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GHG emission reduction measures and alternative fuels in different shipping segments and time horizons – A Delphi study

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ABSTRACT

The bodies governing the global maritime industry have set short- and long-term targets for reducing GHG emissions from shipping. Various emission abatement measures exist, but their applicability in different contexts widely varies. The situation is unclear, especially for the so-called alternative fuels. These fuels hold the biggest emission reduction potential. Conversely, they are expensive, and the feasibility of investments in those technologies has high uncertainty. Despite a growing body of knowledge on the characteristics and potential of alternative fuels, no consensus exists as to which fuels would be best for each segment of the maritime industry – in the near future and the long run. We contribute with a Delphi study to fill this gap. Our results pinpoint the differences between the shipping segments and the short- and long-term choices for alternative fuels.

1. Introduction

Shipping is an essential and cost-efficient mode of transporting goods. In fulfilling that crucial societal function, the shipping industry is responsible for around 3% of the world's CO_2 emissions [18]. There is an evident disappointment with the actions taken by the International Maritime Organization (IMO) [36,3]. Recently, many other policies and private initiatives have been put forward to reduce the air emissions of shipping, constituting a challenge for the industry as the demand for shipping services continues increasing with world trade. Also, many technologies and other measures are available for decreasing greenhouse gas emissions (GHG) from shipping (Bouman et al., 2018; [37]) at various readiness levels (see, e.g., [22]). Significantly, new types of alternative fuels have attracted the attention of shipping companies, consultants, and researchers ([2,20]; DNV GL, 2022).

However, considerable challenges exist in reducing GHG emissions from shipping, including regulatory complexity [1,29], adding to the uncertainty of choosing a mitigation strategy. According to Bach and Hansen [3], the capacity of the IMO to regulate multiple emerging technologies seems insufficient. Indeed, many of the challenges are techno-economic [31,6]. However, the potential and environmental impact of the alternatives also varies considerably (e.g., Kesieme et al., 2019; [35]). As well as the techno-economic and ecological properties of the reduction measures, the shipping market's heterogeneity adds complexity to choosing among them. Different shipping segments, vessel types, and geographical markets have different demands and capabilities for adopting various emission reduction measures. An increasing body of knowledge is shedding light on choosing a mitigation strategy. Despite this wealth of knowledge, there is no consensus on the issue. Although it may not be a condition for sustainable development, establishing consensus on the best mitigation strategies may contribute to the job of policymakers and regulators, especially as we know that the IMO builds on unanimous decisions among its 175 member states.

Therefore, this paper contributes to the discussion with a Delphi

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study seeking to develop an understanding of an emerging consensus on the topic (among a limited set of industry players, namely clean propulsion technology developers), focusing on alternative fuels. For that purpose, we address three research questions: 1) What are the most viable short- and long-term GHG abatement measures in four common shipping segments (short-sea passenger, short-sea cargo, deep-sea, and cruise shipping)? 2) What are the likely future fuels in those segments, and 3) what are the main drivers and barriers for the different measures and the uncertainty associated with each choice?

The remainder of the article is structured as follows. The next section provides an overview of the emission reduction regulations and targets in international shipping, the different abatement strategies (including alternative fuels), and the differences among various shipping segments. Section 3 discusses the methodological choice in general and presents the details of the Delphi panel study. After that, we present the empirical results of the Delphi study (Section 4). Section 5 discusses our results concerning earlier studies on choosing abatement measures. We conclude with implications for shipping companies, policymakers, and researchers.

2. An overview of current policy frameworks and GHG abatement measures

2.1. GHG emission reduction targets and regulations in shipping

Reducing GHG emissions from ships has been a key regulatory challenge for the IMO for years. While the Paris Agreement mandated the IMO to regulate shipping, it did so through national reduction pledges, which are not well suited for emissions caused by international shipping [16]. The focus of the IMO has been on reducing pollution in general from shipping operations, including discharges in the air and water. The respective measures included, for example, setting up SOx emission control areas (SECAs) and NOx emission control areas (NECAs), forcing shipping companies operating in these waters to switch to a cleaner fuel (such as very low sulphur fuel oil [VLSFO], marine gas oil [MGO], or liquefied natural gas [LNG]) or installing scrubbers on their vessels. These actions were necessary as shipping has used the lowest grades of fossil fuels in their operations. Moreover, marine fuels have been exempted from energy taxation in the EU, which can be considered an implicit subsidy for using fossil fuels in the sector [17].

