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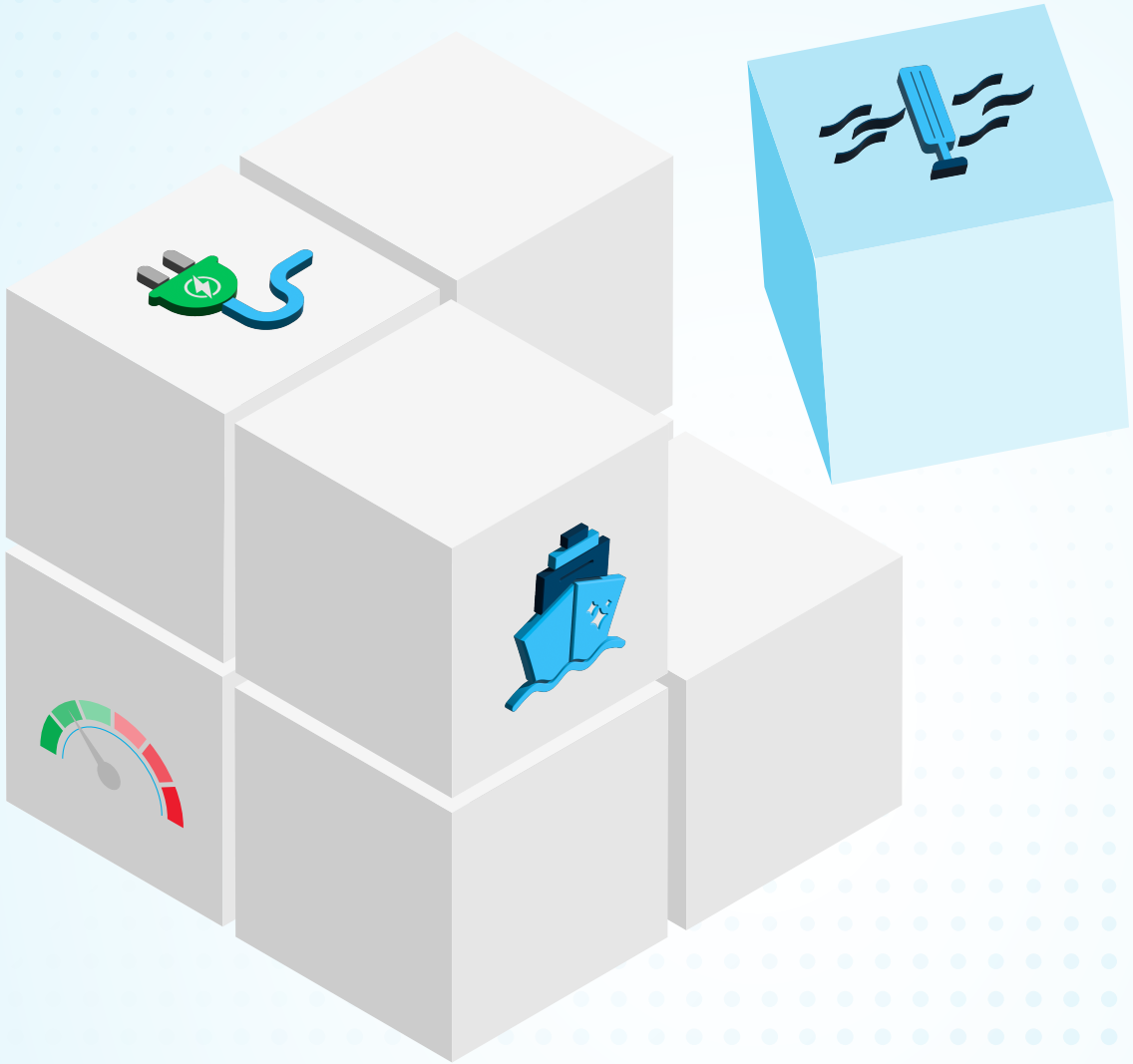
Keys to Energy-Efficient Shipping



PROBLUE

Keys to Energy-Efficient Shipping

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Abbreviations

AER	Annual Efficiency Ratio
AIS	Automatic Identification System
APIs	Application Programming Interfaces
BAU	Business-As-Usual
CII	Carbon Intensity Indicator
CO_2eq	Carbon Dioxide equivalent
CRP	Contra-Rotating Propeller
DCSA	Digital Container Shipping Association
DWT	Deadweight Tonnage
DYNAPORT	Dynamic Navigation and Port Call Optimization in Real Time
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EEXI	Energy Efficiency Existing Ship Index
EMSA	European Maritime Safety Agency
EPL	Engine Power Limitation
ETA	Estimated Time of Arrival
ETB	Estimated Time of Berthing
EU	European Union
EVDI	Existing Vessel Design Index
GFI	GHG Fuel Intensity
GHG	Greenhouse Gas
GIA	Global Industry Alliance
GJ	Gigajoules

GT	Gigatons
HVCC	Hamburg Vessel Coordination Center
IAPH	International Association of Ports and Harbors
IEEC	International Energy Efficiency Certificate
IHO	International Hydrographic Organization
IMO	International Maritime Organization
GIA	Global Industry Alliance
IHMA	International Harbour Masters Association
ITPCO	International Taskforce Port Call Optimization
ITTC	International Towing Tank Conference
JIT	Just-in-time
KPIs	Key Performance Indicators
kW	Kilowatts
MARPOL	The International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MISSION	Maritime Just in Time Optimization Interoperable Port Call and Voyage Optimization Tool
MJ	Megajoules
MPA	Maritime Port Authority Singapore
MW	Megawatts
MWhs	Megawatt-hours
NOR	Notice of Readiness
NOx	Nitrogen Oxides
OECD	Organization for Economic Co-operation and Development

OPS	Onshore Power Supply
ORC	Organic Rankine Cycle
PA	Port Authority
PacMMS	Pacific Maritime Management Services
PBP	Pilot Boarding Place
PCO	Port Call Optimization
PCS	Port Community System
PJ	Petajoule
PM	Particulate Matter
PRISE	Port-River Information System Elbe
RCP	Representative Concentration Pathway
RTA	Requested Time of Arrival
SEEMP	Ship Energy Efficiency Management Plan
SSP2	Shared Socioeconomic Pathway "Middle of the Road"
TEU	Twenty-foot Equivalent Unit
TJ	Terajoule
TRL	Technology Readiness Level
TTW	Tank-To-Wake
VA	Virtual Arrival
vNOR	Virtual Notice of Readiness
WASP	Wind-Assisted Ship Propulsion
WTT	Well-to-Tank
WTW	Well-to-Wake

*The default currency used in this report is US dollars, $.

Keys to Energy-Efficient Shipping

40%

of emissions can be cut by energy efficiency alone

exceeding the IMO's 2030 targets of 20% (base ambition) and 30% (high ambition). Both technical and operational measures are needed to complement the fuel transition over time to meet the IMO's long-term targets.

250 million tons

of emissions can be cut at no cost

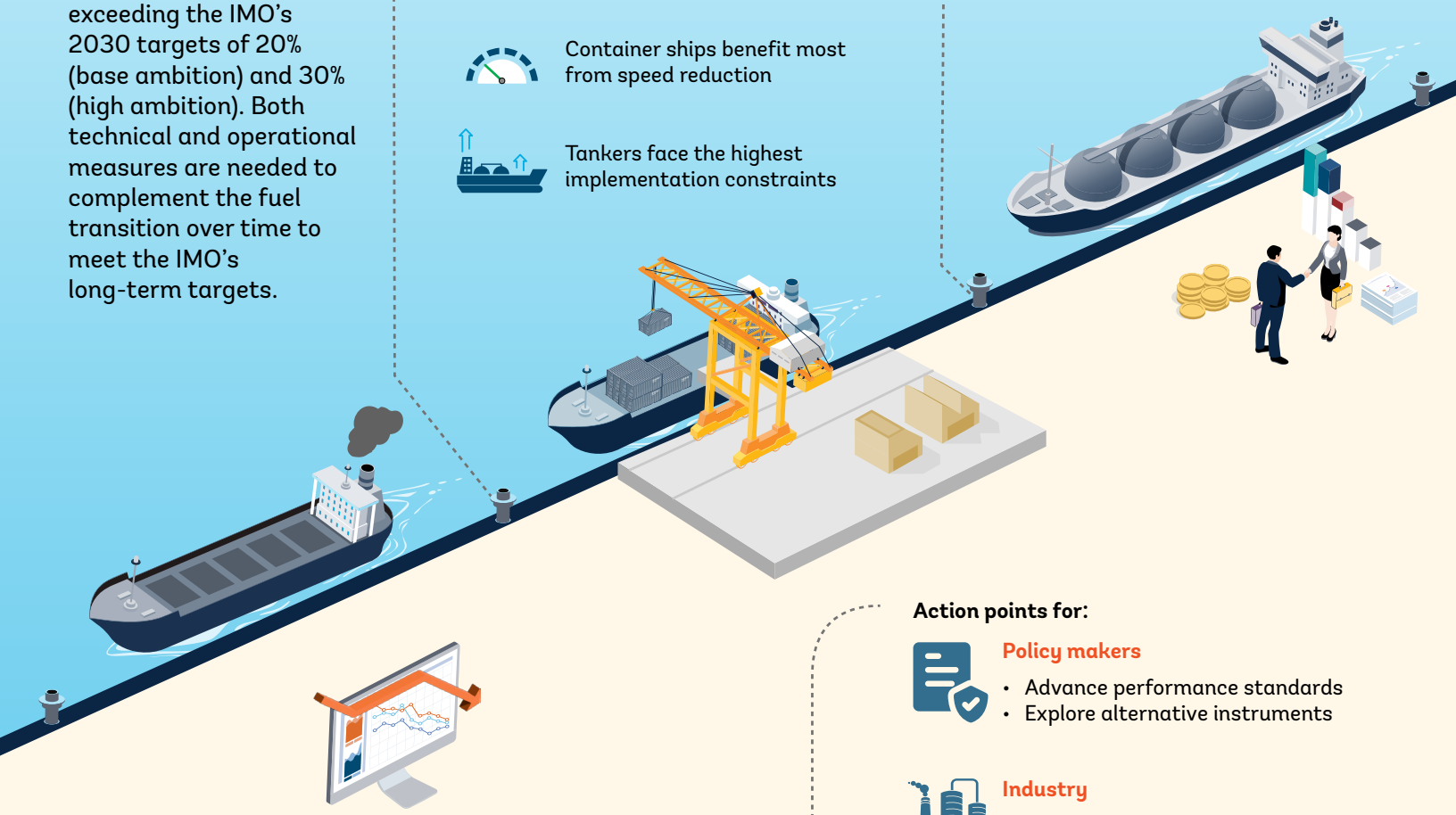
representing half of the savings from energy efficiency in 2030. But savings vary by ship type:

- Bulk carriers are suited for wind-assisted propulsion
- Container ships benefit most from speed reduction
- Tankers face the highest implementation constraints

Up to $220 billion

in savings per year

in the transition to more expensive alternative fuels in 2040 and 2050. Investing $35 billion annually in fleet-wide efficiency upgrades can reduce the high costs of green fuels and market disruptions.



Barriers prevent wide-scale adoption

Economic, behavioral and organizational barriers explain why promising measures remain largely untapped, despite their cost-effectiveness and emissions reduction potential.

Action points for:

Policy makers

- Advance performance standards
- Explore alternative instruments

Industry

- Develop information standards
- Foster demonstration projects

Ports and port community

- Explore national or local policies
- Share best practices
- Adopt digital solutions

Finance

- Innovate risk management
- Integrate financing

Executive Summary

Objective

While discussions about the energy transition in shipping often center on green fuel options to decarbonize shipping, this report highlights the unique role that energy efficiency improvements can play in reducing ships' energy consumption and GHG emissions, as well as cutting fuel costs for the sector. In addition to these direct benefits, energy efficiency measures also yield positive outcomes for ports, including improved port efficiency, decreased local air pollution and greenhouse gas emissions throughout the supply chain, and reduced costs. Overall, a discussion on energy efficiency is closely linked to the intertwined role of ships and ports, to which the World Bank contributes in areas such as trade facilitation, port reform, cybersecurity, and energy transition.

To better understand the tapped or untapped potential of technical and operational energy efficiency measures for maritime transport, and how this can help reduce transport costs for developing countries in the energy transition, this report addresses four main questions:

- What is the overall contribution of energy efficiency measures to meeting the IMO's checkpoints and net-zero target on the path to 2050 for the global fleet and main ship types?
- What is the contribution of individual energy efficiency measures to cut GHG emissions, and how cost-effective are they?
- How can energy efficiency contribute to a cost-effective energy transition pathway, and how do they work in conjunction with the long-term fuel transition?
- What are the remaining barriers to maximizing energy efficiency in shipping, and what are the possible solutions?

Key findings

Following the quantitative and qualitative analysis, the report sets out four key findings for policymakers and industry to consider:

1. **Energy efficiency measures can reduce ship emissions by up to about 40 percent in 2030, exceeding the International Maritime Organization's (IMO) policy objectives.** Technical and operational energy efficiency measures offer a maximum potential to reduce absolute GHG emissions by 23-39 percent in 2030 relative to 2008 levels, clearly exceeding the IMO's base level of ambition of 20 percent in 2030 and at a maximum exceeding the IMO's high level ambition of 30 percent. The largest untapped potential in the short term lies in ship speed reductions for the overall fleet, reducing GHG emissions by 5-15 percent, with additional savings achievable by optimizing voyage speed into congested ports. Beyond 2030, the contribution of technical measures, such as changes in ship design and the addition of new equipment, is expected to increase. As the global fleet's fuel transition to green fuels is still ramping up, energy efficiency improvements are promising short-term solutions. While energy efficiency measures are insufficient to meet the IMO's 2050 target, at a maximum lowering GHG emissions to about 40 percent below 2008 levels, they will also complement the fuel transition beyond 2030 and reduce ships' reliance on fossil fuel.

2. **About half of emissions savings from energy efficiency measures are considered cost-effective in 2030, cutting 250 million tons of emissions at no cost.** By 2030, cost-effective energy efficiency measures could fully pay for themselves by lowering shipping's fuel costs. For bulk carriers, container ships, and tankers, which account for nearly 80 percent of shipping GHG emissions, the majority of energy efficiency measures are cost-effective. However, marginal abatement costs for individual measures vary by ship type, primarily due to differences in ship design and operational requirements. Tankers have the least cost-effective abatement due to relatively higher installation costs of technologies and technical limitations when reducing speed. Bulk carriers offer favorable design features for wind-assisted propulsion, while container ships show high abatement effectiveness in reducing speed.

3. **Energy efficiency measures can reduce the total cost of the maritime energy transition by up to about $220 billion per year.** Improving the energy efficiency of the global merchant fleet is insufficient to meet the IMO's policy objectives alone. Therefore, green fuels, such as methanol and ammonia, will be indispensable in 2040 and 2050, but are more expensive than conventional fuels. A cost-efficient route to meeting the sector's GHG emissions targets is to prioritize energy efficiency, which reduces the fuel consumption of the fleet and, therefore, the overall cost of the transition. Annual capital investments in energy efficiency across the fleet of about $35 billion can save up to $270 billion in green fuel costs per year. Investments in energy efficiency measures also offer mitigation to fuel price volatility and will be a critical component of the fuel transition, when green fuels are still more expensive.

4. **Despite their potential, several top candidate energy-efficiency measures in merchant shipping remain underused because of sector-specific economic, behavioral, and organizational barriers.** While promising, some of the candidate measures with the highest GHG emissions savings and lowest uptake, such as wind-assisted ship propulsion, air lubrication, and port call optimization (PCO), remain untapped to date. An explanation for the lack of investment and implementation of cost-effective measures is due to known economic, behavioral, and organizational barriers, which are also common barriers to implementing energy efficiency improvements in other sectors. Specifically, imperfect information, split incentives, and asymmetric information are the most significant market failures, while non-market failures such as access to capital, hidden costs, perceptions of technology risk, and market heterogeneity, contribute to the lack of uptake of technical measures. Behavioral and organizational barriers are particularly important to address to increase the uptake of PCO by ports and the shipping industry.

Action points

Energy efficiency has significant potential for global shipping but remains largely untapped to date. While there are public and private-led initiatives underway, significant barriers persist. How can the remaining barriers be addressed, and who is best placed to lead such efforts?

Policymakers

Regulatory bodies set the standards for the safety, security, and environmental performance of ships. They play a major role in creating an enabling environment for realizing the full potential of energy efficiency.

- **Advance performance standards:** Performance standards have been the backbone of a uniquely regulated global shipping sector. They hold some of the greatest potential to address the longstanding market failures and barriers, such as information barriers, which prevent firms from responding to only price signals (Gupta and others 2007). International performance standards (for example EEDI, CII) can be strengthened and considered by IMO member states in their future work plans.
- **Explore alternative instruments:** However, other instruments (for example emission levies, subsidies) can also provide additional demand and supply-side incentives, especially as there is a growing recognition that a combination of multiple climate policy instruments may be needed to decarbonize industries (Grubb, Hourcade, and Neuhoff 2014; Mazzucato 2018; IMO 2021b). The large untapped potential of energy efficiency, especially to help make shipping cost more resilient to absolute fuel price volatility, rerouting shocks, and fuel transition cost, hence presents an opportunity for national, regional, and international policymakers.

Industry

The shipping industry is both an enabler and beneficiary of increased energy efficiency. Actors range from shipowners, shippers, to equipment manufacturers.

- **Develop information standards:** Alongside regulatory intervention, voluntary information standards can complement policies to help address imperfect information market failures and harmonize data exchange. Industry initiatives can help innovative technologies gain market acceptance. Here, validation guidelines for technology performance, and ultimately fuel savings, are important to grow investor confidence through consistent terminology (ITTC 2024).
- **Foster demonstration projects:** Third-party verified data on technology demonstrations in real operating conditions would also help improve access to capital and increase the business case for charterers and shipowners.

Ports and port community

Port stakeholders are critical actors to foster the uptake of promising port-centric energy efficiency measures, such as port call optimization, but also infrastructure-related options, such as onshore power supply.

- **Explore national or local policies:** National and local (port) policies can encourage these port development activities by considering how regulatory instruments can be used, as ports do not traditionally fall under the regulatory realm of the IMO.[1]
- **Share best practices:** The learnings from ports that are more advanced in implementing port call optimization can help ports in the beginning or earlier stage of implementation to address adoption challenges. This is especially important for many ports that operate under some type of landlord model in which private terminals control the data around berth planning.
- **Adopt digital solutions:** These initiatives can be supported by a software support system such as a port community system or a maritime single window, which facilitate data sharing across multiple stakeholders. Adoption of global digital data standards that establish definitions of different locations within ports and port call timestamps from universally accepted IMO and International Hydrographic Organization (IHO) standards is also crucial to improve communication on port calls and arrival times between ship operators and ports, enabling port call optimization.

[1] See Resolution MEPC.323(74) (IMO, 2019) which specifically encourages port-side energy efficiency initiatives that support the viability of business cases for the provision of ship and shoreside/onshore power supply from renewable sources, facilitating Just-in-Time Arrival of ships through developing necessary global digital data standards that would allow reliable and efficient data exchange between ship and shore, and promoting incentive schemes that address GHG emissions and sustainability of international shipping and encourage more incentive providers and shipping companies to join these schemes.

Finance

As uptake lags, access to capital is essential for financing investments in energy efficiency technologies and systems, both on board ships and at port facilities.

- **Innovate products:** To justify financing for energy efficiency upgrades, these technologies must demonstrate that they enhance the ship's value, for example, by improving operating cash flow through reduced fuel costs or lower compliance expenses. To allow debt capital to support energy efficiency, ship financiers should collaborate with industry stakeholders to develop new financing solutions for retrofits to address the risk in energy efficiency investments such as when the benefits do not fully accrue to the shipowner. Additionally, financiers can collaborate with industry stakeholders to establish universally accepted information standards, which would help articulate the value of these technologies more clearly.
- **Integrate financing:** For port investments, implementing digital technologies to optimize port calls represents a cost-effective approach to achieving significant development outcomes. These interventions are often overlooked as standalone measures due to their seemingly modest scale. However, they can deliver substantial benefits. Development partners can collaborate with public port authorities to bundle smaller initiatives with broader trade facilitation and port infrastructure investments, ensuring that initiatives aimed at optimizing port calls are effectively implemented. This approach enables the sector to capitalize on these efficient solutions and avoid missing out on valuable opportunities for improvement in air pollution management, GHG emission reductions, and enhanced trade efficiency.

Background

International maritime transport is the backbone of international trade, carrying over 80 percent of global trade by volume (UNCTAD 2022). As such, international shipping can play a significant role in greening the energy supply chain by carrying green fuels,[2] green technologies, and related components from producers to end consumers. At the same time, shipping accounted for around three percent of global anthropogenic greenhouse gas (GHG) emissions in 2018 (Faber and 2020). Projections suggest emissions could increase to 90-130 percent of 2008 GHG emissions by 2050 under Business-as-Usual (BAU) scenarios (Faber and others 2020).

What's new in this report?

Much of the discourse on shipping's energy transition focuses on green fuel pathways. While these are critical, this report examines the distinct contribution of energy-efficiency improvements to enabling lower-emission operations and reducing the sector's fuel costs. To date, investments in energy efficiency measures have been inhibited by barriers such as imperfect information that prevent the adoption of these low-hanging fruits. This report (i) quantitatively models the possible effects of energy efficiency against different socio-economic pathways and emission goals. It also (ii) updates marginal abatement cost (MAC) curves for relevant measures, (iii) quantifies the cost reduction potential to the maritime fuel transition when energy efficiency measures are applied, and (iv) explores the remaining barriers for their uptake, including deep dives on two promising measures and related industry initiatives, for policymakers to consider. Overall, a discussion on energy efficiency is closely linked to the intertwined role of ships and ports, to which the World Bank contributes in areas such as trade facilitation, port reform, cybersecurity, and the energy transition.

Policy context

In July 2023, the International Maritime Organization (IMO) unanimously adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships. This landmark agreement replaces the 2018 Initial Strategy and significantly strengthens shipping's GHG reduction targets. IMO member states agreed to:

- Reach net-zero GHG emissions from international shipping by around 2050, with interim checkpoints of 20-30 percent by 2030 and 70-80 percent by 2040;
- Make zero or near-zero GHG energy, fuels, and technologies 5-10 percent of shipping's energy mix by 2030; and
- Develop a marine GHG fuel standard and a maritime GHG emissions pricing mechanism, which are expected to be adopted in 2025 and could enter into force in 2027 (IMO 2023).

[2] Green fuels in the context of this report, refer to fuels which have zero or near-zero GHG emissions, on a well-to-wake basis, in line with the definitions in the IMO 2023 GHG Strategy.

In general, maritime transport strongly correlates with global trade. Historically, shipping activity has rarely remained constant. The more goods that are traded, the more transport services by ships are needed. From 2012 to 2023, for instance, the size of the fleet increased by 59 percent, while seaborne trade grew by 19 percent (UNCTAD 2025a; UNCTAD 2025b). With any further increase in global trade, the demand for maritime transport is projected to grow as well.

To meet the recently adopted absolute GHG reduction targets in a growing sector, GHG intensity (GHG emissions per transport work) across the fleet needs to decrease more than the numbers of the absolute targets suggest. This means shipping will need to reduce its GHG intensity beyond the 20-30 percent by 2030, or the 70-80 percent by 2040 absolute GHG emissions targets (IMO 2023).

Given the long lifetime of ships of 20-25 years, this implies that ships recently put into service or being ordered now should plan for the ability to run on green fuels in the near future. Otherwise, they risk becoming stranded assets. However, these fuels are estimated to be at least twice as expensive as fossil fuel bunker fuel on a per-ton basis (DNV, 2024). Therefore, minimizing the amount of green fuel required to propel ships by improving their energy efficiency will become increasingly important in the future.

Energy efficiency vs. GHG intensity

The energy efficiency of the fleet, defined as the energy used to achieve a given quantity of output, is an important driver of maritime GHG emissions. Output in the shipping sector is defined as the movement of cargo and passengers. In freight shipping, energy efficiency is express as energy per unit of cargo per unit of distance (for example megajoules per ton-mile (MJ per t-nm); see also Box E.1).

Carbon dioxide (CO_2) emissions are sometimes used as a proxy for energy. This is appropriate if the shares of each fuel in the fuel mix remain approximately constant (and if the fuel mix contains fossil fuels), which means there is a linear relationship between a fuel's energy content and the emitted CO_2. In this report, GHG intensity for the shipping sector is measured in Well-to-Wake CO_2 equivalent per ton-nautical mile.

Box E.1 Definitions of energy efficiency

Energy efficiency can be defined generally as the quantity of energy used to achieve a given quantity of output. In the case of shipping, the output is the movement of cargo and passengers. Therefore, energy efficiency in freight shipping is often represented as the energy required per unit of cargo (mass or volume) per unit of distance. For passenger shipping, it can be defined as the energy per number of passengers per unit of distance. Other definitions are based on transport supply (for example transport capacity of a ship) rather than on the actual transport work. CO_2 emissions are sometimes used (for example, in metrics used in IMO regulation) as a proxy for energy.

Source: World Bank.

The development of shipping emissions and carbon intensity

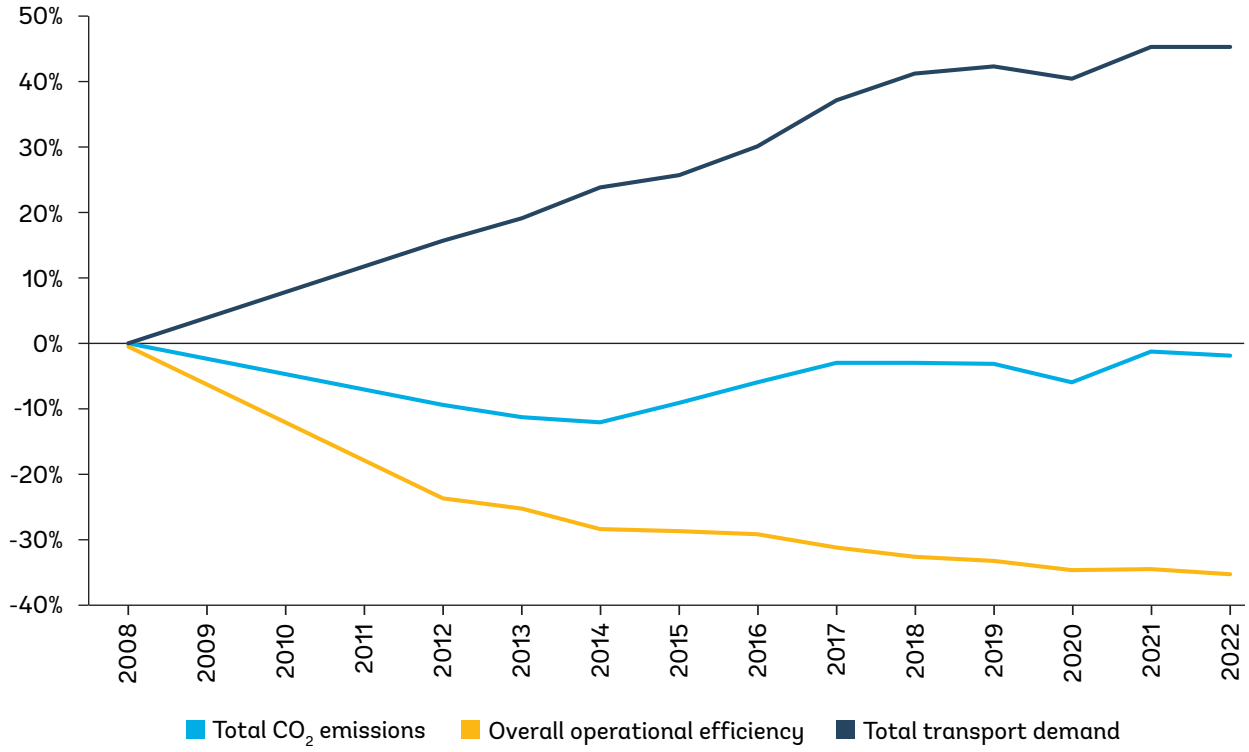
Prior to the advent of relevant energy efficiency regulations (the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP), which came into force in 2013), the development of energy efficiency was primarily due to market forces and technology development. The design efficiency of new ships improved significantly after the oil crises of the 1970s but deteriorated again when oil prices remained low throughout the 1990s and 2000s (Faber and others 2016). After around 2015, design efficiency started to improve again.

Figure E.1 shows that total CO_2 emissions decreased between 2008 and 2014. In the early 2000s, high freight rates triggered a surge in ship orders, rapidly expanding the global fleet. When demand dropped during the 2007–2009 global financial crisis, shipping companies responded by reducing operational speeds, which significantly improved the operational efficiency of ships (IMO 2014). Speed reduction, also referred to as "slow steaming", was a key driver for GHG emissions reductions, especially for bulk carriers, chemical tankers, container ships, and oil tankers since 2008 (Faber and others 2020). However, most ship types ceased slowing down further from 2015 to 2018, due to the improving freight market situation, decreasing fuel oil prices, as well as certain technical limitations.

The COVID-19 pandemic disrupted the relatively stable balance between supply and demand for goods worldwide in 2020, characterized by a reduction in demand and contraction in supply during the first phase of the pandemic. In the second phase, a surge in demand for manufactured goods outpaced supply, placing additional handling pressure on ports and increasing waiting times in ports (UNCTAD 2023). These phases are reflected in the shipping GHG emissions data, with the dip in shipping GHG emissions occurring in 2020, followed by a rebound back to nearly 2008 levels by 2021.

Persistent geopolitical tensions have prompted ships to adjust their trading patterns to circumvent chokepoints. As a result of the logistical disruptions and an increase in long-haul trade from importing countries in Asia, ton-mile demand reached its highest volume since 2011 in 2024 (UNCTAD, 2025c). This has led to increased speeds in some segments, such as container ships, which must maintain their schedules on longer routes. In 2023, container ship waiting times at ports decreased; however, logistical disruptions led to a resurgence in port congestion in 2024. This trend has contributed to higher short-term GHG emissions, but it also highlights the potential to lower port waiting times through targeted port optimization strategies (World Bank 2025c).

Figure E.1 Trends in transport work, ship operational efficiency, and GHG emissions since 2008



Source: Smith and Francis (2024b); Clarksons (ongoing). Operational efficiency is the EEOI, which measures the CO_2 emissions per unit of transport work.

