Trade-offs in Meeting the MARPOL Annex VI Requirements with the Focus on Costs

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Maritime transport is considered the most energy-efficient and environmentally friendly way of transporting large volumes of goods. The environmental aspect of maritime transport is regulated by the MARPOL Convention, which now has six annexes dealing with various elements of pollution from ships. In this paper, the authors address air pollution from ships. Air pollution from ships is dealt with in the MARPOL Annex VI. Ocean-going ships emit climate-changing pollutants (greenhouse gases) and local pollutants that lead to cardiovascular and lung diseases and premature deaths. By transporting around 12 billion tons of cargo per year, maritime transport causes around 3% of all man-made greenhouse gas emissions, 13% of sulphur oxide emissions and 15% of nitrogen oxide emissions. As a result, maritime transport causes around 265,000 premature deaths worldwide. Without remedial actions, maritime transport emissions could increase by 130% by 2050 compared to 2008 levels; however, by 2025, new ships must be 30% more energy efficient than in 2014, and the maritime sector is gradually included in the Emissions Trading System (EU ETS) since 2024. Currently, many propulsion technologies can be installed in newbuilds, while the existing fleet can be retrofitted in various ways to meet the new regulations. It is also possible to use cleaner but more expensive fuel. However, current solutions cannot address all air pollutants simultaneously or at a reasonable cost, so compromises are needed. The aim of the paper is to explore different ways to reduce air emissions from maritime transport and express them in monetary terms, either in terms of capital, operating or voyage costs.

KEYWORDS
~ Maritime transport
~ Air pollution
~ MARPOL Annex VI
~ Costs

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doi: 10.7225/toms.v14.n02.s13

Received: 9 Mar 2025 / Revised: 14 Mar 2025 / Accepted: 21 Apr 2025 / Published: 20 Jul 2025

1. INTRODUCTION

Maritime transport is of crucial importance for world trade. Around 12 billion tonnes of freight are transported by sea every year, and each tonne travels an average of more than 5,000 nautical miles (UNCTAD, 2023). Between 80 and 90 % of global trade (in tonne-kilometres) is transported by sea. Millions of jobs around the world are directly or indirectly linked to shipping and they contribute billions to national budgets. An even greater contribution to society and the economy is made by other activities that would not exist without maritime transport. However, maritime transport does not only have positive effects. Although maritime transport is the most environmentally friendly and often the only way to transport large volumes of freight over long distances, it causes air, water and noise pollution.

Maritime transport consumes large amounts of energy and has a harmful impact on the environment and people. In 2022, nitrogen oxide (NOx) emissions from global shipping amounted to 18.5 million tons, sulfur dioxide (SO2) emissions to 3.7 million tons (Statista, 2024a) and carbon dioxide (CO2) emissions to 706 million tons (Statista, 2024b). However, the numbers differ somewhat depending on the methodology used. Nevertheless, emissions from global shipping cause climate change on the one hand and cardiovascular and respiratory diseases on the other, leading to around 265,000 premature deaths worldwide every year (Mueller et al., 2023). According to a report by The World Economic Forum in 2018, if shipping was a country, it would rank as the sixth biggest carbon polluter (Terpilowski and Sopco, 2024). Without remedial actions, maritime transport emissions could increase by 130% by 2050 compared to 2008 level (IMO, 2021).

The emissions from maritime transport and the decarbonization of shipping are addressed by International Maritime Organisaton (IMO) within the International Convention for the Prevention of Pollution from Ships (MARPOL) and with strategies from 2018 and 2023. The primary objective of MARPOL is to minimize and prevent pollution of the marine environment from ships, including pollution by oil, chemicals, and harmful substances in packaged form. Air pollution from ocean-going ships and the energy efficiency of ships are tackled within the MARPOL Annex VI. IMO wants to achieve net zero CO2 emissions from maritime activities by 2050 with 40 % reduction by 2030 and 70 % by 2040 compared to 2008 baseline levels.

In this article, the authors focus on the solutions for the reduction of emissions caused by maritime transport both for existing fleet as well as for newbuildings, from technical and cost aspect. The paper therefore provides a cost-oriented analysis of strategies to reduce air pollution from maritime transport in accordance with MARPOL Annex VI and other EU regulations. It evaluates different technical and operational solutions, such as alternative fuels, scrubbers, and efficiency measures, and identifies their trade-offs and economic feasibility.

