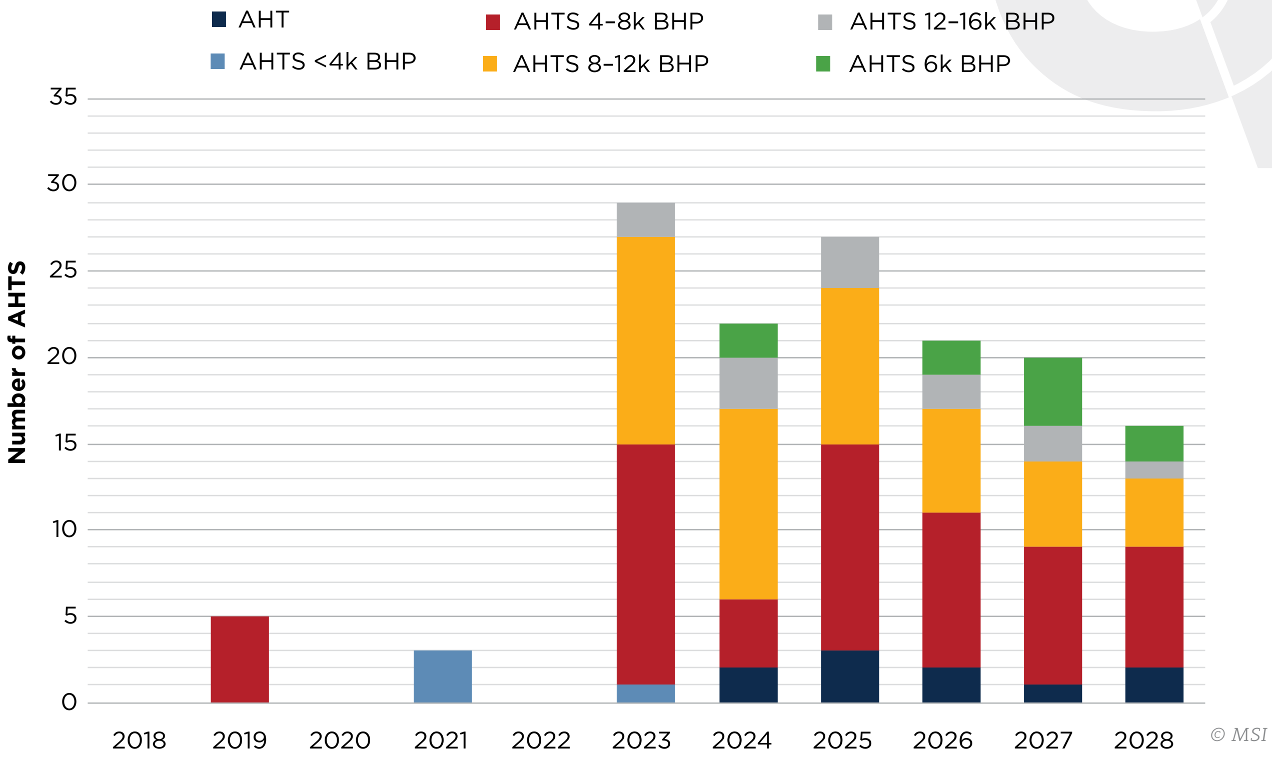


Figure 6.5: AHTS contracting.

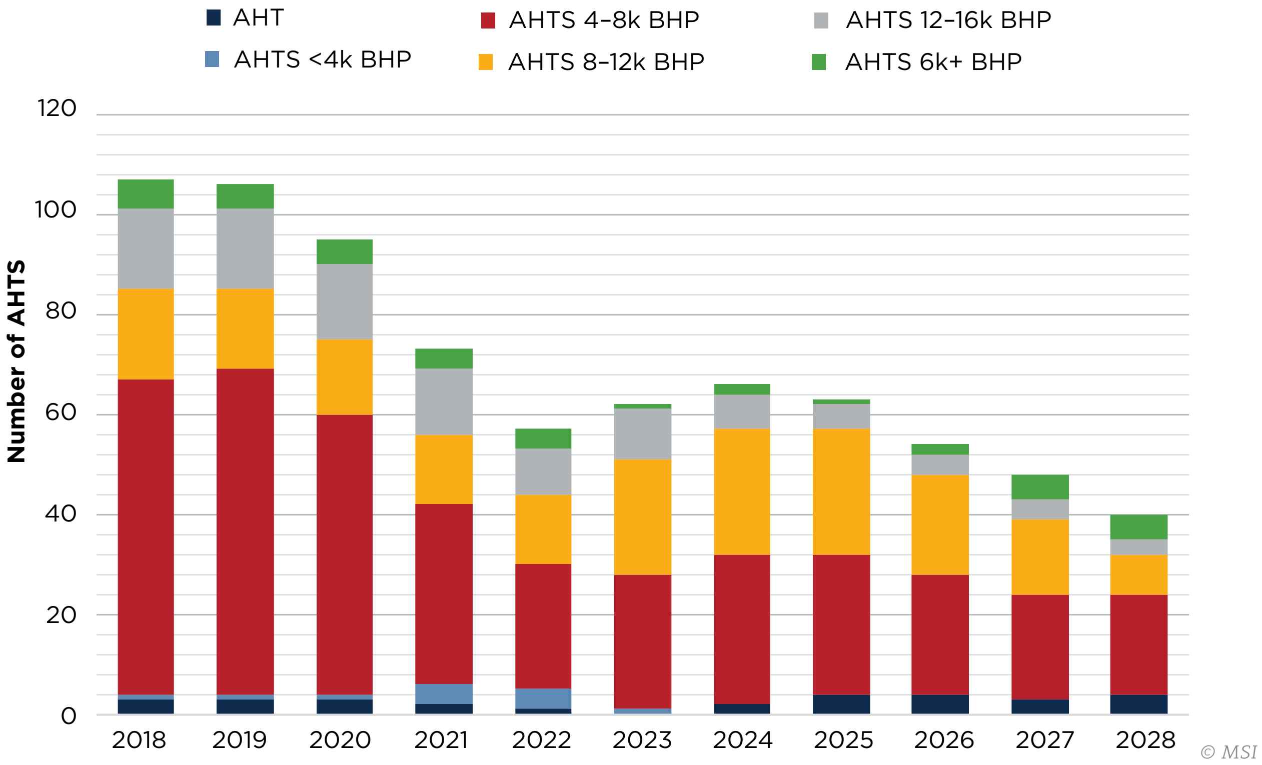


Figure 6.6: AHTS orderbook.

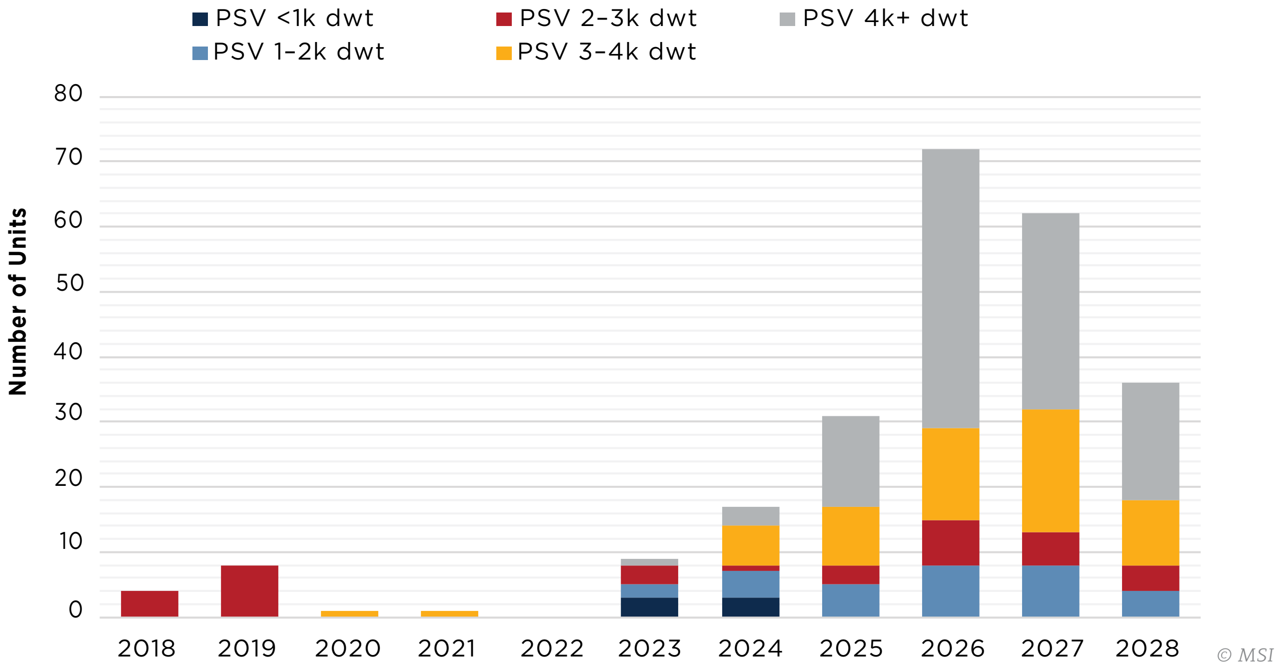


Figure 6.7: PSV contracting.