Carbon intensity steadily improved by around 30 percent over the period 2008-2018 (Faber et al. 2020). A contributing factor to the improvement in carbon intensity after 2008 was the marked increase in the average size of ships, particularly for container ships, bulk carriers, and gas carriers. Another factor was the aforementioned speed reduction.

The improvement in carbon intensity slowed to 1.1 percent per year in the 2018-2022 period, according to data from Smith and Francis (2024b). Crucially, this highlights that a decline in carbon intensity can help reduce GHG emissions. However, if transport work increases enough and ships are overwhelmingly propelled by fossil fuels, absolute GHG emissions can still rise despite improvements in energy efficiency. The reduction in productivity during this period suggests that there is potential to improve carbon intensity by, for example, reducing time spent in port, as GHG emissions generated while berthed are not offset by transport work, unlike those generated while sailing.

Energy efficiency regulation

In addition to market forces, the IMO introduced energy efficiency regulations, which could result in further improvements in efficiency. In 2011, the IMO adopted a regulation on the design efficiency of ships, which required ships built from 2013 onwards to have a design efficiency better than a reference value. The adoption of EEDI was accompanied by an operational measure, the Ship Energy Efficiency Management Plan (SEEMP). This regulation aims to monitor and improve the operational efficiency of all ships throughout their lifespan by requiring shipowners to develop plans for improving energy efficiency and collect data to monitor the carbon intensity of their fleet (IMO 2011).

The EEDI is a technical energy efficiency design metric that requires a minimum energy efficiency level per capacity mile (measured in grams of CO_2 per capacity mile) for different ship type and size segments. The EEDI is based on the vessel's design characteristics, rather than the ship's operational performance. It has a strong enforcement mechanism as a vessel is not allowed to sail without a valid International Energy Efficiency Certificate (IEEC) (IMO 2011).

The average energy efficiency specifications of newbuild ships ordered since 2013 have improved significantly (Faber and others 2020). These improvements have largely been met through derated engines; however, this directly affects the EEDI equation through reduced power, while not impacting a ship's operability, as the market was already operating at lower speeds (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping 2023). However, there has also been an increase in the uptake of energy efficiency technologies across different segments of the shipping fleet.

There are significant advantages to targeting energy efficiency regulation for newbuild ships. Retrofitting a ship with energy efficiency technologies can be more expensive than implementing these technologies during the design and construction stage for newbuilds and could require a vessel to remain in drydock for several months (Nelissen and others 2023). Furthermore, some technical measures, such as hull shape, can significantly reduce power consumption and therefore GHG emissions, but can only be implemented in the design stage of a newbuild vessel.

However, as EEDI only applies to newbuilds, and since ships have an average lifespan of 20-30 years, the impacts of EEDI on the overall design efficiency of the global fleet over the first five years of its implementation have been relatively small (UMAS 2020).

Recently, the IMO has adopted further legislation that requires existing ships to meet similar standards as new ships (the Existing Energy Efficiency Index (EEXI)), as well as regulations which set targets for the operational energy efficiency of ships (the Carbon Intensity Indicator or CII) (IMO 2021a; IMO 2025). Both regulations came into effect in 2023.

The EEXI is a design-based technical efficiency standard that extends the EEDI to ships built before 2013, which were not subject to the original EEDI requirements. Initial surveys revealed that for most vessels, shaft power limitation or engine power limitation are the preferred options to achieve EEXI compliance, due to their ease of implementation and effectiveness in reducing calculated GHG emissions (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping 2023). This reduction of available onboard power is unlikely to lead to a short-term reduction of CO_2 emissions, since most vessels routinely operate at speeds and engine loads between 38 percent and 50 percent of their maximum continuous rating,[3] well below the maximum allowed under the EEXI (Rutherford and others 2020). However, in the future, the EEXI may limit the ability of vessels to speed up under favorable commercial conditions or to catch up on schedules due to port delays.

The Carbon Intensity Indicator (CII) is a measure used to assess a ship's operational efficiency. It is calculated as the CO_2 emissions arising from all laden and ballast legs, anchorage time, and port stays, divided by the ship's deadweight capacity times the total distance sailed in a year, in grams of CO_2 emitted per cargo carrying capacity and nautical mile (IMO 2021a). Following IMO's review of short-term measures, Resolution MEPC.400(83) (IMO 2025) introduced the reduction factors (Z-factors) for the years 2027-2030, at a rate of roughly 2.6 percent per year. It is estimated that

[3] Data for 2019, for containers, oil tankers and bulk carriers. Engine loads that would be allowable under the EEXI range from 65% to 77% of the maximum continuous rating of an engine (Rutherford and others, 2020).

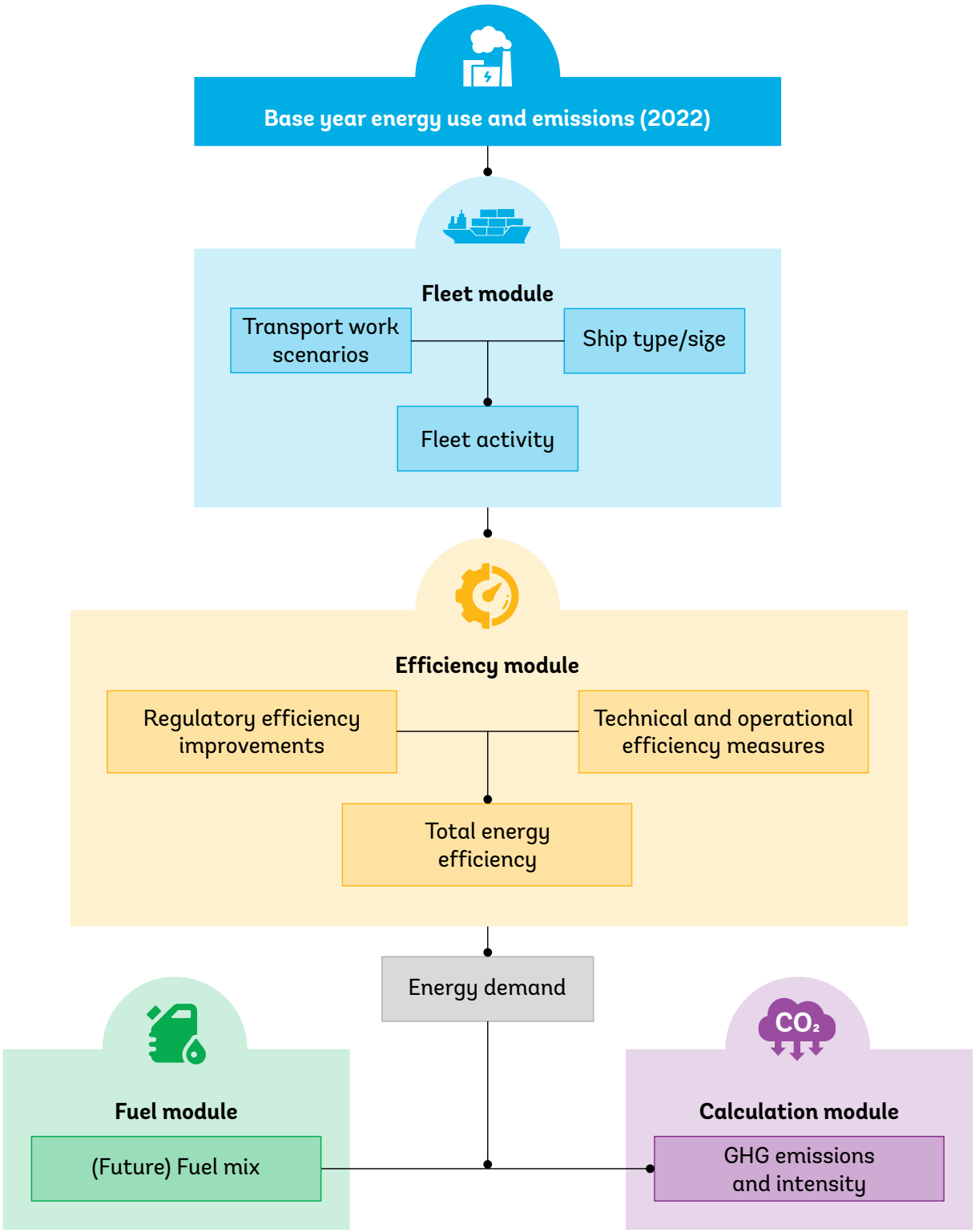
the reduction factor would need to be set at 6-7 percent a year for 2027-2030 to ensure ships meet the IMO's "strive" target for a 30 percent reduction in total annual GHG emissions by 2030 (Bullock and others 2025).

Furthermore, unlike the EEDI and EEXI, which require the ship to have an energy efficiency certificate that complies with the regulation to operate, the CII does not have a strong enforcement mechanism. If only a low (D for 3 years of E for 1 year) CII has been achieved over several years, an action plan (the SEEMP Part III corrective action plan) must be put in place to remedy and achieve a minimum CII.

How does the report measure the impact of energy efficiency measures?

The maximum potential contribution of energy efficiency measures is modeled using a techno-economic model called CE-Ship. CE-Ship projects future shipping activity and estimates the resulting energy use and GHG emissions under different scenarios. Figure E.2 provides a schema of the model's modules and steps to calculate the impact energy efficiency measures could have on energy use and GHG emissions.

Figure E.2 Structure of the CE-Ship techno-economic model



Source: World Bank, based on CE Delft.

The analysis considers:

- **Base year energy use and GHG emissions:** Historical fleet and GHG emissions data for 2008, as the IMO GHG reduction targets are set relative to 2008. Historical GHG emissions are also benchmarked to 2018 (the last year studied in the GHG emissions inventory of the Fourth IMO GHG Study) and to 2022 data to reflect the trends from 2018 to 2022. Both international and domestic shipping GHG emissions are considered, following vessel classifications from IMO's Third and Fourth GHG studies (IMO 2014; Faber and others 2020).[4]
- **Fleet module:** In the model, baseline GHG emissions are extended to 2050 using two BAU pathways, with low and high demand scenarios from the Fourth IMO GHG Study (Faber and others 2020). For bulkers and containers, a significant growth in transport demand is projected, reaching up to 200 percent by 2050. The tanker sector experiences a decrease in demand for oil transport, but an increase in gas and chemicals transport. In addition to transport demand, GHG emissions are driven by changes in fleet composition (the number and average vessel size per ship type and size category). Bulk carriers and gas carriers are assumed to increase in size to reflect recent trends. It is expected that the increase in the size of container ships will be limited by the large associated terminal investment; however, the number of container ships in the largest size bins is expected to grow.
- **Energy efficiency module:** GHG emissions are influenced by the IMO's energy efficiency policies and the uptake of energy efficiency measures. Marginal abatement cost curves are used to determine the order of measures that are applied sequentially.
- **Fuel module:** The model does not assume any changes to the future fuel mix due to a potential increase in the uptake of green fuels. This is a simplifying assumption to understand the impact of energy efficiency measures on GHG emissions, GHG intensity, and energy efficiency.
- **Results calculations:** In the BAU, the uptake of energy efficiency measures is driven by regulation, where only the IMO's EEDI and EEXI regulations are applied. This baseline is compared to energy efficiency abatement scenarios. The energy efficiency potential of the abatement scenarios is constrained by the fleet uptake of the energy efficiency measures, which take into account the technical applicability and technology maturity. Measures are applied sequentially from most cost-effective to least cost-effective.

The individual modules of the CE-ship model are used to provide insights into the possible scale of GHG emissions reduction through energy efficiency alone.

[4] For cruise ships, ferries, yachts and miscellaneous service vessels, fixed demand and no energy efficiency improvements into the future were assumed.

The report is structured as follows:

- **Chapter 1:** Estimates the overall theoretical contribution of energy efficiency measures to meeting the IMO's checkpoints and net-zero target on the path to 2050 for the global fleet and largest emitting fleet segments, namely bulk carriers, container ships, and tankers.
- **Chapter 2:** Assesses the individual theoretical contribution of different energy efficiency measures to meeting the IMO's policy objectives for the global fleet and the largest emitting fleet segments and discusses the cost-effectiveness of abatement for these measures.
- **Chapter 3:** Explores the cost of a transition to green fuels where energy efficiency measures are employed compared to a scenario with only green fuels.
- **Chapter 4:** Introduces the general barriers to the uptake of energy efficiency measures in the shipping industry and deep dives into some of the most promising measures and stakeholder initiatives, the barriers to their uptake, and lessons learned, outlining best practices and solutions.
- **Chapter 5:** Concludes and translates the findings into key messages for policymakers, industry, ports, and port community stakeholders.

1

How much can Energy Efficiency Measures Reduce Ship Emissions?

Alongside the use of green fuels, improving the energy efficiency of the global shipping fleet is important to meet the sector's emission reduction goals. But how much can energy efficiency improvements really contribute to achieving these targets? The analysis in this chapter quantifies how much operational and technical energy efficiency measures can contribute to (i) overall greenhouse gas (GHG) reductions, (ii) GHG intensity, and (iii) energy efficiency of the global fleet.

The model assesses the impact of energy efficiency measures based on two key factors: the growth of trade and the level of energy efficiency applied. The reductions from the energy efficiency scenarios are compared to the two BAU scenarios, reflecting the IMO's current energy efficiency regulations[5] and different transport demand growth pathways. They are also compared to the IMO's 2023 GHG Strategy goals, including its 2030, 2040, and 2050 targets.[6] To be consistent with the IMO's policy goals, the study incorporates the full lifecycle of GHG emissions, or Well-to-Wake emissions, covering indirect emissions from fuel production through to emissions from direct combustion by the ship's engine.

To understand the applicability of energy efficiency measures on specific ship types, the analysis zooms in on bulk carriers, container ships, and tankers[7] as they account for nearly 80 percent of the global shipping GHG emissions.

1.1 Maximum abatement scenarios

The outcomes for maximum GHG emissions reductions, or abatement, result from the uptake of energy efficiency measures, including ship speed reductions. In total, 30 energy efficiency measures, divided into over 15 unique groups, are considered.[8] Reducing ship speed can significantly reduce fuel consumption and, therefore, emissions.

The modeling in this study does not consider possibilities for enhancing capacity by improving the productivity of the fleet (for example, by reducing berth time through port call optimization). The emissions reductions from speed reduction therefore represent a conservative estimate because the model assumes more ships are needed to fulfil the same demand. Onshore power supply is also not explicitly considered, although reduced auxiliary power demand is included among other technology groups.

The implementation rate of technical and operational measures is assumed to increase over time, as measures become more technologically mature and new vessels enter the market, as shown in Figure 1.1. The uptake rate attempts to model what is technologically feasible, assuming no barriers exist. The model distinguishes between the uptake rates of market-ready technical measures and innovative technical measures. For innovative measures, specifically wind-assisted ship propulsion, air lubrication, solar panels, and a super-light ship, there is a limited uptake of five percent among eligible vessels in 2030. Most of the measures have significant uptake levels of 90 percent in eligible vessels in 2030. Both cost-effective and non-cost-effective energy efficiency measures are used for the maximum abatement scenarios.

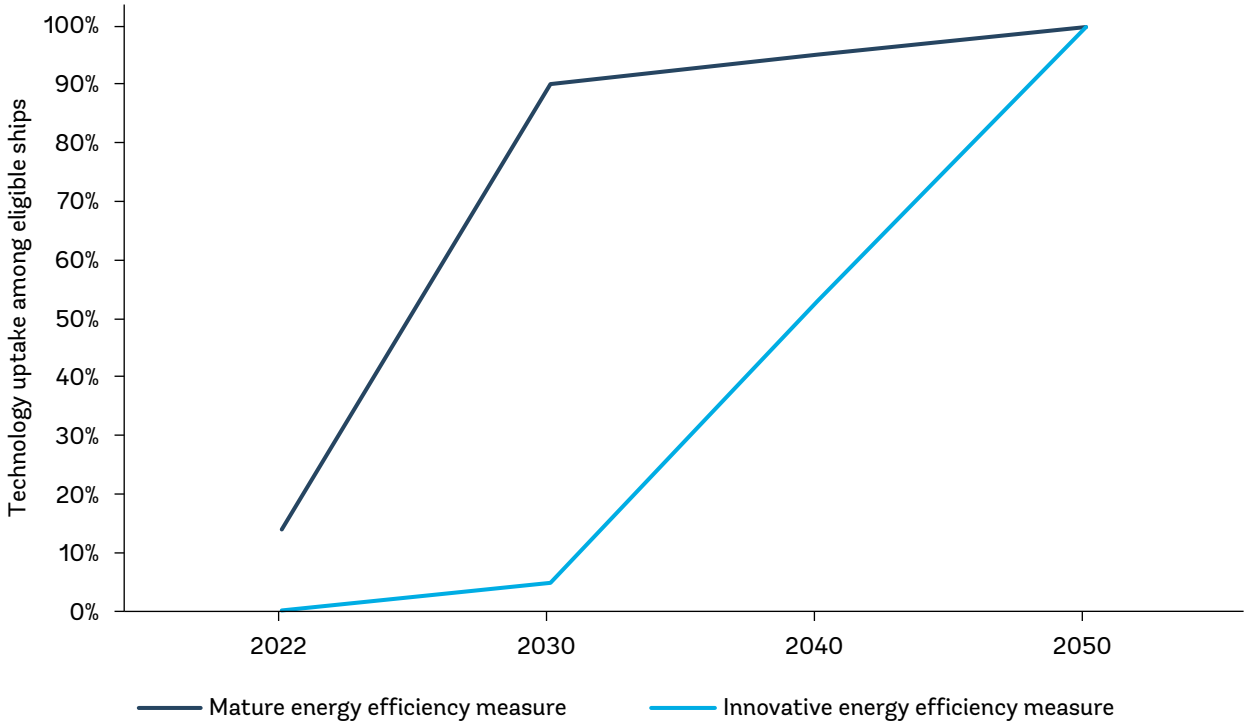
[5] The EEDI and EEXI are the only IMO regulations considered.

[6] IMO's 2023 GHG Strategy explicitly states that "the levels of ambition and indicative checkpoints should take into account the well-to-wake GHG emissions of marine fuels" and the IMO's GFI standard. Well-to-wake emissions include upstream emissions. Excluding upstream emissions could lead to an underestimation of the total emissions associated with marine fuels, potentially favoring a fuel that has lower downstream but higher upstream emissions.

[7] Tankers include oil tankers, chemical tankers, liquified gas tankers, and other liquids tankers according to IHS Markit's StatCode 5 Ship Type Level 2 classification.

[8] The measures use the same categorization as the Fourth IMO GHG Study.

Figure 1.1 The modeled uptake speed of measures among eligible ships



Source: World Bank.

In the model, four abatement scenarios account for variations in transport demand growth and the degree of feasible speed reduction (Table 1.1). The difference between the Moderate Efficiency and Maximum Efficiency scenarios is the application of a 10 percent and 30 percent speed reduction, respectively. The speed reductions are compared to 2022 average ship speed values and represent the range of technically feasible speed reductions for all ship types and sizes. Accordingly, the GHG emissions reduction potential is significantly larger in the Maximum Efficiency scenarios. The scenarios are further divided into High Demand and Low Demand scenarios based on their transport demand growth. The resulting four scenarios are compared to 2008 GHG emissions levels, or to Business-As-Usual emissions growth with High Demand and Low Demand.

To isolate the effects of energy efficiency, the abatement scenarios do not consider a shift towards green fuels. Therefore, vessels are assumed to continue using fossil fuels, namely HFO, MGO, and LNG, which are quite similar in carbon content. Hence, the trend for improved GHG intensity is directly related to energy efficiency. Therefore, changes to GHG emissions and GHG intensity in the scenarios result from improvements in energy efficiency alone.

Table 1.1 Overview of abatement scenarios

	Scenario	Energy efficiency abatement	Transport demand growth
1	Moderate Efficiency-Low Demand	Maximum energy efficiency measures with a 10 percent speed reduction	Low
2	Moderate Efficiency-High Demand	Maximum energy efficiency measures with a 10 percent speed reduction	High
3	Maximum Efficiency-Low Demand	Maximum energy efficiency measures with a 30 percent speed reduction	Low
4	Maximum Efficiency-High Demand	Maximum energy efficiency measures with a 30 percent speed reduction	High

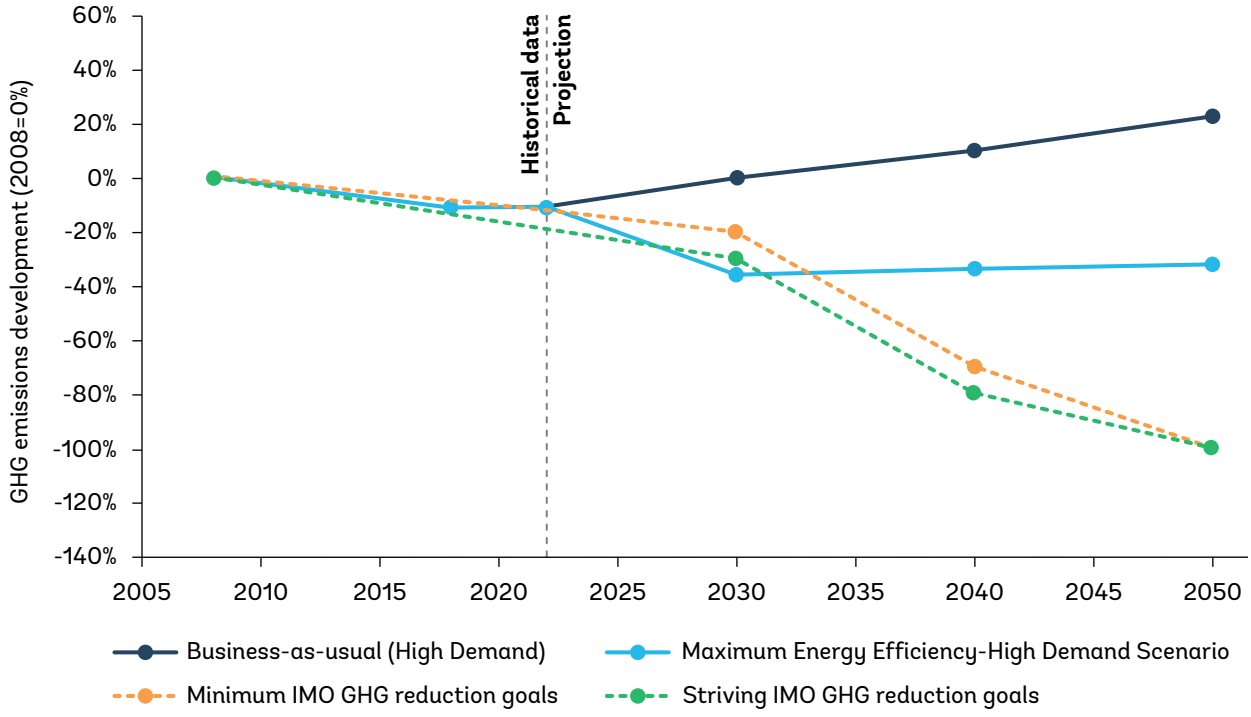
Source: World Bank.

As transport demand increases towards 2050 in the scenarios, the effects of energy efficiency improvements on total GHG emissions become more limited. This is because in a scenario with higher overall transport demand, more ships are needed to carry cargo between countries. The reduction in greenhouse gas intensity of global shipping would therefore need to offset the increase in transport demand (in ton-miles), for total emissions to decline.

1.2 Maximum abatement potential

The modeling indicates that the implementation of energy efficiency measures has significant abatement potential, but this potential varies in its ability to meet the IMO's GHG emissions reduction goals over time. The maximum abatement potential of three out of four abatement scenarios achieves higher emissions reductions than the 20 percent target set by the IMO in 2030, and the Maximum Efficiency scenario exceeds the 30 percent target in both low and high demand scenarios (Figure 1.2). However, for the IMO's 2040 and 2050 targets, the maximum abatement potential for all four abatement scenarios cannot achieve the required reductions in GHG emissions. This means that even in a scenario with maximum uptake of energy efficiency measures, there is a clear need for green fuels before 2040.

Figure 1.2 The Maximum Efficiency-High Demand emissions reduction pathway, relative to 2008



Source: World Bank.

Table 1.2 shows the abatement potential through energy efficiency measures for the total cargo-carrying fleet as well as three main ship segments (bulk carriers, container ships, tankers). The emission reduction potential is largest for bulk carriers and container ships, especially for scenarios with low growth in transport demand. For certain ship segments, there is projected growth in GHG emissions by 2050 compared to 2008, attributed to increases in transport demand and changes in fleet composition. There is less overall emission reduction potential from energy efficiency measures for non-major fleet segments such as vehicle carriers and ferries, segments that are included in the global fleet. For these vessel types, the model assumes either no growth or reduced growth in transport demand, making the results more stable over time (see Appendix A for details).

Table 1.2 Modelled absolute emissions reduction potential, relative to 2008

Year	2030	2040	2050
Total fleet*	23% up to 39%	18% up to 40%	13% up to 42%
Bulk carriers	22% up to 50%	14% up to 51%	0% up to 50%
Tankers	-6% up to 18%	-16% up to 21%	-22% up to 30%
Container ships	13% up to 43%	-1% up to 43%	-19% up to 41%

* Includes miscellaneous ship types such as pleasure yachts for which no improvements are modeled. Negative values mean GHG emissions increase.

Source: World Bank.

For a more accurate comparison of the energy efficiency potential, it is worthwhile examining model outcomes using GHG emissions intensity rather than total emissions savings. Table 1.3 shows the range of outcomes in terms of emission intensity. These results control for changes in transport demand and therefore provide a more accurate comparison of energy efficiency between ship types. The improvement potential for energy efficiency is lowest for tankers, which experience a shift in trade composition from oil to gas and chemicals. Chemical and gas tankers are in general transported by smaller vessels which have a higher average GHG intensity, and therefore the weighted average for tankers increases.

Table 1.3 Modelled GHG intensity reduction potential, relative to 2008

Year	2030	2040	2050
Total fleet*	53% - 63%	58% - 68%	61% - 71%
Bulk carriers	58% - 71%	63% - 76%	67% - 78%
Tankers	40% - 51%	40% - 53%	34% - 52%
Container ships	52% - 66%	59% - 71%	62% - 74%

* Only includes ships which transport freight goods.

Source: World Bank.

Because there are no major changes in the modelled fuel types, the trend in GHG intensity is directly related to energy efficiency and therefore follows the same trajectory as GHG intensity.

1.3 Detailed results for the overall global fleet

As outlined earlier, GHG emissions were modeled under scenarios of low and high growth in transport demand over time. Accordingly, the maximum abatement scenarios yield different emissions savings, depending on which transport demand scenario and energy efficiency scenario is modeled relative to the 2008 baseline (Figure 1.3). The GHG emissions of the BAU scenarios follow similar pathways to the projections of maritime ship emissions in the Fourth IMO GHG study. Emissions in the two BAU scenarios increase as transport demand rises towards 2050.

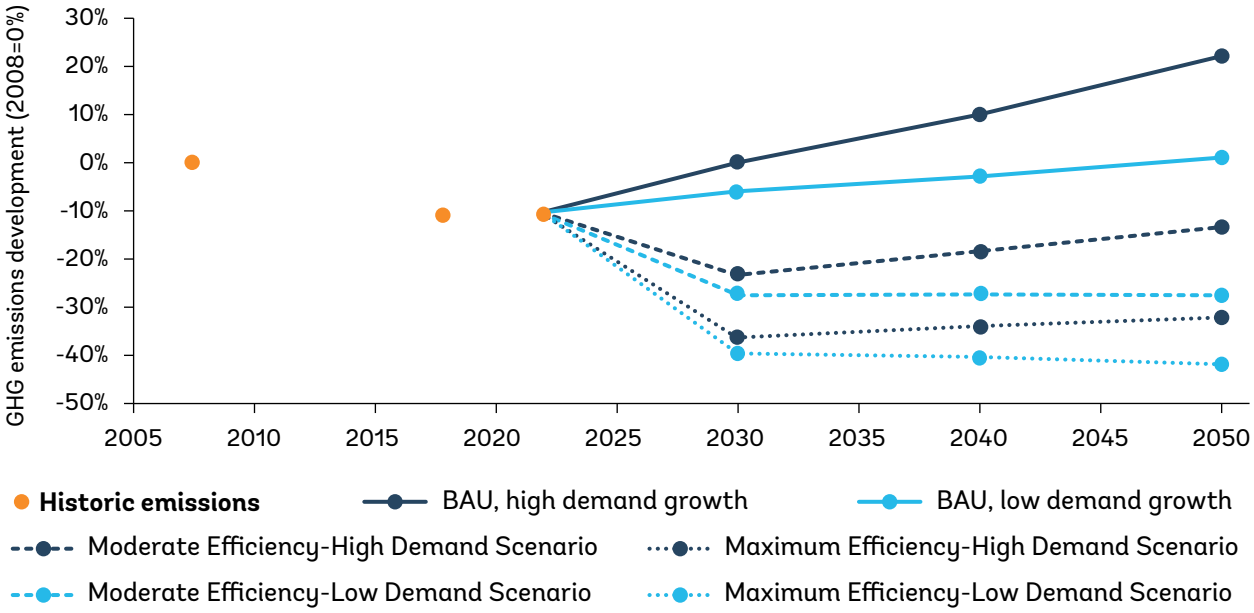
Due to the application of technical and operational measures, the two abatement scenarios show significantly lower GHG emissions. The improvements are best visible for 2030, for four reasons:

- The increase in transport demand from a 2022 baseline is relatively less for 2030 compared to 2040 and 2050
- All energy efficiency measures are applied to existing and newbuild vessels, depending on applicability
- As many mature energy efficiency measures can already be implemented in 2030, there is a high peak in energy efficiency improvement in 2030. However, as uptake potential is reached,

reduced improvements towards 2040 and 2050 are possible. For mature energy efficiency measures, the residual uptake potential is only 10 percent after 2030, as by that time, a 90 percent uptake among eligible vessels could be achieved

- Speed reduction has a large emissions reduction potential. The model assumes that vessels reduce operating speeds compared to 2022 in 2030. Between 2030 and 2050, the reduced speed in 2030 remains constant. As a result, the largest benefits from an operating speed reduction occur only until 2030.