The paper is divided into five chapters. The introductory chapter describes the research problem and the general contribution. This is followed by a description of the methodology in the second chapter. The third chapter deals with legislation on shipping pollution and decarbonization. The added value of this chapter is the figure showing the timeline for the main provisions on decarbonization of shipping in the EU. The fourth chapter is the core chapter of the paper. In this chapter, various techniques and aspects for reducing air emissions from shipping are presented. Two separate tables list the main advantages and disadvantages of alternative propulsion systems as well as the capital costs and bunker costs. The final chapter contains a discussion and conclusions. A total of 45 references were used in the preparation of the paper.

2. METHODS

The authors did the literature review by searching the Science Direct database with the following keywords: “green shipping”, “shipping decarbonization” and “sustainable shipping”. After removing duplicates and irrelevant papers, the corpus of 360 contributions remained for the analysis. In addition, reports and websites were searched to be able to comprehensively answer the research question: What is currently the most cost-effective alternative fuel for maritime transport?

2.1. Literature analysis

The authors used VosViewer to present the most frequently used words in the analyzed corpus of 360 scientific papers. After applying the thesaurus to combine similar keywords into a single keyword, 28 keywords with at least 5 occurrences remained (previously there were 44), as can be seen in Figure 1. These keywords were divided into 5 clusters. The largest cluster is related to energy efficiency and the methods used to measure it (red cluster). The second cluster is related to environmentally friendly and sustainable shipping and alternative fuels (green cluster), although some alternative fuels such as liquefied natural gas (LNG), ammonia or biofuel were assigned to other clusters. The third cluster revolves around the keywords decarbonization and shipping, linking the causes and consequences (blue cluster). Two smaller clusters mainly deal with measures and regulations.

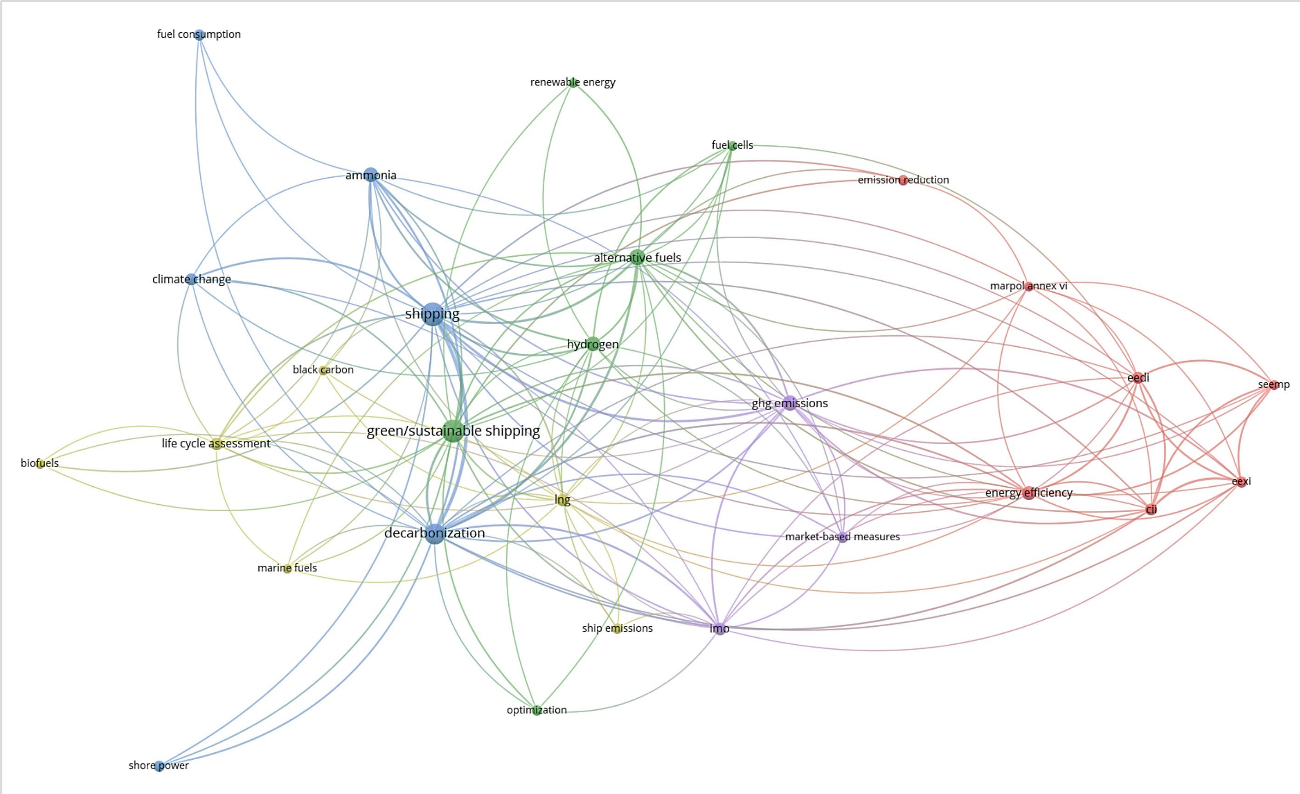

Figure 1. The most frequently used keywords in corpora of academic texts formed using keywords “green shipping”, “shipping decarbonization” and “sustainable shipping” in Science Direct database (Source: Authors).