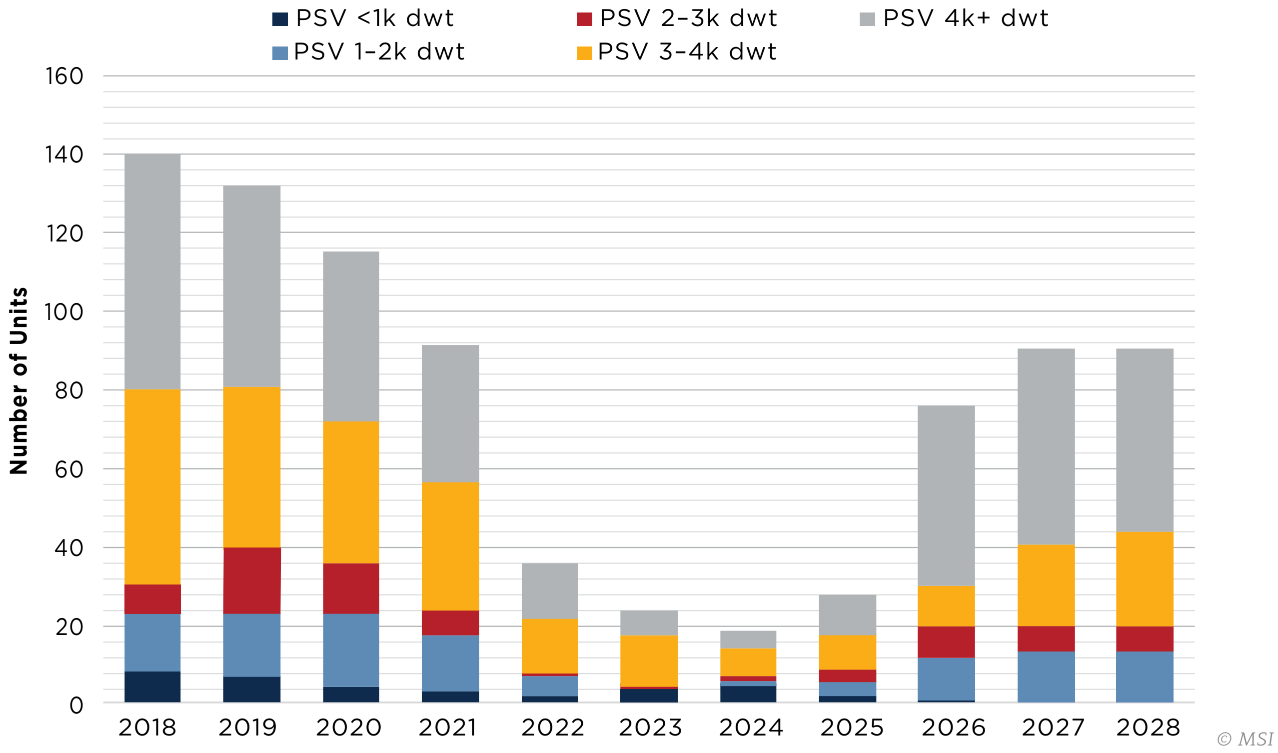


Figure 6.8: PSV orderbook.

Focusing on OSV newbuilds, the majority are still powered by standard mechanical propulsion diesel engines (Figure 6.9), however, there is some movement with 31 percent of deliveries since 2020 utilizing diesel-electric power.

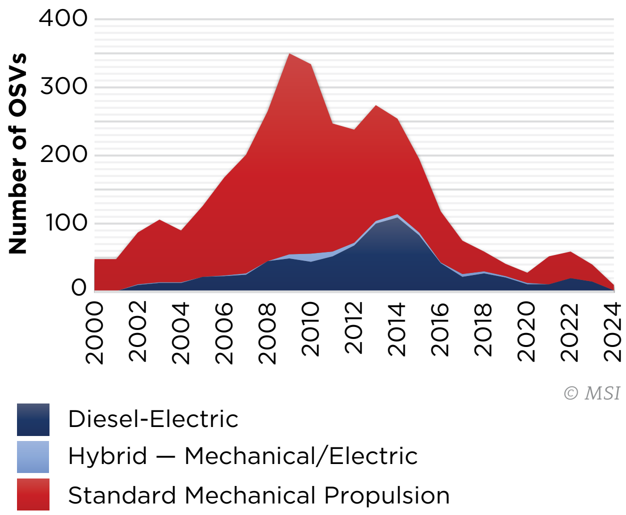


Figure 6.9: OSV deliveries by fuel-type.

Alternative fuels are slowly being introduced to the market, but the uncertainty around which fuel will be the fuel of the future remains. Owners remain reluctant to risk additional capital expenditure (capex) on dual-fuel newbuilds if lower or net-zero carbon fuels are not available. Some alternative fuels, including biofuel, are generally considered unviable in the long-term, due to the inability to produce and distribute these globally on the scale required to power the entire OSV fleet.

The offshore sector has also recently witnessed its first dual-fuel methanol order for service vessels.

Other owners have taken the economical approach by converting existing vessels. One operator converted a PSV to run on ammonia fuel in early 2024, whilst some others are retrofitting vessels to run on methanol. These conversions are likely to become more common as companies strive to reduce emissions at a time when newbuilds are considered too costly by many.

The short-term nature of OSV contracts is also proving to be a sticking point against emission-saving newbuilds and conversion projects, with many OSV owners being left to foot the entire bill without a guarantee of medium-to-long-term work. This has led some oil and gas companies to commit to longer-term charters for more efficient OSVs, but this will not be an option for all oil and gas operators with charter rates being higher than they are used to paying due to demand in the market and their goal to maintain current profitability and shareholder returns.

The OSV sector has a number of alternative emissions-reducing solutions and technologies to help the sector decarbonize, these can be broadly categorized into the following:

Advanced Engine Combustion Technology

High fuel efficiency reducing CO_2 output
Low PM emissions. Low Life Cycle Costs

Waste Heat Recovery

Energy from engine cooling system or exhaust, used for heating, cooling on board

Exhaust Gas Aftertreatment

SCR solutions engineered with the engine emission comliance over lifetime, and in extreme ambient conditions

Variable Speed Gensets

Engine efficiency gains from adapting the engine speed to the real electrical power

Alternative Fuels

Carbon-neutral fuels which reduce the CO_2 footprint

Hybrid and Energy Storage

Batteries make it possible to reduce number of gensets in operation at partial load, and to cover peak loads

Some key highlights:

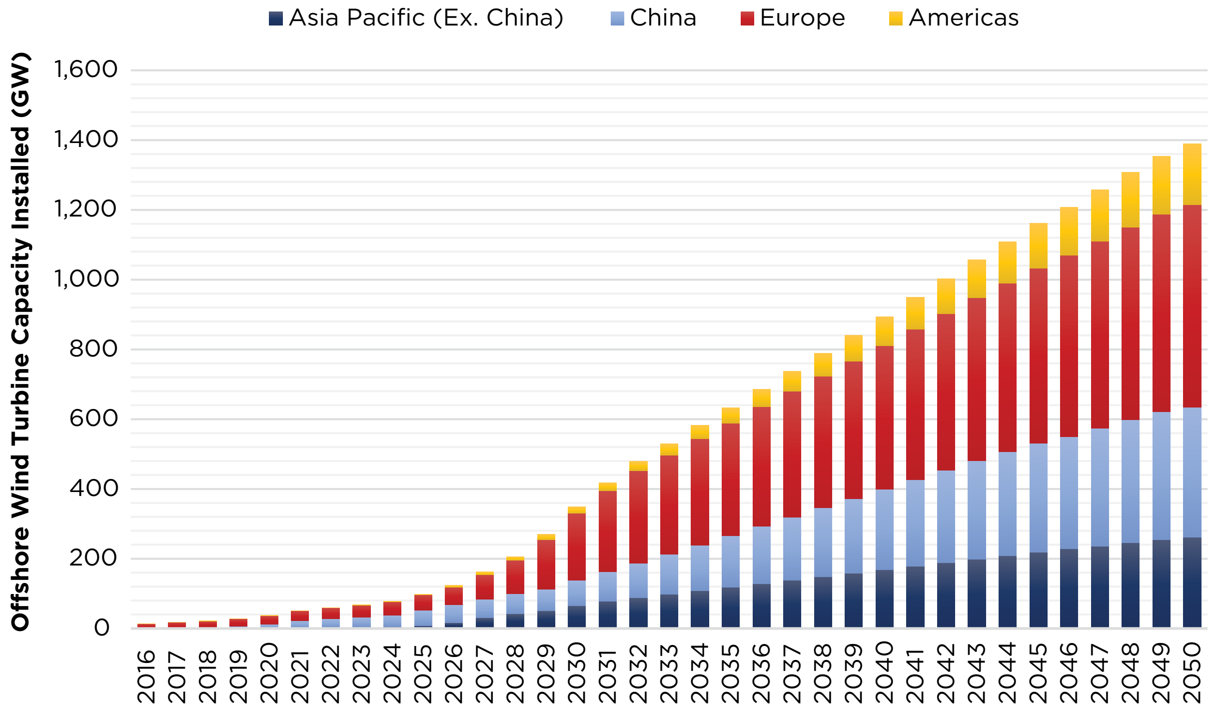
- The combination of high interest rates, high newbuilding costs and long lead times has meant that the current orderbook is only around 1 percent of the fleet. Therefore, there are a limited number of new, more efficient vessels entering the fleet in the short-term.
- However, during 2023, the OSV market moved ahead with fuel monitoring and data analysis to eventually help improve energy efficiency in the sector. This data will be critical to the OSV market becoming more efficient.
- After years of low costs and low charter rates, charterers are seeing costs increase sharply due to high fuel prices and rapidly increasing charter rates. This is driving a push toward digital systems that enable operations monitoring, which can help improve fuel efficiency in the short term. However, the lack of certainty around future fueling and technologies has left many OSV owners unsure of what technologies to invest in when upgrading their fleets. Decarbonization solutions for the short-term are more focused on immediate gains and typically do not require significant capex investment.

6.3 Emerging Offshore Value Chains

6.3.1 Offshore Wind

Offshore wind power can be a complementary source of renewable energy for electrified floating production installations. This technology can be divided into wind power generation systems that are floating or bottom fixed. Floating systems are highly anticipated as they can be located farther offshore than bottom fixed systems. Structures such as tension leg platforms (TLPs) and semi-submersible platforms can be converted to support wind turbines for these further offshore locations. TLPs can be used with 10 megawatt (MW) or larger turbines and offer stability with minimal mooring footprint.

ABS has revised its installed capacity outlook, with 350 GW now forecasted to be installed by 2030, down from 365 GW forecast in the fourth quarter of 2023. This comes following global project cancellations and delays due to soaring costs and supply chain constraints. Still, by 2030, the installed capacity of offshore wind is projected to quadruple driven by decreasing costs and increasing competitiveness with traditional energy sources. This growth is underpinned by both private and public sector investment, with significant contributions from green finance initiatives. Figure 6.10 shows the projected turbine capacity installed up until 2050.



© MSI

Figure 6.10: Total cumulative offshore wind turbine capacity installed.

The forecast for the number of turbine installations is due to peak in 2030 with 3850 fixed bottom turbines installed before gradually declining as projects move into maintenance phases and floating wind starts to play a larger role. A distribution of offshore wind farms versus their distance to the coast is illustrated in Figure 6.11.

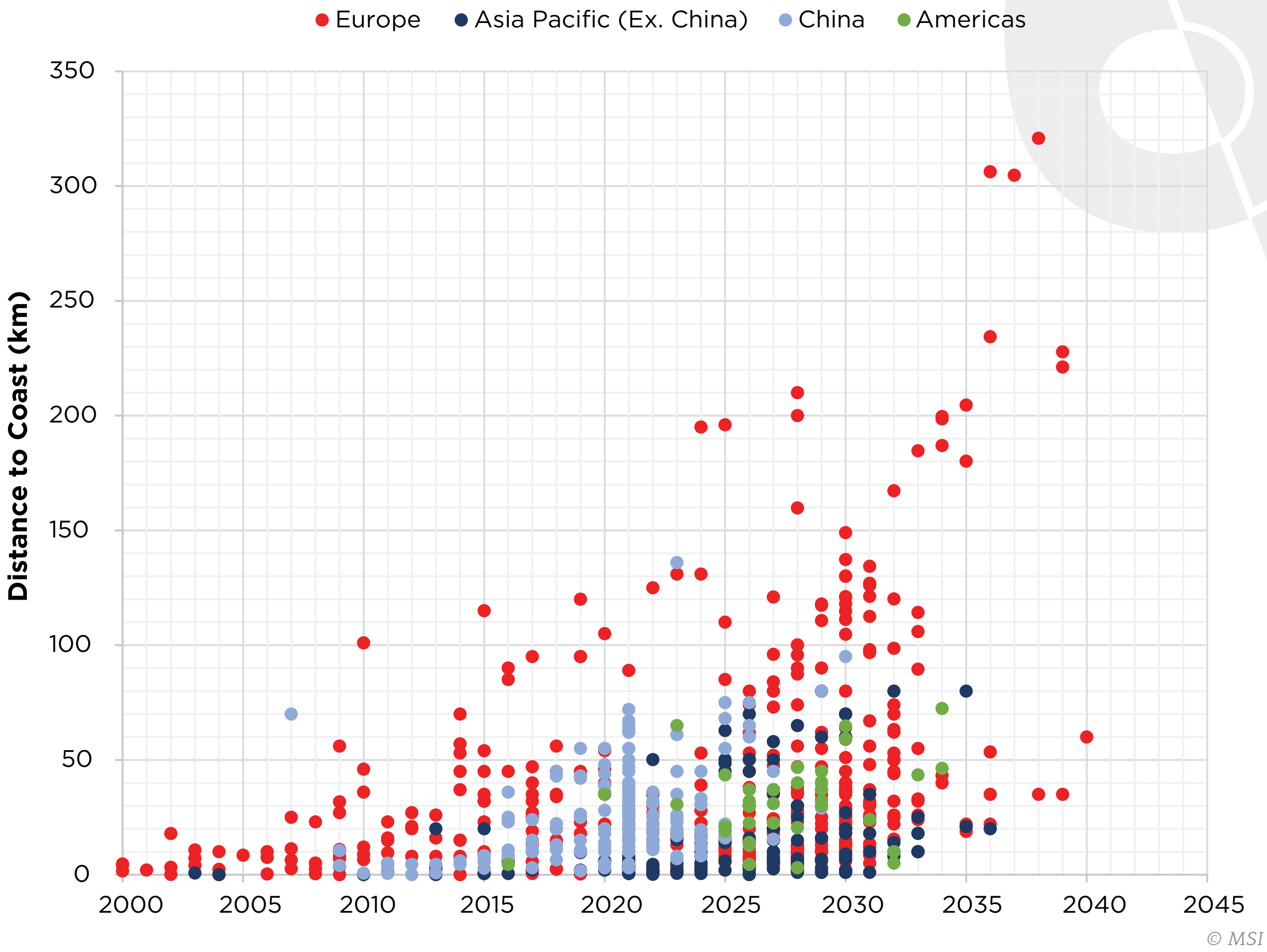


Figure 6.11: Offshore wind farms distance to coast (km).

Floating wind turbine installations are expected to become more prominent toward the end of the decade, with 450 forecasted to be installed in 2030 and growing to 770 by 2035. There is a downside risk to this forecast with the delay in fixed bottom projects potentially pushing back floating wind farm development.

While the industry faces challenges such as supply chain bottlenecks and environmental concerns, ongoing innovations in turbine technology and installation methodologies are expected to address these effectively. The development of high-voltage direct current (HVDC) technology is particularly noteworthy, as it could revolutionize energy transmission from offshore wind farms to onshore grids.

The integration of offshore wind with energy storage and hydrogen production is expected to mitigate the variability of wind energy and enhance grid stability. This synergy is anticipated to be a major focus in the coming years as countries aim to balance their energy mixes and achieve decarbonization targets.