Figure 1.3 Modeled absolute emissions development to 2050



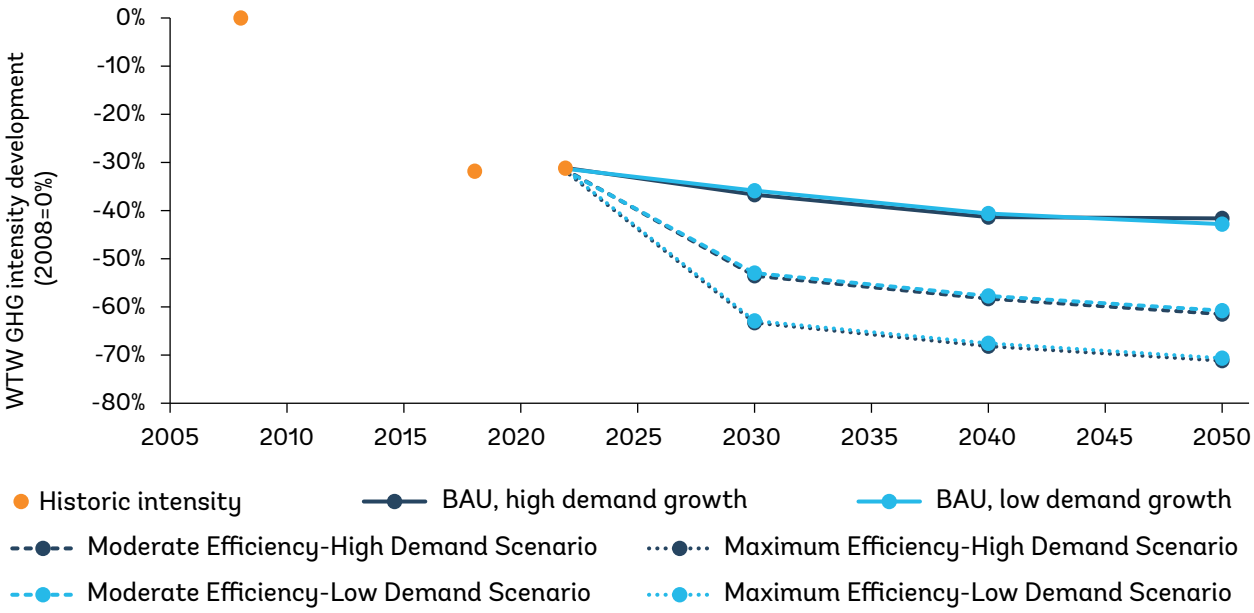
Source: World Bank.

After 2030, energy efficiency improvements on vessels are offset by increases in transport demand. For the low transport demand scenarios, this results in stable emission levels, whereas for the high demand scenarios, GHG emissions begin to increase towards 2050. The results show that the 30 percent ("striving for", or upper bound of the IMO's emission reduction ambition in 2030) can already be achieved through the Maximum Efficiency-High Demand and the Maximum Efficiency-Low Demand scenarios.

The IMO's commitment to ensuring an uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources of at least 5 percent ("striving for 10 percent uptake") of the energy used by international shipping by 2030 cannot be met using only energy efficiency measures. Wind-assisted propulsion has an abatement potential of five percent in 2030, but it is assumed that it cannot be applied to all ship types, including container ships. As a result, an additional uptake of zero or near-zero GHG emission fuels is necessary to meet the targets.

As mentioned earlier, emission intensity shows improvements in energy efficiency more clearly than looking at total GHG emissions only. The GHG intensity of the fleet improves in both the energy efficiency abatement scenarios and in the BAU scenarios (Figure 1.4). This is because existing ships become more efficient, and more efficient newbuilds enter the fleet. Also, as measures mature, the uptake in the total fleet increases. This is especially true for innovative measures, such as wind-assisted propulsion. However, the improvement in GHG intensity does not offset the increasing transport demand, required to keep reducing overall emissions (Figure 1.4).

Figure 1.4 Modeled emissions intensity development to 2050

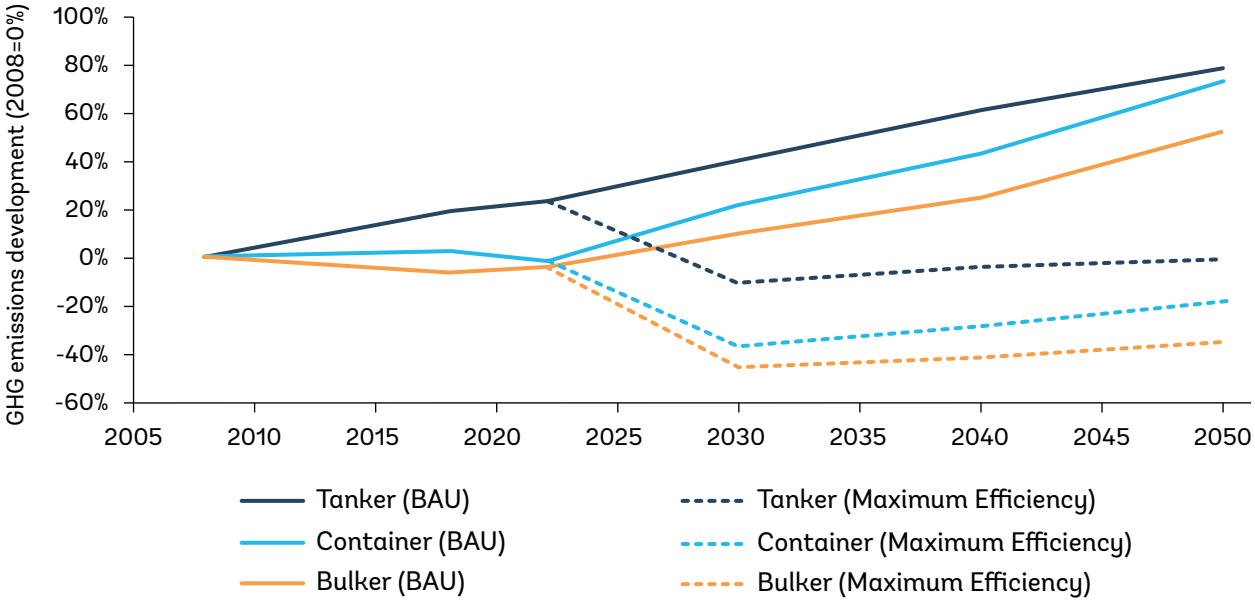


Source: World Bank.

1.4 Detailed results for bulk carriers, tankers, and container ships

In the BAU scenario, the GHG emissions of all ship types are expected to grow due to the growth in transport demand. Interestingly, the emissions increase is largest for tankers, while the growth in transport demand is smaller than that of bulk carriers and container ships. As mentioned earlier, this effect results from a shift in transport demand within the segment, moving from relatively GHG-efficient oil tankers to less efficient chemical tankers and gas carriers. In the Maximum Efficiency-High Demand scenario, GHG emissions reduce until 2030 but start increasing again to 2050 for all three main ship types (Figure 1.5). This is due to the significant impact of energy efficiency measures in 2030, during which transport demand growth remains limited.

Figure 1.5 Absolute GHG emissions for the three fleet segments to 2050



Source: World Bank. GHG emissions for three fleet segments (bulker, container, tanker) under BAU-High Demand and the Maximum Efficiency-High Demand scenario to 2050.

For GHG intensity, the reduction in GHG intensity in the Maximum Efficiency-High Demand scenario is significantly larger due to the increased application of energy efficiency measures (Figure 1.6). The increase in energy efficiency uptake is highest in 2030 and then becomes more limited towards 2050. As a result, the main decrease in GHG intensity is in 2030.

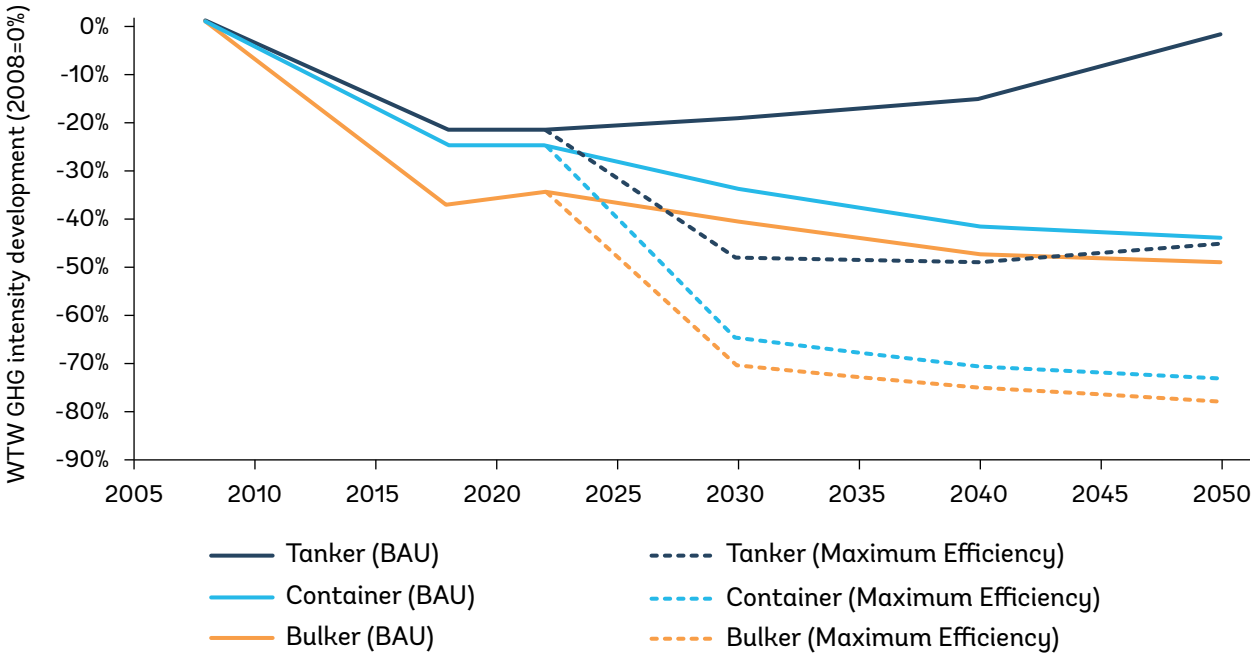
Tankers

As noted earlier, the High Demand BAU scenario shows an increase in intensity for tankers, driven by a shift in underlying commodities from oil to gas and chemicals. Chemicals and gas are, in general, transported by smaller vessels which have a higher average GHG intensity than oil tankers. The weighted average GHG intensity for tankers therefore increases towards 2050 for the BAU scenario. Looking at the maximum abatement scenario (Maximum Efficiency-High Demand), tankers would decrease their GHG intensity between 2022 and 2030; however, due to the change in fleet structure, GHG intensity increases between 2030 and 2050. Consequently, total GHG emissions increase between 2030 and 2050, especially in the high demand scenario (Figure 1.5). Having said this, in the Low Demand scenario, total tanker transport demand decreases between 2022 and 2050, leading to a decrease in total GHG emissions between 2030 and 2050 for both abatement scenarios.

Bulk carriers and container ships

Bulk carriers and container ships show an improvement in GHG intensity for both the BAU and the Maximum Efficiency-High Demand scenarios (Figure 1.6). For container ships, the overall GHG emissions reductions are increasingly offset over time due to a comparably larger growth in transport demand, widening the gap relative to bulk carriers (Figure 1.5).

Figure 1.6 Emissions intensity for the three fleet segments to 2050



Source: World Bank. GHG intensity is shown for the three fleet segments (bulker, container, tanker) under BAU-High Demand and the Maximum Efficiency-High Demand scenario to 2050.

2

How much do Specific Measures cut Emissions, and how Effective are they?

Improved energy efficiency contributes to overall reductions in GHG emissions and the emissions intensity of the shipping fleet. But how much do individual measures contribute to these benefits, and how cost-effective are they? This chapter analyzes the modeled contributions of individual measures to total GHG emissions reductions.

2.1 Types of energy efficiency measures

Energy efficiency measures are divided into technical and operational measures. Technical measures typically involve modifications to the ship's design or equipment, whereas operational measures can improve energy efficiency by optimizing ship operations. Some measures are handled onboard by the owner or operator, while others require close coordination between the ship and the port. For example, ports can provide onshore power supply solutions, which will enable ships to cut fuel oil consumption for auxiliary power[9] when docked. Just-in-Time (JIT) arrival systems aim to improve overall port call efficiency, but require ships and ports to exchange frequent information in a coordinated fashion upfront.

2.1.1 Technical measures

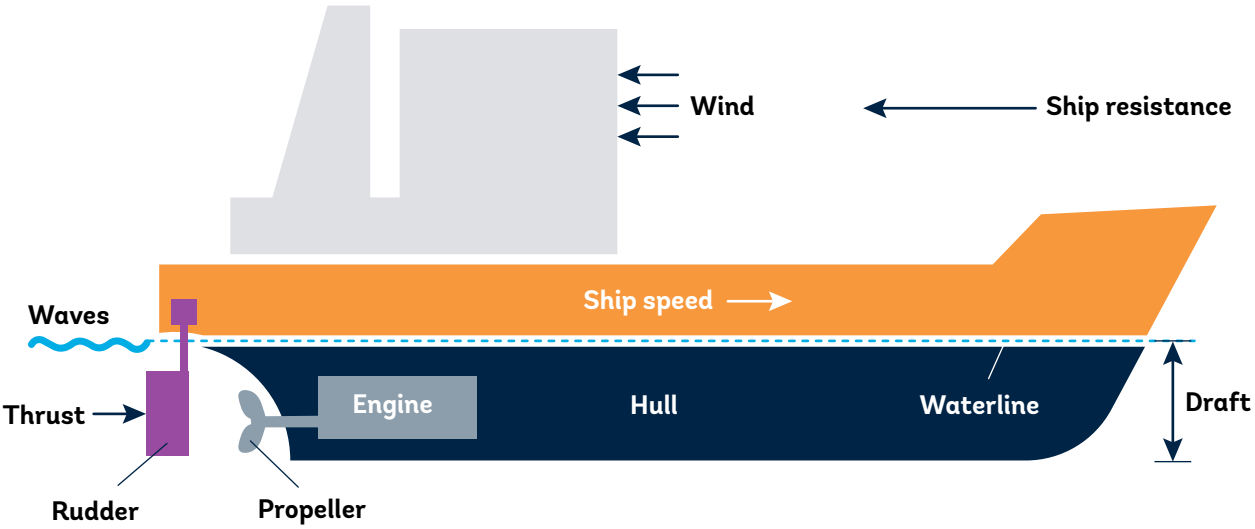
A technical energy efficiency measure refers to physical technology or equipment that can increase the ship's energy efficiency during operations. They can be categorized as ship design measures, hydrodynamic measures, machinery measures, alternative energy measures, maintenance strategies, and after-treatment measures.

The propulsion system is essential for navigating a ship through water by transforming energy into thrust. It plays a crucial role in determining fuel consumption and comprises the main engine and sometimes multiple propellers, linked by a propeller shaft (Figure 2.1). The main mechanisms to enhance a ship's efficiency from energy-saving technologies are to reduce the power needs of the engines. For example, reducing the frictional resistance of the ship in the water or by using wind-assisted propulsion to reduce the power demand from the engines, thereby enhancing the overall efficiency of the machinery system.

[9] In some cases, boilers can also be connected to onshore power and could be electrified onboard a ship (Osipova and Carraro 2023).

While the main engine provides propulsion and operates primarily at sea, the ship's auxiliary engines (for example diesel generators) supply electrical power both at sea and in port. For steam production, the exhaust gas boiler recovers heat mainly from the main engine's exhaust during sailing, whereas auxiliary boilers use fuel to produce steam when the main engine is not running, such as during port stays.

Figure 2.1 Marine propulsion system and sources of resistance



Source: World Bank.

Sources of resistance

Resistance comes from air (aerodynamic resistance) and water (hydrodynamic resistance). Hydrodynamic resistance constitutes most of the total resistance encountered when moving a ship through water. This resistance arises from both frictional resistance and residual (wave-making) resistance. Frictional resistance, determined by the length of the hull, the condition of the hull, and the speed, among other factors, can represent up to 75 percent of hydrodynamic resistance (Faber and others 2020). The draft of the ship, or how deep the ship immerses in the water, increases when the ship is carrying cargo. The resulting total surface area below the waterline, also known as the wetted surface area, therefore, increases frictional resistance. Larger, fuller bodied ships, such as bulk carriers and tankers, have a larger wetted surface area, leading to a higher frictional resistance. At lower speeds, frictional resistance dominates as other resistance types are small. Frictional resistance represents about 70-90 percent of the ship total resistance for low-speed ships, such as bulk carriers and tankers, and sometimes less than 40 percent for high-speed ships, such as container and passenger ships (Wärtsilä 2020). With increasing ship speed, the residual, or wave-making resistance grows more rapidly than the frictional resistance until it eventually becomes the more dominant component. Thus, reducing a ship's speed reduces residual resistance and its share of total resistance.

Hydrodynamic, mostly wave-making, and aerodynamic resistance are impacted by prevailing weather conditions. Weather impacts the speed, direction, and frequency of wind and waves (Faber and others 2020). Reducing speed in bad weather saves fuel because it reduces the ship's struggle against increased resistance and instability caused by waves, wind, and motion. The ship's outer shell, or hull, attracts marine organisms, which accumulate over time during operations. Also known as hull fouling, marine growth impacts the condition of the hull as it deteriorates the formerly smooth paint coating and deforms steel plating. As a result, frictional resistance increases.

2.1.2 Operational measures

Operational measures can improve energy efficiency by improving ship operations. Unlike technical measures, operational measures do not modify the ship's design, machinery, or equipment. Such improvements can be made to the operating profile of the vessel, such as through speed reductions, logistical enhancements (including port call optimization), data-driven decision-making, or improved maintenance and crew training. Better use of data and training can, for example, help to operate a vessel at optimum engine loads, reducing fuel consumption. Implementing operational measures generally does not require significant capital expenditure. However, studies highlight the need for quality and continuous training to enhance crew capabilities for energy-efficient operations (Bayrak, Derya and Muslu 2025; Zoubir and others 2025).

2.2 Promising energy efficiency measures

The savings potential of technical and operational energy efficiency measures varies. There is little consensus on default assumptions for specific measures. Based on a literature review, this sub-chapter details the most promising technical and operational measures and their assumed range of GHG emissions savings when implemented. To determine what measures can be considered promising, the review requires that the measure meet at least one of three criteria:

- Measures that have high average savings potential and low uptake
- Measures that cost-effectively decarbonize emissions at berth
- Measures that effectively enhance the savings of measures with a high savings potential when they are combined.

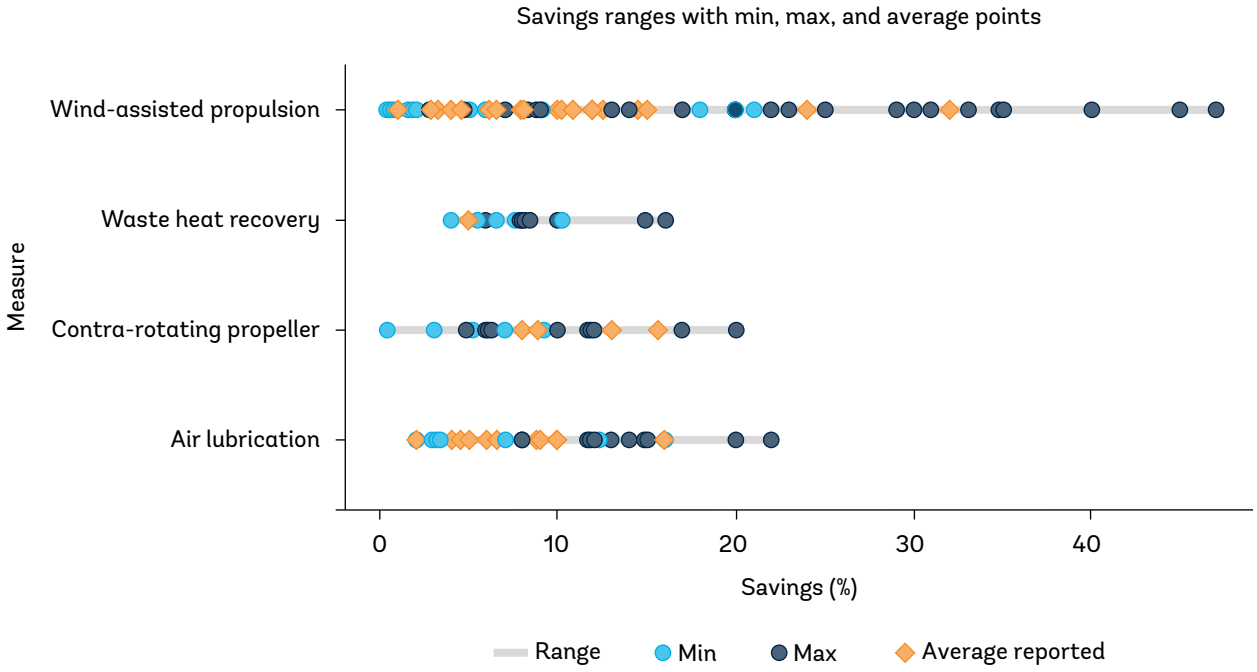
Information about the savings potential is fragmented. While some studies only report the minimum and maximum savings, others provide only the average savings.

Promising technical measures include wind-assisted ship propulsion (WASP), waste heat recovery,[10] contra-rotating propeller (CRP), and air lubrication. Figure 2.2 illustrates the wide range of reported savings,[11] where the average savings can even overlap with the minimum values reported in other studies (see Appendix D for savings details and sources).

[10] From applications which use Organic Rankine Cycles (ORCs), which convert low to medium temperature heat, such as engine exhaust, to usable power.

[11] Savings reported include emissions, fuel, net fuel, power, and net power. See Appendix D for the specific units reported per measure.

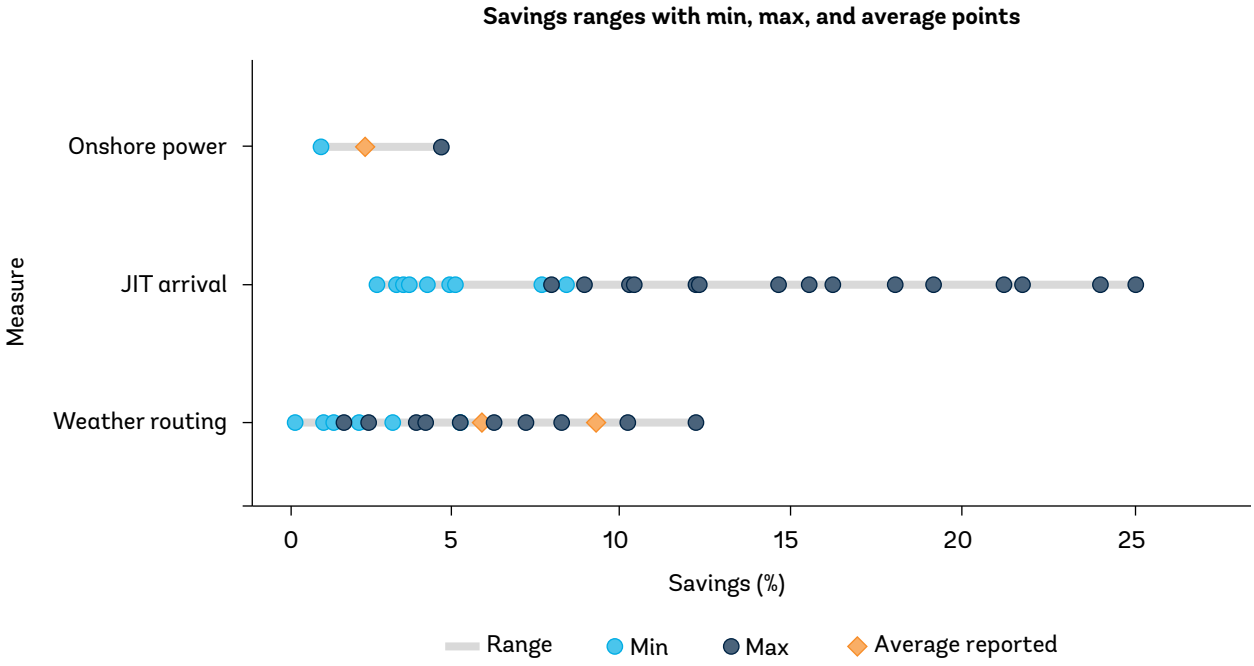
Figure 2.2 Range of savings from different technical measures



Source: World Bank.

Figure 2.3 shows the range of savings from promising operational measures, which are onshore power supply (OPS), Just in Time Arrival (JIT Arrival), and weather routing. While onshore power has a lower savings potential, it is necessary to decarbonize GHG emissions at berth. Weather routing, in turn, has synergies with technical measures, such as wind-assisted propulsion.

Figure 2.3 Range of savings from different operational measures



Source: World Bank.

2.3 The contribution of individual measures to GHG reduction

A key question is how much individual technical and operational measures can reduce total GHG emissions from ships over time and how cost-effective these measures are. This section isolates the contribution of technical and operational energy efficiency measures to reducing emissions relative to 2008. It then presents marginal abatement cost curves that show the tons of emissions reduced (or energy saved) above business as usual relative to their cost-effectiveness.

2.3.1 Different measures

The GHG reduction potential in 2030, 2040, and 2050 compared to 2008 can be divided into the following contributors:

- Historical reduction achieved in the period 2008-2022
- Reduction or increase from BAU changes (for example due to transport demand and fleet size and composition)[12]

[12] Fleet size equals the number of ships in a fleet. Fleet composition describes the structure of the fleet in terms of the average size of ships within a ship type and size category.

- Reduction from wind-assisted ship propulsion systems (WASP)
- Reduction from other technical measures (technical improvement)
- Reduction from speed reduction
- Reduction from other operational measures (operational improvement).

Emissions in the abatement scenarios are impacted by changes in future transport demand, fleet size and composition, and energy efficiency measures. For example, an increase in the number of larger ships in a ship type category would increase efficiency in meeting the same transport demand. Similarly, a higher transport demand scenario would require more ships, thereby reducing the potential for emissions reduction. To separate out the effects of changes that would naturally occur in a BAU scenario, changes in emissions are analyzed using two scenarios:

1. BAU scenarios that measure the effects of current IMO policies, changes in transport demand, and fleet size and composition compared to 2022.
2. Energy efficiency abatement scenarios to model abatement potential only, assessing the emissions reduction effects of technical and operational measures. Wind-assisted propulsion and speed reductions were identified as promising technical and operational measures, respectively, and analyzed separately.

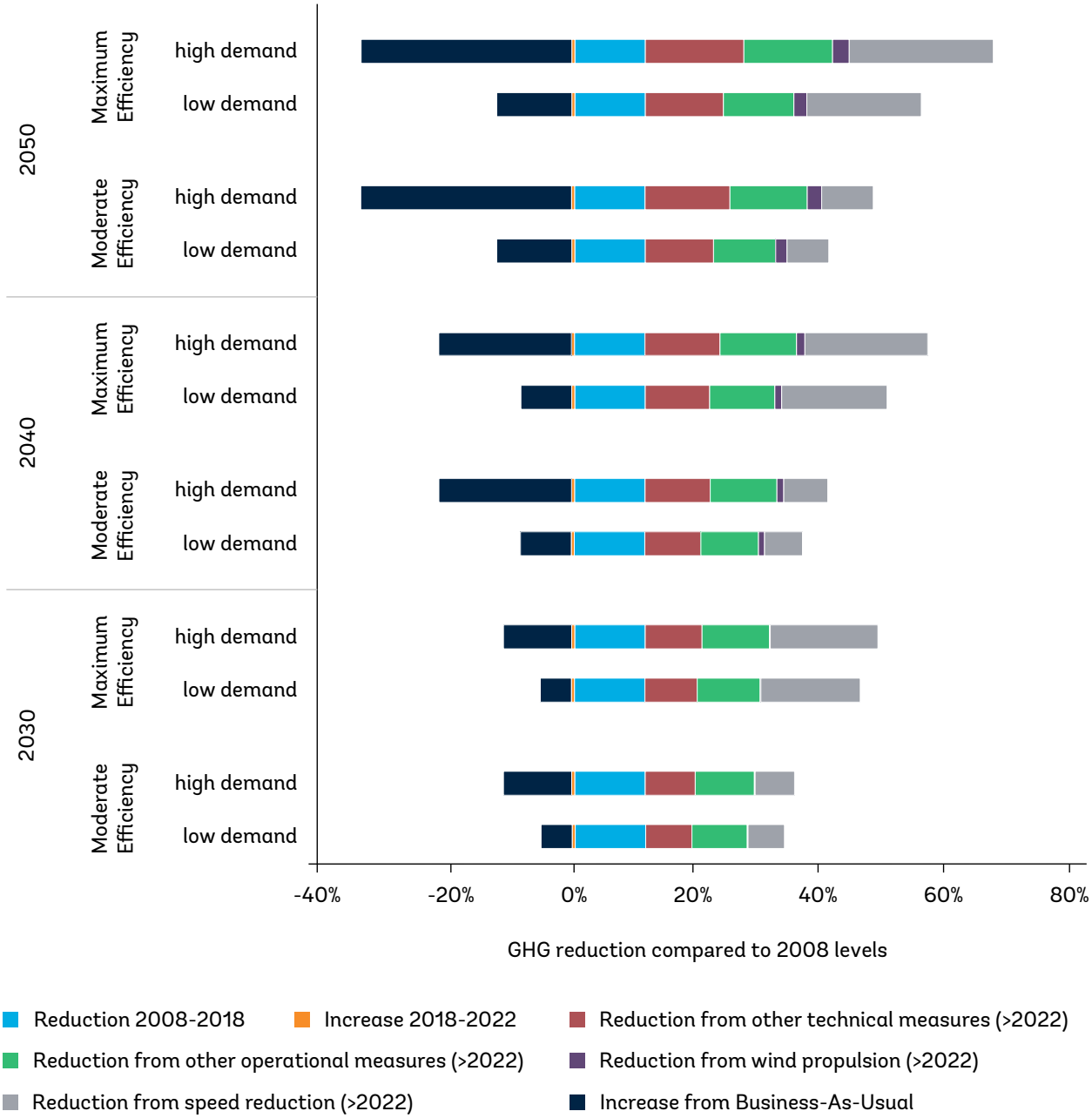
For the period 2022-2050, emission levels are calculated for scenarios without energy efficiency measures (as detailed above), which makes it possible to isolate effects from a BAU scenario. The remaining emission reduction can be attributed to the energy efficiency measures employed in the energy efficiency abatement scenarios. The emission reductions can then be allocated to wind-assisted propulsion, other technical measures, speed reduction, and other operational measures based on their order in the marginal abatement cost curve and uptake at the ship type and ship size level.