Much political attention has recently been drawn to the need for the shipping sector and other industrial sectors to contribute to reducing GHG emissions. Notably, the International Maritime Organization (IMO) has set the industry on a course to reduce CO_2 emissions per transport work by at least 40% by 2030 (as an average across international shipping) and pursue further efforts towards net zero GHG emissions from international shipping by 2050 (with an indicative checkpoint by at least 70% by 2040), setting emissions from shipping in 2008 as a baseline. IMO aims to reduce the total annual GHG emissions from shipping by at least 50% by 2050 compared to 2008. Thus, IMO has introduced several legal requirements for vessels' design and performance during operations. The Energy Efficiency Design Index (EEDI), introduced in 2011, requires a minimum energy efficiency level per capacity mile (e.g., tonne mile) for different ship types and size segments. EEDI is a measure targeted at new ships. A similar measure for existing ships – the Energy Efficiency Existing Ship Index (EEXI) – has come into force for most of the vessels in 2023, referring to the efficiency requirements for the existing ships. These measures focusing on improved energy efficiency have been criticised for being insufficient, raising the question of whether or not a total ban on fossil fuels should be implemented [36]. Another essential legal requirement to improve ships' emission performance is the Carbon Intensity Indicator (CII), which sets requirements on CO_2 emissions per transport work and should facilitate operational measures to reduce emissions.

However, the EU considered these targets and measures not ambitious enough and proposed other measures. Thus, the EU launched several initiatives as part of its 'Fit for 55′ package to reach the goal of reducing GHG emissions from shipping by 55% by 2030 [13]. These include the proposal to include shipping in the Emission Trading Scheme (ETS) and other so-called market-based measures, which aim at phasing out fossil fuels and eliminating GHG emissions from shipping by, among others, making the use of alternative fuels in shipping more competitive compared to currently prevailing fossil fuels.

The current proposal to include shipping in the EU ETS would make shipping companies acquire emission allowances by auctioning or buying them from the market. The revenues from the EU ETS would be allocated to the EU budget and Member States and used for various purposes in addressing climate change. A proposal to create a separate Ocean Fund for 2022–2030 will make ships more energy-efficient, support investment in innovative technologies and infrastructure – such as alternative fuels and green ports – and protect, restore, and efficiently manage marine ecosystems [14].

Another initiative, FuelEU Maritime, has been set to promote uptaking alternative low-GHG fuels in shipping. GHG energy intensity is required to improve by 2% in 2025 compared to 2020 and 75% by 2050. The revision of the Energy Taxation Directive (ETD) implies a removal of the current tax exemptions on marine fuels sold within and for use within the European Economic Area (EEA). The existing mandatory tax exemption for marine fuels is abolished while, at the same time, new tax exemptions are introduced to stimulate the use of fuels with lower GHG emission factors. While the former initiative would motivate using alternative fuels, the latter would make them more competitive than fossil fuels.

Nevertheless, another relevant initiative is the Alternative Fuels Infrastructure Regulation (AFIR), which sets requirements for adequate LNG bunkering infrastructure by 2025 and minimum electric shore-side power supply by 2030. In the proposed AFIR adopted in October 2022, hydrogen and ammonia were added to the list of necessary refuelling points next to LNG. A core network of those fuels should be made available by 2025 [15]. LNG's unwanted and transitional role was also recognised, with several amendments adding that any investment in LNG should be only demand-driven.

To summarise, many regulatory and political initiatives aim to reduce GHG from shipping (see Fig. 1 for an overview), most of which directly impact up-taking alternative marine fuels by improving their competitiveness, setting requirements for the GHG potential of the fuels used in the sector, or facilitating fuel infrastructure development. While some of the measures this section discusses are not yet in force, and the implementation of others will be delayed, the political will is clearly in place to reduce GHG emissions (e.g. the IMO is working on a revised GHG strategy). Thus, the future marine fuel market will have much more variety.