3. MARPOL ANNEX VI REQUIREMENTS AND DECARBONIZATION OF SHIPPING

Decarbonization in shipping industry has become an important issue due to the increasing concern about the impact of greenhouse gas (GHG) emissions on the environment (Hirata et al., 2024); however, shipping decarbonization is more than eliminating only ships’ CO2 or GHG emissions, it is also about eliminating the NOx, SOx and other emissions (Terpilowski and Sopco, 2024). Decarbonization of the shipping industry and success in energy transition require a shift in technology and operations as well as the introduction of alternative low and zero-GHG fuels (UNCTAD, 2023). Like other industries, also shipping faces barriers to decarbonization which can be defined as economic (e.g. the access to the capital, high implementation cost or hidden cost) and non-economic (e.g. policy and technical issues) barriers, while it also encounters complications due to the high number of stakeholders and its international character (Peyman et al., 2022) and in addition due to the lack of a clear regulatory framework (Bach and Hansen, 2023).

Emissions from maritime transport are dealt by IMO MARPOL Annex VI which contains requirements for the manufacture, certification and operation of ships and engines, as well as the characteristics of fuels used in ships (United States Environmental Protection Agency, 2024). MARPOL Annex VI was introduced in 1997 and entered into force in 2005. Later it was amended several times, with key amendments being the inclusions of NOx Technical Code, the regulations on energy efficiency for ships, and designation of emission-controlled areas for which stricter conditions apply (IMO, 2025b). Key provisions of MARPOL Annex VI are limits on SOx and NOx emissions from ship exhausts, standards for bunker quality, and proposal of energy efficiency measures which could reduce the amount of GHG emissions from ships.

To deal with the GHG emissions, the IMO adopted Initial Strategy on the reduction of GHG emissions from ships in 2018 and upgraded it in 2023. The last document foresees the reduction of total annual CO2 emissions from international by at least 20% (hopefully 30%) by 2030, compared to 2008, and the use of 5 to 10% of zero or near-zero GHG emissions fuels in the fuel mix in international shipping by 2030 to support the United Nations 2030 Agenda for Sustainable Development (IMO, 2023). Furthermore, as by 2024 the EU Emissions Trading System (EU ETS) was extended to maritime transport which initially covers only CO2 emissions, with further expansion to methane (CH4) and nitrous oxide (N2O) emissions. The FuelEU Maritime Regulation entered into force on January 1 2025 serves as complementary regulation to the EU ETS, but they differ in the extent to which the life cycle emissions of the fuels are covered (Nelissen et al., 2022).

IMO also developed four indices that support the decarbonization of shipping and the UN Sustainable development goals (IMO, 2025a):

- The Energy efficiency design index (EEDI) relates to newbuildings that must be designed to achieve a minimum level of energy efficiency per capacity mile. The EEDI relates to ship design, engine optimization, propulsion technology, waste heat recovery, power consumption, etc.
- The Ship energy efficiency management plan (SEEMP) stipulates that ships must be operated in an energy-efficient manner through the application of new technologies and/or improved practices.
- The Energy efficiency of existing ships index (EEXI) is used for existing ships to demonstrate the "technical" or "design" efficiency of the ship.
- The Carbon intensity indicator (CII) is designed to provide an indication of how a ship's CO2 emissions relate to the amount of cargo carried and is mandatory for ships of 5,000 gross tonnage and above.