Figure 2.4 shows the following contributors:

- GHG emissions from global shipping between 2008 and 2018 have decreased by about 11 percent
- GHG emissions from global shipping between 2018 and 2022 were flat, increasing by less than 0.5 percent
- Future changes in transport demand and fleet composition lead to an increase in emissions (negative emission reduction). Expected increases in transport demand outweigh any gains from trends in increasing ship size for some ship types and size categories and BAU improvements in energy efficiency
- The absolute emission reduction contributions of energy efficiency measures increase from 2030 to 2050, due to (i) higher adoption levels and (ii) an increase in the size of the fleet, i.e., number of vessels that use energy efficiency measures.

Accordingly, the net total reduction in emissions, relative to 2008, for each year, i.e., 2030, 2040, and 2050, and for each scenario, is equal to the sum of each contributor.

Figure 2.4 Emissions abatement potential to 2050, per contributor



Source: World Bank. Shows the GHG emission abatement potential from energy efficiency scenarios for the total fleet towards 2050 relative to 2008 split up into positive and negative drivers of emission efficiency.

For energy efficiency measures, the largest potential for emissions reduction comes from speed reduction, particularly in the Maximum Efficiency-High Demand scenario. Operational improvements, such as hull maintenance, have the second highest potential to reduce emissions in the short run to 2030. Beyond 2030, the contribution of technical measures to emissions reduction increases. By 2050, wind-assist propulsion systems can reduce absolute emissions from global shipping by up to three percent, assuming full uptake.

2.3.2 Marginal abatement cost for ship energy efficiency measures

In general, measures are selected in order of cost-effectiveness, with the most cost-effective measure applied first. Therefore, each of the modelled measures was assessed in terms of its Marginal Abatement Cost (MAC). This can be graphically represented using a MAC curve, which shows the tons of GHG emissions abated ordered from the most cost-effective measure to the least cost-effective (Figure 2.4).[13] Cost effectiveness is typically expressed in USD per ton CO_2 eq, where costs include capital expenditure (CAPEX), incremental operational expenditures (OPEX) of the measure, and fuel costs savings (Appendix C). If fuel costs savings exceed annual CAPEX and OPEX, the measure achieves net savings. Here, the marginal abatement cost, expressed in USD per ton CO_2eq, is negative, showing that a measure is cost-effective. In cases where annual CAPEX and OPEX are higher than the fuel savings, an energy efficiency measure is not cost-effective. In such a scenario, the marginal abatement cost, expressed in USD per ton CO_2eq, is positive.

The MAC curves presented in Figure 2.5 to Figure 2.9 are shown for the Maximum Efficiency-High Demand scenario in 2030. The fuel prices reflect fossil fuel prices, as most vessels will still be propelled by fossil fuel.

2.3.3 Results for the global fleet

To understand the cost-effectiveness of energy efficiency measures and possible investment into such measures onboard ships in the short-term, Figure 2.5 presents the MAC curve for the total fleet for 2030, compared to the BAU-High Demand scenario.[14] Comparing to a BAU scenario helps to clearly see how much GHG emissions change due to specific actions or policies, while controlling for other factors like how much transport is used and the size of the fleet. This provides a clearer picture of the actual impact of actions to reduce emissions, rather than changes caused by market forces, fleet shifts, or existing energy efficiency policies.

For the total fleet, energy efficiency measures are grouped as the applicability of individual measures varies for different fleet segments. For instance, while rotor sails (a type of wind-assisted propulsion technology) are well-suited for bulk carriers, they are not compatible with all types of tankers. For tankers, hard sails have a better use case and, therefore, potential. By analyzing measures in a grouped approach, the analysis can consider different measures within a ship segment. Hence, the analysis considers fifteen different groups of measures, of which nine are cost-effective at total fleet level. This translates to approximately half of the total GHG emissions savings from energy efficiency measures, resulting in a reduction of 250 million tons of emissions at no net cost.

At the total fleet level, the largest emission reduction is achieved from reducing speed, which accounts for 42 percent of the total emissions abatement. Under the Moderate Efficiency-High Demand scenario, the emissions reduction represents 23 percent of total emissions abatement. Speed reduction has a positive marginal abatement cost. This is a conservative cost estimate, as it assumes that the fleet size would need to grow to maintain current transport supply levels, thereby raising the capital costs for newbuild vessels. However, in certain segments, the demand for additional ships could be reduced by improving fleet productivity, such as minimizing waiting times

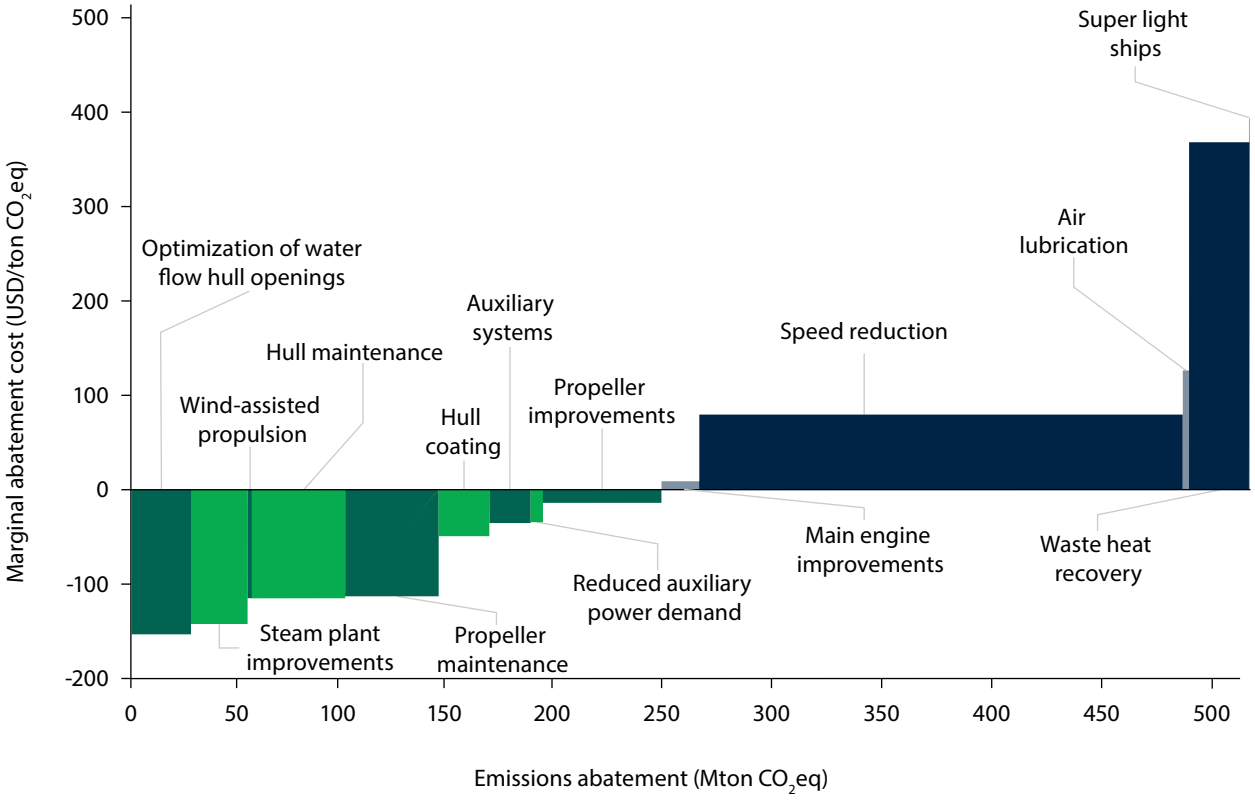
[13] A MAC curve is read from left to right, with the lowest-cost, highest-impact measures appearing first. The width of the horizontal line shows the annual GHG emissions reduction potential, while its height is showing the average cost per GHG emissions reduced.

[14] Figure 2.5 and Figure 2.9 are weighted by GHG emissions across fleet segments, reflecting differences in both fleet size and energy use by vessel type.

through port optimization strategies, like JIT Arrival. This is especially the case for the Moderate Speed scenario, where findings from Smith and Francis (2024a) show that the average speed reduction potential from optimizing voyage speed to minimizing time in anchor is 5-10 percent for most of the major cargo segments (bulkers, container ships, gas tankers, and oil tankers) between 2018 and 2022.

Amongst the innovative measures included in the modeling, wind power and air lubrication have the highest emissions savings, but only represent less than one percent of total savings due to their low uptake in 2030.

Figure 2.5 Cost-effectiveness and abatement potential of individual measures for the total fleet in 2030 under fossil fuel prices



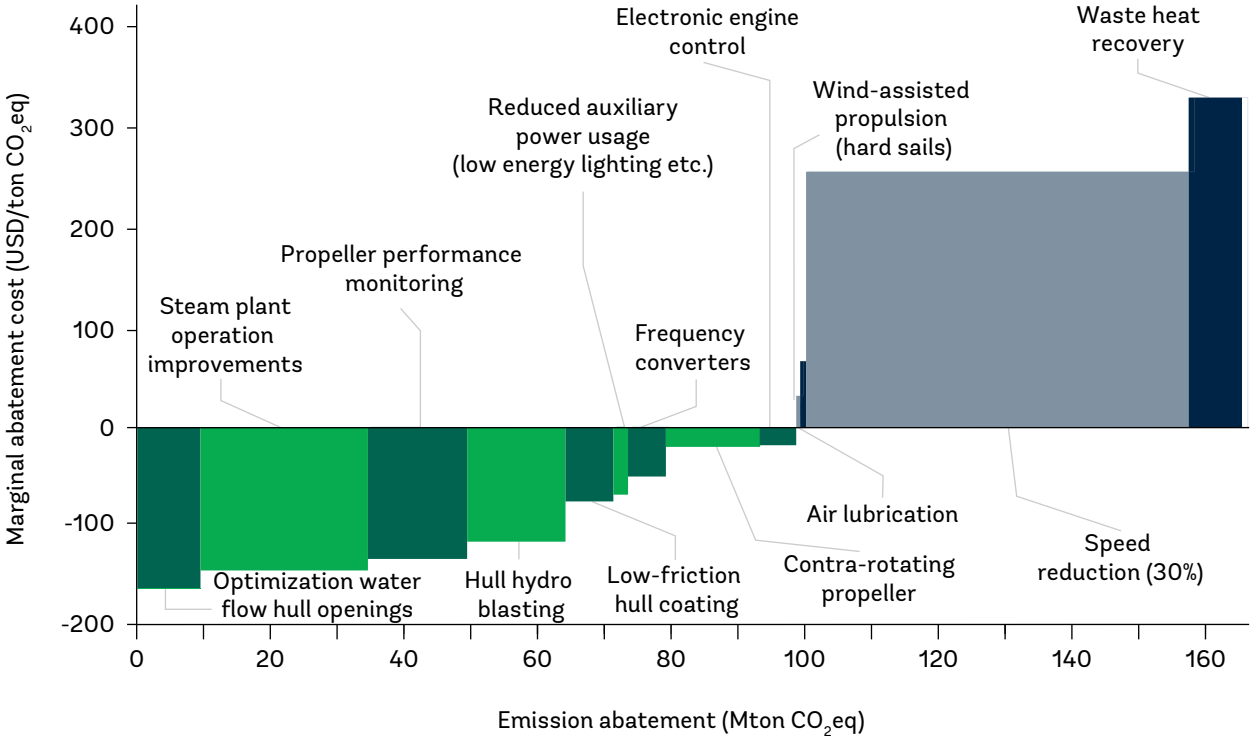
Source: World Bank. Results are presented for the Maximum Efficiency-High Demand scenario. Solar panels were included in the modelling but were omitted from the visual for presentation purposes due to their small contribution to emissions abatement.

2.3.4 Results for tankers

For tankers, nine out of fourteen measures are cost-effective by 2030, representing 60 percent of the total tanker GHG emissions savings (Figure 2.6). Steam plant operation improvements, a measure specific to tankers, is among the most cost-effective. Reducing sailing speeds is not cost-effective but still has a high potential to reduce emissions. Speed reduction is not cost-effective

for tankers due to the higher share of auxiliary engine energy use. Although main engine fuel consumption decreases with slower speeds, the auxiliary engine, which powers onboard systems like cargo temperature control equipment, often operates continuously regardless of ship speed. Assuming that the voyage length increases at slower speeds, the overall energy from auxiliary engines forms a larger proportion of the total energy demand. This increases the cost of speed reduction while also dampening the decrease in emissions of propulsion engines.

Figure 2.6 Cost-effectiveness and abatement potential of individual measures for the tanker fleet in 2030 under fossil fuel prices

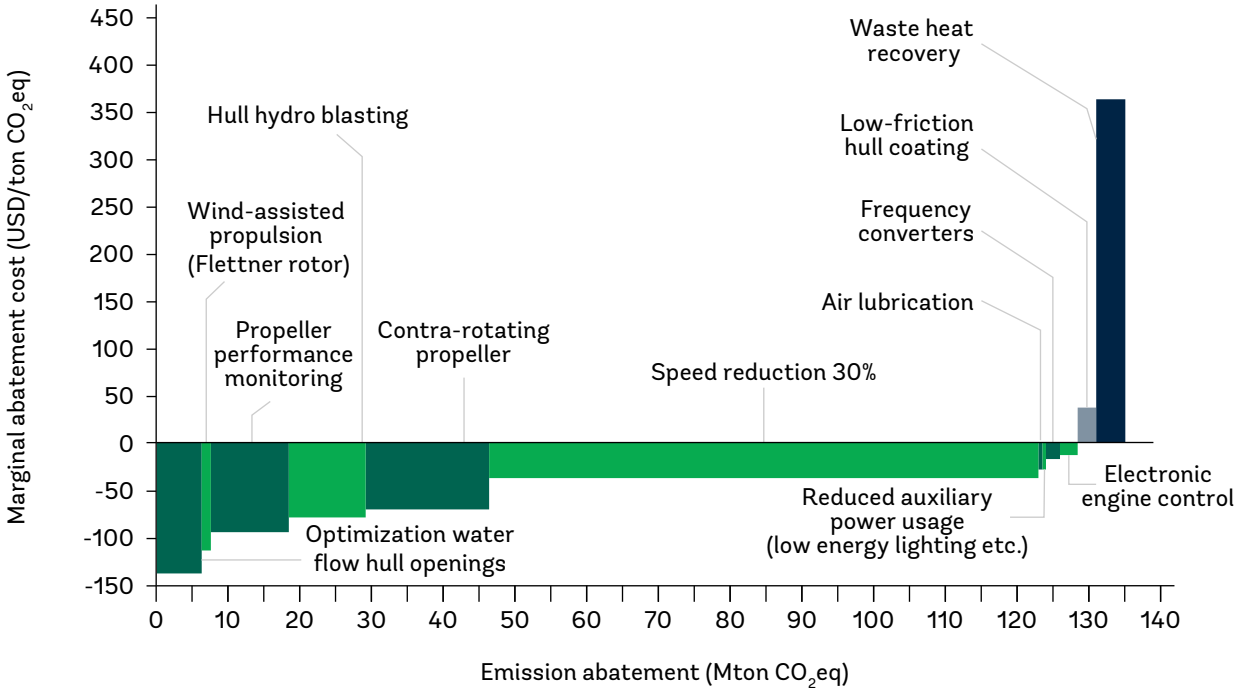


Source: World Bank. Results are presented for the Maximum Efficiency-High Demand scenario. Solar panels were included in the modelling but were omitted from the visual for presentation purposes due to their small contribution to emissions abatement.

2.3.5 Results for bulk carriers

While different in size, bulk carriers can be viewed as a relatively homogenous vessel type in their design specifications. For instance, bulk carrier designs feature large deck areas that can be used for the installation of equipment and technology. Most energy efficiency measures are cost-effective for bulk carriers by 2030, accounting for 95 percent of total bulk carrier GHG emissions savings, with rotor sails being among the most cost-effective (Figure 2.7). Measures that account for the highest emissions reduction with negative marginal abatement cost are notably speed reduction, contra-rotating propellers (CRPs), and propeller performance monitoring.

Figure 2.7 Cost-effectiveness and abatement potential of individual measures for the bulker fleet in 2030 under fossil fuel prices

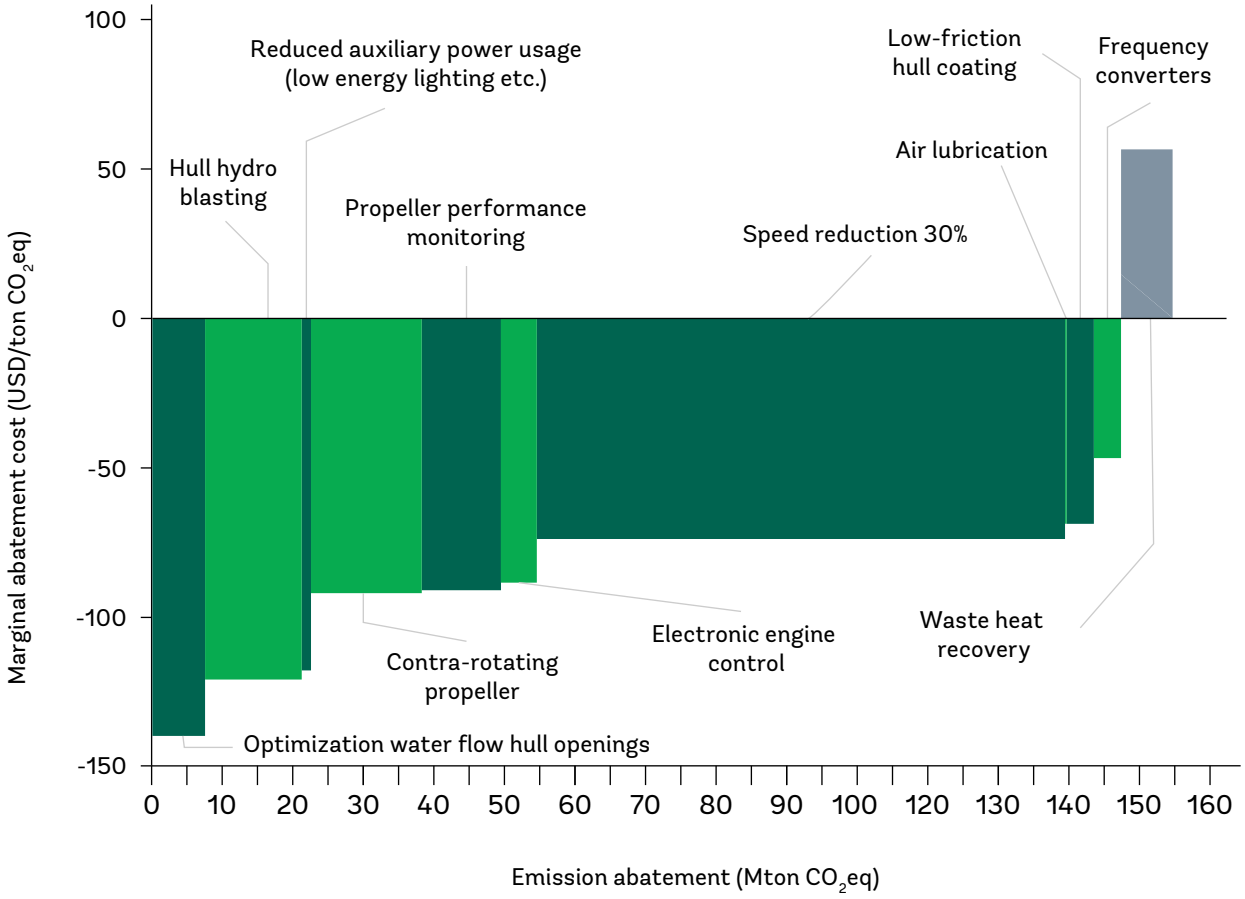


Source: World Bank. Results are presented for the Maximum Efficiency-High Demand scenario. Solar panels were included in the modelling but were omitted from the visual for presentation purposes due to their small contribution to emissions abatement.

2.3.6 Results for container ships

Around eleven energy efficiency measures can be applied on container vessels. Fewer measures are applicable compared to bulk carriers and tankers, as deck space is needed for container stowage and the free movement of cranes and containers required during loading and discharging. Wind-assisted propulsion was therefore excluded from the model as it currently has a limited applicability. The results show that most measures are cost-effective for container ships; cost-effective GHG emissions savings represent 95 percent of the total container ship emissions savings. Speed reduction has the highest reduction potential. As the average sailing speeds of containers exceed that of bulk carriers and most tankers, speed reductions for container ships also result in better cost-effectiveness if applied.

Figure 2.8 Cost-effectiveness and abatement potential of individual measures for the container fleet in 2030 under fossil fuel prices



Source: World Bank. Results are presented for the Maximum Efficiency-High Demand scenario.

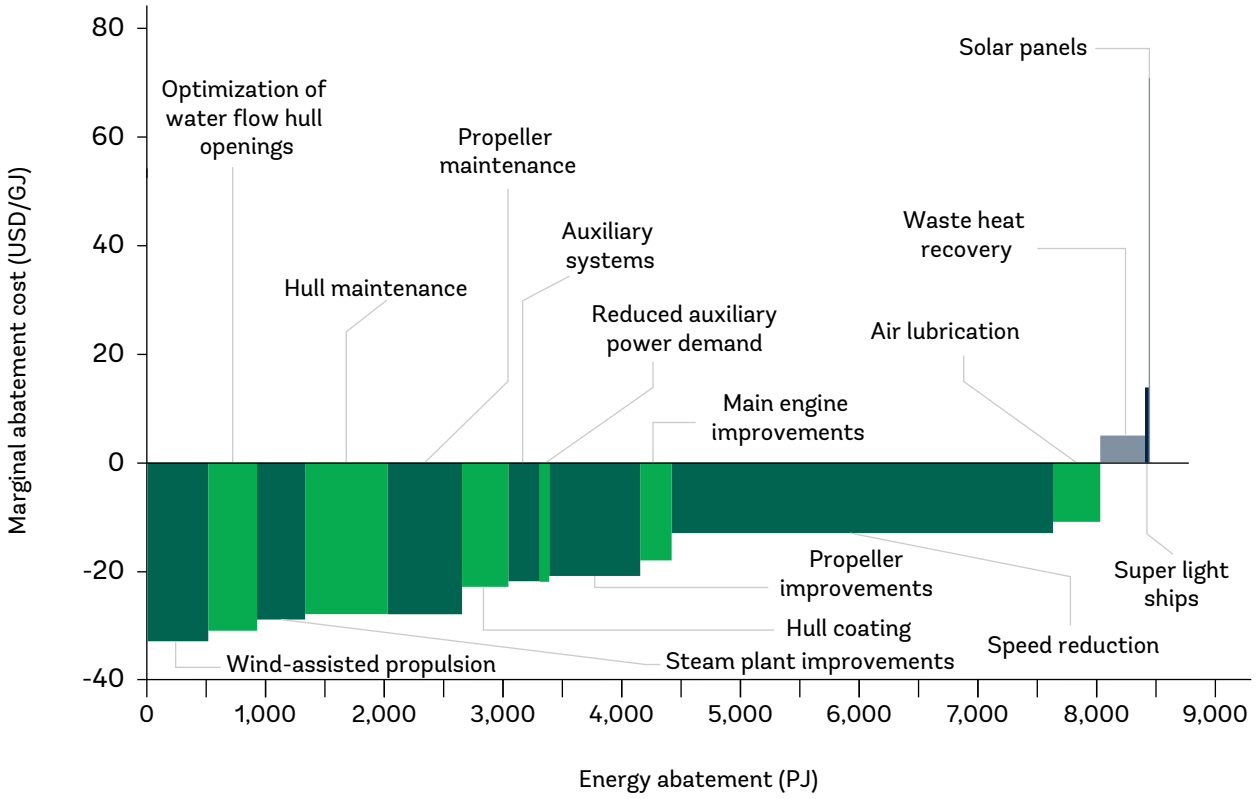
2.3.7 Considerations for green fuels

To achieve the IMO's policy objective of reaching net-zero GHG emissions by approximately 2050, the adoption of green fuels will be necessary. Ammonia, produced from renewable electricity, is a promising candidate fuel to replace conventional fossil-based marine fuels (Englert, Losos, Raucci, & Smith, 2021). Additionally, green ammonia is used as a proxy for a zero-emission fuel, which is estimated to be the least costly fuel in the long term but remains more expensive than conventional fuels (Salgmann, Weidenhammer, & Englert, 2024; DNV. 2024a). The abatement potential is expressed in energy abatement (in petajoules, PJ).

For the total fleet, the analysis developed MAC curves for 2050 using ammonia fuel prices as the benchmark fuel price (as opposed to a fossil-fuel based marine fuel). The results show that almost all energy efficiency measures are cost-effective, except for waste heat recovery systems, super light ships, and solar panels (Figure 2.9). Cost-effective measures represent 95 percent of total energy savings. First, the analysis reveals that in an environment with high or volatile fuel prices, energy efficiency measures pay off more often. Second, for ships sailing on green fuels, energy efficiency

measures have more cost reduction potential even at long term prices (which may be lower than today's green ammonia production cost). For those ships, investing in energy efficiency offers long-term rewards.

Figure 2.9 Cost-effectiveness and abatement potential of individual measures for the total fleet in 2050 under ammonia prices



Source: World Bank. Results are presented for the Maximum Efficiency-High Demand scenario.

3

How can Energy Efficiency Reduce the Cost of the Maritime Energy Transition?

3.1 Cost of the energy transition

Chapter 1 analyzed how energy efficiency measures can contribute to IMO member states' policy objectives, concluding that making the global merchant fleet more energy efficient is insufficient to meet the IMO's more stringent GHG emissions reduction targets in 2040 and 2050. Hence, even before 2040, green fuels need to be in the fuel mix. Currently, green fuels emissions fuels, such as methanol and ammonia, which could help achieve these targets, are, however, more expensive. To chart a cost-effective pathway to reaching the strategy's milestones, it is important to understand how energy efficiency can lower the overall transition cost, balancing cost-efficiency with emissions reduction benefits for global shipping. This chapter assesses the cost-efficiency of a pathway that maximizes energy efficiency measures complemented by green fuels, compared to an energy transition that only deploys green fuels.

3.2 Cost reductions through energy efficiency

The analysis calculated the total cost of reaching the IMO's GHG reduction goals, considering annual fuel cost, as well as CAPEX and OPEX of energy efficiency measures and green fuels. The cost of zero-emission shipping operations is modeled based on the lowest-cost green fuel in the Comprehensive Impact Assessment requested by the IMO (DNV 2024). Hence, for this analysis, e-ammonia, ammonia produced from renewable electricity, is used as a proxy. For ammonia, CAPEX is reflected in fleet investments to make vessels ammonia-capable, with the annuity of these capital outlays taken into account. OPEX includes bunkering, maintenance and repair, and crew training (DNV 2024). Fuel costs are considered separately and include raw material, production, distribution of fuel, and supply and demand considerations.

The analysis was conducted using three types of scenarios, each with both high- and low-growth variants for transport demand:

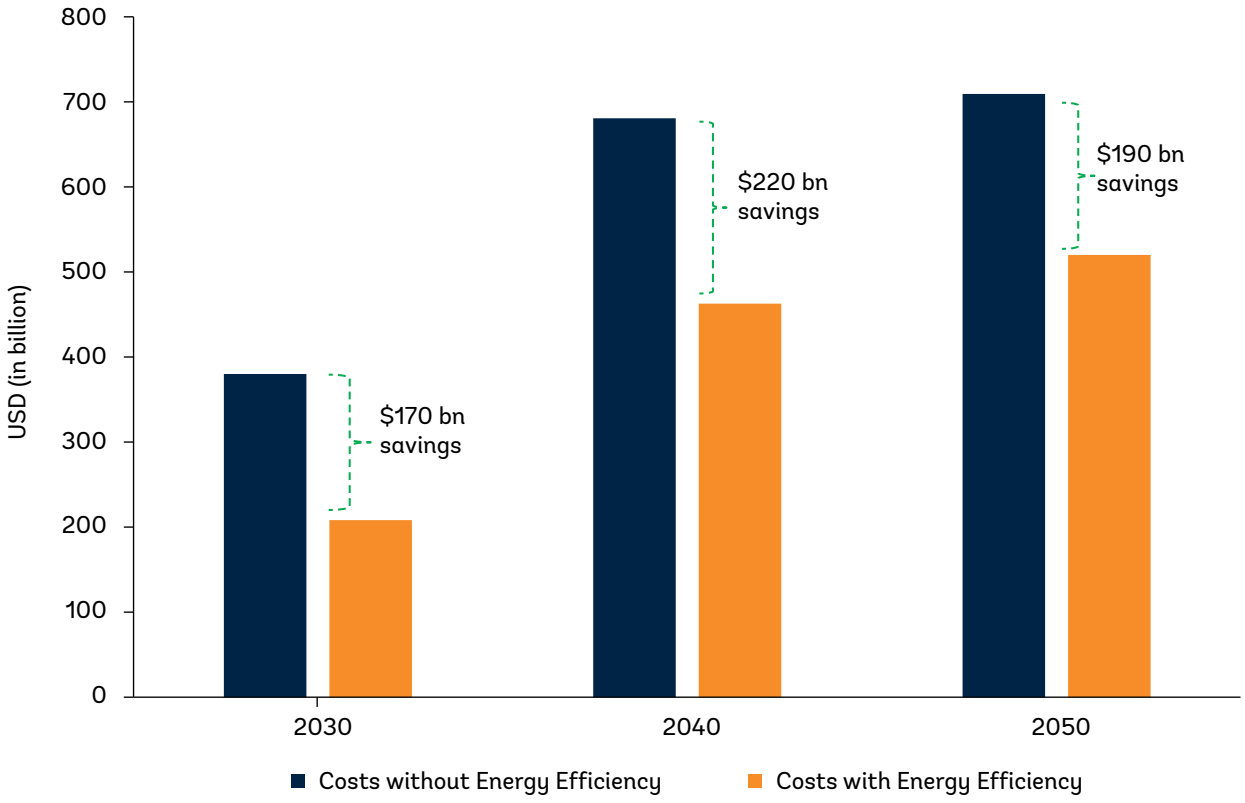
- A BAU scenario, where the shipping fleet uses fossil fuels, and as a result does not meet the IMO goals
- An ammonia scenario, where the shipping fleet relies on e-ammonia to meet the IMO goals. Production costs for green ammonia are reflected in the fuel costs rather than in CAPEX costs
- A maximum energy efficiency scenario, where the shipping fleet reduces speed by 30 percent and employs energy efficiency measures, combined with e-ammonia to meet the IMO goals.