2.2. Measures for abating GHGs in shipping

Numerous measures abate greenhouse gas emissions in the maritime sector. However, only a few of these measures have been implemented sufficiently; the most implemented measures have tended to be those with small energy efficiency gains [28]. Xing et al. [37] divide the measures for GHG emission reduction onboard the ship into five categories. The first is technical measures, such as reducing ship resistance or improving propulsion efficiency. Also, developing marine power plants with innovative propulsion plants, waste heat recovery, and auxiliary machinery are listed as optional solutions under technical measures. Operational measures are the second category of abatement solutions. Slow steaming, cold ironing (getting electricity from the shore when in port), voyage optimisation, human factors (awareness of energy consumption and savings), and optimised maintenance are possible operational measures to reduce emissions. Optimising logistics and supply chains are also considered under operational measures, including economies of scale, trading network design, and port services. The third and fourth categories – sustainable fuels and alternative power sources –

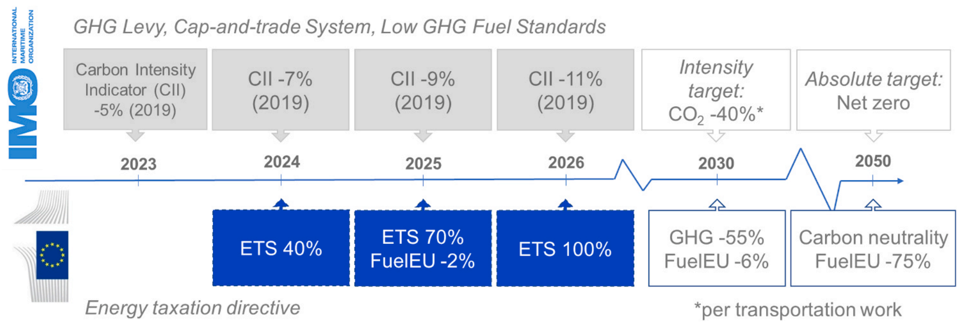

Fig. 1. Regulations relevant to adopting alternative fuels in the maritime sector.

can also be used to reduce greenhouse gas emissions. Wind, solar, or nuclear energy are examples of alternative power sources, whereas biofuels and synthetic fuels are examples of alternative fuels. The fifth category refers to carbon capture and storage systems onboard ships. This paper focuses on utilising sustainable fuels. We use Xing et al.'s (2020) categorisation for this article.

The effectiveness of different measures has also been analysed in the literature. For instance, Bouman et al. [5] presented possible emission abatement solutions with their emission reduction potentials in their article based on the conducted literature review of previous studies. Later, Balcombe et al. [4] reviewed various studies considering emission abatement in shipping with different solutions. Romano and Yang [30] collected information about the most critical greenhouse gas mitigation technologies and considered the advantages and disadvantages of these solutions in 2017–2020 based on a literature review. Whereas most academic studies on the subject seem to have techno-economical assessments relating to potential, choosing an alternative fuel (or an abatement measure in general) is more complex. Industry reports on alternative fuels typically also mention fuel density and availability, infrastructure readiness, and various other maturities of readiness aspects of the fuels, such as feedstock availability, the production process, fuel storage and handling, vessel conversion requirements, onboard safety, and existing regulations [11,22,24,8]. Overall, various ways exist to reduce GHG emissions, but alternative fuels hold the most significant potential to reduce emissions.

2.3. Alternative ship fuels

Three types of power sources and prime movers for ship propulsion are based on fuel consumption: conventional fuel-consuming prime movers (gas turbines, internal combustion engines, steam turbines with boilers, and fuel cells), radioactive fuel-consuming prime movers (nuclear-powered systems), and no fuel-consuming prime movers (photovoltaic, wind-assisted, and battery-electric systems) [38]. In this regard, it is essential to understand the different categorisations of alternative fuels based on their carbon content and lifecycle GHG potential. Table 1 describes and compares different kinds of alternative maritime fuels (the table is based on Nakhle's [25] categorisation with the addition of nuclear power, examples of alternative fuels and comments on the drawbacks of each category).