Demand for AHTS vessels will also increase once floating wind volumes pick up, as these vessels are used to position and anchor floating turbines. By 2030, we forecast the floating wind market will require 27 AHTS vessels, with demand expected to continue to grow over the next couple of decades.

6.3.2 Offshore Hydrogen Production

As the world seeks sustainable energy solutions, offshore hydrogen production is emerging as a key technology marking a significant shift in the renewable energy landscape. This innovative approach combines the strengths of offshore wind power with cutting-edge hydrogen technologies, setting the stage for a more sustainable and resilient energy future. As nations strive to meet ambitious climate goals, offshore hydrogen production emerges as a key strategy, leveraging the untapped potential of the sea to foster energy independence and drive decarbonization efforts.

There are various production configurations based on the location of the electrolyzer, each catering to different technological, economic, and environmental considerations. The primary configurations currently explored or being implemented in the industry are:

1. Onshore Electrolyzers with Offshore Wind Farms
In this setup, the wind farms are located offshore, but the electrolyzers are stationed onshore. Electricity generated by the offshore wind turbines is transmitted via undersea cables to the onshore facility where hydrogen is produced. This setup benefits from more stable onshore infrastructure while still harnessing the strong and consistent winds available offshore.

2. Offshore Electrolyzers on Fixed or Floating Platforms
For near-shore configurations, electrolyzers are installed directly on offshore platforms, similar to those used in the oil and gas industry. These platforms can be fixed to the ocean floor in shallower waters. The hydrogen is generated at sea and then piped back to shore or to ships for transport. This method reduces energy loss in transmission and leverages the proximity to wind turbines for direct electrical connection.

For deeper waters where fixed platforms are not viable, floating platforms equipped with electrolyzers can be used. These are often integrated with floating wind turbines, creating a mobile and flexible hydrogen production unit that can be positioned in optimal wind locations.

3. Integrated Wind-to-Hydrogen Offshore Systems
Some projects aim to fully integrate the wind turbine with hydrogen production on the same platform. This could mean having electrolyzers directly beneath or adjacent to the turbine on the same floating or fixed platform. This setup aims to minimize energy loss, reduce infrastructure costs, and simplify the logistics of energy transport.

Each of these configurations has its advantages and challenges. Onshore electrolyzers benefit from easier access for maintenance and lower costs due to established infrastructure but suffer from energy losses during transmission. Offshore setups, while more expensive and logistically challenging, benefit from higher efficiency and energy utilization, as they are closer to the energy source.

The choice of setup often depends on specific project goals, local geography, regulatory environment, and economic considerations. As technology advances and new innovations come into play, these setups may evolve to further optimize the efficiency and sustainability of hydrogen production from offshore wind energy.

The viability of offshore hydrogen production has moved from theoretical discussions to practical demonstration projects. There are currently a few projects demonstrating the feasibility of harnessing wind-generated electricity to produce hydrogen directly at sea (e.g., testing of a 1 MW electrolyzer on a floating platform, which not only provided insights into the operational challenges but also highlighted the potential for future scalability).

European initiatives further underscore the strategic importance of this technology, with significant investments and policy support aimed at integrating hydrogen production into the offshore energy sector. Such support is pivotal in advancing these technologies from pilot projects to mainstream energy solutions.

While the development of hydrogen using offshore wind energy shows promise, it faces challenges. The main issue is the technology and infrastructure needed for the process. This includes building and maintaining wind farms, the equipment for electrolysis to create hydrogen, and storing and transporting the hydrogen. The levelized cost of hydrogen (LCOH$_2$) for offshore production has several influencing factors, and current projects are working toward making it more economical. BloombergNEF estimates that the mid-range price for offshore wind-to-hydrogen could be around \$7/kg by 2025, with a potential decrease to \$1/kg by 2050 as the technology matures and production scales up. This cost reduction is expected due to advancements in electrolyzer technology, which is necessary for hydrogen production, and improvements in offshore wind efficiency. Refer to Figures 6.12 and 6.13.

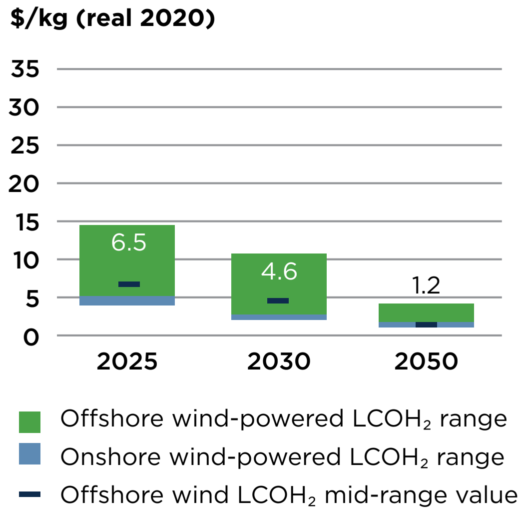


Figure 6.12: LCOH$_2$ range for an onshore electrolyzer powered by offshore wind or onshore wind.

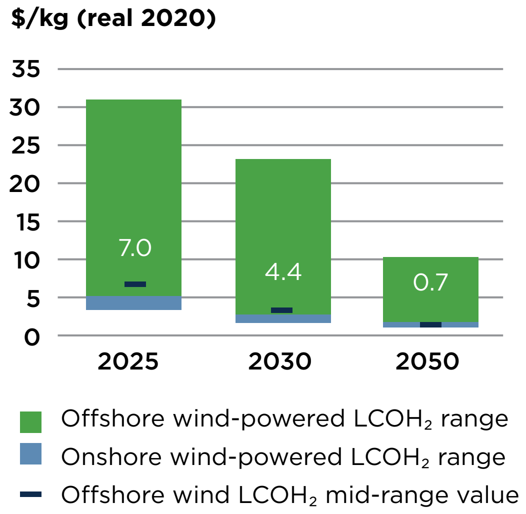


Figure 6.13: LCOH$_2$ range for an offshore electrolyzer powered by offshore wind vs. onshore wind plus onshore electrolyzer.

BloombergNEF

Furthermore, integrating offshore wind with hydrogen production might also involve adapting existing offshore platforms and infrastructure, which could include retrofitting and upgrading gas pipelines to transport hydrogen. There is ongoing development in the electrical concepts for offshore wind farms to enable off-grid operation, which is crucial for remote electrolysis setups.

The industry is actively seeking technological innovations and operational efficiencies that will ensure the long-term viability and economic competitiveness of offshore hydrogen production.

6.4 Biodiversity and Ecosystem Impacts

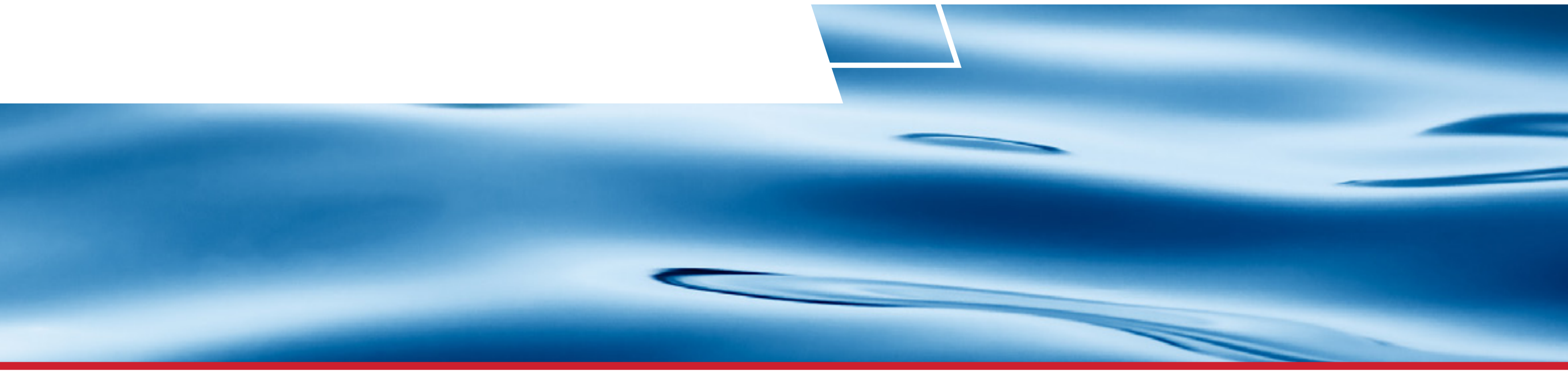
Marine biodiversity refers to the variety and variability of life forms within all marine environments, including the oceans, seas, coral reefs and estuaries. It encompasses the diversity of species, from the smallest microorganisms to the largest marine mammals, as well as the genetic diversity within and between species and the complex ecosystems in which they live.