Currently, the cost of using fossil-based marine fuel is about $200 billion per year. This is the baseline fuel cost, which would continue to grow due to an increase in trade demand, and, consequently, the fossil energy used by ships over time.

To meet the IMO's interim GHG emissions targets, using e-ammonia as a green fuel is more expensive, primarily because it is priced higher than conventional fossil fuels. The total annual fuel cost of the shipping fleet could grow up to $600-700 billion by 2050. The annual cost of reaching the lower (Figure 3.1) and upper (Figure 3.2) end of IMO's interim reduction targets in 2030 and 2040 varies in accordance with the different ambition levels.

However, these transition costs can be lowered significantly by investing in energy efficiency measures. Increased investment and the application of energy efficiency measures can achieve a total cost reduction of up to nearly $220 billion per year, and up to $190 billion per year by 2050 compared to the ammonia scenario (see Figure 3.1). To save up to $270 billion in green ammonia fuel costs per year, an additional annualized investment of about $35 billion in energy efficiency across the fleet is required.

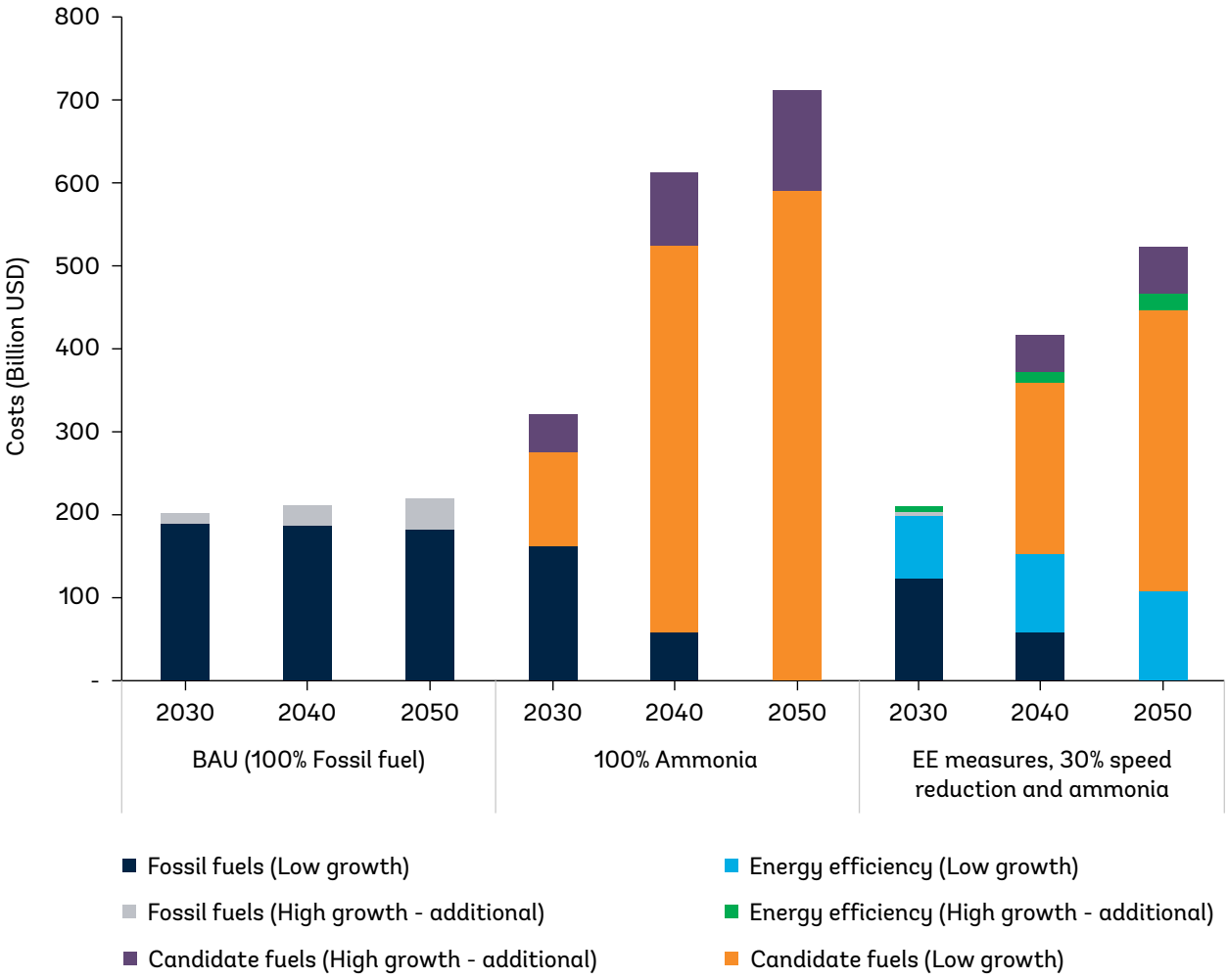
Figure 3.1 Annual cost savings from deploying energy efficiency during the energy transition



Source: World Bank.
Note: Represents annual savings in a High Demand growth scenario, when meeting the higher end of the IMO GHG reduction goals.

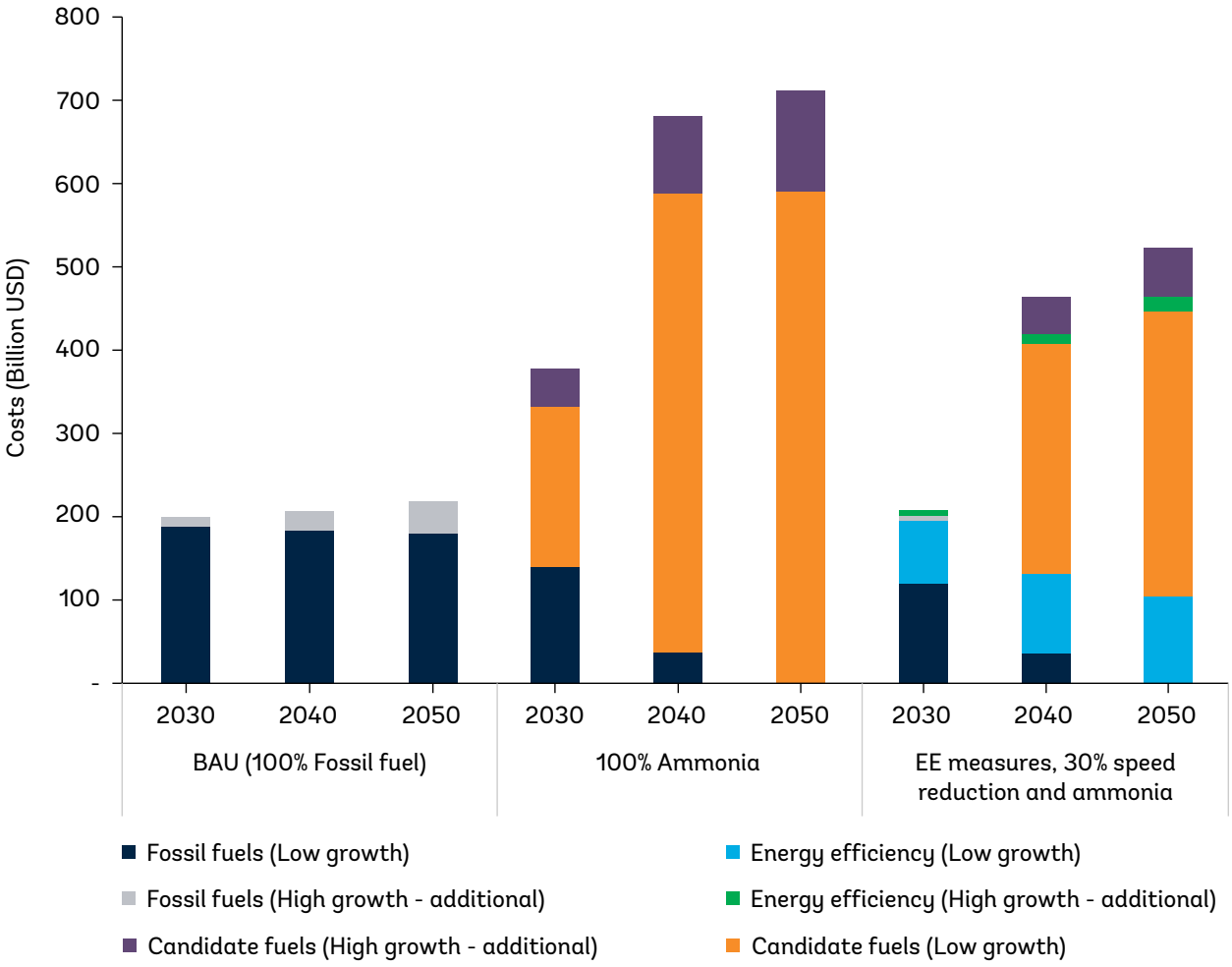
Figure 3.2 and Figure 3.3 show the annual costs for reaching the lower and upper end of IMO GHG reduction goals. Meeting future emissions reduction goals with only e-ammonia results in an increase of up to $380-500 billion in 2050, depending on the transport demand. These costs can be significantly lowered by increased investment in energy efficiency measures.

Figure 3.2 Annual costs of meeting the lower end of the IMO GHG reduction goals



Source: World Bank. Total annual costs (in $ billion) for the global shipping fleet for reaching the lower end of the IMO GHG reduction goals according to IMO's 2023 GHG Strategy.

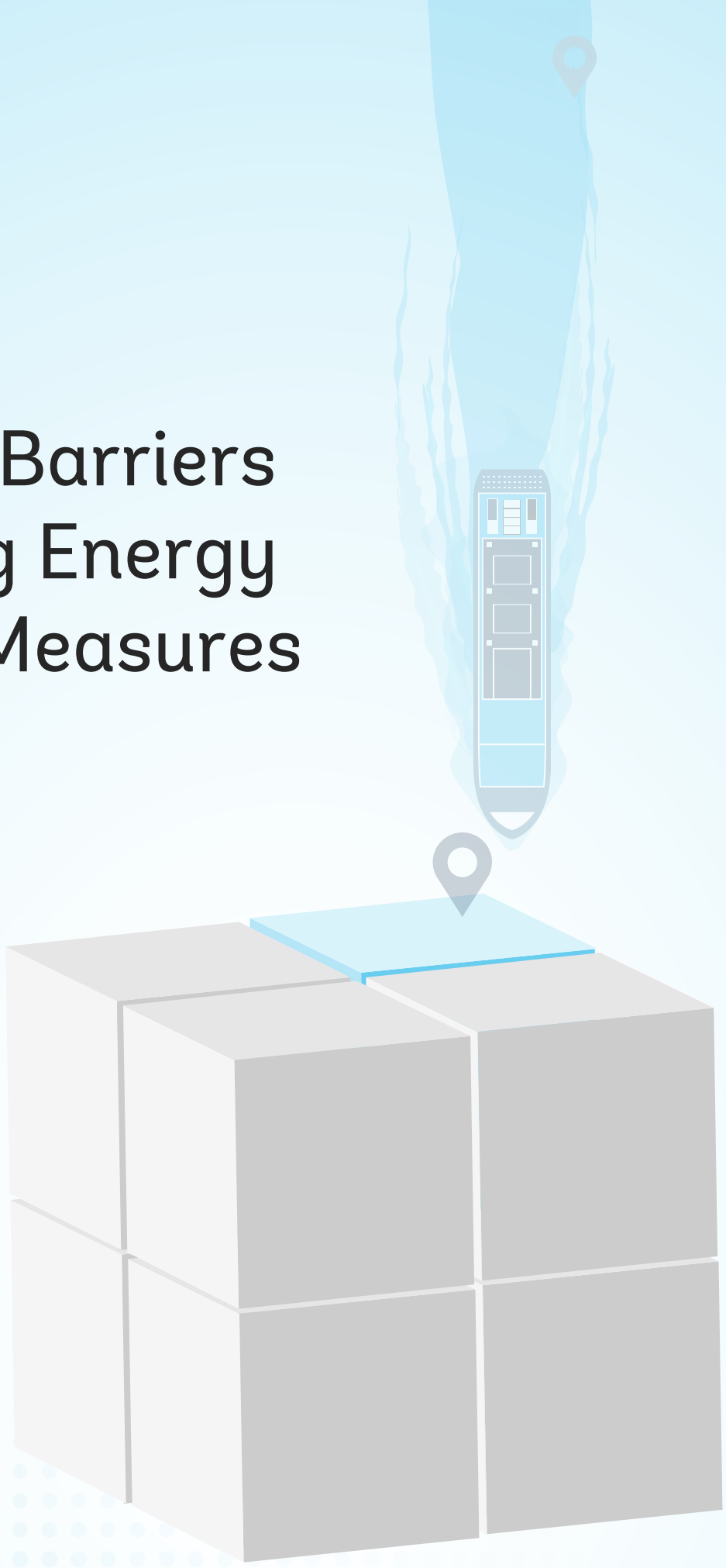
Figure 3.3 Annual costs of meeting the higher end of the IMO GHG reduction goals



Source: World Bank. Total annual costs (in $ billion) for the global shipping fleet for reaching the higher end of the IMO GHG reduction goals according to IMO's 2023 GHG Strategy.

4

Remaining Barriers to Adopting Energy Efficiency Measures



The existence of various barriers in shipping explains the low implementation rate of technical and operational energy efficiency improvements in today's global fleet. This chapter outlines the primary barriers to the uptake of energy efficiency measures. Two examples of promising measures—wind-assisted propulsion and port call optimization—are used to highlight the barriers specific to these measures. Solutions currently being applied by shipping stakeholders are provided.

4.1 Uptake

The industry lacks comprehensive data on the universal adoption of energy efficiency technologies, necessitating reliance on data samples to gauge the extent of their uptake. A cross-sectional survey of 275 shipowners and ship operators, covering 5,500 ships (Rehmatulla, Calleya, and Smith 2017), showed that while a variety of different technologies have been implemented, only a small number of those measures are widely adopted by a large proportion of shipowners.

Amongst the hydrodynamic and machinery categories, pre-/post-swirl devices,[15] propeller/rudder integration, energy-saving lighting, and engine tuning had the highest absolute level of implementation. In general, the survey found that the most widely implemented devices had only a small energy efficiency savings potential at the ship level, while measures with the highest savings potential (for example, air lubrication, contra-rotating propellers, and wind-assisted propulsion) had the lowest levels of implementation. Even for technologies with the highest uptake, the share was low, ranging from 11-18 percent for pre-/post-swirl devices and 20-26 percent for energy-saving lighting for the ships in the sample.

RightShip introduced the design efficiency based GHG Rating (A-E) in 2012 to support supply chain decarbonization and have tracked the uptake of energy saving technologies across the global fleet drawing on verified data submitted by vessel operators. Analysis of a ~7,000-vessel bulk carrier sample (≈60 percent of the in-service fleet) shows that the most prevalent energy efficiency technologies are hydrodynamic improvements (for example rudder optimization, hull ducts/fins, propeller boss cap fins) (RightShip 2025). Air lubrication, wind-assisted propulsion, and advanced low-friction anti-fouling coatings remain less common but have grown over the past five years. The entry into force of the 2023 EEXI regulation has also driven a marked increase in engine power limitation (EPL) and shaft power limitation, which may have contributed to reduced near-term investment in other energy efficiency technologies. Technologies that are less mature (such as wind-assisted propulsion) are expected to take longer to diffuse into the industry (Section 4.3.1 provides a deep dive of the barriers to uptake of wind-assisted propulsion).

[15] Pre- or post-swirl devices reduce fuel consumption by improving the flow around the propeller. Pre-swirl devices improve the flow conditions into the propeller and post-swirl devices improve the flow out of the propeller.

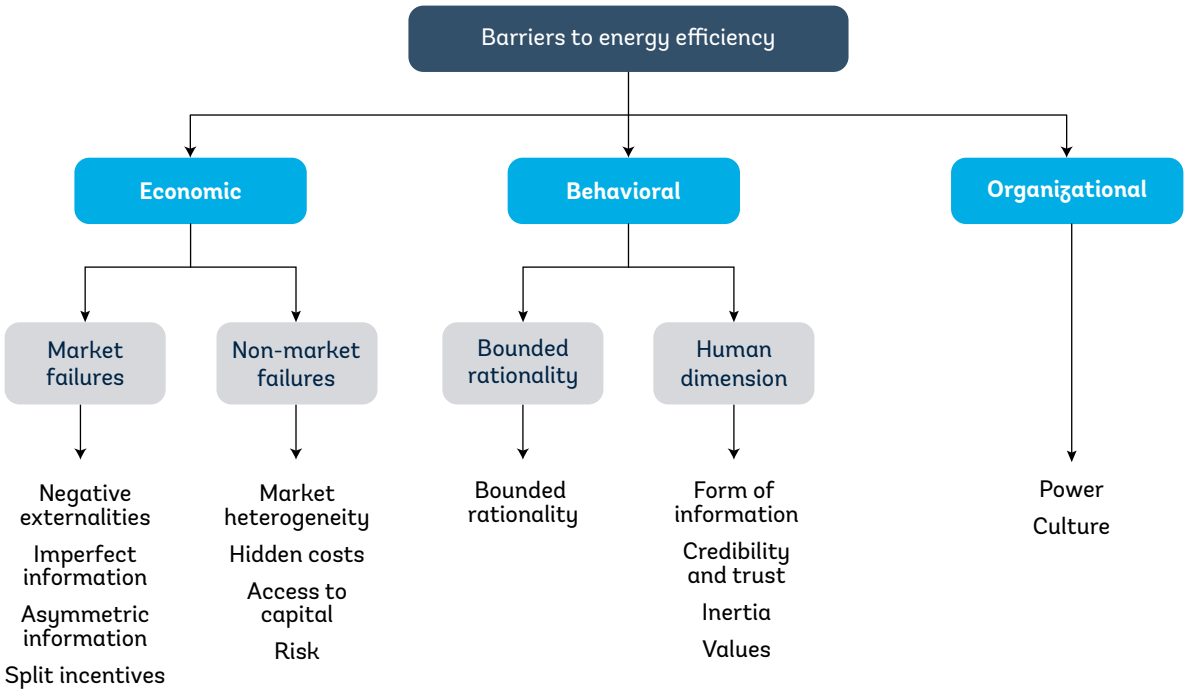
4.2 Different barriers

In general, three different groups of barriers to energy efficiency can explain the low uptake of energy efficient measures to date: economic, behavioral, and organizational (Figure 4.1, described in more detail in Table 4.1). Economic barriers are explained by market failures and non-market failures.[16] Market failures lead to an inefficient allocation of resources due to, for example, imperfect information (Sorrell and others 2000), whereas non-market failures are driven by responses to factors such as the cost of capital or technological risk.

In return, behavioral barriers relate to decision makers' non-financial behavior. These include their inability to process information, their inertia in adopting energy efficiency measures, their values about energy efficiency, and credibility and trust issues with an information provider or party they need to collaborate with to implement an energy efficiency measure.

Finally, organizational barriers acknowledge that organizational structures affect the implementation of energy efficiency measures. They also reflect how the different groups within an organization have different priorities that prevent the rational and efficient implementation of energy efficiency measures.

Figure 4.1 Classification of barriers to energy efficiency



Source: World Bank. Adapted from Sorrell and others 2000 & 2004, and Rehmatulla and Smith (2015).

[16] Non-market failures are sometimes also referred to as "market barriers".

Table 4.1 Overview of barriers in shipping

Barrier	Description	Shipping-specific example
Economic		
Market failures	Situations where market outcomes do not maximize efficiency.	Energy savings may not be fully realized if costs/benefits are misaligned across actors.
Negative externalities	Markets do not price the full cost of production.	The climate impact of GHG emissions, and health impact of air pollutants, is not included in fuel or shipping costs.
Imperfect information	Decision-makers lack full knowledge of efficiency options or savings potential.	Shipowners may not know the true fuel savings of new technologies.
Asymmetric information	One party has more/better information than another.	Charterers may not trust owners' claims about ship efficiency, leading to underinvestment.
Split incentives	The party paying for efficiency is not the one reaping the benefits.	Owners pay for retrofits, but do not receive a premium from charter rate in a time charter that pays back the investment.
Non-market failures	Barriers representing real features of decision-making, which are not captured in techno-economic modelling.	Barriers such as hidden costs (downtime in retrofitting) and funding prevent uptake.
Market heterogeneity	Variations across actors make "one-size-fits-all" solutions ineffective.	Different ship types and routes mean that savings and applicability of measures varies.
Hidden costs	Additional costs beyond purchase/installation not always accounted for.	Downtime during retrofits, training, increases in operational costs, or certification requirements deter investment.
Access to capital	Difficulty obtaining financing for efficiency improvements.	Smaller operators may lack credit to invest in new technologies.
Risk	Uncertainty around future fuel prices, policy, or technology performance.	Shipowners hesitate to invest if payback periods are unclear.

Barrier	Description	Shipping-specific example
Behavioral		
Bounded rationality	Sub-optimal decision making.	
Bounded rationality	Limited cognitive capacity leads to suboptimal decisions.	Operators focus on short-term costs rather than lifetime fuel savings.
Human dimension	Social factors that influence the adoption of measures.	
Form of information	Presentation of information affects decision-making.	Complex technical data may not be understood by shipowners or financiers.
Credibility and trust	Lack of trust in the source of information or data.	Owners may distrust technology suppliers' performance claims.
Inertia	Preference for the status quo or resistance to change.	Companies continue established operating practices despite available solutions.
Values	Cultural or personal attitudes influence choices.	Some owners prioritize reliability and reputation over efficiency.
Organizational		
Power	Internal decision-making authority shapes outcomes.	Technical teams may recommend upgrades, but financial departments block them.
Culture	Shared norms and attitudes affect organizational behavior.	Companies with conservative cultures may be slower to adopt new technologies.

Source: World Bank.

Box 4.1 The interaction between shipping markets and energy efficiency measures

The shipping industry uses several contractual arrangements to provide transportation services. The main types of chartering are voyage (spot) charter, time charter, contract of affreightment, and bareboat charter. The contract determines the entity controlling the operation of the ship and the entity paying for fuel, which has implications for the uptake of energy efficiency measures.

Voyage and time charters are the most common types of contracts, and their distribution varies depending on ship type. In a voyage charter, a charterer contracts a shipowner to transport a specified amount of cargo from one location to another, like a taxi service. The amount paid by the charterer is for a unit of cargo transported, which includes an allocation of all the costs incurred by the shipowner, including fuel costs for that voyage.

In a time charter, a charterer hires a vessel, along with the crew, for a specified period or for a single trip (known as a trip time charter), similar to hiring a vehicle with a driver. Under this type of contract, the charterer maintains the operational control of the vessel for the duration of the hire period. The charterer pays a daily rate for hiring the ship and crew in addition to bearing the fuel costs related to the voyages undertaken during the hire period.

Table 4.2 shows the allocation of different types of costs between the shipowner and the charterer for different types of contracts.

Source: World Bank.

Table 4.2 Cost allocation between shipowner and charterer in the different types of contracts

	Voyage charter	Contract of affreightment	Time charter	Bareboat charter
Remuneration	Per unit of cargo for example $/ton/TEU	Per unit of cargo over a fixed duration and route	Per day	Per day
Control of the ship (trading, routes sailed)	Owner	Owner	Charterer	Charterer
Cargo handling (stowage and storage)	Charterer	Charterer	Charterer	Charterer
Voyage expenses (port and fuel costs)	Shipowner	Shipowner	Charterer	Charterer
Operating expenses (crew wages, maintenance, repairs, stores & supplies, insurance, overheads)	Shipowner	Shipowner	Shipowner	Charterer
Capital expenses (interest and capital repayment)	Shipowner	Shipowner	Shipowner	Shipowner

Source: Adapted from Rehmatulla and Smith (2020), Stopford (2009) and Plomaritou (2014).

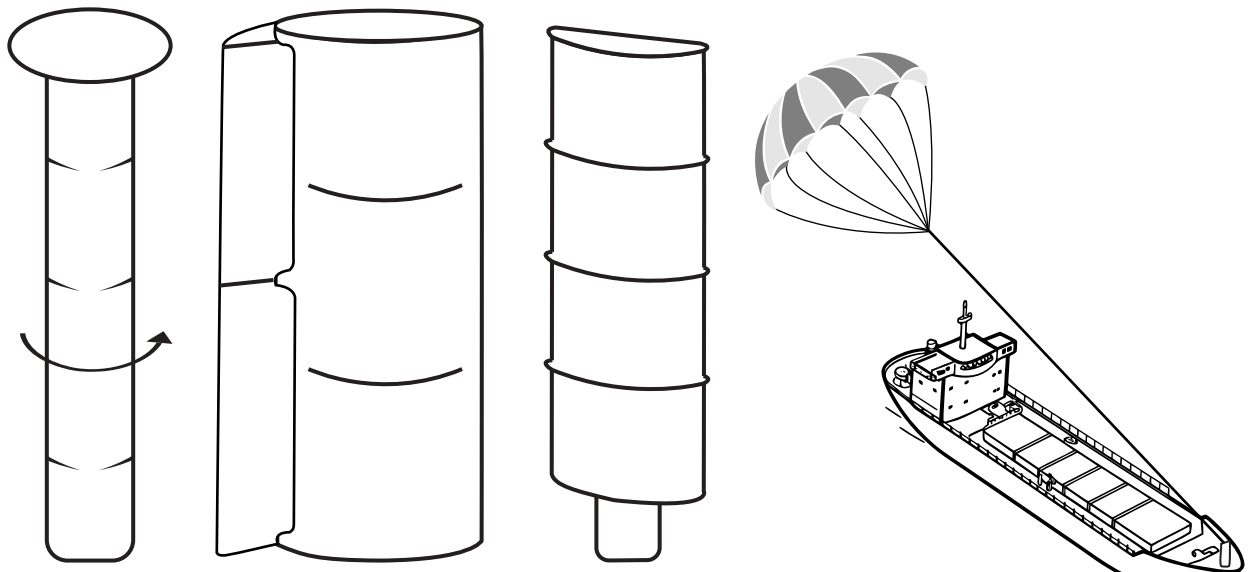
In voyage charters, the charterparty contract contains a charter speed and a due despatch clause (i.e., without unreasonable delay). As a result, ships "Sail Fast, Then Wait" outside of ports in anchorage if there is port congestion. Shipowners are compensated for this operational inefficiency through demurrage, which pays them a daily rate for waiting to unload or load cargo before the berth is available. Demurrage rates can be a significant source of remuneration for the owner, incentivizing a "Sail Fast, Then Wait" behavior.

4.3 Barriers for specific promising measures

4.3.1 Wind-Assisted Ship Propulsion (WASP)

Wind-assisted propulsion refers to technologies that harness wind energy to reduce power requirements from engines in maritime transport, thereby reducing fuel consumption and GHG emissions. These technologies can either fully or partially propel a vessel. Wind-assisted propulsions are typically grouped into four categories: rotor sails, suction wings, hard (also known as rigid wing) sails, and kites (Figure 4.2). Modeling studies, sea trials, and operational data suggest fuel savings from wind-assisted propulsion can range from as low as 1–2 percent to more than 40 percent, depending on the specific vessel configuration and operational context.

Figure 4.2 Different wind-assisted ship propulsion technologies



Source: World Bank, based on Reche-Vilanova and others, (2021).

Rotor sails, suction wings, and hard (wing) sails have been technologically proven (TRL 9[17]) and are commercially available (EMSA 2023). Kites have undergone sea trials, but these applications are generally still supported by government funding (TRL 7) (EMSA 2023). The International Windship Association (IWSA 2025) maintains a list of wind-assisted propulsion technologies installed on large commercial ships. Of the 71 vessels with wind-assisted propulsion technology onboard at the end of Q1 2025, rotor sails and suction wings have been installed on bulk carriers, ferries, general cargo ships, ro-ro vessels, and tankers. Soft sails, kites, or inflatable or retractable wing sails have been installed on some of these ship types. One container vessel has a containerized suction wing system on board.

Barriers to the uptake of wind-assisted propulsion

Wind-assisted propulsion faces both market failures and non-market failures. Table 4.3 summarizes the barriers to the uptake of wind-assisted propulsion from an economic perspective. A survey commissioned by the European Union (EU) in 2016 identified that some of the most important challenges seen by shipowners and operators for wind-assisted propulsion uptake were economic barriers: trusted information on the performance, operability, safety, durability and economic implications; access to capital for the development of WASPs, especially building/testing of full-scale demonstrator projects; and incentives to improve energy efficiency (Nelissen and others 2016). The EU study identified that developing a standardized method to assess WASPs was the most important remedy to tackling the first barrier (a market failure), as this would unlock access to capital from financiers who would otherwise distrust performance information.

A follow-up survey was conducted in 2021 and 2023 by the IWSA (IWSA 2023), which showed substantial progress on third-party verification with standard appraisal KPIs developed by the ITTC (ITTC 2024). Still, suppliers are not using a standardized method to calculate fuel savings from wind-assisted propulsion. Datasets on the performance of wind technologies are currently owned by each technology provider, who struggle to communicate the average savings as they depend on several factors (for example ship type, size, and route).

Despite the clear potential, reported fuel and GHG emissions savings from wind-assisted propulsion installations show wide variability due to a combination of technological, environmental, commercial, and on-board factors (see Table 4.3). Due to this variability, it is challenging to specify an average effectiveness of wind-assisted propulsion (Chou and others 2021) without considering the type of wind-assisted propulsion technology, the ship type and size, route and weather conditions, among other factors. The factors in Table 4.3 are interrelated and should not be considered independently. For example, a ship's trade pattern (a commercial factor) determines the wind speed, wind angle, and seasonality (environmental factors).

[17] TRL refers to technological readiness level, a scale from 1 to 9 estimating the maturity of a technology.

Table 4.3 Factors affecting fuel savings from wind-assisted propulsion

Category	Factor
Technological	• Wind-assisted propulsion technology type • Ship type and size • Ship hull design • Location on ship
Environmental	• Wind speed • Wind angle • Sea state • Seasonal pattern
Commercial	• Trade pattern • Ship speed • Presence of Cargo • Voyage duration
On-board	• Voyage optimization • Crew training • Master's decision making • Idling time due to maintenance, failure, safety etc.

Source: World Bank.