Liquified natural gas (LNG) has been considered a transition fuel as it is a fossil fuel that produces less CO_2 than marine gas oil (MGO) or heavy fuel oil (HFO) per ton of fuel combusted [12]. However, methane slip and the release of unburned methane into the atmosphere is a massive problem for LNG-powered ships from the perspective of global warming because the global warming potential (GWP) of methane is significantly greater than the GWP of CO_2. In some analyses, LNG-fuelled ships have caused even more greenhouse gas emissions (CO_2 equivalent) than conventional MGO-fuelled ships, especially when the fuel's life cycle (well-to-wake) is considered [21]. Partly for this reason, more emphasis can be placed on carbon-neutral and zero-carbon fuels, such as hydrogen or ammonia. Balcombe et al. [4] have reviewed research papers considering the abatement potential of different types of fuels and presented the findings in illustrative figures.

2.4. Differences among different shipping segments

Several potential solutions exist concerning propulsion technologies (e.g., energy efficiency and operational/technical optimisation) and alternative fuels (e.g., methanol, hydrogen, ammonia, etc.). As internal combustion engines (ICE) are commonly believed to remain relevant in the following years, GHG savings and costs (e.g., differential against

Table 1
Alternative maritime fuels (adapted from [25]).

Type of alternative fuel	Description	Examples	Potential to reduce GHG emissions	Drawbacks of the alternative fuel category
Low-carbon fossil fuels	Fossil fuels with a lower carbon footprint than conventional fossil fuels.	LPG LNG Methanol	Reduction by max 20–30% vs. conventional fuels.	Fossil fuels cause remarkable GHG emissions.
Carbon-neutral biofuels	Fuels made from organic feedstock such as oils, sugars, or waste.	Biodiesel Biomethane Bio-methanol	It can be carbon-neutral.	Scalability of production might be limited.
Carbon-neutral hydrocarbon fuels (often referred to as synthetic fuels or electrofuels)	Synthetically produced (using renewable energy and chemical compounds based on hydrogen and carbon).	e-diesel e-methane e-methanol	It can be carbon-neutral if produced with renewable energy, and CO_2 is captured.	Potential limited availability of renewable energy and green CO_2.
Zero-carbon fuels and energy sources	The energy that does not emit any CO_2 to generate power or directly use electricity.	Hydrogen Ammonia Electricity (batteries)	It can be carbon-free if produced with renewable energy.	The production of zero-carbon fuels requires remarkable amounts of energy. Ammonia is highly toxic. Hydrogen has a low energy density compared to other fuels.
Nuclear	Nuclear-powered systems are utilised primarily in military solutions such as submarines.	Uranium	Nuclear power plants do not cause direct greenhouse gas emissions.	Nuclear waste harms people and the environment, and handling it requires special attention.

HFO and diesel) are critical for alternative fuel adoption. However, Prussi et al. [27] argue that the market penetration potential for future innovations in these dimensions, particularly regarding alternative fuels, will be affected by technical (e.g., engine requirements, safety, space on board, autonomy, etc.) and nontechnical considerations (e.g., market trends, regulations, infrastructure development, needed expertise, and fuel supply availability, and the development of alternative competing technologies such as batteries and wind). Moreover, a need exists to consider the transport service's main aspects concerning the requirements of different customer groups: price, speed, reliability, and security [34]. Thus, the above considerations will impact different vessel types differently.

Whether the optimal mid-term solution will be based on the supremacy of one alternative fuel or a mix or how fuels will be blended will depend on the ship type and shipping segment. Therefore, a detailed discussion on uptaking alternative fuels requires a proper segmentation to consider the abovementioned conditions. No single segmentation option exists; if it does, it should include homogeneous segments regarding the vessel and operational characteristics concerning the best fuel, depending on each fuel's chemical properties (e.g., volume and safety). For instance, a primary distinction between deep-sea and short-sea shipping can be made [34]. Accordingly, deep-sea shipping is the only economically viable mode of transport for high-volume cargoes moving between continents. Instead, short-sea transportation (ships/ferries) ships transport cargo over short ranges and frequently distribute cargo brought in by deep-sea services. The flexibility and adaptability of these smaller ships are essential features. Thus, the critical difference between short-sea and deep-sea shipping is the length of the voyages or the internationality, with consequences concerning different bunkering capabilities. In this context, differences among different vessel types exist in short-sea shipping, for instance, considering cargo vessels (container feeders, bulkers) and cargo plus passenger vessels (RoPax, RoRo, ferries), making safety considerations for passengers highly relevant in the latter. Additionally, cruise shipping seems to be a separate segment, not shipping as in transportation but as a travel destination, with a need for higher power and increased safety concerns.