The Kunming-Montreal Global Biodiversity Framework is a pivotal international agreement adopted by the parties to the Convention on Biological Diversity (CBD) during the 15th meeting of the Conference of

the Parties (COP15) in December 2022. This framework represents a global commitment to halt and reverse biodiversity loss by the end of the decade, aiming to ensure biodiversity's recovery for the benefit of all people and the planet. The framework is intricately linked to the offshore industry through its goals of preserving and enhancing marine biodiversity. Although it is not legally binding, the global goals and targets in this agreement give countries a set of markers to guide action equal to their ambition, from targets for protecting and restoring ecosystems to halting the loss of species and working with a human-rights based approach.

Given that the offshore industry, particularly offshore renewable energy (ORE), operates within marine environments, the framework's targets have direct implications for how to minimize environmental impacts and contribute to biodiversity conservation.

1. Protected Areas: One of the framework's key targets is to protect at least 30 percent of the world's marine areas by 2030. This directly affects the offshore industry as it may limit the areas available for new developments and require more stringent environmental impact assessments for projects in or near protected areas.
2. Sustainable Practices: The framework encourages the integration of biodiversity considerations into all sectors, including the offshore industry. This means that offshore operations, from oil and gas extraction to wind energy production, will need to adopt more sustainable practices that mitigate their impact on marine ecosystems.
3. Pollution Reduction: The framework aims to reduce pollution, which includes minimizing the input of plastic and other waste into the ocean. Offshore platforms and vessels are significant potential sources of marine pollution and thus would be under greater pressure to implement cleaner operations and waste management practices.
4. Technology and Innovation: To align with the framework, the offshore industry is likely to invest in innovative technologies that reduce environmental impacts. This includes developing and deploying technologies for cleaner drilling and extraction processes, quieter construction techniques that reduce noise pollution affecting marine life, and designs that enhance the ecological benefits of infrastructure like artificial reefs created around wind turbines.
5. Community and Stakeholder Engagement: Given the framework's emphasis on respecting the rights and knowledge of indigenous peoples and local communities, offshore projects will need to ensure that these stakeholders are actively involved in the planning and decision-making processes. This is particularly pertinent for projects near coastal communities who rely on marine biodiversity for their livelihoods.



The alignment of offshore operations with the objectives of the Kunming-Montreal Global Biodiversity Framework will prepare the industry for the expected tightening regulatory landscape. The framework may influence national and international regulations, creating stricter guidelines and standards for offshore activities to ensure they are conducted in a manner that supports global biodiversity goals.

The offshore industry may have impacts on the marine ecosystems through its operations. These impacts range from habitat destruction to noise pollution, which can disrupt marine life. Figure 6.14 summarizes the main potential impacts to the marine ecosystem. However, the industry is increasingly recognizing these impacts and is adopting measures to mitigate them. Offshore wind projects are seen as relatively benign compared to other marine activities. Environmental assessments over the past two decades have shown that these projects generally have low levels of negative effects on the marine environment.

With the expansion of offshore wind capacity, driven by global commitments to reduce carbon emissions, the potential for impacts on marine ecosystems will likely increase. However, advancements in technology and operational strategies, such as the use of quieter construction techniques and real-time environmental monitoring, are expected to mitigate these impacts significantly.

Technologies like visual and eDNA sampling from uncrewed vessels are being integrated into routine operations, allowing for ongoing monitoring of marine ecology. Moreover, the offshore wind sector is increasingly adopting the Mitigation Hierarchy recommended by the Cross Sector Biodiversity Initiative, which outlines steps to avoid, minimize, restore, and enhance biodiversity during project development.

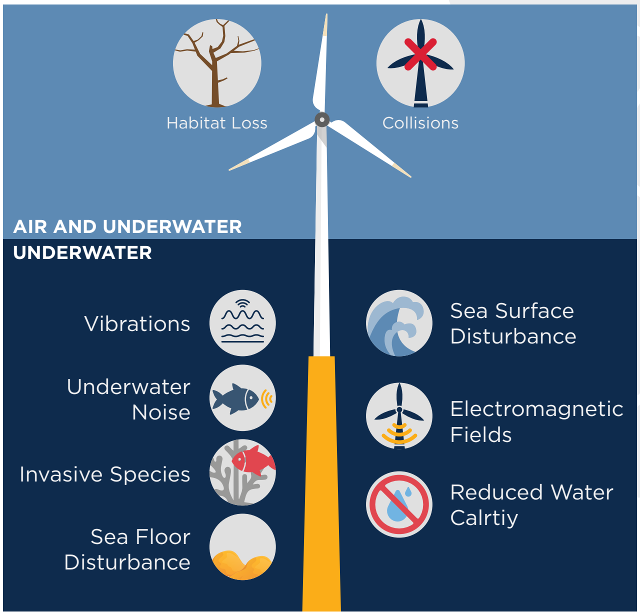
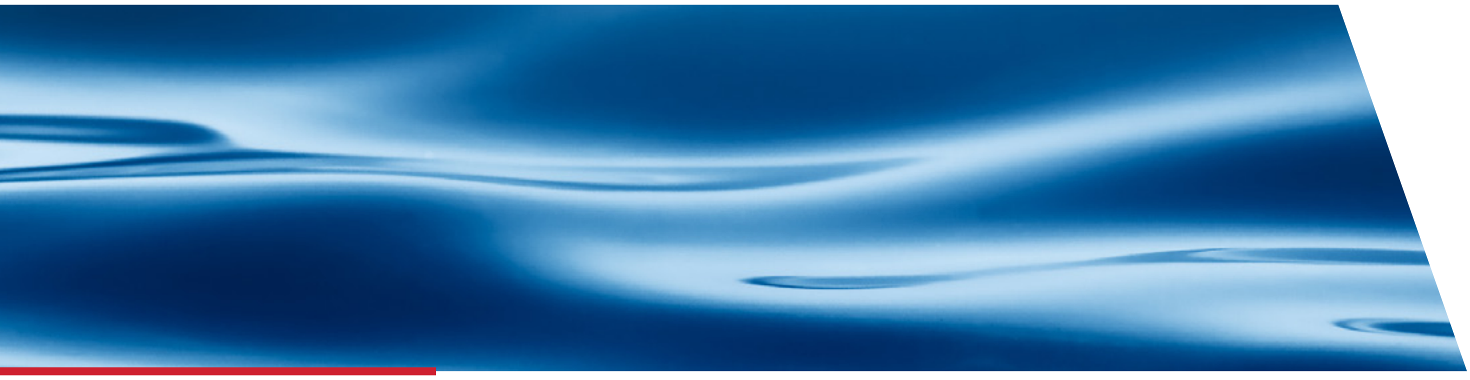
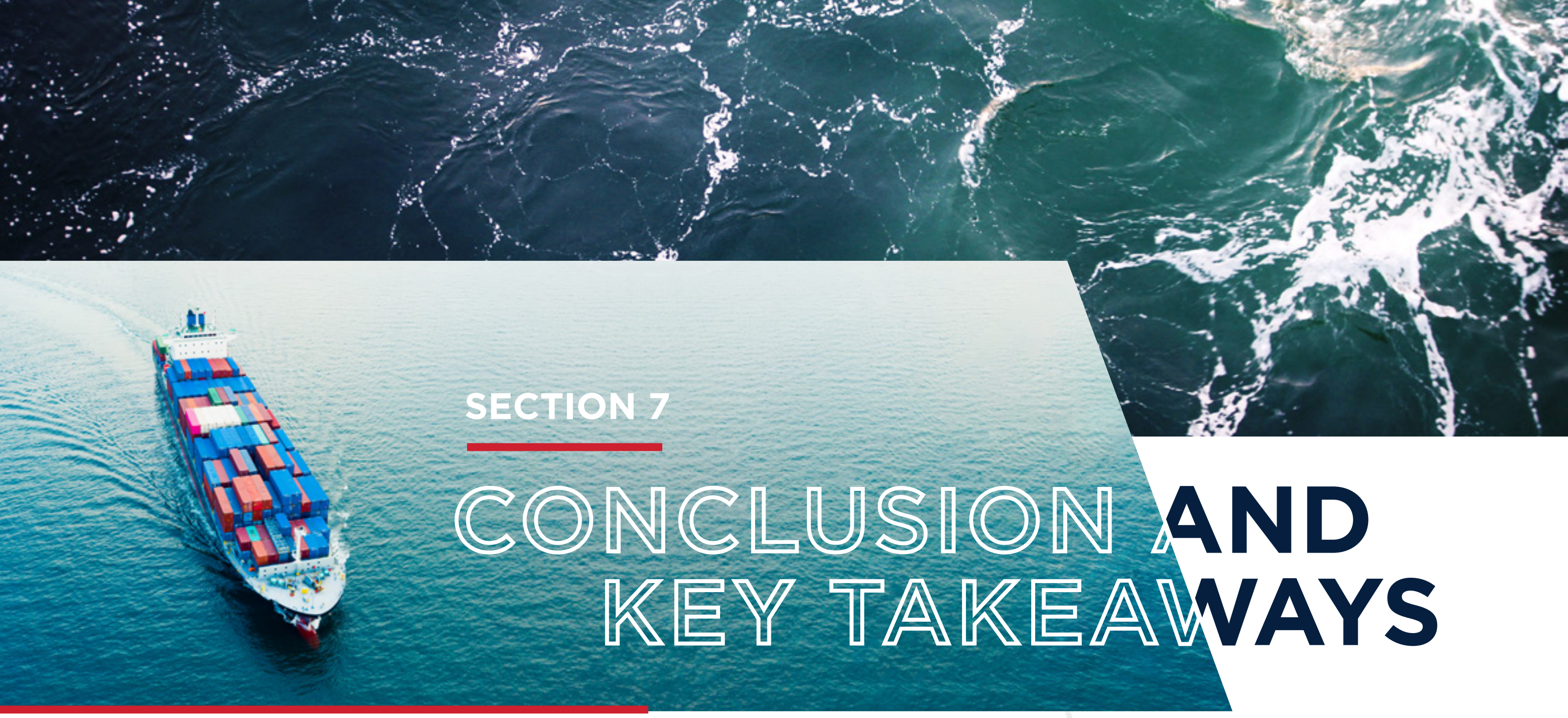