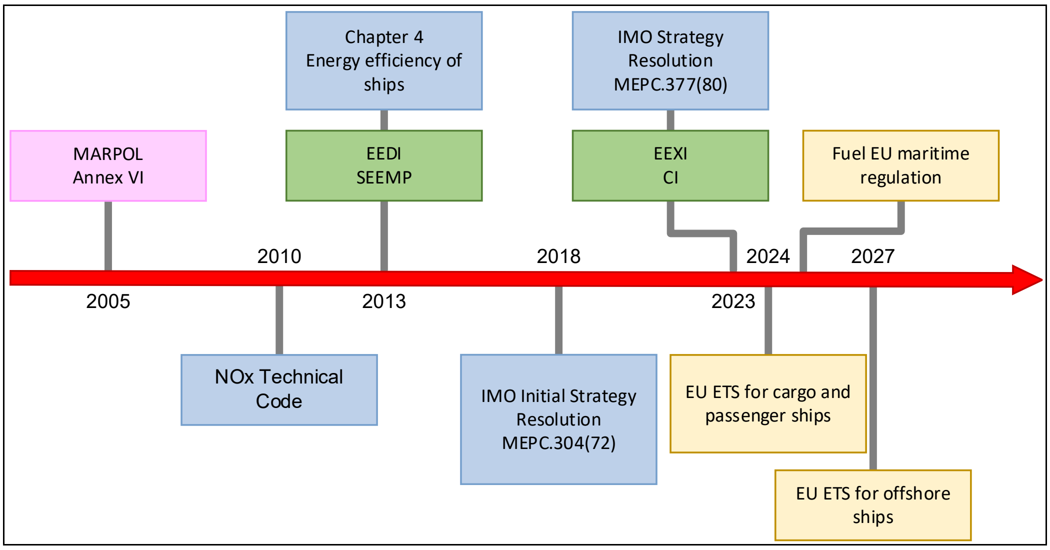

Figure 2. The key provisions for shipping decarbonization in EU (Source: Authors).

Many strategies can be considered to reduce air pollution from shipping, like technology innovations to reduce fuel usage (e.g. hull design, propeller design or engine optimization) or replace fossil fuel usage (e.g. LNG, ammonia or hydrogen), ship management strategies (e.g. specific routing or slow steaming) or port infrastructure and operations changes (e.g. shore power, renewable energy or port digitalization). However, Gössling et al. (2021) found that only a limited number of countries and regions have implemented stringent pollution control measures. Moreover, there is currently no globally coordinated decarbonization strategy built on a reliable net-zero emissions framework for 2050. This absence of a unified approach poses a significant challenge to achieving a systematic and steady transition toward cleaner shipping, although IMO Member States have taken steps to improve energy efficiency.

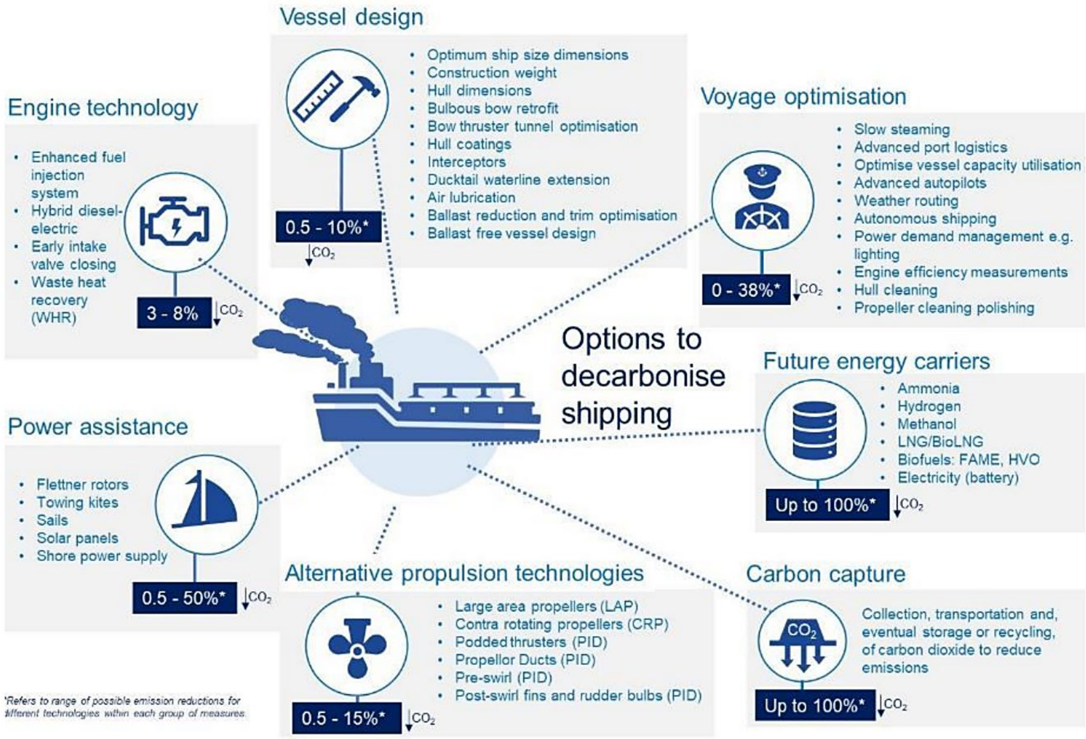

Figure 3. Options to decarbonize shipping (Source: Horton et al., 2022).