Alternatively, Prussi et al. [27] proposed a segmentation of the fleet composition involving several segments, such as 1) bulkers, 2) cargo/containers, 3) tankers, 4) Ro-Ro/Ro-Pax, 5) fishing, 6) passengers, and 7) inland waterways. Instead, based on the above discussion and considering commonalities and differences among the different types of vessels (c.f. IMO's vessel type classification), their uses, and the needs from the customer viewpoint, we distinguish among short-sea (RoRo, RoPax, and ferries), deep-sea (tankers, bulkers, and container vessels), cruise, and short-sea cargo shipping (feeders and bulkers). Finally, other segments include naval ships, research vessels, and offshore vessels. Still, we do not consider them in our study due to low fuel consumption and overall impact on GHG emissions compared to the other shipping segments. Although our categories are not directly comparable to the categories that IMO's [18] GHG study uses, the deep-sea shipping segment can still be said to be the largest GHG emitter by far, followed by short-sea cargo and short-sea RoRo/RoPax/ferry shipping. The cruise shipping segment causes the smallest amount of GHG emissions, according to IMO [18]: around 30 million tonnes of CO_2 equivalents. However, the emissions per ship are very high, and the economic drivers and premises are pretty different, so the cruise shipping segment is intriguing to study.

3. Method

Although an increasing body of literature deals with the above-discussed GHG mitigation strategy choice, there seems to be no consensus. Therefore, the Delphi method was used for the study. The method involves a systematic, anonymous, and iterative process to develop consensus (or an understanding of emerging consensus) among experts about a complex problem. Experts are requested to provide their opinions in a several-round survey until a consensus is reached. A minimum of two rounds is required for consensus development; many studies have reached consensus in two rounds using the Delphi method [19,33]. The Delphi method has also been widely applied in the marine policy area and has proven useful, for example, in setting limits for effective conversation measures [23] and understanding the choice of GHG reduction measures in shipping. The study was conducted in connection to a larger R&D project among clean propulsion technology developers (both from industry and academia).

3.1. Questionnaire development

The four-part questionnaire used for the survey was developed based on the literature Section 2 presented. In the first part, we collected data on the respondents' profiles and professional experiences. The second part dealt with the choice of GHG abatement strategy on a general level. The abatement strategies were chosen based on the categories Xing et al. [37] proposed (see.
Table 2).

The third and central part of the survey considered the most feasible fuel in four shipping segments for two different time horizons. The following fuels were listed: LNG, LPG, biogas, biodiesel, methanol (bio, green and blue), ammonia (green and blue), hydrogen (bio, green and blue), and others. Hence, we limit our study to alternative fuels based on their capacity to reduce GHG emissions from a Well-to-Wake (WTW) perspective. For the category "other", the respondents could add their own choice(s) aligning with the Delphi method procedure. Based on the discussion in Section 2, selecting four shipping segments was considered a compromise between the questionnaire length and the research's granularity. We decided to consider short-sea (RoRo, RoPax, and ferries), deep-sea (tankers, bulkers, and container vessels), cruise, and short-sea cargo shipping (bulkers and feeders), as Section 2.4 discussed. Aligning with IMO's targets, we inquired about the choice for the short term (until 2030) and the long term (after 2030).

The fourth part of the survey dealt with uncertainties regarding using and applying alternative fuels in shipping. The options the questionnaire offered experts derived from two primary sources: the literature review and notes from discussions among experts in over 15 webinars in which the co-authors participated over the past four years.

For all questions, the experts were asked to rate the different choices on a Likert scale from 1–5; 1 = Highly disagree (or, depending on the question, Very Low Feasibility), 2 = Disagree (or Low Feasibility), 3 = Neutral, 4 = Agree (or High Feasibility), 5 = Highly Agree (or Very High Feasibility) ("I have no opinion" was also offered as an option). The questionnaire also included some open-ended questions to gather additional information. Once the first version of the questionnaire was prepared, it was sent to a group of five experts for comments and implemented in the final version.

Table 2
Solutions for decarbonising the shipping industry.