Figure 6.14: Offshore wind impact to the marine ecosystems.

Additionally, with the discovery of the Rice's Whale, there have been restrictions that hinder production in the United States Gulf of Mexico oil and gas industry based on the Stipulated Stay Agreement. Striking a balance is key when considering biodiversity as the Gulf of Mexico has some of the lowest carbon intensity barrels in the world.

Continued development of international guidelines and adoption of best practices in biodiversity management are vital for ensuring that the offshore industry can continue its essential role in the global economy while protecting and enhancing the marine environments it operates within. Future efforts must focus on refining these practices and fostering global cooperation to ensure the sustainability of both industry activities and marine biodiversity.





SECTION 7

CONCLUSION AND KEY TAKEAWAYS

The maritime industry faces the challenge of how to manage the competing demands of rising energy consumption to meet increasing consumer demand and regulatory pressures to minimize and ultimately achieve net-zero carbon emissions.

Alternative fuels are a crucial component for solving this puzzle. But as the industry attempts to pick winners from the raft of potential alternative fuel options, it is increasingly clear that it is the availability and scalability of fuel production that will be the decisive factor in their uptake.

ABS' sixth annual Outlook publication highlights the pivotal role alternative fuels and energy efficiency technologies play in reaching 2050 while also highlighting the need to consider more novel technologies such as carbon capture.

Achieving net-zero emissions by 2050 requires that the economics of using green fuels and carbon capture technologies become favorable well before 2050, through a combination of progressive cost reduction and a carbon price/tax high enough to transition all liquefied natural gas (LNG), ammonia and methanol production to renewable fuels.

The general uncertainty in the industry over fuel availability ensures that the need for fuel flexibility will be the dominant trend for the foreseeable future, as operators look to hedge against geo-politically driven price volatility and patchy global bunkering arrangements.

Dual-fuel ships represent 27 percent of the number of vessels currently on order or about half (49 percent) of the orderbook by gross tonnage (gt). This will increase as the available fuel mix widens this year, with methanol retrofit trials beginning in earnest and ammonia engines becoming available early next year.

As a powerful combination of regulation, technology, geopolitics and shifting global supply and demand patterns shake up the landscape of international trade and shipping, ABS is continuing to focus on the safety consequences of the energy transition. Whatever the emissions-lowering potential of alternative fuels, it is safety in their transport, handling and consumption that will be the hallmark of a truly sustainable industry.

1

Fuel Mix Projection

a. Large-scale trends for fuel mix remain the same as in ABS' 2023 Outlook. The most important shift has been the focus on the deliverability of targets and production projects across the whole decarbonization chain.

b. Under our base case scenario, a 20 percent reduction in carbon dioxide (CO_2) equivalent emissions in 2030 relative to 2008 is achievable on a Well-to-Wake (WtW) basis, but 70 percent by 2040 cannot be met.

c. Under the Net-Zero Scenario #1, energy efficiency technologies (EETs) achieve a global aggregate reduction in emissions of 15 percent by 2040. We also assume that e-diesel replaces portions of oil and biodiesel in the years leading up to 2050.

d. However, by applying a steady approach to the application of these factors we find that the goal of a 70 percent reduction in emissions relative to 2008 would not be met by 2040. This is because the cumulative impact of many of the transitions in technology and fuel gathers pace in the later years of the forecast.

e. Under Net-Zero Scenario #2, achieving the 70 percent target would mean a hugely accelerated reduction in the use of conventional oil and gas, which would require a significantly more rapid renewal of the fleet to replace oil-fueled vessels or a high degree of retrofitting suitable engines.

f. A high retrofit rate and carbon-neutral fuel uptake rate are the keys to achieving the International Maritime Organization's (IMO) 2030 and 2040 greenhouse gas (GHG) emissions milestones.

2

Geopolitical Impact on Energy Transition

a. The rapidly changing geo-political landscape has increased the complexity of the international maritime energy transition.

b. This has generally caused some near-term recalibrations for maritime trade and fleet growth in the industry due to recent geopolitical events.

c. The geopolitical events generally result in supply chain disruptions leading to higher earnings in some sectors and overall higher fuel consumption in the short term due to vessel rerouting, particularly to avoid the Red Sea/Suez Canal.

d. The decarbonization chain is not directly linked to the deterioration of the global geopolitical situation over the last six months, but the impact of progress can be felt.

3

Global Fleet Orderbook

a. Following the recent spike in newbuild contracting from the end of 2020 onwards, the global orderbook has increased, reaching 208 million gross tons (m gt) by the end of 2023.

b. However, the newbuild market has cooled rapidly since Q4 2023. While there continues to be notable interest in the tanker and gas carrier markets, fresh newbuild contracting for dry bulk carriers (sectors that are hard to decarbonize) and containerships have been limited in recent months.

c. Vessels powered by alternative fuels represent 49 percent of the newbuild orderbook in terms of gt. The major alternative fuels are LNG and methanol, which account for 34 percent and 9 percent respectively in the global fleet.

d. ABS analysis expects the orderbook to shrink as the ships ordered in the last few years start hitting the water in earnest and newbuild contracting activity remains subdued. The orderbook is forecast to fall to a low of around 170m gt in 2026. The orderbook is expected to remain stable before trending upwards in the first half of the next decade.

4

Fleet Renewal

a. A large portion of the fleet (about a third) is over 15 years old and the average fleet age is 12.5 years.

b. These are indications that there will be a need for a significant fleet renewal in the near future considering the IMO's GHG reduction targets that make it even more challenging for older tonnage to remain compliant.

5

Fleet Retrofit

a. Among the many solutions currently under consideration, one of the most prominent is retrofitting engines on board ships to use carbon-neutral or zero-carbon fuels.

b. The most popular fuel for retrofitting has historically been LNG, though there is a clear preference for methanol dual-fuel retrofits in upcoming years.

c. The majority of pending retrofits are owned by a small number of major containership lines. As such, the preferred fuel for higher-volume retrofits remains far from certain.

d. A potential pool of 3,300 ships has been identified that are broadly suitable candidates for fuel retrofit based on characteristics typically cited as being key determinants in a ship's retrofit suitability.

e. When considering the forecast for future supply-side developments this pool of candidates expands to close to 5,000 ships of an aggregate 500m gt.

6

Shipyard Capacity — Newbuilds

a. Global shipyard capacity is set to increase moderately over this decade. Shipyard capacity is expected to remain at consistently elevated levels of 70–76m gt through the middle of the century.

b. The "Big Three" Asian shipbuilding nation will collectively continue to dominate the industry.

c. Other nations will begin entering commercial shipbuilding in a significant way, with potential candidates including Vietnam, the Philippines and India.