There needs to be more information in gathering and disseminating third-party verified information on wind-assisted propulsion technologies (for example general technology information, savings, real case studies that demonstrate the operability, seakeeping, manoeuvring, and cargo operations). Better information could also help reduce the technical risk that owners include in their investment risk assessment.

Access to capital for R&D, pilots, and installations is one of the most significant non-market failures. Although there has been progress in the availability of R&D funding in some regions (for example the EU), R&D funding remains insufficient (IWSA 2023). Finance for installations has been available from larger suppliers, but smaller suppliers have struggled due to financial risk appraisals and loan security requirements. Financiers' lack of knowledge about technology and trusted third-party verification data have also exacerbated access to capital (affected by the imperfect information barrier).

Table 4.4 Barriers to uptake of wind-assisted ship propulsion technologies

Perspective	Sub-division	Barrier	Claim
Economic	Market failure	Negative externalities	*Shipping:* Excluding the GHG impact of fossil fuels reduces the perceived cost-effectiveness of wind-assisted propulsion technologies.
		Imperfect information	*Shipping/financiers:* Lack of third party verified information about wind-assisted propulsion technologies and energy savings.
		Split incentive	*Shipping:* Principal-agent problem in time chartering; savings are higher with slower speeds, but owners not incentivized to slow steam.
		Asymmetric information	*Shipping:* Suppliers have more information about the savings of their technology than owners. Owners may mistrust the savings claims of tech providers especially if it has not been verified by third parties.
	Non-market failure	Technical risk	*Shipping:* Uncertainty about technology's physical performance (for example energy savings, its operability, durability and safety at sea and in port).
		Access and cost of capital	*Suppliers:* Inadequate R&D funding. *Shipping:* Challenges to secure funding for installations, especially from SME suppliers.
		Hidden costs	*Shipping:* Hidden installation costs, training, potential to reduce cargo space, installation disruptions, and opportunity cost of voyage optimization for wind. *Suppliers:* The supplier bears more of the technical risk in contracts.
		Market heterogeneity	*Shipping:* Better suited to some ship types/sizes (for example ships with adequate deck space and routes with sufficient wind).

Source: World Bank.

Innovative uptake examples of WASP

The initial cost challenge for shipowners has been tackled by different business models and state funding. For example, Norsepower – a Flettner rotor manufacturer – is shifting the upfront cost of its technology to a monthly fee based on the actual fuel saved, effectively implementing a pay-as-you-save model (Ovcina 2023). Other options explored by the industry are lease and modular rental (Allwright 2021). State funding has been used to install wind-assisted propulsion technologies on ships. For example, a system installation on a ship chartered by Cargill was supported by a grant from the European Union's Horizon 2020 research and innovation program (Cargill 2024; CHEK 2023).

Other non-market failures (for example technical risks and hidden costs such as commissioning or disruption costs), highlighted by Rehmatulla and others (2014), have been overcome through trials, installations, and innovations in installation approaches that do not require drydocking or extensive periods out of operation (Chou and others 2020).

4.3.2 Port call optimization

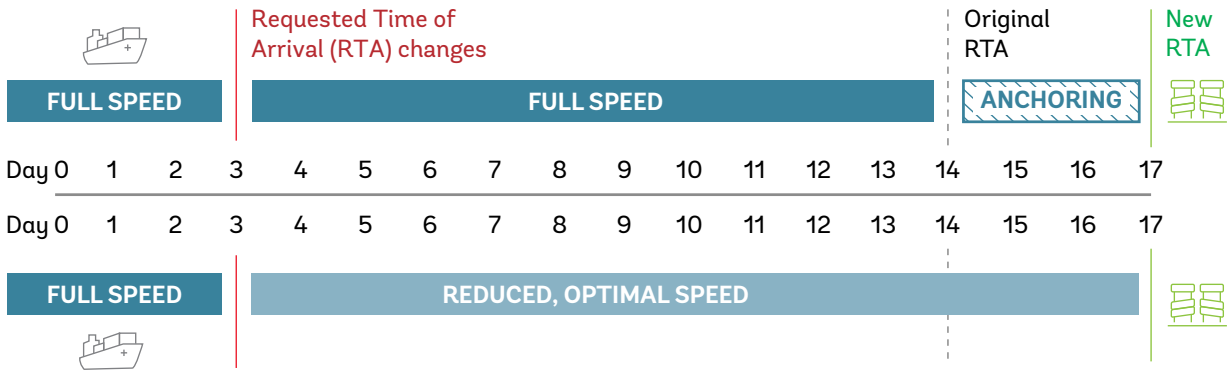
Port call optimization (PCO) entails the strategic management of ship arrivals, with the goal of minimizing vessel idle time and enhancing berth planning to alleviate port congestion. Digitalization plays a crucial role in this process by enabling real-time data exchange between ships and ports, supporting just-in-time arrivals, and reducing anchorage durations.

Just-in-time Arrival (JIT Arrival) is a strategy of port call optimization. It allows a ship to optimize its speed to arrive at the Pilot Boarding Place when the availability of the berth, fairway (the navigable channel), and nautical services (pilots, tugs, and linesmen) is ensured. The current contracting process using standard voyage charterparty clauses stipulates that vessels proceed at "due despatch" towards a port, regardless of port congestion. The fuel savings from JIT Arrival range from 3 to 25 percent depending on the ship type, model assumptions, the period over which speed is optimized, and the length of the voyage.

The concept of JIT Arrival of ships is central to PCO. As illustrated in Figure 4.3, this approach involves a ship maintaining an optimal operating speed to arrive precisely at the pilot boarding place (PBP) when the berth, fairway, and marine services are ready. JIT Arrival therefore optimizes both the ship's sailing speed and the port operations. The aim is to avoid a "Sail Fast, Then Wait" situation (shown at the top of Figure 4.3) and minimize waiting time in port and higher fuel consumption due to higher sailing speeds (bottom of Figure 4.3), thus reducing the associated GHG emissions (Psaraftis and Lagouvardou 2023). Under a JIT voyage, a ship can optimize its speed from the point at which it receives the information about a new Requested Time of Arrival (RTA) and eliminate (or minimize) waiting time.

Figure 4.3 illustrates an early alteration in the RTA during the voyage and the anchorage time as a consequence of "Sail Fast, Then Wait". In most ports, the captain is informed of their RTA at the PBP only about 1.5 to 3 hours before reaching the first calling-in point in the port (GIA 2020).

Figure 4.3 Today's operation vs. JIT Arrival



Source: World Bank (2025b) based on GIA (2020).

In absolute terms, most of the fuel savings in a JIT voyage come from reducing sailing speed before entering the port. The reduction of GHG emissions in ports also has the added benefit of reducing the CII because emissions in port cannot be offset by ton-miles (the denominator of CII).

Ships spend up to an average of 9 percent of their time per year in anchorage before entering the port (GIA 2020). The duration varies depending on the ship type; wet and dry bulk carriers spend over 8 percent of their time in anchorage, while container ships spend over 4 percent (GIA 2020). Container ships spend 30 percent of their total port time before arriving at berth, including anchorage, waiting, and transit time to berth (World Bank 2024b).

Time in port also varies greatly across ports. In 2018, the least developed countries spent, on average, 135 percent more time in port compared to developed countries across all ship types (Rojon and others 2021).

PCO is a solution to minimize the opportunity cost of wasted time for shipowners, cargo owners, and ports. Port congestion and delays in port can also have knock-on effects for later port calls, which then require ships to speed up to be on time for the next port. While this section focuses on Just-in-time Arrival, PCO is considered to be a prerequisite to enabling JIT Arrival (GIA 2020) because it lays the foundational coordination between stakeholders involved in a port call and efficiency needed for JIT Arrival to function effectively (see the Tanger Med case study in Section 4.3.4 for an example of where PCO has led to a decrease in anchorage time).

4.3.3 Barriers to uptake of JIT arrival

The barriers to the adoption of JIT Arrival span behavioral, economic, and organizational barriers, as shown in Table 4.5. One of the major economic barriers (market failures) is imperfect information. Nautical[18] and operational data[19] shared can be inaccurate. "Inaccurate information sharing"

[18] Nautical data is used for navigation, chartering, and planning of vessels. Examples of nautical data include the location of terminal, berths, anchor areas, maximum sizes, depths and tides, weather features, nautical services, communication procedures, port emergency procedures.

[19] Operational data is data used to facilitate the day-to-day planning of vessels, berths and their related services and is submitted to non-authority parties. Examples of operational data include arrival and departure times of ships, starting and completion times of nautical, cargo and ship services.

was cited the most times by an interview conducted with 42 shipping and port stakeholders for a network of Port Call Optimization initiatives (van Scherpenzeel and Buch 2024). There is also a lack of standardization of key timestamps for the arrival and departure of ships in port, which can lead to confusion among shipping and port stakeholders (van Scherpenzeel and Buch 2024; GIA 2020).

The fuel savings potential from JIT Arrival is determined in the literature through a 'what-if scenario' that calculates the difference between the fuel consumption of a voyage and the fuel consumption using a counterfactual speed. The savings therefore reflect the theoretical model used and the duration over which the voyage speed was optimized (Merkel and others 2022). Published JIT Arrival sea trials typically only provide limited data on the savings.

In markets where voyage contracts are common (for example bulker and tanker), the contract also needs to be modified to allow for a breach of the "due despatch" obligation (requiring the ship operator to sail at a mandated speed to port) to protect owners from claims.

A port optimization concept called Virtual Arrival (VA) was first introduced in 2011 by INTERTANKO (an association of tanker owners) and OCIMF (an association that represents the interests of oil majors) with the purpose of reducing bunker fuel bills in the oil tanker industry for voyage charters. VA is a bilateral contract between a shipowner and a charterer to accept the vessel's notice of readiness (NOR) at the time it would have arrived at the port had it sailed at "due despatch" (known as Virtual Notice of Readiness [vNOR]). This allows the shipowner to reduce a vessel's speed when there is a known delay at the discharge port (INTERTANKO & OCIMF 2010).

New contracts with "Virtual Arrival" or "Just-in-Time" clauses were put in place to reduce the risk of disputes. However, the uptake of these types of contracts has been low. One of the reasons is the hidden cost due to the lack of jurisprudence between the owner and charterer, leading to the possibility of a lengthy and costly dispute (IHMA, forthcoming).

There may also be mandatory port regulations, as mandated by national law, that cannot be overridden. The majority of charter parties have a clause stating that owners are responsible for complying with the port regulations and restrictions. Therefore, the port regulation would need to be changed by the port authority to include a requirement not to arrive early in the waiting area (IHMA, forthcoming).

The uptake has also been low because of split incentives. The value of the cargo outweighs the fuel savings benefits and shipowners are incentivized to wait in port to earn demurrage revenue. Other financial considerations are the lack of financial resources for implementing a JIT solution, which typically requires moving from email communication to a digital platform.

The interviews also revealed the lack of awareness of guidelines on PCO. When interviewees had heard of supporting PCO documents, they did not have the time to read them, highlighting the hidden costs of information gathering.

There is also market heterogeneity in the applicability and GHG emissions reduction potential across different ship types. Although JIT Arrival can be applied to all ship types, container ships have more flexibility to reduce their speeds because they operate on fixed schedules and on a time charter or owned basis and often have a berthing plan. They typically have contracts with terminals, which makes it easier to advocate for data exchange.

In addition, because container ships travel at higher speeds than other large segments (for example bulk carriers and tankers), a marginal reduction in speed is more impactful over shorter time periods,

whereas tankers and dry bulkers sail at lower speeds and therefore need a longer time interval to obtain the same savings. Modeling from Smith and Francis (2024a) shows that containerships have the highest savings potential for JIT Arrival in terms of absolute emissions.

Table 4.5 Barriers to uptake of JIT arrival

Perspective	Sub-division	Barrier	Claim
Economic	Market failure	Imperfect information	Accuracy and frequency of information hinders nautical and operational data quality; inconsistent data definition of key timestamps across stakeholders.
		Split incentive	*Shipping:* 'Utmost despatch' speed clause in bulk and tanker markets; other market incentives (demurrage, commodity price). *Ports:* Tides, weather, and accessibility concerns for inland ports.
	Non-market failure	Hidden costs	*Shipping:* Lack of jurisprudence between charterer and owner for a "JIT clause" in charter party clause, leading to possible lengthy dispute. Unawareness of standards and guidelines. *Ports:* Lack of personnel to support and coordinate across multiple stakeholder groups. Unawareness of standards and guidelines.
		Access and cost of capital	*Ports:* Ports lack financial resources for JIT solution.
		Market heterogeneity	*Shipping:* Some ship types like bulk carriers and oil tankers have unpredictable schedules and do not know in advance the port they are sailing to.

Source: World Bank.

Behavioral and organizational barriers

There are also several important organizational and behavioral issues, shown in Table 4.6. A lack of willingness to change was cited as the second-highest barrier (van Scherpenzeel and Buch 2024). Shipping and port stakeholders found it challenging to adapt their processes and terminology to a standardized format due to longstanding practices (van Scherpenzeel and Buch 2024; Mubder 2024).

Trust issues arise with data sharing by stakeholders (for example shipping companies and terminals) who are concerned that this information could be used by third parties to infer commercially sensitive information, such as the type of commodities being traded or terminal productivity (GIA 2020). There is also a lack of trust between shipowners and ports to hold a ship's place in the queue (Paulsen and Sampson 2019).

A key organizational barrier is the landlord governance structure, in which the Port Authority (PA) acts as a landlord of port infrastructure while the terminal is privately operated. The PA lacks the agency to unilaterally mandate PCO initiatives. This was evident in some of the ports' PCO initiatives studied, where stakeholder buy-in between shipping companies and terminals was the mechanism for high uptake of PCO.

Table 4.6 Non-economic barriers to uptake of JIT arrival

Perspective	Sub-division	Barrier	Claim
Behavioral	Human dimension	Inertia	Lack of willingness to change.
		Credibility and trust	*Shipping:* Lack of willingness to share data due to trust issues about commercially sensitive information. The shipowner does not trust the port that they will hold their place in the queue if arriving virtually.
Organizational		Power	*Shipping:* Sustainability manager within firm lacks agency due to other departments having different priorities (for example charterers' trading division incentivized by commodity profits). Potential regulatory restrictions for arriving just in time. *Ports:* In landlord port, port authority often lacks agency to mandate JIT Arrival.

Source: World Bank.

4.3.4 Innovative uptake examples from ports implementing PCO strategies

Table 4.7 describes ports that have PCO strategies, collected using desk research and interviews for select ports. A port's governance model and the terminal ownership structure can affect the port authority's ability to act unilaterally. The overview shows that all ports have some type of landlord port, and most initiatives come from Organization for Economic Co-operation and Development (OECD) countries. Landlord ports come in different forms. In a traditional landlord port, the public sector provides basic infrastructure while the private sector handles superstructure (for instance, buildings and equipment) and operations. This division of responsibilities can vary, for example, some ports in Sweden (Port of Gothenburg, Port of Gävle) have a mixed ownership model, where the energy terminals are publicly owned.

In most of the ports, the port authority facilitates the PCO strategies. Most ports include safety as the motivating factor for PCO. Other motivating factors include improving coordination, transparency, efficiency and situational awareness; reducing GHG emissions; reducing costs; reducing air pollution; and mitigating disputes arising from the First Come, First Serve system.

Table 4.7 Eleven port call optimization initiatives from around the world

Port	Governance model	Port authority ownership	Terminal operation	Motivation	PCO strategies	PCO facilitator	Coverage	PCO policies effectively mandatory?	Indicative maturity
Algeciras, Spain	Landlord	National	Private	Data sharing, efficiency, emissions, achieve formula-style "pit stop port"	ETA prediction, schedule management, aim for JIT Arrival	Port Authority	Container ships	Not applicable	Operational
Bremen and Bremerhaven, Germany	Landlord	Municipal	Private	Data standards, fostering trust for information sharing, safety	Berth and schedule management	Port Authority with involvement of regions managing river and sea access	All vessels	No	Pilot
Gävle, Sweden	Landlord	Municipal	Mixed; public for Energy Port	Enhanced coordination and planning, emissions	Booking system (request to book berth must be done before arrival); Berth planning	Port Authority	Tankers	Mandatory for tankers calling at the Energy Port	Operational
Gothenburg, Sweden	Landlord	Municipal	Mixed; public for Energy Port	Time, emissions, costs	Data sharing platform; JIT Arrival	Port Authority	All ships	No	Operational
Hamburg, Germany	Landlord	Municipal	Private	Time, safety	Digitalized passage planning; JIT Arrival	Hamburg Vessel Coordination Center	Ocean, feeder and barge ships	No	Operational
Long Beach and Los Angeles, California	Landlord	Municipal	Private	Air pollution, safety	Queue based system: ships enroll with port at last port call and placed in queue	PacMMS	Container ships	Violators will be notified to stay outside port. Actions will be taken against non-compliance.	Operational

Port	Governance model	Port authority ownership	Terminal operation	Motivation	PCO strategies	PCO facilitator	Coverage	PCO policies effectively mandatory?	Indicative maturity
Newcastle, Australia	Moving from traditional landlord model to integrated owner operator	State	Private	Safety	Vessel arrival system with an ETA	Port Authority	Bulk carriers carrying coal	Yes, under New South Wales Law, Port Authority exercises certain port safety functions including its Vessel Arrival System	Operational
Rotterdam, Netherlands	Landlord	Municipal and national	Private	Safety, efficiency, emissions, costs	Adoption of international data standards, data sharing platform, geofenced ETA system	Port Authorities	All vessels	All container ships must send a vessel notification	Operational
Singapore	Landlord	National	Private	Digitalization, efficiency, safety, emissions	Data sharing platform, JIT Arrival	Port Authority	Container ships, bulk carriers, general cargo; extending to tankers and other vessels	If the vessel arrives early, the Port Authority will request the reason for waiting.	Implemented for container ships, bulk carriers, general cargo; pilot for tankers and other vessels
Tanger-Med, Morocco	Landlord	Public limited company	Private	Optimizing vessel management, safety	Berth plan, priority management system, firm booking, JIT Arrival	Port Authority	All vessels	Firm booking for container ships	Operational
Valencia, Spain	Landlord	National	Mostly private	Efficiency, optimize vessel management, emissions	Data sharing platform, vessel ETA and departure planning	Valenciaport Foundation	Pilot stage coverage unclear	Not applicable	Pilot

Source: World Bank.

In the case of Port of Newcastle (Australia) and ports of Los Angeles and Long Beach (United States), there was a defining event that served as a catalyst for PCO. The grounding of a bulk carrier served as a catalyst for implementing a form of Just-In-Time (JIT) Arrival at the Port of Newcastle, prompted by the extended periods vessels were spending at anchorage near the port. A surge in container ships waiting outside of the ports of Long Beach and Los Angeles and its consequences for air pollution motivated its queue-based system. Some ports are also naturally required to have situational awareness of ship movements in port because they are restricted by tidal windows (for example, Port of Hamburg and Port of Bremerhaven).

The implementation of PCO strategies varies across these ports (see Box 4.2 for case studies of a subset of these ports in North Africa, Europe & Central Asia, and Southeast Asia). For instance, some ports are focusing on situational awareness through better Estimated Time of Arrival (ETA) predictions and facilitating berth and schedule management through a data sharing platform with port stakeholders.

Other ports have implemented a queue-based system, in which each ship needs to enroll with the port authority in advance. For example, at the ports of Long Beach and Los Angeles, container ships need to enroll with Pacific Maritime Management Services (PacMMS) at least 24 hours before departing from their last port of call (PMSA 2022). The estimated time of loading is communicated to the ship in advance and ships are placed in a queue so that they can manage their sailing time to arrive for the specific slot. This doesn't require the vessel to use a platform to communicate with the port authority, which may lead to more inefficiencies if the required time of arrival changes, whereas more advanced systems (for example, Port of Singapore and Port of Tanger Med) update the vessel and other stakeholders in real-time through a digital platform. While this allows for the exchange of real-time information, it also adds additional administrative burden on shipowners who need to be adept at using different port call optimization platforms.

A commonality across all case studies is that implementation of PCO required collaboration across several stakeholders to establish a PCO process. In many of these cases, an entity or facilitator was appointed to consult with various stakeholders including charterers, shipowners, terminals, multiple government agencies and the port community. This was important in designing the right system but also to gain buy-in from the stakeholders who would be required to use PCO.

Only a few ports have been able to effectively mandate their PCO policy. The Port of Newcastle and the Port of Gävle have made their queuing systems mandatory through law for specific terminals or types of vessels. The Port of Gävle has implemented its PCO policy at the terminals where the port authority manages the operational activities.

Box 4.2 Case studies of PCO initiatives

Port of Tanger Med

The port of Tanger Med is a modern landlord port launched in 2007 to be the center of maritime trade for routes between Asia, Europe, Africa, and the Americas. The port is taking a holistic approach to just-in-time arrival by viewing it within a wider framework of port call optimization. Before 2018, it became apparent to the Port Authority (PA) that there was a need for transparency in the sequence of vessel movements. The PA also wanted a system that would ensure safety by mitigating large ships drifting in the narrow waters in the port area (the port is located on the Strait of Gibraltar, which is a narrow passageway between Spain and Morocco).

The PA started digitalizing its operations by working with terminals to develop a berth plan that provides the ships' arrival and departure schedule. This allowed them to create an exchange platform through a Port Community System (PCS) where shipping companies and terminals and other stakeholders can view certain details of the ships at Tanger Med (currently stakeholders can view ships' Estimated Time of Cargo Completion, with the aim to share more information on the timeline of future movements that will include the estimated, requested, planned, and actual time of port calls and how this can deviate using well-known timestamp standards from ITPCO and DCSA).

The berth plan was the foundation for creating a priority management system. The priority management system (launched in 2018) is a system designed to give priority to vessels based on certain criteria, aligned with a just-in-time (JIT) mechanism that allows shipping companies to book a specific time slot for their vessels' movements hours in advance for transit. The PA's priority management system provides a provisional priority (number in the queue) and updates it based on actual timestamps communicated by different stakeholders and the JIT movements. Through these port call optimization initiatives, the use of anchorage waiting to berth was reduced by more than 82 percent, and the average time spent in anchorage fell from 17.5 hours in 2017 to 7.3 hours in 2023, while the port call volume was doubled over the same time period. Having advanced notice of their number in the queue allows ships to plan ahead their voyages and adjust their speed.

The PA is in the process of implementing just-in-time arrival. Through a stakeholder engagement process and just-in-time trials with major carriers, they learned that carriers have different protocols for determining vessels' arrival and departure times. This created the need to develop a flexible approach for JIT that would consider all scenarios. For example, one major carrier prefers to have JIT facilitated by the fleet operator who communicates with the captain of the ship. Whenever there is a change in the terminal, the queue, etc., they inform the fleet management by including the new requested time of arrival to port, and automatically the fleet management team gets an email with the new request and can accept the new arrival time or request a different one. Another major carrier has successfully trialled an approach that uses their local marine agent to receive information on the Requested Time of Arrival/Departure from the PA and then communicates this information to the fleet manager.

The PA has completed several JIT voyages with multiple major carriers since 2021, starting the process from when the ship departed from the last port of call using its PCS, and is working on creating APIs with major shipping lines and ports to exchange data seamlessly. It is planning to launch its new platform with just-in-time arrival in 2025.

Source: TMSA.

Port of Singapore

The Maritime & Port Authority of Singapore (MPA) has developed a Just in Time Planning and Coordination Platform (JIT Platform) to facilitate just-in-time operations for optimal vessel passage planning calls. This digitalization initiative was driven by the port authority's recognition of the significance of digitalization as a crucial driver to foster innovation in the maritime industry, boost port operation efficiency, enhance sea safety, and advance maritime decarbonization.

MPA commenced the JIT initiative in 2019 with a research study for process mapping. In 2020, MPA started the development work of the JIT Platform. Since October 2023, the JIT Platform has been available for vessels berthing at PSA Terminal and Jurong Port for cargo operations. The platform is being developed to include tankers and vessels sailing to anchorage in the port. Ship agents, shipping liners, and marine service providers can utilize the JIT Platform to facilitate optimal arrival and departure of vessels to and from the Port of Singapore, thereby reducing the time at anchor prior to berthing.

The JIT Platform provides advance information on the vessel's in-port schedule, allowing vessels to maintain an optimal operating speed before arriving at the Port of Singapore and reduce the time vessels spend at Singapore's anchorages prior to berthing. Under the JIT initiative, the estimated time of berthing (ETB) of the vessel's first berthing will be made available at least 72 hours prior to vessel's arrival. The JIT system will notify all stakeholders of any subsequent changes in ETB, and the ship master/operator will have the option to plan and revise their passage plans accordingly.

MPA has been conducting briefings and training for all stakeholders since early 2023 and has gathered feedback from these stakeholders. MPA has also been gathering feedback from users to enhance the platform.

Source: MPA

Port of Hamburg

Facing bottlenecks due to the increase in ship size and its impact on ships' navigation through the port's narrow River Elbe, the Port of Hamburg saw the need for central coordination to coordinate the arrivals and departures of ships from the port's terminals. The port of Hamburg is a landlord port, with nautical management (public and private), port infrastructure (public), and superstructure (private), as well as competing private terminal operators. The port authority (PA) has responsibility for ensuring the waters within the port area are safe and there is ease of vessel traffic. Arrival planning, which requires communicating with shipping companies and terminals, is outside the port authority's jurisdiction under the federal regulation of waterways in Hamburg. Comprehensive arrival and departure planning requires extensive communication to ensure safe navigation and benefits from an earlier exchange of information and coordination, supporting the operational planning of all port call stakeholders. Safe navigation is mostly part of short-term vessel traffic control, while resource optimization of private port call actors remains the responsibility of the individual private actor.

Port of Hamburg (cont.)

Against this background, a unique port call collaboration between private and public actors was formed in 2015 to enable reliable, efficient, and smooth vessel traffic. The Hamburg Vessel Coordination Center (HVCC) is a joint venture between two competing terminal operators, Terminal Operator EUROGATE and HHLA, which have been collaborating on the central coordination of feeder ships in the Port of Hamburg. The two terminals set up a digital data exchange platform called The Port-River Information System Elbe (PRISE) to share data transparently in the port with terminals, shipping companies, nautical service providers, and public authorities under the technical leadership of DAKOSY, who also operates their port community system. While container ships represent the majority of vessel traffic into the port, there are also bulk carriers and multipurpose terminals. Arrival planning among shipowners, terminals, nautical service providers, and HVCC is the first step for achieving just-in-time arrival. The current process still relies on email exchange/online schedules from the shipowners to the terminals to provide their operational data early on (this can be up to two months in advance, used for efficient use of the port authority's infrastructure, the berths). The terminal planners can provide this information from an API directly to the HVCC - PRISE system, which can check compatibility with other ship arrivals/departures.

While HVCC monitors the movements of ships from nearby ports in advance of their arrival and collaborates with neighboring ports (for example it has a direct API with the ports of Rotterdam and Le Havre), arrival planning is updated 5-31 days in advance. This is within the time window when ships typically depart from nearby ports to the port (for example Felixstowe, Bremerhaven, and Antwerp). All vessel arrival and departure planning is mutually discussed with the involved private parties to understand their operational needs and the responsible Hamburg port authority (harbor masters office), which monitors vessel traffic 36 hours before arrival to ensure safety on the waterways. The division of processes between HVCC, which handles operational coordination planning, and the port authority, which manages the navigation and vessel traffic services, is a unique collaborative operating model. The execution of these processes results in the creation and submission of digitalized passage plans for the carrier, including a suggested arrival speed, arrival/departure time, drafts, and relevant traffic. If the passage plans change, the HVCC informs the shipowner immediately. An example of a JIT journey provided by HVCC shows that an 18,000 TEU container ship was able to reduce its speed from 18 knots to 14 knots travelling from the port of Rotterdam, saving 22 tons of bunker fuel and 66 tons of carbon emissions.

Port of Hamburg (cont.)

HVCC has also been developing solutions to digitalize communications from shipping companies to terminals. In 2020, HVCC, Wärtsilä, and the cruise line company Carnival Maritime presented a Proof of Concept for ship-port digital communication. The project showed how the Requested Time of Arrival (RTA) could be sent from the HVCC platform to the carriers' shore team responsible for fleet planning. Following approval from the carrier, the RTA was shared with the ship's Electronic Chart Display and Information System (ECDIS), which is used by the captain for navigation. The project involved several digital just-in-time arrivals with ships from AIDA Cruises, a German cruise line that is part of the Carnival Corporation. HVCC is also collaborating with the Digital Container Shipping Association (DCSA) to test the standards they have developed. As a result of the findings from the pilot with DCSA, DCSA developed the Just-In-Time Port Call and Operational Vessel Schedule standard. HVCC is using the Operational Vessel Schedule standard, which offers carriers the option to submit their coastal schedules digitally to HVCC and the port of Hamburg stakeholders.

Customer trust in HVCC has been the backbone of a port collaborative decision-making approach where port call solutions benefit the entire port community, instead of a single terminal or carrier. This trusted centralized real-time communication enables JIT arrival and departure as well as minimizing bunker, CO_2 emissions, or required resources at the terminals or maritime service provider (for example tug operators, bunker operators). Collaboration with the major carriers did not come overnight, however, taking several years to get all carriers onboard. While JIT can be performed for all ships calling at the port, other ship types, such as smaller bulk carriers, have been slower to adapt their practices. Bulk carriers have much less predictable port visits, and don't often inform the port of their arrival plans until 1-2 days before (the port requires all ships to notify the port 24 hours in advance).

Source: Hamburg Vessel Coordination Center (2024)

Related port call optimization initiatives

Box 4.3 Digital Container Shipping Association (DCSA)

The Digital Container Shipping Association (DCSA), a non-profit organization established to further the digitalization of container shipping technology standards, is collaborating with nine member carriers. It has published port call data definitions, interface standards, and messaging API (application programming interface) specifications for 112 event timestamps, which address the 6 main parts of a port call. The interface standards enable carriers, ports, terminals, and other service providers involved in a port call to exchange event data uniformly, facilitating automated data exchange. DCSA has built port call data definitions based on existing standards from the International Taskforce Port Call Optimization (ITPCO) and the IMO.

Source: DCSA (2025).

Box 4.4 Port Call Optimization Network (PCO Network)

The Port Call Optimization Network (PCO Network) provides essential guidance to optimize voyages from port-to-port and berth-to-berth. Its mission is to accelerate the adoption and harmonization of global standards and solutions for three core data domains (nautical, operational, and administrative) that are necessary for port call optimization. The network is an informal network encompassing a selection of ports, terminals, shipping lines, associated nautical and ship services, and project consortia.