Solutions	Average	SD
Alternative fuels	4.89	0.51
Optimisation of supply chain and logistics (trading network designs, economies of scale, emerging trading routes)	4.48	0.58
Marine power plant (innovative propulsion plants, waste heat recovery, auxiliary machinery)	4.44	0.58
Voyage optimisation	4.33	1.00
Propulsion efficiency	4.26	0.81
Slow steaming	4.22	1.05
Cold ironing (shore-side electricity or shore-to-ship power)	4.19	0.92
Reduction in ship resistance (e.g., hull hydrodynamics)	4.07	1.00
Human factors (energy-saving behaviour)	4.04	0.98
Optimised maintenance	3.85	1.03
Carbon capture and storage (CCS) onboard	3.37	1.21

3.2. Expert recruitment

A list of 110 experts was compiled to recruit a panel and filtered out to match the study's aim. We identified experts from various sources, such as authors of publicly available reports, participants and panellists at seminars (e.g., webinars and conferences organised by DNV), and researchers focussed on GHG abatement in shipping. We listed people from our networks with extensive maritime business experience. We were primarily targeting experts from within the industry rather than, for example, policymakers, as we were more interested in the techno-economic (as opposed to political or regulatory) considerations.

Finally, we followed snowballing, where experts recommended new experts as potential candidates to participate in our study. After sorting, over 90 participants were contacted by e-mail for the survey. In the first round, 39 respondents replied to the survey after multiple reminders (over three months). In the second, 27 responses were received, resulting in a consensus (based on averages and standard deviations). As we learned from previous Delphi studies, 10 to 18 expert respondents are typically considered enough to achieve a representative result through a dynamic discussion [26].

The final list of 27 respondents was geographically and demographically dispersed. Most respondents (24) were from Europe; a few were from Asia (1) and North America (2). Furthermore, the experts had diverse profiles and work experiences. Regarding the area of expertise, four are researchers, four are consultants, four are involved in ship operations, and three belong to engineering companies. The rest are distributed among classification societies (3), technology providers (2), energy producers (1), and others (6). Finally, among the 27 experts, seven have more than 20 years of experience, and nine have between 10 and 20 years of experience. Instead, five have between five and ten years of experience, and six have less than five years of experience.

3.3. Data collection and analysis process

Responses were collected online through Webropol 3.0 from November 2021 to March 2022 (including several reminders). After closing the first round, we applied statistical analysis (average and standard deviation) to assess to what extent consensus was reached for each question. Options with the highest averages and lowest standard deviations were interpreted as those representing the common opinion, for example, for the most suitable fuel for a specific shipping segment. The experts also proposed new options in the first round but did not reach a consensus because only a few respondents voted for them in the following round.

The experts could see their first-round responses and the average scores when responding in the second round, allowing them to compare and reconsider their answers if needed or confirm the initial response. Open-ended questions were added to explore why the initial answer was changed if there were changes in the answers given in the first round.

4. Results

4.1. Available solutions for the decarbonisation of shipping

In the first part of the survey, the experts were asked to rate different technological and operational options for emission reduction. According to the respondents, alternative fuels seem to be the most effective way of reducing emissions, followed by solutions such as optimising the supply chain and logistics and developing the marine power plant. Further options were also considered for decarbonising the shipping industry, relating to the different practices in the industry, such as propulsion efficiency, slow steaming, cold ironing, and many others.

Table 2 shows the study's results.

In the second part, the experts were asked to rate the feasibility of the respective alternative fuel for the chosen shipping segments: short-sea, deep-sea, cruise, and short-sea cargo shipping. The main conclusions for each segment are presented below.

4.2. Future fuels for short-sea shipping

According to the experts, LNG, biodiesel, and biogas are seemingly the most feasible alternative fuels for short-sea shipping (RoRo, RoPax, and ferry) in the next decade. Some experts highlighted using batteries, but this cannot be seen as a consensual opinion because the number of experts providing and supporting new options was too low. Ammonia was considered the least favourable fuel option in this segment from a ten-year perspective. The experts also made other suggestions, including wind energy and synthetic diesel. Respondents were also asked to select alternative fuels for short-sea shipping (RoRo, RoPax, and ferry) in the longer term. Accordingly, methanol seems to be the most feasible alternative fuel. Hydrogen is another possible alternative fuel in the same context. Finally, the experts added battery-operated ships as a long-term solution (see Fig. 2).