One estimation on shipping industry decarbonization predicts costs of around US$ 70 billion per year (MAN, 2023). Another estimation suggests that decarbonizing the world's fleet by 2050 could require from US$ 8 to 28 billion annually, and setting up the infrastructure for 100% carbon-neutral fuels could cost up to US$ 90 billion each year (UNCTAD, 2023).

4. THE APPROACHES TO REDUCE SHIPS' EMISSIONS

Currently, almost 99% of the 60,000 ships in the merchant fleet run on fossil fuels, and the average age of merchant ships is 22.2 years, with more than half of the global fleet older than 15 years (UNCTAD, 2023). This means that a large part of the merchant fleet will need to be replaced by more sustainable ships in the coming decade. Until then the shipping companies need to find the efficient way to operate the ships while meeting all the environmental requirements imposed.

Container ships and bulk carriers are the biggest emitters of CO2 emissions in international shipping; in 2022, container ships emitted an estimated 221.5 million tonnes of CO2 and bulk carriers around 209 million tonnes (Statista, 2024c). CO2 emissions are closely related to fuel consumption, and fuel consumption is closely related to ship's speed. One tonne of fuel oil burned causes an average of 3.17 tonnes of CO2 emissions (Psaraftis, 2008), thus speed reductions of 10%, 20% and 30% could reduce CO2 emissions by 19%, 36% and 51% respectively (Terpilowski and Sopco, 2024). If speed reduction is accompanied by wind supported propulsion the reduction of CO2 emissions can be substantial without significantly increasing voyage time (Mason et al., 2023). The consumption and thus emissions can be reduced also by better voyage planning. Voyage optimization models now include the impact of emission policies on the operator's navigation decisions instead of fixed routes (J. Gao et al., 2024). Hu et al. (2022) and Wang et al. (2023) created two separate models that can effectively predict the ship fuel usage under different conditions. Hu et al. (2022) went further and tested the model in real environment against seven other models and determined that also trim optimization can reduce the fuel consumption and carbon emissions by 0.69%–1.82%. Zhang et al. (2024) developed a learning model for the prediction of ship fuel consumption in relation to sailing speed, heading, displacement/draft, trim, weather, sea conditions, etc. On the other hand, Wei et al. (2023) demonstrated the potential of digital twin for voyage routing optimization.

One of the most important regulatory changes in the maritime industry in recent years is the sulphur cap introduced by the IMO. From January 1, 2020, the permissible sulphur content in marine bunkers worldwide was reduced from 3.50 % to 0.50% %, while a limit of 0.10 % was set in areas with controlled sulphur emissions (SECAs) already in 2015. One tonne of fuel oil burned by ships produces 0.02×S tonnes of SO2 emissions, where S stays for sulphur content in fuel (Psaraftis, 2008). The stricter limit of sulphur content limit in marine fuels led to a drastic decline of around 75% in SOx emissions from shipping (Hausfather and Forster, 2023). To better illustrate the complexity of situation; prior to this measure a single large container ship emitted cancer and asthma-causing pollutants equivalent to that of 50 million cars or with other words, 16 super-ships emitted as much sulphur as the world fleet of cars (Varsami et al., 2011). However, fuel desulphurization from

3.5% to 0.5% increases the CO_2 emissions in shipping by around 1.2% (Faber et al., 2020) which translates into increased global temperature by around 0.05C by 2050. This is equivalent to approximately two additional years of emissions (Hausfather and Forster, 2023).

Cleaner fuel is more expensive. In February 2025, the average price at 20 global ports was 610 $ per tonne for very low sulphur fuel oil (VLSFO), while the intermediary fuel oil (IFO 380) was priced around 510 $ per tonne (Ship and bunker, 2025), resulting in a difference of around 100 $ per tonne; however, this difference was more than 400 $ back in 2022 (Miller, 2024). Marine gas oil (MGO) costed around 788.00 $ per tonne. Both VLSFO and MGO have lower density and viscosity which can lead to inadequate hydrodynamic lubrication, causing wear and scuffing (Fitch, 2015). One of the best alternatives to cleaner fuels is the installation of exhaust gas cleaning system (EGCS), known as scrubber. Scrubbers are designed to remove around 95% of SOx from ships' exhaust gases while burning high sulphur fuels. In addition, lower combustion temperatures of heavy fuels result in less NOx production at sea, and scrubbers partially remove also particulate matter (PM), while the consumption remains unaffected.