The PCO Network is creating a guide, which outlines how ports can join a global network of ports that provide access to data elements that have been identified as most critical for ensuring safe and sustainable navigation from port to port and berth to berth through a global and ready-to-use connection. Built on universally accepted IMO and IHO standards, which are the same for every port and every vessel, ensuring consistency across all ports and vessels, the guide is intended to support harbor masters and their equivalents with the implementation of this minimum data set. It is expected to be published in 2026.

Other initiatives aligning with the mission of the PCO Network include Chainport, DYNAPORT, Global Maritime Forum, Green Digital Shipping Corridor between Singapore and Rotterdam, ITPCO, IAPH, IMO GIA, MISSION, PortCall.Zero, and Port Authority Round Table.

Source: IHMA (forthcoming).

Box 4.5 Blue Visby Solution (BVS)

The Blue Visby Solution (BVS) is a multilateral optimization platform that notifies ships of the optimal date and time for arriving at their destination to mitigate the effects of the "Sail Fast, Then Wait" strategy, with a focus on the dry bulk and tanker sectors. The solution also includes a contractual mechanism for sharing the costs and benefits of coordinated arrivals into port (for example, fuel savings and opportunity cost of demurrage revenue).

The concept differs from the perspective of port/berth management, as in JIT Arrival, because it does not seek to optimize berthing (which is the responsibility of ports and terminals) and operates at a time and place prior to the engagement of current JIT systems. BVS is compatible with weather routing or voyage optimization systems that shipowners or operators may use, inventory management systems in port, and JIT Arrival systems.

The BVS has been supported by the Blue Visby Consortium, which has over 44 members and is coordinated by the software company NAPA Oy and the law firm Stephenson Harwood LLP. The Consortium comprises industry members from ship owning, commodities trading, port management, and operations, including the Port Authority of New South Wales (Australia), the Port of Newcastle (Australia), Port of Yokohama, Port of Rotterdam, Port Sao Sebastiao (Brazil), as well as the Panama Canal Authority. The project has progressed from academic studies and proofs of concept to digital twin pilots and prototype trials, which led to deployment in December 2024 at several ports in Australia.

Source: BIMCO (2024), Prevljak (2024).

5

Looking Ahead for Policymakers and Industry

5.1 Key findings

The report has quantitatively and qualitatively explored the potential of energy efficiency measures for global shipping, and conveys four key findings:

1. **Energy efficiency measures can reduce ship emissions by up to about 40 percent in 2030, exceeding the International Maritime Organization's (IMO) policy objectives.** Technical and operational energy efficiency measures offer a maximum potential to reduce absolute GHG emissions by 23-39 percent in 2030 relative to 2008 levels, clearly exceeding the IMO's base level of ambition of 20 percent in 2030 and at a maximum exceeding the IMO's high level ambition of 30 percent. The largest untapped potential in the short term lies in ship speed reductions for the overall fleet, reducing GHG emissions by 5-15 percent, with additional savings achievable by optimizing voyage speed into congested ports. Beyond 2030, the contribution of technical measures, such as changes in ship design and the addition of new equipment, is expected to increase. As the global fleet's fuel transition to green fuels is still ramping up, energy efficiency improvements are promising short-term solutions. While energy efficiency measures are insufficient to meet the IMO's 2050 target, at a maximum lowering GHG emissions to about 40 percent below 2008 levels, they will also complement the fuel transition beyond 2030 and reduce ships' reliance on fossil fuel

2. **About half of emissions savings from energy efficiency measures are considered cost-effective in 2030, cutting 250 million tons of emissions at no cost.** By 2030, cost-effective energy efficiency measures could fully pay for themselves by lowering shipping's fuel costs. For bulk carriers, container ships, and tankers, which account for nearly 80 percent of shipping GHG emissions, the majority of energy efficiency measures are cost-effective. However, marginal abatement costs for individual measures vary by ship type, primarily due to differences in ship design and operational requirements. Tankers have the least cost-effective abatement due to relatively higher installation costs of technologies and technical limitations when reducing speed. Bulk carriers offer favorable design features for wind-assisted propulsion, while container ships show high abatement effectiveness in reducing speed

3. **Energy efficiency measures can reduce the total cost of the maritime energy transition by up to about $220 billion per year.** Improving the energy efficiency of the global merchant fleet is insufficient to meet the IMO's policy objectives alone. Therefore, green fuels, such as methanol and ammonia, will be indispensable in 2040 and 2050, but are more expensive than conventional fuels. A cost-efficient route to meeting the sector's GHG emissions targets is to prioritize energy efficiency, which reduces the fuel consumption of the fleet and, therefore, the overall cost of the transition. Annual capital investments in energy efficiency across the fleet of about $35 billion can save up to $270 billion in green fuel costs per year. Investments in energy efficiency measures also offer mitigation to fuel price volatility and will be a critical component of the fuel transition, when green fuels are still more expensive

4. **Despite their potential, several top candidate energy-efficiency measures in merchant shipping remain underused because of sector-specific economic, behavioral, and organizational barriers.** While promising, some of the candidate measures with the highest GHG emissions savings and lowest uptake, such as wind-assisted ship propulsion, air lubrication, and port call optimization (PCO), remain untapped to date. An explanation for the lack of investment and implementation of cost-effective measures is due to known economic, behavioral, and organizational barriers, which

are also common barriers to implementing energy efficiency improvements in other sectors. Specifically, imperfect information, split incentives, and asymmetric information are the most significant market failures, while non-market failures such as access to capital, hidden costs, perceptions of technology risk, and market heterogeneity, contribute to the lack of uptake of technical measures. Behavioral and organizational barriers are particularly important to address to increase the uptake of PCO by ports and the shipping industry.

5.2 Outlook

Energy efficiency has significant potential for global shipping but remains largely untapped to date. How can the remaining barriers be addressed, and who is best placed to lead such efforts?

Regulations, policies, and standards are key to address barriers

Several options exist to address the barriers, but each option in isolation is not sufficient. A combination of policies is therefore required.[20] Performance standards hold some of the greatest potential to address the longstanding market failures and barriers, such as information barriers, which prevent firms from responding to price signals alone (Gupta and others 2007). In the context of global shipping as a uniquely regulated sector at the global level, international performance standards (for example EEDI, CII) can be strengthened and considered by member states of the IMO in their future work plan. However, other instruments (for example emission levies, subsidies) can also provide additional demand and supply-side incentives, especially as there is a growing recognition that a combination of multiple climate policy instruments may be needed to decarbonize industries (Grubb, Hourcade and Neuhoff 2014; Mazzucato 2018; IMO 2021b). The large untapped potential of energy efficiency, especially to help make shipping cost more resilient to absolute fuel price volatility and fuel transition cost, presents an opportunity for the IMO, too.

Alongside regulatory intervention, voluntary information standards can complement international policies to help address imperfect information market failures and harmonize data exchange. This report has attempted to increase the transparency of the savings potential of individual energy efficiency measures by showing that savings data from publicly available data sources vary widely based on the method used. Further efforts to standardize GHG emissions savings are required in the future. The recommended procedures and guidelines for validating the wind performance of ships established by the International Towing Tank Conference (ITTC 2024) offer one example of how consistent terminology for evaluating the performance of wind propulsion can be used to build a shared understanding for organizations involved in performance predictions for wind-assisted and wind-powered vessels. Other innovative technologies would benefit from similar initiatives. Third-party verified data of technology demonstrations in real operating conditions would also help improve access to capital, where financial investors need to have reliable third-party knowledge of the technology and savings for assessing technology risk in their investment appraisal.

[20] Also known as the Tinbergen Rule, which states that each for each target or failure to be corrected, at least one instrument is needed.

Ports are critical stakeholders to facilitate energy efficiency uptake

Ports and port stakeholders are critical actors to foster the uptake of promising operational energy efficiency measures, such as port call optimization, but also infrastructure-related options such as onshore power supply. National and local policies can encourage these port development activities, which do not traditionally fall under the regulatory realm of the IMO.[21] Ports and their national governments can consider how regulatory instruments can be used to encourage these initiatives while ensuring that they fit within their existing national and port-level regulations and port operating model.

Learnings from ports that are more advanced in implementing port call optimization initiatives can help other ports at earlier stages of implementation to address adoption challenges. While voluntary initiatives are not effective to decarbonize the shipping industry on their own, they are needed to bring stakeholders together so that efforts do not need to be repeated. In this report, all ports with a port call optimization initiative operate under some type of landlord model that delegates operations to private terminals, which control the data around berth planning. Strong multi-stakeholder collaboration is needed both for buy-in of port call optimization by various stakeholders, including charterers, ship operators, terminals, multiple government agencies and the port community, and to design the appropriate system.

The roadmap to successful implementation also includes initial steps such as voluntary berth planning to share data about key ship movements in port before moving to more advanced just-in-time arrival solutions. These initiatives can be supported by a maritime single window or a port community system, which facilitate data sharing across multiple stakeholders. Adoption of global digital data standards that establish definitions of different locations within ports and port call timestamps from universally accepted IMO and IHO standards, which are the same for every port and every vessel, are also crucial to improve communication on port calls and arrival times between ship operators and ports, enabling port call optimization. Ultimately, improving energy efficiency through port call optimization facilitates frictionless maritime trade, which World Bank initiatives, such as the Container Port Performance Index (CPPI) (World Bank 2025c), the Port Reform Toolkit (World Bank 2025b), and maritime digitalization (SSATP 2024; World Bank 2024a) solutions support.

[21] See Resolution MEPC.323(74) (IMO, 2019) which specifically encourages port-side energy efficiency initiatives that support the viability of business cases for the provision of ship and shoreside/onshore power supply from renewable sources, facilitating Just-in-Time Arrival of ships through developing necessary global digital data standards that would allow reliable and efficient data exchange between ship and shore, and promoting incentive schemes that address GHG emissions and sustainability of international shipping and encourage more incentive providers and shipping companies to join these schemes.

Financing solutions are needed to support uptake of energy efficiency

For ship investments, energy efficiency technologies are inherently linked to the underlying asset—the ship itself. In traditional ship financing, such as asset-backed lending, the ship serves as collateral. To justify financing for energy efficiency upgrades, these technologies must demonstrate that they enhance the ship's value, for example, by improving operating cash flow through reduced fuel costs or lower compliance expenses. To allow debt capital to support energy efficiency, ship financiers should collaborate with industry stakeholders to develop new financing solutions for retrofits to address the risk in energy efficiency investments such as when the benefits do not fully accrue to the shipowner. Additionally, financiers can collaborate with industry stakeholders to establish universally accepted information standards, which would help articulate the value of these technologies more clearly.

For port investments, implementing digital technologies to optimize port calls represents a cost-effective approach to achieving significant development outcomes. These interventions are often overlooked as standalone measures due to their seemingly modest scale. However, they can deliver substantial benefits. Development partners can collaborate with public port authorities to bundle smaller initiatives with broader trade facilitation and port infrastructure investments, ensuring that initiatives aimed at optimizing port calls are effectively implemented. This approach enables the sector to capitalize on these efficient solutions and avoid missing out on valuable opportunities for improvement in air pollution management, GHG emission reductions, and enhanced trade efficiency.

Appendix

Appendix A: Model Inputs and Assumptions

2018 GHG emissions

The original baseline year of the CE-Ship model is 2018 and is based on the 2018 fleet and GHG emissions data inventory for total global (international and domestic) shipping from the Fourth IMO GHG Study (see Table A.1 for the fleet scope included in the model) including so-called Type 2, 3 and 4 vessels. The Fourth IMO GHG Study distinguished different vessel identification criteria (Type 1-4) depending on the extent that IMO numbers, AIS identification numbers and ship registries match. CE-Ship includes all vessels, thus also without a valid IMO number, to best match total global shipping emissions.

The model makes one adjustment to the 2018 inventory of the Fourth IMO GHG Study for tankers. This adjustment is consistent with the emission projections of the Fourth IMO GHG Study. Product tankers, which fall under the category of chemical tankers, can switch between carrying oil products and chemicals, and many are engaged in the transport of oil products. To align oil transport demand with vessel supply, a portion of the chemical tanker fleet has been reallocated to the oil tanker fleet to account for the fact that some chemical tankers also transport oil.

Table A.1 Classification of vessel types and sizes in the model

International		**Domestic**	
Vessel type	**Vessel sizes (unit)**	**Vessel type**	**Vessel sizes (unit)**
Bulk carrier	All sizes	Ferry – pax only	0 – 1,999 (GT)
Chemical tanker	All sizes	Ferry – ro-pax	All sizes*
Container	All sizes	Yacht	All sizes*
General cargo	All sizes	Service – tug	All sizes*
Liquefied gas tanker	All sizes	Miscellaneous – fishing	All sizes*
Oil tanker	All sizes	Offshore	All sizes*
Other liquids tankers	All sizes	Service – other	All sizes*
Ferry – pax only	All sizes*	Miscellaneous – other	All sizes*
Ro-ro	All sizes		
Vehicle	All sizes		
Cruise	All sizes*		
Refrigerated bulk	All sizes		

Source: World Bank. *For these ship types, we assumed fixed demand and no energy efficiency improvements.

2022 GHG emissions

The 2018 baseline of CE-Ship is updated to 2022 using trends in the number of vessels and CO_2 emissions by fleet type and size class category presented in Smith and Francis (2024b). This study follows the fleet categorization of the Fourth IMO GHG Study. There are two differences in scope however:

- The Fourth IMO GHG Study and Smith and Francis (2024b) use a different vessel identification criterion (Type 1-4 vs. Type 1 only). CE-Ship assumes that all Type 1-4 vessels develop like Type 1 vessels reported by Smith and Francis (2024b). This means the datasets contain different vessels and therefore the absolute values of parameters at the fleet or vessel-type level cannot be directly compared (Smith and Francis 2024b). The largest discrepancies between AIS data and IMO numbers are observed among vessels in the smallest size categories
- CE-ship reallocates a share of the chemical tankers to the oil tanker fleet for 2018 as discussed above. It applies the UMAS index figures to the reallocated tanker fleets. This means that the re-allocation also applies to the 2022 results.

Table A.2 provides the historical energy consumption and GHG emissions of total global shipping which are used as input data for the current analysis. The 2022 emissions are about 0.5 percent above 2018, which is slightly lower compared to Smith and Francis (2024b). This difference can be explained by differences in scope as this study focuses on the total fleet, while Smith and Francis (2024b) reports results for international shipping only.

Table A.2 Historical baseline of CE-Ship

	2008	2018	2022
Energy consumption (TJ)	15,712,391	13,984,028	14,039,353
TTW CO_2 GHG emissions (Mton CO_2)	1,186	1,055	1,058
WTW GHG emissions (Mton CO_2eq)	1,435	1,277	1,282

Source: World Bank.

The emission factors used to convert between fuels and GHG emissions are listed in Table A.3. The fuel share as a share of energy use is assumed to be the same as the Fourth IMO GHG Study in the baseline year. Recent data from Clarksons show no major changes in the fuel mix of fuel oil, gas oil and LNG between 2018 and 2022 (Gordon 2023). The fuel mix is kept constant in the projection in order to isolate the effects of energy efficiency measures.

Table A.3 Emission factors for various fuels

	WTT (g CO_2eq/MJ)	TTW (g CO_2eq/MJ)	WTW (g CO_2eq/MJ)	Source
Heavy Fuel Oil (HFO)	13.5	78.24	91.74	(European Union, 2023)
Low Fuel Oil (LFO)	13.2	78.19	91.39	(European Union, 2023)
Marine Gas Oil/Diesel Oil (MGO/MDO)	14.4	76.37	90.77	(European Union, 2023)
Liquefied Natural Gas (LNG)*	18.5	70.70	89.20	(European Union, 2023)

Source: European Union (2023). * Otto dual fuel medium speed (one of the commonly used engines for LNG).

2008 GHG emissions

The IMO GHG reduction targets are set relative to 2008. It is therefore important to correctly identify the level of emissions in that year. This study is based on the tank-to-wake 2008 international emissions estimates of 1,135 MT from the Third IMO GHG Study (IMO 2014), which the Revised IMO Strategy is also anchored to. Given that the scope of the fleet is global shipping, the ratio of 2008 international GHG emissions to 2018 international emissions is applied to estimate the global shipping emissions in 2008,[22] where 2018 emissions are about 89 percent of 2008 emissions.

For the allocation of total 2008 GHG emissions to the ship type and size segments, the split to fleet segments from the Third IMO GHG Study (IMO 2014) for 2008 is applied. The Fourth IMO GHG Study provides estimates for the carbon and energy efficiency for 2008 for bulkers, containers and tankers as well as the total fleet. To account of differences in scope between CE-Ship and Fourth IMO GHG study intensities, the relative developments between 2008 and 2018 of carbon and energy efficiency from the Fourth IMO GHG study are applied to the 2018 baseline of CE-ship model.

Fleet transport activity and composition

Transport demand is a major driver of GHG emissions. Projection paths for transport demand can vary significantly depending on economic and political circumstances. Two default BAU scenarios are applied that provide a reasonable range of possible outcomes, the highest (SSP2-RCP2.6-L) and lowest (OECD-RCP2.6-G) transport demand corresponding to a global temperature increase below 2°C by 2100 (see Table A.4).

[22] The Fourth IMO GHG Study provides a rounded estimate of 2018 international GHG emissions. The model uses the exact figure of 1,006 MT.

Transport demand for most categories is increasing, with the exception of coal and oil where there is less transport foreseen due to the energy transition required to meet climate targets.

Table A.4 Transport demand by type of goods (billion ton nautical-miles)

	2008	2018	2022	Low growth scenario (OECD-RCP2.6-G)			High growth scenario (SSP2-RCP2.6-L)		
				2030	2040	2050	2030	2040	2050
Coal	3,352	5,226	5,134	3,439	1,953	2,312	3,619	2,121	2,550
Non-coal	14,689	22,590	23,706	29,602	36,224	42,396	32,939	44,439	56,269
Oil	11,737	13,719	13,364	13,258	12,358	9,113	13,370	12,521	9,247
Chemicals	862	1,410	1,559	1,903	2,295	2,666	2,280	3,403	4,860
Gas	963	1,852	2,380	2,850	3,578	4,031	3,393	4,836	5,802
Containers	6,086	8,447	8,537	10,459	12,468	14,235	11,855	15,867	19,952
Other unitized cargo	3,489	4,657	4,801	5,774	6,889	7,912	5,225	4,984	3,951
Total	**41,178**	**57,901**	**59,481**	**67,285**	**75,765**	**82,665**	**72,681**	**88,171**	**102,631**

Source: Clarksons Research (ongoing), Faber and others (2020). The CE-ship model includes the baseline and transport demand of all ship types, thus also for 'other' (passenger ships) and 'miscellaneous' (for example work at sea, recreational vessels). However, only ship types with cargo are in the scope for transport demand for this study.

Energy efficiency measure classification and uptake assumptions

Table A.5 lists the technical and operational measures included in the quantitative model CE-Ship. Individual measures are grouped according to type, and mutually exclusive measures are grouped together. Table A.6 shows uptake of each group of measures at ship and fleet level. Fleet level uptake shows uptake for the subset of vessels that are eligible for the measure.

Table A.5 Energy efficiency measure classification

Measure name	Group number	Measure group	Type
Main engine tuning	1	Main engine improvements	Technical
Common rail upgrade	1	Main engine improvements	Technical
Electronic engine control	1	Main engine improvements	Technical
Frequency converters	2	Auxiliary systems	Technical
Speed control pumps and fans	2	Auxiliary systems	Technical
Steam plant operation improvements	3	Steam plant improvements	Technical
Waste heat recovery	4	Waste heat recovery	Technical
Exhaust gas boilers on auxiliary engines	4	Waste heat recovery	Technical
Propeller-rudder upgrade	5	Propeller improvements	Operational
Propeller upgrade (nozzle, tip winglet)	5	Propeller improvements	Operational
Propeller Boss Cap Fins	5	Propeller improvements	Operational
Contra-rotating propeller	5	Propeller improvements	Technical
Propeller performance monitoring	6	Propeller maintenance	Operational
Propeller polishing	6	Propeller maintenance	Operational
Air lubrication	7	Air lubrication	Technical
Low-friction hull coating	8	Hull coating	Operational
Hull performance monitoring	9	Hull maintenance	Operational
Hull brushing	9	Hull maintenance	Operational
Hull hydro blasting	9	Hull maintenance	Operational
Dry-dock full blast (old ships)	9	Hull maintenance	Operational
Optimization water flow hull openings	10	Optimization of water flow hull openings	Technical
Super light ship	11	Super light ships	Technical
Reduced auxiliary power usage (low energy lighting etc.)	12	Reduced auxiliary power demand	Technical
Wind-assisted propulsion (kite)	13	Wind-assisted propulsion	Technical
Wind-assisted propulsion (hard sails)	13	Wind-assisted propulsion	Technical

Measure name	Group number	Measure group	Type
Wind-assisted propulsion (suction wings)	13	Wind-assisted propulsion	Technical
Wind-assisted propulsion (Flettner rotor)	13	Wind-assisted propulsion	Technical
Solar panels	14	Solar panels	Technical
Speed reduction 10%	15	Speed reduction	Operational
Speed reduction 20%	15	Speed reduction	Operational
Speed reduction 30%	15	Speed reduction	Operational

Source: World Bank.

Table A.6 Summary of abatement technologies and modelled uptake

Group	Average abatement potential, ship level (%)	Uptake (%)			
		2022	2030	2040	2050
Group 1 Main engine improvements	2.2	14	90	95	100
Group 2 Auxiliary systems	2.2	14	90	95	100
Group 3 Steam plant improvements	2.6	14	90	95	100
Group 4 Waste heat recovery	4.6	14	90	95	100
Group 5 Propeller improvements	4.6	14	90	95	100
Group 6 Propeller maintenance	6.3	14	90	95	100
Group 7 Air lubrication	6.0	0.3	5	53	100
Group 8 Hull coating	2.5	14	90	95	100
Group 9 Hull maintenance	4.9	14	90	95	100
Group 10 Optimization of water flow hull openings	2.7	14	90	95	100
Group 11 Super light ships	0.5	0.3	5	53	100

Group	Average abatement potential, ship level (%)	Uptake (%)			
		2022	2030	2040	2050
Group 12 Reduced auxiliary power demand	0.7	14	90	95	100
Group 13 Wind-assisted propulsion	4.0	0.3	5	53	100
Group 14 Solar panels	0.4	0.3	5	53	100
Group 15 Speed reduction*	Up to 28% depending on speed reduction level	n/a	90	95	100

*Speed reduction is measured at fleet level.
Source: World Bank.

Appendix B: Model Calculations

Fleet composition

The model distributes the transport work of goods over ship types based on developments in the average size of ships[23] (DWT) and average productivity (ton-miles per DWT) by ship type based on the following steps:

- Average productivity is calculated by mapping the ship types and their total fleet capacity (DWT) to the base year ton-mile demand. Average productivity is assumed to remain equal to the base year
- Required fleet capacity by ship type (DWT) for future years is estimated using the productivity (ton-miles per DWT) and the demand by type of good (ton-miles), assuming that demand equals supply
- Capacity by ship type (DWT) is allocated to size bins based on the historical share of the capacity per ship type and expected future developments in average size
- Transport demand by ship type and size bin (ton-miles) is derived from each category's capacity (thousand DWT) and the productivity (ton-miles per DWT)
- Number of ships by ship type and size bin is derived from the capacity (thousand DWT) by ship type and size bin and the average size in the base year (DWT).

Energy use and GHG emissions

The calculations module estimates GHG emissions from the fleet by combining energy use with emission factors. Results are provided by ship type and size category in five-year intervals.

Energy use per ship type and size bin is equal to the energy use in the base year multiplied by the efficiency improvement or total energy efficiency factor (percentage energy use per ton-nautical-miles (tnm) relative to the base time period). The total energy efficiency factor is a weighted average of the energy efficiency factor of existing vessels and the energy efficiency factor of newbuild ships.

The energy efficiency factor per ship type and size bin for existing vessels is calculated from the previous time step's energy efficiency factor multiplied by the current period's energy efficiency factor. The energy efficiency factor in the current time period chooses the highest efficiency improvement between the energy efficiency in the BAU scenario and the energy efficiency in the abatement scenario. The energy efficiency factor in the abatement scenarios is the product of the fleet level abatement potential of each applicable measure.

Energy efficiency in the BAU scenario considers the EEXI policy for existing ships and the EEDI for newbuilds. Data on specific measures used to meet current IMO policies is not known, but it is

[23] See the Background chapter for assumptions on the development of average size per ship type.

estimated that most ships will meet EEXI targets with little or no adjustments (UNCTAD 2021). Estimates for emission reductions range between 0-4 percent (Rutherford and others 2020) and 6 percent (NAPA 2021) depending on ship characteristics. The estimate from NAPA (2021) are used for the EEXI policy as they better match the CE-ship approach at the ship level. The required technical efficiency reductions from the EEDI Phase 2 and 3 are considered for newbuilds in the projected time period.

The energy efficiency factor for newbuild ships is calculated in a similar way to the existing fleet but contains technology, operational, and policy measures (i.e., the EEDI) only applicable to newbuild ships.

Total GHG emissions are calculated by aggregating the energy use per fuel (TJ/year) times its corresponding emission factor (gram CO_2/TJ) across all fuel types. Table A.3 is used for the GHG emissions factors including WTW scope.

Speed reduction

Reducing speed lowers energy consumption nonlinearly, as the main engine energy savings are approximated to scale with the cube of speed reduction (GloMEEP, ongoing). For example, a 10 percent speed reduction reduces main engine energy consumption by 27 percent per unit of time. However, to maintain the same amount of transport demand, the travel time increases inversely with speed reduction, so an 11 percent increase in total time is required to cover the same distance at 10 percent lower speed. Hence, more time at sea is required while, in principle, the time required in port to unload or load cargo remains the same.

The modeling in this study does not consider the possibility of improving the productivity of the fleet by reducing slack in the system (for example, by reducing time waiting in port through measures like JIT Arrival). Therefore, more ships are assumed to be needed to fulfil the same demand. Thus, a 10 percent speed reduction reduces the energy consumption of the main engine by 19 percent when considering the required increase of the fleet.

Total energy consumption includes consumption from the main engine, auxiliary engine, and boilers. Energy consumption of the main engine reduces at lower speeds, while increases in the energy consumption of the auxiliary engine and boiler are proportional to the extra time at sea. The energy consumption of auxiliary engine differs between ship types, impacting the potential for speed reduction between ship types. Furthermore, the baseline sailing speeds are important as these influence the ratio of energy consumption for propulsion engines and auxiliary engines. On average, auxiliary engines account for about 30 percent of total fuel consumption on tankers, whereas on bulkers and container ships, this figure is approximately 15 percent. Table B.1 shows the difference in the emission reduction potential when the average auxiliary engine and boiler consumption is incorporated. The GHG reduction potential is significantly larger for 30 percent speed reduction compared to 10 percent. This is especially the case for vessels with less auxiliary engine consumption.

The example shown in Table B.1 is shown for a vessel that spends 25 percent of its time in port.[24] A speed reduction of 10 percent would lead to an increase of ~30 days at sea. To meet the same amount of transport work (and therefore the same number of days in port), the vessel would need

[24] Port time includes time waiting outside the port at anchorage. Most vessels spend about 25 to 50 percent of their total operating time in port.

395 days. Both sea and port days are therefore scaled down to be constrained to 365 days in a year, reducing port days by 8 percent. This means the fleet must expand by 8 percent to meet demand. This adjustment is applied to determine the fleet size over each five-year period.[25]

Table B.1 Example calculation for speed reduction

	Tanker		Bulker/Container	
Speed reduction level	**10%**	**30%**	**10%**	**30%**
GHG reduction main engine	27%	66%	27%	66%
Extra days/time required at sea	11%	43%	11%	43%
Main engine GHG reduction considering growth in fleet	19%	51%	19%	51%
AE & boiler consumption at sea per day	30%	30%	15%	15%
Total GHG reduction without growth in fleet	16%	33%	22%	49%
GHG reduction with growth in fleet	10%	23%	15%	37%

Source: World Bank.

The costs for speed reduction are based on the data used in the Fourth IMO GHG Study (Faber and others 2020), which includes the cost of new ships from increasing the fleet. This assumes that shipowners are owner operators, a simplifying assumption that excludes cases where the operator of the vessel is not the owner. In such cases, the cost of slow steaming would reflect the time charter rate which could be different to the equivalent cost of the ship due to freight market volatility. The opportunity costs of slow steaming also do not include inventory costs for the cargo owner.

CAPEX and OPEX

The CAPEX and OPEX have been estimated for each measure by ship type and size bin. The annual investment cost of each abatement technology is calculated by annuitizing the capital expenditures considering a fixed lifetime of 25 years for technical measures. For certain operational measures with a shorter lifespan such as hull maintenance, the depreciation period is either 1, 5, 10 or 15 years. The OPEX consists of annual incremental recurring costs and fuel costs. Annual incremental recurring costs include maintenance and operational costs other than fuel.

For the CAPEX of innovative technologies, a moderate or high-cost reduction is applied to reflect learning effects. A cost reduction of 20 percent in 2030 and 30 percent in 2050 is assumed for a moderate cost reduction, while for a high-cost reduction, a cost reduction of 50 percent in 2030 and 60 percent in 2050 is applied.

Fuel costs are based on the energy reduction potential (in percentage), the fuel type, the baseline fuel consumption, and fuel price.

[25] The model CE-Ship uses five-year periods to model GHG emissions.

Appendix C: Model Results

GHG emission abatement potential

Table C.1 provides the detailed results of the GHG emissions abatement potential relative to 2008 underlying Figure 2.4. Table C.2 provides these results relative to BAU. Table C.3, Table C.4 and Table C.5 provide further emissions and emissions intensity breakdowns per fleet segment.