4.3. Future fuels for deep sea shipping

The results of deep-sea shipping (tankers, bulkers, and container vessels) show that LNG has the highest average and seems to be the most feasible fuel in the next decade, followed by biodiesel and biogas. Far from consensus, experts added alternative fuels such as wind energy, synthetic diesel, and batteries. Wind energy seems to be the most favourable option among the additions. In the longer term, methanol was considered the most feasible fuel, followed by ammonia, biogas, and biodiesel. Some experts proposed adding wind and nuclear energy among the alternatives. Although wind energy was regarded as a feasible alternative in the next 30 years, it was not ranked among the most relevant options (see Fig. 3).

4.4. Future fuels for cruise shipping

According to experts, LNG seems to be the most feasible alternative fuel for the next ten years. Other potential fuels are biodiesel and biogas. Methanol also appears to be a viable fuel for cruise vessels but with a lower score. The experts added three possible energy sources or carriers to this segment: wind energy, synthetic diesel, and batteries. Among these, the most feasible seems to be wind energy based on the answers from the second round of the Delphi on which these additional options were made available. In the long term, methanol was considered the most feasible fuel for cruise vessels, followed by biogas, biodiesel, and hydrogen. The experts added wind energy (see Fig. 4).

4.5. Future fuels for short-sea cargo shipping

The last market segment is short-sea cargo (feeders and bulkers). Biodiesel was considered the most feasible fuel for the next decade, followed by LNG, biogas, and methanol. Similarly, as per the other fuel-related questions, experts added wind energy as an alternative fuel for short-sea cargo, but it is far from the top of the ranking. According to the experts, methanol would be the most feasible alternative fuel from a 30-year perspective, followed by ammonia, hydrogen, and biodiesel. The experts added wind and nuclear energy. Again, wind energy seems more feasible than nuclear energy, but they are far from the top of the ranking (see Fig. 5).

4.6. Sources of uncertainty for the choice of abatement measure

The last part of this study deals with the uncertainties regarding using and applying alternative fuels in shipping. One of the most significant uncertainties the shipping sector will face is the choice of alternative fuel for different shipping segments (for example, short-sea shipping, deep-sea shipping, etc.). According to our panel (see above), LNG seems the most feasible choice in all shipping segments in the short