The installation of scrubber can cost from about $ 2 million to 8 million depending on the ship's size and type as well as scrubber type (Glender international bunkering, 2024). Given the fact that high sulphur fuel oil is cheaper than low sulphur oils, the payback period is relatively short (usually in a couple of years) and the profit margin increases in the remaining life-span of scrubber (usual life-span can be from 5 to 20 years). Currently there are around 4,400 merchant ships equipped with scrubbers (Statista, 2023). More than 95% of the ships with scrubber systems installed reach break even point within five years after installation (Lunde Hermansson et al., 2024), many of them much earlier.

Currently several alternative fuels seek to replace fuel oil as bunker for ocean going ships, either for existing ships or for newbuildings. These fuels are liquefied natural gas (LNG), liquefied petroleum gas (LPG), methane, ammonia, methanol, hydrogen, biofuels or batteries. These alternative fuels can be divided into carbon fuels (LNG, LPG and methanol/ethanol), carbon neutral (biofuels and synthetic methane) and zero carbon also known as synthetic fuels (ammonia and hydrogen). Ammonia and hydrogen can significantly reduce carbon emissions, especially if they are produced with green electricity (green) or when carbon capture and storage is applied (blue). It is expected that synthetic fuels and methanol, will be the main source of energy by 2050; however, they are costly and from today's perspective this will represent a major technical challenge (Lorentz et al., 2024). Each of these fuels has certain advantages and disadvantages as can be seen from Table 1.

Propulsion System	Advantages	Disadvantages
LNG	- Cleaner fuel with reduced SOx, NOx, and PM emissions - Already relatively established supply chain and infrastructure - Until recently consider as fuel future, now (more as) transitional fuel in shipping decarbonization process	- Still produces CO_2 and methane (Ch4) emissions; however, 20-30% reduction in comparison to other fuels - Gap between LNG bunkering supply and demand is expected to increase as specialized storage and fueling infrastructure is needed - Price volatility
Ammonia	- Potential for zero carbon emissions if produced from renewable energy (green ammonia) - Can be adapted for use in both combustion engines and fuel cells	- Toxic and corrosive, posing significant safety and handling challenges. - Limited global fueling infrastructure - May produce NOx emissions if not properly controlled - Requires extensive engine modifications
Methanol	- Cleaner fuel resulting in lower emissions of pollutants - Easier to store and handle than LNG or hydrogen due to its liquid state at ambient conditions - Can be produced from both fossil and renewable sources (green methanol)	- Lower energy density (cca 10%) than conventional marine fuels, resulting in larger fuel volumes requirements - Engine modifications or dedicated engine designs are needed - Production sustainability depends on process used
Biofuel	- Renewable and can be carbon-neutral, depending on the production method - Often used as a "drop-in" fuel in existing engine systems, reducing the need for engine modifications - Lowers lifecycle GHG emissions	- Feedstock sustainability issues - Limited availability (competition with food production) - Variability in fuel quality and performance - Generally higher production costs and limited supply infrastructure
Hydrogen	- Very high energy content	- Challenges include storage and transport

Propulsion System	Advantages	Disadvantages
	- Produces zero CO_2 emissions if used in fuel cells	- High cost of green hydrogen production
Battery-Electric	- Zero local emissions during operation - Very quiet operation and high energy efficiency - Ideal for short-sea shipping, ferries, and smaller vessels (in closed seas)	- Restricted range due to limited energy density - Long charging times and significant battery weight and space requirements - Charging infrastructure is still under development in many areas - High battery cost
Dual-fuel	- Operational flexibility by switching between power sources - Improves fuel efficiency and reduces overall emissions - Provides operating reliability	- Increased system complexity, leading to higher maintenance challenge and costs - Higher capital investments - Can limit the success of decarbonization

Table 1. Advantages and disadvantages of alternative propulsion systems (Source: Authors).

Advanced biofuels or second-generation biofuels are considered a feasible option to decarbonize maritime transport in the short to medium term (Panoutsou et al., 2021). In fact, due to the EU emissions trading systems and FuelEU regulation the demand for biofuels will increase. On the other hand, dual-fuel engines can operate on both traditional fossil fuels and cleaner alternatives. Ejder et al. (Ejder et al., 2024) analyzed dual-fuel engine (LNG and conventional liquid marine fuels) performance and the CII on eleven voyages. The results showed that LNG reduced CO_2 emissions by around 30 %, however, that is insufficient to meet the IMO 2050 targets. In addition, multi-energy hybrid propulsion systems are emerging. These ships use sophisticated optimization models focused on lowering operating costs, meeting emission standards, or improving performance (Guo et al., 2024) by using different types of energy for various operating conditions (Yuan et al., 2020).