Table C.1 Detailed GHG emissions abatement potential towards 2050 per contributor relative to 2008

		Low demand growth OECD-RCP2.6-G			High demand growth SSP2-RCP2.6-L		
		2030	2040	2050	2030	2040	2050
10% speed reduction	**Total GHG reduction potential relative to 2008**	**27%**	**27%**	**27%**	**23%**	**18%**	**13%**
	Overall reduction 2008-2018	11%	11%	11%	11%	11%	11%
	Overall reduction 2018-2022	0%	0%	0%	0%	0%	0%
	Reduction from speed reduction (>2022)	5%	5%	5%	5%	6%	7%
	Reduction from other operational measures (>2022)	9%	10%	11%	10%	11%	13%
	Reduction from wind propulsion (>2022)	0%	1%	2%	0%	1%	2%
	Reduction from other technical measures (>2022)	7%	9%	11%	8%	10%	13%
	Extra GHG emissions due to BAU (>2022)	-5%	-8%	-12%	-11%	-21%	-33%
30% speed reduction	**Total GHG reduction potential relative to 2008**	**39%**	**40%**	**42%**	**36%**	**34%**	**32%**
	Overall reduction 2008-2018	11%	11%	11%	11%	11%	11%
	Overall reduction 2018-2022	0%	0%	0%	0%	0%	0%
	Reduction from speed reduction (>2022)	14%	15%	16%	15%	17%	20%
	Reduction from other operational measures (>2022)	11%	12%	13%	12%	14%	16%
	Reduction from wind propulsion (>2022)	0%	1%	2%	0%	1%	3%
	Reduction from other technical measures (>2022)	8%	10%	12%	9%	11%	15%
	Extra GHG emissions due to BAU (>2022)	-5%	-8%	-12%	-11%	-21%	-33%

Source: World Bank.

Table C.2 Detailed GHG emission abatement potential for the total fleet per contributor relative to BAU

		Low demand growth OECD-RCP2.6-G			High demand growth SSP2-RCP2.6-L		
		2030	2040	2050	2030	2040	2050
10% speed reduction	**Total GHG reduction potential relative to BAU**	**23%**	**25%**	**28%**	**23%**	**26%**	**29%**
	Reduction from speed reduction	5%	5%	6%	5%	6%	6%
	Reduction from other operational measures	10%	10%	11%	10%	11%	12%
	Reduction from wind-assisted ship propulsion	0%	1%	2%	0%	1%	2%
	Reduction from other technical measures	8%	8%	9%	8%	8%	10%
30% speed reduction	**Total GHG reduction potential relative to BAU**	**35%**	**39%**	**42%**	**36%**	**40%**	**44%**
	Reduction from speed reduction	15%	16%	17%	15%	17%	18%
	Reduction from other operational measures	12%	12%	13%	12%	13%	14%
	Reduction from wind-assisted ship propulsion	0%	1%	2%	0%	1%	3%
	Reduction from other technical measures	8%	9%	10%	9%	9%	10%

Source: World Bank.

Table C.3 Detailed GHG emissions of abatement scenarios for fleet segments relative to BAU

Fleet	Speed reduction relative to 2022	Low demand growth OECD-RCP2.6-G			High demand growth SSP2-RCP2.6-L		
		2030	2040	2050	2030	2040	2050
Total global fleet	10% speed reduction	-23%	-25%	-28%	-23%	-26%	-29%
	30% speed reduction	-35%	-39%	-42%	-36%	-40%	-44%
Bulk carriers	10% speed reduction	-29%	-31%	-35%	-29%	-31%	-35%
	30% speed reduction	-50%	-53%	-57%	-50%	-53%	-57%
Tankers	10% speed reduction	-24%	-27%	-31%	-25%	-28%	-31%
	30% speed reduction	-36%	-40%	-44%	-36%	-40%	-44%
Containerships	10% speed reduction	-28%	-30%	-31%	-28%	-30%	-31%
	30% speed reduction	-47%	-50%	-53%	-47%	-50%	-53%

Source: World Bank.

Table C.4 Detailed GHG intensity of the abatement scenarios relative to 2008

Fleet	Speed reduction relative to 2022	Low demand growth OECD-RCP2.6-G			High demand growth SSP2-RCP2.6-L		
		2030	2040	2050	2030	2040	2050
Total global fleet	10% speed reduction	-53%	-58%	-61%	-53%	-58%	-61%
	30% speed reduction	-63%	-67%	-71%	-63%	-68%	-71%
Bulk carriers	10% speed reduction	-59%	-64%	-67%	-59%	-64%	-67%
	30% speed reduction	-71%	-76%	-78%	-71%	-76%	-78%
Tankers	10% speed reduction	-42%	-44%	-41%	-40%	-40%	-33%
	30% speed reduction	-51%	-53%	-52%	-49%	-50%	-46%
Containerships	10% speed reduction	-52%	-59%	-62%	-53%	-59%	-62%
	30% speed reduction	-65%	-71%	-74%	-66%	-71%	-74%

Source: World Bank.

Table C.5 Detailed GHG intensity of the abatement scenarios relative to BAU

Fleet	Speed reduction relative to 2022	Low demand growth OECD-RCP2.6-G			High demand growth SSP2-RCP2.6-L		
		2030	2040	2050	2030	2040	2050
Total global fleet	10% speed reduction	-26%	-29%	-32%	-26%	-29%	-32%
	30% speed reduction	-42%	-45%	-49%	-42%	-45%	-50%
Bulk carriers	10% speed reduction	-29%	-31%	-35%	-29%	-31%	-35%
	30% speed reduction	-50%	-53%	-57%	-50%	-53%	-57%
Tankers	10% speed reduction	-24%	-27%	-31%	-25%	-28%	-31%
	30% speed reduction	-36%	-40%	-44%	-36%	-40%	-44%
Containerships	10% speed reduction	-28%	-30%	-31%	-28%	-30%	-31%
	30% speed reduction	-47%	-50%	-53%	-47%	-50%	-53%

Source: World Bank.

Marginal abatement cost tables

This section evaluates the cost-effectiveness of individual measures in 2030, 2040, and 2050, across the total fleet and specific segments (bulk carriers, container ships and tankers). The cost-effectiveness is measured by calculating the marginal abatement cost, expressed in USD per ton of CO_2eq or USD per gigajoule. The latter can be interpreted as the cost per unit of energy saved. A measure is considered cost-effective when it is zero or negative, because it does not add any net cost. In cases where annual CAPEX and OPEX exceed the fuel costs savings, a measure is not cost-effective (for example, the USD per ton CO_2eq is positive).

The cost-effectiveness of energy efficiency measures is influenced by fuel prices (see Table C.6 for the baseline fossil fuel prices and the e-ammonia price used for the green ammonia scenario). While the amount of fuel saved by a measure remains constant, the monetary savings increase when fuel prices are higher. A sensitivity analysis was conducted by varying fuel prices as follows:

- 50 percent of the fossil fuel price;
- 200 percent of the fossil fuel price; and
- the fuel price of green ammonia.[26]

[26] Only the measures that yield the highest reduction potential within their own category are included. Here, these measures are shown in order of their cost-effectiveness.

Table C.6 Fuel price inputs for sensitivity analysis

Fuel type	Fuel cost (USD/GJ)			Fuel cost (USD/ton)		
	2030	2040	2050	2030	2040	2050
HFO	10.5	9.5	8.5	425	385	344
VLSFO/MGO	18.2	18.2	18.2	615	559	500
LNG	10.3	10.2	10.1	506	501	496
Fossil average mix	12.8	12.5	12.2	486	442	397
E-ammonia	46.5	39.1	31.2	865	727	580

Source: DNV (2024a).

In all sensitivity analyses, the energy saving potential per individual energy efficiency measure is assessed on a ship level[27] and therefore the effects of uptake and fleet composition are not included.

In general, the higher the fuel price, the more cost-effective the energy efficiency measure becomes. The relative difference per measure differs as there are different ratios in CAPEX, OPEX and fuel costs. The expected green ammonia fuel prices are higher in the future compared to fossil fuel prices, which makes abatement measures more cost efficient.

[27] The exception is speed reduction, which is shown at the fleet level.

Table C.7 Abatement potential and cost effectiveness for the total fleet in 2030, for standard fossil fuel and green ammonia prices

Measure	MAC (USD/Ton WTW GHG)			MAC (USD/GJ)	
	50% of fossil fuel price	100% of fossil fuel price	200% of fossil fuel price	Fossil fuel	Ammonia
Optimization of water flow hull openings	-74	-156	-318	-12	-46
Steam plant improvements	-61	-145	-313	-11	-45
Wind-assisted propulsion	-25	-117	-302	-9	-51
Hull maintenance	-36	-117	-280	-9	-43
Propeller maintenance	-34	-115	-277	-9	-43
Hull coating	32	-50	-212	-4	-38
Auxiliary systems	45	-36	-199	-3	-37
Reduced auxiliary power demand	46	-35	-198	-3	-37
Propeller improvements	68	-14	-176	-1	-35
Main engine improvements	90	9	-154	1	-34
Speed reduction*	161	81	-78	6	-28
Air lubrication	210	129	-34	10	-25
Waste heat recovery	456	375	212	28	-6
Super light ships	496	393	189	30	-1
Solar panels	1458	1377	1215	105	70

*Speed reduction results are provided at fleet level.
Source: World Bank.

Table C.8 Abatement potential and cost effectiveness for the total fleet in 2040, assuming standard fossil fuel prices

Technology group	MAC (USD/Ton WTW GHG)	MAC (USD/GJ)	Abatement potential (Ship level)
Optimization of water flow hull openings	-146	-11	2.7%
Steam plant improvements	-137	-10	2.6%
Hull maintenance	-108	-8	4.9%
Wind-assisted propulsion	-107	-8	4.0%
Propeller maintenance	-105	-1	4.6%
Hull coating	-40	-3	2.5%
Auxiliary systems	-27	-2	2.2%
Reduced auxiliary power demand	-26	-2	0.7%
Propeller improvements	-10	-1	6.3%
Main engine improvements	18	1	2.2%
Speed reduction*	91	7	27.6%
Air lubrication	130	10	6.0%
Waste heat recovery	353	27	4.6%
Super light ships	398	30	0.5%
Solar panels	1,290	98	0.4%

*Speed reduction results are provided at fleet level.
Source: World Bank.

Table C.9 Abatement potential and cost effectiveness for the total fleet in 2050, for standard fossil fuel and ammonia prices

Technology group	MAC (USD/GJ) (Fossil fuel)	MAC (USD/GJ) (Ammonia)	Abatement potential (Ship level)
Optimization of water flow hull openings	-10	-31	2.7%
Steam plant improvements	-9	-29	2.6%
Wind-assisted propulsion	-7	-33	4.0%
Hull maintenance	-7	-28	4.9%
Propeller maintenance	-7	-28	4.6%
Hull coating	-2	-23	2.5%
Auxiliary systems	-1	-22	2.2%
Reduced auxiliary power demand	-1	-22	0.7%
Propeller improvements	0	-21	6.3%
Main engine improvements	2	-18	2.2%
Speed reduction*	8	-13	27.6%
Air lubrication	10	-11	6.0%
Waste heat recovery	25	5	4.6%
Super light ships	30	14	0.5%
Solar panels	92	71	0.4%

*Speed reduction results are provided at fleet level.
Source: World Bank.

Table C.10 Abatement potential and cost effectiveness for the container fleet in 2030, assuming standard fossil fuel and ammonia prices

Measure name	MAC (USD/Ton WTW GHG) (Fossil fuel)	MAC (USD/GJ) (Fossil fuel)	MAC (USD/GJ) (Ammonia)	Abatement potential (Ship level)
Optimization water flow hull openings	-140	-11	-46	3.0%
Hull hydro blasting	-121	-9	-44	5.5%
Reduced auxiliary power usage (low energy lighting etc.)	-118	-9	-44	0.7%
Contra-rotating propeller	-92	-7	-42	6.6%
Propeller performance monitoring	-91	-7	-42	5.3%
Electronic engine control	-88	-7	-42	2.5%
Speed reduction 30%*	-74	-6	-41	41.7%
Air lubrication	-69	-5	-40	5.5%
Low-friction hull coating	-69	-5	-40	2.9%
Frequency converters	-47	-4	-39	3.0%
Waste heat recovery	57	4	-31	6.4%

*Speed reduction results are provided at fleet level.
Source: World Bank.

Table C.11 Abatement potential and cost effectiveness for the tanker fleet in 2030, assuming standard fossil fuel and ammonia prices

Measure name	MAC (USD/Ton WTW GHG) (Fossil fuel)	MAC (USD/GJ) (Fossil fuel)	MAC (USD/GJ) (Ammonia)	Abatement potential (Ship level)
Optimization water flow hull openings	-164	-12	-46	3.0%
Steam plant operation improvements	-145	-11	-45	8.4%
Propeller performance monitoring	-134	-10	-44	5.3%
Hull hydro blasting	-119	-9	-43	5.5%
Low-friction hull coating	-69	-5	-39	2.8%
Reduced auxiliary power usage (low energy lighting etc.)	-59	-4	-38	0.9%
Frequency converters	-50	-4	-38	2.2%
Contra-rotating propeller	-20	-1	-35	5.9%
Electronic engine control	-18	-1	-35	2.5%
Wind-assisted propulsion (hard sails)	31	2	-31	2.3%
Air lubrication	66	5	-29	7.0%
Speed reduction 30% *	258	20	-14	25.9%
Waste heat recovery	333	25	-9	4.7%
Solar panels	1,102	84	49	0.8%

*Speed reduction results are provided at fleet level.
Source: World Bank.

Table C.12 Abatement potential and cost effectiveness for the bulk carrier fleet in 2030, assuming standard fossil fuel and ammonia prices

Measure name	MAC (USD/Ton WTW GHG) (Fossil fuel)	MAC (USD/GJ) (Fossil fuel)	MAC (USD/GJ) (Ammonia)	Abatement potential (Ship level)
Optimization water flow hull openings	-136	-10	-46	3.0%
Wind-assisted propulsion (Flettner rotor)	-112	-9	-44	13.8%
Propeller performance monitoring	-91	-7	-42	5.3%
Hull hydro blasting	-76	-6	-41	5.5%
Contra-rotating propeller	-68	-5	-41	9.4%
Speed reduction 30%*	-36	-3	-38	46.0%
Air lubrication	-27	-2	-38	9.1%
Reduced auxiliary power usage (low energy lighting etc.)	-27	-2	-38	0.5%
Frequency converters	-14	-1	-37	2.1%
Electronic engine control	-11	-1	-36	2.5%
Low-friction hull coating	40	3	-32	2.8%
Waste heat recovery	365	28	-8	4.4%
Solar panels	1,650	127	91	0.3%

*Speed reduction results are provided at fleet level.
Source: World Bank.

Appendix D: Literature Review on Energy Saving Measures

Table D.1 Literature review on technical measures

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Air Lubrication	Air Lubrication	Air Bubble	Model	Net Power		2	5	Bulk Carrier, Chemical Tanker, Container, General Cargo, Oil Tanker		Kim and Steen (2023)
Air Lubrication	Air Lubrication	Air Layer	Model	Net Power		8	14	Bulk Carrier, Chemical Tanker, Container, General Cargo, Oil Tanker		Kim and Steen (2023)
Air Lubrication	Air Lubrication	Air Cavity	Model	Net Power		16	22	Bulk Carrier, Chemical Tanker, Container, General Cargo, Oil Tanker		Kim and Steen (2023)
Air Lubrication	Air Lubrication	Air Cavity	Model	Fuel		5	15	Bulk Carrier, Liquefied Gas Tanker, Oil Tanker		IMaREST (2011)
Air Lubrication	Air Lubrication	Air Cavity	Model	Fuel		5	9	Container		IMaREST (2011)
Air Lubrication	Air Lubrication	Air Layer	Model	Net Power		5	6	Bulk Carrier	66,000	Jang and others (2014)
Air Lubrication	Air Lubrication	Air Bubble	Model	Fuel		3.4	11.8	Bulk Carrier	91,867	ICCT (2019)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Fuel		3	5	Bulk Carrier	91,867	SeaJapan (2014)

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Air Lubrication	Air Lubrication	Air Bubble	Model	Fuel		3	8	Bulk Carrier	91,867	ICCT (2019)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Net Power		5	10	Bulk Carrier		Hoang and others (2009)
Air Lubrication	Air Lubrication	Air Layer, Air Cavity	Model	Net Fuel		10	20	Bulk Carrier		Makiharju, Perlin, and Ceccio (2012)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Net Power	4.5	4		Chemical Tanker	40,000	Silberschmidt and others (2016)
Air Lubrication	Air Lubrication	Air Cavity	Model	Net Power			20	Container		Butterworth and others (2015)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Net Fuel	5	5		Cruise	115,875	Silverstream (2018)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Net Power	2			Ferry		Hoang and others (2009)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Net Power	6			Ferry		Hoang and others (2009)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Fuel	16			Ferry-Pax Only		Kumagai and others (2015)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Fuel	5			Ferry-Ropax	3,800	Mitsubishi (2012)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Fuel	9			Ferry-Ropax		Kumagai and others (2015)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Power	10			General Cargo	2,950	Kumagai and others (2015)
Air Lubrication	Air Lubrication	Air Layer	Sea Trial	Net Fuel		7	10	General Cargo	2,300	AlfaLaval (2024)

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Air Lubrication	Air Lubrication	Air Bubble	Model	Fuel		12.3	13	General Cargo	14,538	ICCT (2019)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Power	10			Heavy Load Carrier	19,818	Kawakita and others (2015)
Air Lubrication	Air Lubrication	Air Layer	Sea Trial	Net Power	4.5			Liquefied Gas Tanker	180,000	Lee and others (2017)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Net Fuel	6.6			Liquefied Gas Tanker	170,000	Riviera (2021)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Fuel	4			Miscellaneous - Fishing		Kumagai and others (2015)
Air Lubrication	Air Lubrication	Air Cavity	Sea Trial	Power			15	Miscellaneous - Other		Foeth (2011)
Air Lubrication	Air Lubrication	Air Bubble, Air Layer, Air Cavity	Model	Net Power		3	10	Miscellaneous - Other		ABS (2019)
Air Lubrication	Air Lubrication	Air Layer	Sea Trial	Power	8.8			Miscellaneous - Other		Lee and others (2017)
Air Lubrication	Air Lubrication	Air Bubble	Sea Trial	Net Power		8	12	Ro-Ro		Mizokami and others (2010)
Propeller Improvements	Contra-Rotating Propeller	CRP-Pod	Sea Trial	Fuel	13			Ferry-Ropax	34,181	Ueda and others (2004)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel		0.5	5	Container, Ro-Ro		GLOMEEP (2018)

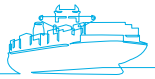
Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel		3	10	Bulk Carrier, Chemical Tanker, Container, Cruise, Ferry-Pax Only, Ferry-Ropax, General Cargo, Liquefied Gas Tanker, Oil Tanker, Other Liquids Tankers, Refrigerated Bulk, Ro-Ro		ABS (2013)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel			12	Bulk Carrier, Chemical Tanker, Container, Cruise, Ferry-Pax Only, Ferry-Ropax, Liquefied Gas Tanker, Offshore, Oil Tanker, Other Liquids Tankers, Refrigerated Bulk, Ro-Ro		OECD (2009)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel	8.8			Miscellaneous - Other		Kravitz (2011)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel		7	10	Bulk Carrier	97,000	Seatrade-Maritime (2014)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel		9.2	11.7	Bulk Carrier	27,690	Tadros (2022)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel		5.2	6.2	Bulk Carrier	27,690	Tadros (2022)
Propeller Improvements	Contra-Rotating Propeller	CRP-Pod	Sea Trial	Fuel	15.6			Ferry-Ropax	5,681	gCaptain (2014)

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel			12	Container		Tupper and others (2013)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Fuel	8			Container		van Kluijven and others (2017)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Power	13	6	20	Container, Ro-Ro		Brunvoll (2015)
Propeller Improvements	Contra-Rotating Propeller	CRP	Model	Power		3	6	Container, Ro-Ro		IMO (2009)
Propeller Improvements	Contra-Rotating Propeller	CRP	Sea Trial	Power		10	17	Ro-Ro		Nakamura and others (1991)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Literature Review	Fuel		5	15	Bulk Carrier, Chemical Tanker, Container, Oil Tanker		Deng and others (2020)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Literature Review	Fuel		7.6	9.7	Bulk Carrier	75,000	Mondejar and others (2018)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Literature Review	Fuel		6.5	8.4	Chemical Tanker, Oil Tanker	50,000	Mondejar and others (2018)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel		5.9	7.8	Container	4,500	Mondejar and others (2018)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Literature Review	Fuel		10	15	Bulk Carrier, Chemical Tanker, Container, Oil Tanker		Mondejar and others (2018)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel		4	16	Chemical Tanker, Oil Tanker	47,000	Baldi (2015)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel	5	5.4	5.9	N/A		Lion and others (2019)

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel			8	Bulk Carrier	98,000	Lindstad and others (2015)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel			8	General Cargo	7,000	Lindstad and others (2015)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel			8	Container	77,000	Lindstad and others (2015)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel			8	Refrigerated Bulk	7,000	Lindstad and others (2015)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel			8	Ro-Ro	11,000	Lindstad and others (2015)
Waste Heat Recovery	Waste Heat Recovery	Organic Rankine Cycle	Model	Fuel			8	Vehicle	11,000	Lindstad and others (2015)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Sea Trial	Power	3.25	2	15	General Cargo	5,023	SSPA (2022)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Sea Trial	Fuel	6.1			Ro-Ro	9,700	Norsepower (2018)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Sea Trial	Fuel	4			Ferry		Norsepower (2018)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Sea Trial	Fuel	8.2			Tanker	10,9647	Maersk Tankers (2019)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Sea Trial	Fuel		20	25	Ro-Ro		Shipsmonthly (2024)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Sea Trial	Fuel	12.5			Bulk Carrier	64,000	Anemoi Marine (2018)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel	8			Bulk Carrier	324,230	MarineLink (2021)

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel		6.5	8.9	Oil Tanker	80,000	Lu & Ringsberg (2020)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel		8	12	Bulk Carrier	40,000	Lu & Ringsberg (2020)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Power		17	23	Bulk Carrier	90,000	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Power		5	7	Bulk Carrier	7,200	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Power		9	13	Oil Tanker	90,000	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Power		5	7	Oil Tanker	5,400	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel	10			Bulk Carrier	82,000	Anemoi Marine (2018)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel	8			Bulk Carrier	388,000	Anemoi Marine (2024)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel	12			Bulk Carrier	82,000	Anemoi Marine (2023)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Power		10	20	General Cargo	4,211	Eco Flettner (2019)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel		6	10	Bulk Carrier	200,000	Norsepower (2023)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel		8.3	47	General Cargo	10,020	Comer and others (2019)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel		1.6	9	Ro-Ro	9,700	Comer and others (2019)

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel		0.4	2.8	Ferry-Pax Only	2,800	Comer and others (2019)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel		1	6.6	General Cargo	4,250	Comer and others (2019)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel		1.8	4.7	Oil Tanker	109,647	Comer and others (2019)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Power		14	31	General Cargo	17,500	Bentin and others (2018)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	Fuel	14.5			Oil Tanker	312,622	Sarsila (2022)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Rotor Sails	Model	GHG emissions	10.8	0.797	34.9	Bulk Carrier	80,000	Mason and others (2023)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	Power		20	30	Bulk Carrier	180,000	Ouchi, Uzawa, Kanai, and Katori (2013)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Sea Trial	Fuel	6.5	5	17	Bulk Carrier	100,422	MOL (2024)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	Fuel		6.1	8.8	Oil Tanker	80,000	Lu & Ringsberg (2020)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	Power	15	7	22	Ferry-Ropax		Díaz (2020)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	Power		18	24	Bulk Carrier	90,000	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	Power		5	7	Bulk Carrier	7,200	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	Power		9	13	Tanker	90,000	CE Delft and others (2016)



Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	Power		5	8	Tanker	5,400	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	N/A			10	N/A		Viola, Sacher, Xu, & Wang (2015)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Sea Trial	Fuel			32	Bulk Carrier	80,962	MarineLog (2024)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Hard Sails	Model	Fuel		20	45	Ro-Ro		DNV (2022)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Soft Sails	Model	Fuel		15	33	Chemical Tanker	10,000	Smith and others (2013)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Soft Sails	Model	Power		21	35	General Cargo	17,500	Bentin and others (2018)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Soft Sails	Model	Fuel		4.2	5.6	Oil Tanker	80,000	Lu & Ringsberg (2020)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Fuel		10	15	Container		Misra-Godwin (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power	3			Ro-Ro	7,000	Traut, and others (2014)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power	24			Tanker	8,000	Traut, and others (2014)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power	32			General Cargo	5,500	Traut, and others (2014)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power	6			Bulk Carrier	50,000	Traut, and others (2014)

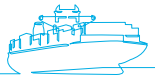
Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power	1			Container Ship	30,000	Traut, and others (2014)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power		5	9	Bulk Carrier	90,000	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power		9	14	Bulk Carrier	7,200	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power		3	4	Tanker	90,000	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power		9	15	Tanker	5,400	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power		2	4	Container Ship	1,000	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power		1	2	Container Ship	5,000	CE Delft and others (2016)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Fuel	9	4	13	Ferry-Ropax		Díaz (2020)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Kites	Model	Power		10	29	General Cargo	17,500	Bentin and others (2018)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Suction Wings	Sea Trial	Power		2	1.9	General Cargo		SSPA (2022a)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Suction Wings	Model	Fuel	10			General Cargo	6,477	Boomsma Shipping (2025)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Suction Wings	Sea Trial	Fuel	15		40	Chemical Tanker	49,000	Cyprus Shipping News (2025)

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Suction Wings	Model	Fuel	9.8			Liquefied Gas Tanker	17,000	Camps (2024)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Suction Wings	Model	Fuel	10			General Cargo	2,214	Bonner (2024)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Suction Wings	Sea Trial	Power		2	4	General Cargo	4,298	SSPA (2022)
Wind-Assisted Propulsion	Wind-Assisted Propulsion	Suction Wings	N/A	Fuel	4.5			General Cargo	2,528	Kołodziejski and Sosnowski (2025)

Source: World Bank.

Table D.2 Literature review on operational measures

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Operational	Weather Routing	Weather Routing	Model	Fuel		2	6	Container		Taskar and others (2023)
Operational	Weather Routing	Weather Routing	Model	Emissions		0.13	2.3	Container		Mason and others (2023)
Operational	Weather Routing	Weather Routing	Model	Fuel	5.6			Chemical Tanker		Wang and others (2021)
Operational	Weather Routing	Weather Routing	Model	Fuel				General Cargo	38,800	Sang and others (2023)
Operational	Weather Routing	Weather Routing	Model	Fuel			12	Container		Latinopoulos and others (2025)
Operational	Weather Routing	Weather Routing	Model	Fuel		1.33	1.59	Oil Tanker		Du and others (2022)
Operational	Weather Routing	Weather Routing	Model	Fuel		2	7	Dry Bulk Carrier		Yan and others (2020)
Operational	Weather Routing	Weather Routing	Literature Review	Fuel		1	10	N/A		Chen and others (2025)
Operational	Weather Routing	Weather Routing	Sea Trial	Fuel		2	5	N/A		DTN (2021)
Operational	Weather Routing	Weather Routing	Sea Trial	Emissions		1	4	N/A		DTN (2021)
Operational	Weather Routing	Weather Routing	Model	Fuel			10	N/A		IAMU (2015)
Operational	Weather Routing	Weather Routing	Model	Fuel		2	4	N/A		IAMU (2015)



Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Operational	Weather Routing	Weather Routing	Model	Emissions		0.1	3.7	Bulk Carrier, Container, Cruise, Ferry Ro-Pax, General Cargo, Oil Tanker, Ro-Ro, Vehicle		IMO (2009)
Operational	Weather Routing	Weather Routing	Sea Trial	Fuel	9			Liquefied Gas Tanker		SOFAR (2024)
Operational	Weather Routing	Weather Routing	Sea Trial	Fuel		4	8	N/A		SOFAR (2024)
Operational	Weather Routing	Weather Routing	Sea Trial	Fuel		5	7	Liquefied Gas Tanker		ABB (2024)
Operational	Weather Routing	Weather Routing	Model	Fuel		3	10	Bulk Carrier, Chemical Tanker, Container, Cruise, Liquefied Gas Tanker, Ro-Ro		DNV (2025)
Operational	JIT Arrival	JIT Arrival	Model	Emissions		7.45	21.64	Container		Marine Traffic (2022)
Operational	JIT Arrival	JIT Arrival	Model	Emissions		8.17	23.98	Container		Marine Traffic (2022)
Operational	JIT Arrival	JIT Arrival	Model	Emissions		4.9	17.88	Container		Marine Traffic (2022)
Operational	JIT Arrival	JIT Arrival	Model	Emissions		3.12	12.07	Container		Marine Traffic (2022)
Operational	JIT Arrival	JIT Arrival	Model	Emissions		4.03	14.44	Container		Marine Traffic (2022)
Operational	JIT Arrival	JIT Arrival	Model	Emissions		3.51	11.97	Container		Marine Traffic (2022)
Operational	JIT Arrival	JIT Arrival	Model	Emissions		3.35	10.13	Container		Marine Traffic (2022)

Technology group	Technology	Sub-tech	Savings derivation	Savings type	Average reported	Min reported	Max reported	Ship types	Size	Reference
Operational	JIT Arrival	JIT Arrival	Model	Emissions		2.52	8.67	Container		Marine Traffic (2022)
Operational	JIT Arrival	JIT Arrival	Model	Emissions		2.55	7.74	Container		Marine Traffic (2022)
Operational	JIT Arrival	JIT Arrival	Model	Fuel			21.1	Bulk Carrier, Oil Tanker		Sung, Zografakis, and Nielsen (2022)
Operational	JIT Arrival	JIT Arrival	Model	Fuel		4.68	15.31	Bulk Carrier, General Cargo, Liquified Gas Tanker, Oil Tanker		Merkel and others (2022)
Operational	JIT Arrival	JIT Arrival	Model	Fuel			19	Oil Tanker		Jia and others (2017)
Operational	JIT Arrival	JIT Arrival	Model	GHG emissions			10	Container		Smith and Francis (2024)
Operational	JIT Arrival	JIT Arrival	Model	GHG emissions			10	Bulk Carrier		Smith and Francis (2024)
Operational	JIT Arrival	JIT Arrival	Model	GHG emissions			25	Chemical Tanker		Smith and Francis (2024)
Operational	JIT Arrival	JIT Arrival	Model	GHG emissions			16	Liquified Gas Tanker		Smith and Francis (2024)
Operational	JIT Arrival	JIT Arrival	Model	GHG emissions			16	Oil Tanker		Smith and Francis (2024)
Operational	Onshore Power	Onshore Power	Model	GHG emissions	2.2	1	4.9	Bulk Carrier, Chemical Tanker, Container, Ferry-Pax Only, General Cargo, Liquefied Gas Tanker, Oil Tanker, Refrigerated Bulk, Ro-Ro, Vehicle		Marine Traffic (2022)

Source: World Bank.

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