7

Shipyard Capacity — Retrofits

a. Despite this apparent surplus of potential capacity, the pool of yards capable of carrying out fuel retrofits is significantly smaller.

b. Turnkey fuel retrofits are complex projects, requiring capabilities that are not available at all yards.

c. We estimate that only a small number of shipyards can undertake fuel retrofits.

d. It is important to note that if the fuel retrofit option gains traction, the number of yards capable of completing fuel retrofits is likely to increase. However, in all probability, the larger yards in Northeast Asia and the Middle East and the more specialist yards in Europe will capture most of the business.

8

Alternative Fuel Pathways and Timelines

a. Compared to the well-recognized Tank-to-Wake (TtW) GHG emissions factors, Well-to-Wake (WtW) emissions factors are more sensitive to operating locations and fuel production pathways.

b. The viable pathways to reach long-term decarbonization goals are identified as blue ammonia, blue hydrogen, e-methane, e-methanol, e-ammonia, e-hydrogen, e-diesel, biodiesel, biomethane and biomethanol.

c. When considering WtW GHG emissions savings, the carbon neutral pathways in 2050 are identified as e-methane, e-diesel, e-methanol, e-ammonia, e-hydrogen, biodiesel, biomethanol and biomethane.

d. In terms of cost-effectiveness, ABS developed the GHG Abatement Cost (GAC) index to statistically assess the trade-offs between cost and GHG emission savings, specifically focusing on the WtW approach.

e. Based on the GAC analysis of the three developed scenarios (e-fuels high uptake, bi-fuels high uptake and blue fuels high uptake), a projected ranking of the different fuel pathway's cost-effectiveness at 2050 was calculated. According to ABS' GAC methodology and current fuel prices, biofuels and blue fuels will have lower carbon abatement cost compared to others.

9 Energy Efficiency Technologies

a. The EET adoption rate for the current fleet is relatively low, but it is growing fast in the orderbook. Compared to last year's EET uptake, the latest rate for global fleet orderbook has jumped from 28 percent to 37.4 percent.

b. The highest EET uptake ship type for the existing fleet is bulk carriers, followed by containerships, LNG carriers, and liquefied petroleum gas (LPG) carriers, while the highest EET uptake ship type in the orderbook is roll-on roll-off (ro/ro)/pure care carrier (PCC), followed by containerships, LNG carriers and bulk carriers.

c. By analyzing the energy-saving potentials of EETs, we conclude that EETs are considered short-term options since, in most cases, they cannot serve as the primary decarbonization solutions to meet long-term emission reduction targets.

d. The EETs High Uptake Scenario can save up to 46 percent energy consumption compared to the Business As Usual (BAU) case in 2030, and this value jumps to 55 percent in 2050 based on IMO EET high uptake rate.

e. The EET Low Uptake Scenario, which is more likely to be achieved, may save up to 13 percent of energy consumption in 2030 and 26 percent in 2050 compared to the BAU case.

f. Although the projected results for EETs alone cannot individually lead the maritime industry to net-zero carbon emissions, the encouraging results do suggest that EETs should play a key role in the maritime industry's decarbonization journey.

g. For long-term decarbonization, stakeholders in the shipping industry need to look at alternative fuel system retrofits and onboard carbon capture installations to meet the more stringent regulatory requirements the industry will be facing in the next decades.

10

Key Transformational Technologies

Onboard Carbon Capture and Storage (OCCS) Systems

a. Onboard carbon capture rates of 80 percent and higher are achievable, making OCCS applicable for meeting the IMO's long-term decarbonization strategy. However, disproportionately more energy and equipment may be required making it less economically attractive.

b. OCCS on LNG carriers showed more promising results than OCCS on methanol carriers and OCCS on diesel vessels from both emissions saving and cost perspectives.

Wind Assisted Propulsion Systems (WAPS)

c. WAPS are continuously evolving and are now considered as a potential energy saving solution.

d. The proper methodology of predicting the fuel consumption savings is of high importance. For WAPS the prediction is bespoke and parametric, (i.e., the predicted savings will vary to the assumed conditions and route).

e. The installation of a WAPS is not a common retrofit, and therefore owners should plan such a project with close collaboration from the WAPS vendors.

f. The installation of a WAPS will need to be integrated both to the vessel structure and systems as well as to the vessel's operation.

Fuel Cells

g. The application of fuel cells depends on factors such as efficiency, operating temperature, fuel availability and vessel specifications.

h. The most promising solutions for marine applications are found to be proton exchange membranes, molten carbonate and solid oxide fuel cells (SOFCs).

Battery/Hybrid Ship Propulsion Systems

i. Battery/hybrid ship propulsion systems have already been used to power smaller vessels and port handling equipment, and the transition to larger ships is underway.

j. Battery/hybrid systems are deemed clean for TtW, though not for WtT, making them less attractive as a WtW decarbonization solution under the current TRL.

Nuclear Power as an Alternative Energy Source

k. Advanced nuclear reactors have many possible implementations within the maritime value chain due to their potential flexibility, offering various arrangements of size and power output, long fueling cycles, the possibility of factory fabrication and small carbon footprints.

l. The main barriers limiting nuclear adoption are the regulatory gaps regarding mobile and non-traditional reactors, as most regulatory bodies address only traditional reactors.

11

Offshore Insights

a. Most offshore support vessel (OSV) newbuilds employ standard mechanical propulsion diesel engines, but alternative fuels are slowly being introduced in the market.

b. The short-term nature of OSV contracts is proving a sticking point against emissions-saving newbuilds and conversion projects, leading some oil and gas companies to commit to longer-term charters for more efficient OSVs.

c. Electrification of the jackup fleet has been happening at an increasing rate in regions such as Europe and the Middle East Gulf.

d. The majority of low-emission, retrofitted mobile offshore drilling units (MODUs) are working in the North Sea, with most vessels operating in Norwegian waters due, in part, to high carbon taxes. Other retrofitted units are carrying out contracts in the U.S. Gulf of Mexico and South America, with some awaiting work in Africa, the Mediterranean and Australasia.

SECTION 8

REFERENCES

ABS (2020). -Sustainability Whitepaper: Ammonia as Marine Fuel

ABS (2021). -Sustainability Whitepaper: Hydrogen as Marine Fuel

ABS (2021). -Sustainability Whitepaper: Methanol as Marine Fuel

ABS (2022). -Guide for Methanol and Ethanol Fueled Vessels

ABS (2023). -Requirements for Ammonia Fueled Vessels

ABS (2023). -Requirements for Hydrogen Fueled Vessels

ABS (2023). -Beyond the Horizon: View of the Emerging Energy Value Chains

Environmental Defense Fund (2022). -Ammonia at sea: Studying the potential impact of ammonia as a shipping fuel on marine ecosystems.

European Maritime Safety Agency (2023), Potential of Hydrogen as Fuel for Shipping, EMSA, Lisbon. -American Bureau of Shipping, CE Delft and Arcsilea

European Maritime Safety Agency (2023), Potential of Ammonia as Fuel for Shipping, EMSA, Lisbon. -American Bureau of Shipping, CE Delft and Arcsilea

Howarth RW, Jacobson MZ. How green is blue hydrogen? Energy Sci Eng. 2021; 9:1676– 1687. -https://doi.org/10.1002/ese3.956

Ji, Chenxi, and Mahmoud M. El-Halwagi. "A data-driven study of IMO compliant fuel emissions with consideration of black carbon aerosols." Ocean Engineering 218 (2020): 108241.

Ji, Chenxi, and Stergios Stamopoulos. "Holistic Sustainability and Cost Evaluation for Green Shipping Corridor Framework-based Alternative Marine Fuels." SNAME Maritime Convention. SNAME, 2023.

Ji, Chenxi, et al. "Post-combustion carbon capture for tank to propeller via process modeling and simulation." Journal of CO_2 Utilization 51 (2021): 101655.

Ji, Chenxi. "Predicting fuel consumptions and exhaust gas emissions for LNG carriers via machine learning with hyperparameter optimization." SNAME Offshore Symposium. SNAME, 2021.

Linde (2020). -Anhydrous Ammonia Safety Data Sheet

Linde (2022). -Hydrogen, refrigerated liquid Safety Data Sheet

Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (2023). -Managing Emissions from Ammonia-Fueled Vessels.