Newbuilds in the forthcoming years must be zero emission by design, while other merchant ships will need to be retrofitted. Younger ships, aged from 0 to 5 years are strong candidates for retrofit (as scrubber doesn't address the CO_2 emissions), ships aged from 5 to 10 years old are candidates for less costly retrofits (mainly methanol) and older ships probably will not undergo significant retrofit, instead they are the potential users of "drop -in" fuels (biofuels) (Bourboulis et al., 2022). Retrofitting the existing fleet with dual engine systems provides long-term solution, and by 2046 the number of retrofits will reach around 35,000 vessels. In addition to increased capital and operating cost, but potentially lower bunker costs, space on board is also an issue when retrofitting of existing ships. Furthermore, in average it takes from 12 to 14 months to retrofit the ship, meaning that the ship will be off-hire for long period.

Orders for newbuilds powered by alternative fuels in 2024 will increase the global fleet to over 2,000 ships; however, only 1.0% (in terms of number of ships) or 3.3% (in terms of gross tonnage) of the global fleet in operation can run on LNG, LPG, methanol, hydrogen or ammonia (Snyder, 2025).

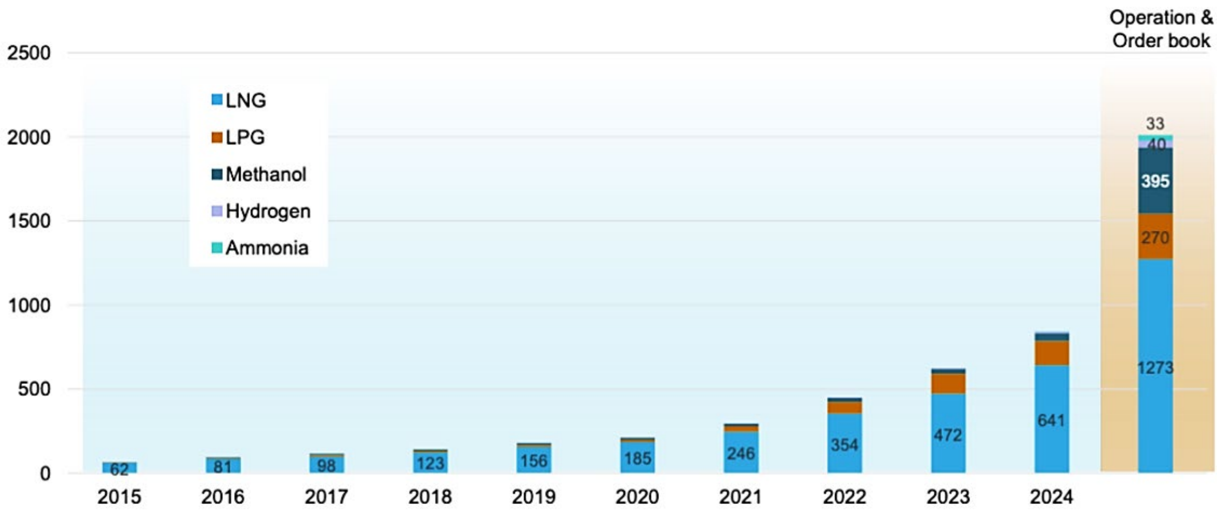

Figure 4. Number of ships with alternative propulsion in operation and on order (Source: Snyder, 2025).

In 2024 a record number of LNG-fueled ships were delivered; 169, totaling in 641 LNG powered ships in operation in 2024. In the same year 264 LNG-fueled, 166 methanol-fueled and 27 ammonia-fueled ships were ordered. The total orderbook for alternative-fueled vessels, including LNG, methanol, ammonia, hydrogen and LPG, reached 515 vessels in 2024; a 38% increase compared to the previous year. Most of alternative fueled ships that were ordered in 2024 were container or ro-ro ships.

The most prevalent disadvantage of alternative propulsions can be attributed to costs. The capital costs associated with installing alternative propulsion are high, while voyage (bunker) cost depend on the price of the fuel per tonne and its energy content.

Fuel	Cost of installation (million $)	Bunker price ($/tonne)	Energy content (MJ/kg)
LNG	25	500-1,000	50
Ammonia	25	400-800	18.6
Methanol		350-550	20
Biofuel	5		37-39
Hydrogen	30	3,500-6,000	120

Table 2. Capital and bunker cost for different alternative propulsion systems (Source: Authors, based on Curcio, 2025).

In recent years, attention has been paid to emission reductions and energy savings associated with shipping. There are several alternative technologies, or even their combination, that can be used to improve the sustainability of the maritime transport sector; however, at this stage there is no single best solution, as each of them has certain advantages and disadvantages. Scrubbers are therefore still a common solution for newbuildings as they are cheaper to install than other alternative propulsion options. Their installation gives shipping companies time to operate in a relatively cheap and environmentally friendly way until alternative propulsion systems are developed and tested and the best option is identified. The implementation of EU emissions trading system made the usefulness of scrubbers alone questionable.

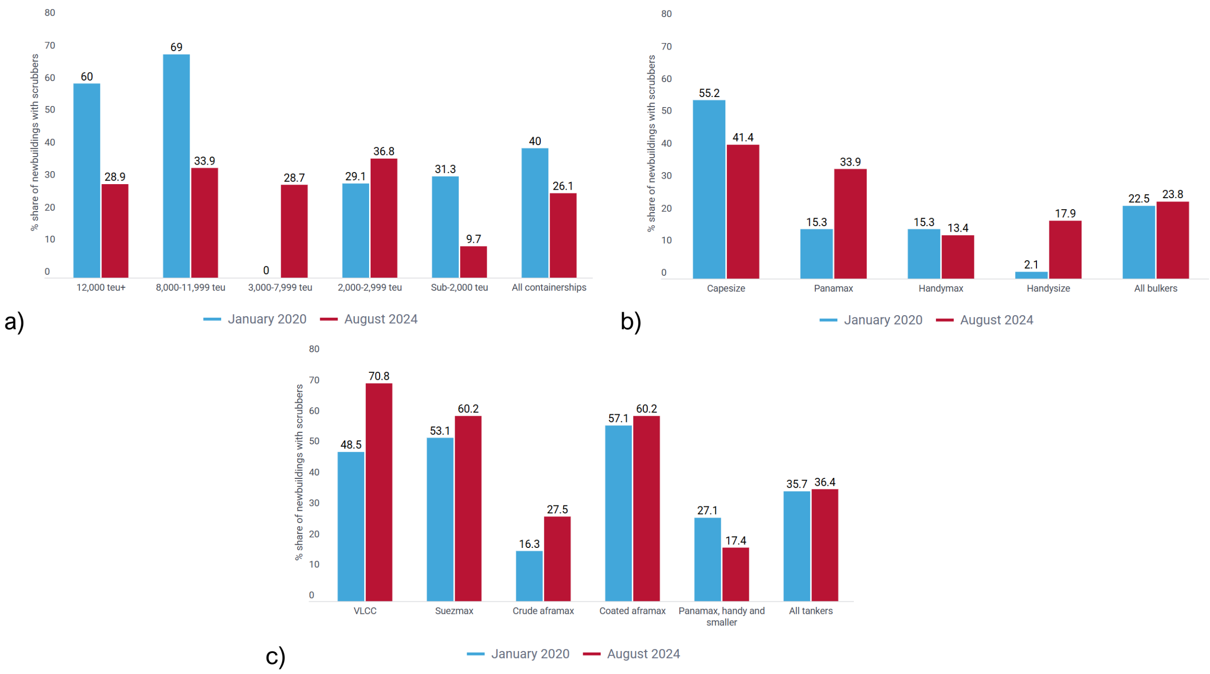

Figure 5. Share of newbuildings with scrubbers a) container ships, b) bulk carriers, c) crude/product tankers (Source: Miller, 2024)

Nevertheless, the study by Ji and El-Halwagi (2020) showed that the global warming potential (GWP) gas emissions of burning HFO with scrubber are 38% more than those of one LNG dual-engine option. Therefore, the installation of a scrubber alone is the best emission reduction solution where marine emission trading system (METS) regulation is not considered (T. Wang et al., 2025). A scrubber installed on a dual engine with methanol is more economical than mixing VLSFO and methanol, considering the existing emission standards (T. Gao et al., 2025).

The most cost-effective shipping decarbonization measure depends on the type of vessel, trade routes, and operational profile. New technologies, operational measures (e.g. voyage routing or slow steaming), and regulative measures (e.g. the Emissions trading scheme in the EU) are needed for a successful transition towards a greener future of shipping sector. Based on cost-benefit analysis, operational efficiency improvements tend to provide the highest return on investment in the short term; in the long-term alternative fuel propulsion systems will need to be applied. Among alternative solutions the biofuel has the shortest payback period.

CONFLICT OF INTEREST

Authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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