SGMF (2023). -Hydrogen as a marine fuel, an introduction. -Version 1.0

SGMF (2024). -Methanol as a marine fuel, an introduction. -Version 1.0

SGMF (2024). -Ammonia as a marine fuel, an introduction. -Version 2.0

SIGTTO (2016). -Liquefied Gas Handling Principles on Ships and in Terminals (LGHP4). -Fourth Edition.

Ship and Bunker, Accessed by March 16, 2024

EU, 2023. DIRECTIVE (EU) 2023/2413 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

Argus Marine Fuel Price, Accessed by March 2024

BCG, 2024. Biogas Can Help Global Shipping Go Green https://www.bcg.com/publications/2024/biogas-can-help-global-shipping-go-green#:~:text=Finallypercent2Cpercent20thesepercent20twopercent20fuelspercent20are,productionpercent20costspercent2Cpercent20notpercent20salespercent20prices.

Sea LNG, 2022. THE ROLE OF BIO-LNG IN THE DECARBONISATION OF SHIPPING

S and P Platts Hydrogen Price Wall, Accessed by March 16, 2024

Sea-LNG, 2024. LNG – Leading Maritime Decarbonization

https://www.methanol.org/renewable/ Accessed by May 1, 2024

IMO, 2020. IMO Fourth GHG Study 2020

Green Voyage 2050. https://greenvoyage2050.imo.org/technology-groups

EERE Comparison of Fuel Cell Technologies. Available online: https://www.energy.gov/eere/fuelcells/comparison-fuel-celltechnologies (Accessed on 22 March 2024).

Cigolotti, V.; Genovese, M.; Fragiacomo, P. Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems. Energies 2021, 14, 4963

Elkafas, Ahmed G., et al. “Fuel cell systems for maritime: a review of research development, commercial products, applications, and perspectives. “Processes 11.1 (2022): 97.

Wang Xiaoyu, Jianzhong Zhu, and Minfang Han. “Industrial development status and prospects of the marine fuel cell: a review.” Journal of Marine Science and Engineering 11.2 (2023): 238.

Xing, Hui, et al. “Fuel cell power systems for maritime applications: Progress and perspectives.” Sustainability 13.3 (2021): 1213.

World Nuclear News, “Russia Commissions Floating NPP,” 22 May 2020. [Online]. Available: https://www.world-nuclear-news.org/Articles/Russia-commissions-floating-NPP.

S. Leimbach, “Newcleo, Viaro Energy Look to Nuclear Technology for Oil and Gas decarbonization,” 6 March 2024. [Online]. Available: https://www.environmentenergyleader.com/2024/03/newcleo-viaro-energy-look-to-nuclear-technology-for-oil-and-gas-decarbonization/.

Nuclear Engineering International, “BHP to consider nuclear-powered cargo ships,” 27 February 2024. [Online]. Available: https://www.neimagazine.com/news/newsbhp-to-consider-nuclear-powered-cargo-ships-11551624.

World Nuclear News, “Korean shipbuilder joins maritime SMR project,” 7 February 2024. [Online]. Available: https://www.world-nuclear-news.org/Articles/Korean-shipbuilder-joins-maritime-SMR-project.

S. Chambers, “Canadian project to develop marine-nuclear reactors moves ahead,” 24 January 2024. [Online]. Available: 2024.

A. Tore, “Norway takes Swedish nuclear technology to the high seas,” [Online]. Available: https://klimavenner.no/norway-takes-swedish-nuclear-technology-to-the-high-seas/.

Lloyd’s Register, “Lloyd’s Register Press Release: LR, Zodiac, HD KSOE and KEPCO E&C ink nuclear propulsion JDP,” 19 December 2023. [Online]. Available: https://www.lr.org/en/knowledge/press-room/press-listing/press-release/lr-zodiac-hd-ksoe-and-kepco-ec-ink-nuclear-propulsion-jdp/.

J. O. Mandra, “Jiangnan Shipyard unveils design for the ‘world’s largest’ nuclear-powered containership,” 6 December 2023. [Online]. Available: https://www.offshore-energy.biz/jiangnan-shipyard-unveils-design-for-the-worlds-largest-nuclear-powered-containership/#:~:text=Home%20Nuclear-,Jiangnan%20Shipyard%20unveils%20design%20for,world’s%20largest’%20nuclear%2Dpowered%20containership&text=China’s.

F. Bahtić, “HD KSOE, Kepco win ABS’ AiP for floating nuclear power barge,” 4 October 2023. [Online]. Available: https://www.offshore-energy.biz/hd-ksoe-kepco-win-abs-aip-for-floating-nuclear-power-barge/.

Crowley, “Crowley, BWXT Debut Nuclear Power Generation Vessel Concept,” 20 September 2023. [Online]. Available: https://www.crowley.com/news-and-media/press-releases/crowley-bwxt-debut-nuclear-power-generation-vessel-concept/.

World Nuclear News, “X-energy to develop second project pele microreactor design,” 14 September 2023. [Online]. Available: https://www.world-nuclear-news.org/Articles/X-energy-to-develop-second-Project-Pele-microreact.

Newcleo, “Newcleo press release: Newcleo, Fincantieri and RINA working together on feasibility study for nuclear naval propulsion,” 25 July 2023. [Online]. Available: https://www.newcleo.com/press-releases/newcleo-fincantieri-and-rina-working-together-on-feasibility-study-for-nuclear-naval-propulsion/.

N. Blenkey, “New ABS study explores potential of commercial ship nuclear propulsion,” 24 July 2023. [Online]. Available: https://www.marinelog.com/news/new-abs-study-explores-potential-of-commercial-ship-nuclear-propulsion/.

World Nuclear News, “Samsung completes design of CMSR Power Barge,” 4 January 2023. [Online]. Available: https://www.world-nuclear-news.org/Articles/Samsung-completes-design-of-CMSR-Power-Barge.

World Nuclear News, “NuScale and Prodigy conceptual design for marine-based SMR plant,” October 27, 2022. [Online]. Available: https://www.world-nuclear-news.org/Articles/NucScale-and-Prodigy-announce-new-marine-based-SMR.

Ulstein, “Ulstein Press Release: Ship design concept from Ulstein can solve the zero emissions challenge,” April 26, 2022. [Online]. Available: https://ulstein.com/news/ulstein-thor-zero-emission-concept.

The National Academies Press, Washington DC, “Laying the Foundation for New and Advanced Nuclear Reactors in the United States,” 2023. [Online]. Available: hhttps://doi.org/10.17226/26630.

Massachusetts Institute of Technology led by Prof. Jacopo Buongiorno, “Decarbonizing and Strengthening the Global Energy Infrastructure Using Nuclear Batteries,” [Online]. Available: https://climategrandchallenges.mit.edu/wp-content/uploads/2022/04/CGC_factsheet-Decarbonizing_and_Strengthening_the_Global_Energy_Infrastructure_using_Nuclear_Batteries.pdf.

Office of Nuclear Energy, “What is a Nuclear Microreactor?,” February 26, 2021. [Online]. Available: https://www.energy.gov/ne/articles/what-nuclear-microreactor.

Nuclear Innovation Alliance, “Advanced Nuclear Reactor Technology Primer July 2023 Update,” July 2023. [Online].

Available: https://nuclearinnovationalliance.org/advanced-nuclear-reactor-technology-primer.

American Bureau of Shipping, “Setting the Course to Low Carbon Shipping: Zero Carbon Outlook,” 2022. [Online]. Available: https://ww2.eagle.org/en/publication-flip/zero-carbon-outlook.html.

https://www.weforum.org/agenda/2022/11/offshore-wind-farms-future-renewables/

https://www.dolphynhydrogen.com/

The S&P Global Commodity Insights, top-ten-clean-energy-technology-trends-2024

https://about.bnef.com/blog/offshore-wind-to-hydrogen-sounds-a-starting-gun/

IEA, https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage

https://www.iea.org/reports/ccus

https://www.iea.org/reports/global-methane-tracker-2024

https://carbontracker.org/reports/paris-maligned-2/

Oil and Gas Development | Threats | WWF (worldwildlife.org)

ABS Offshore Production of Green Hydrogen

ABS Carbon Capture, Utilization and Storage

https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

https://www.blueoceanresearchalliance.com/

https://www.konkraft.no/contentassets/9652374dfefe4d50b2b6bc17165d3e08/the-energy-industry-of-tomorrow-2023.pdf

https://www.norskpetroleum.no/en/environment-and-technology/emissions-to-air/

https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co$_2$-transport-and-storage#tracking

1701 City Plaza Drive | Spring, TX 77389 USA
1-281-877-6000 | sustainability@eagle.org
www.eagle.org