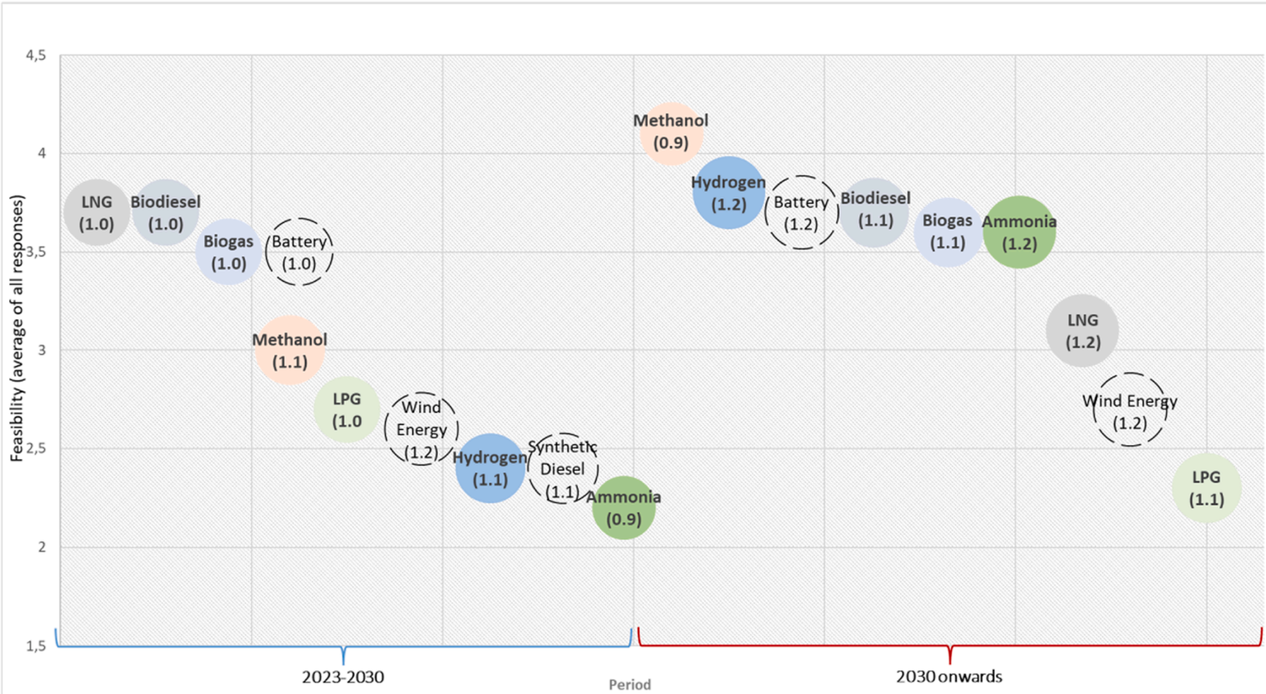

Fig. 2. The economic feasibility of the following fuels for decarbonising short-sea shipping (RoRo, RoPax, ferry) (standard deviation in brackets).

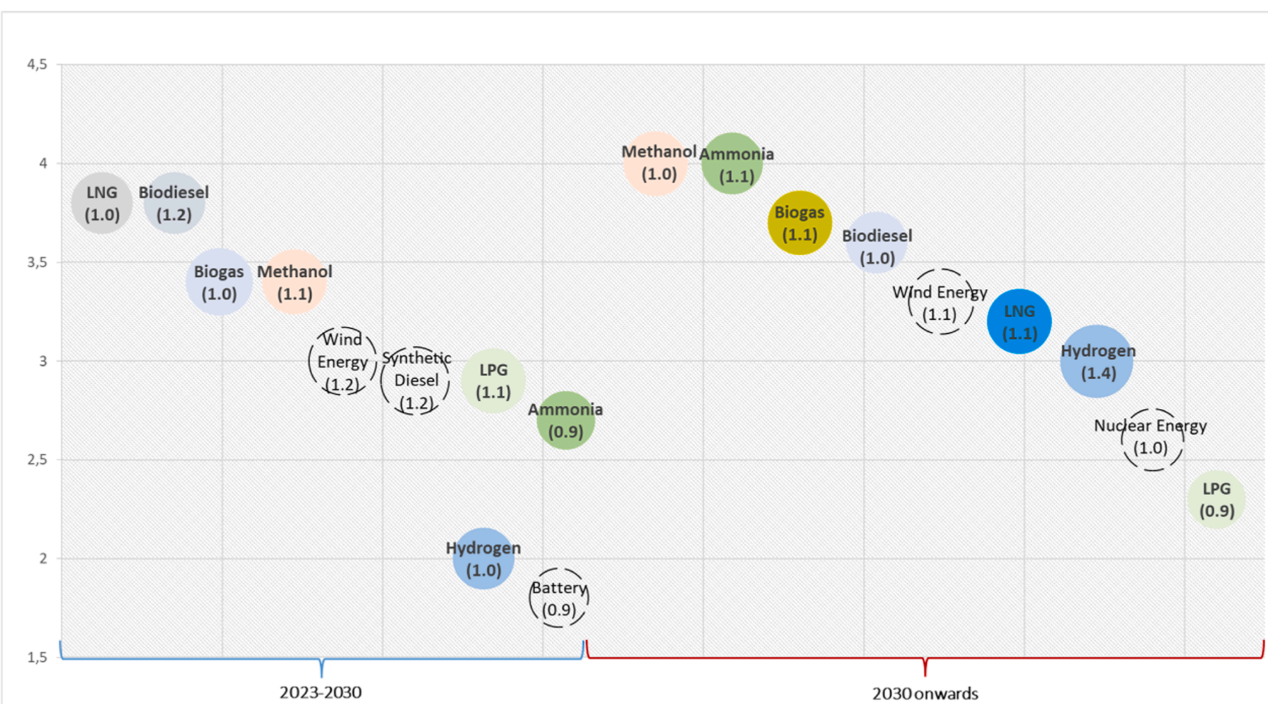

Fig. 3. The economic feasibility of the following fuels for decarbonising deep-sea shipping (tankers, bulkers, container vessels) (standard deviation in brackets).

term. In contrast, methanol appears to be the most viable alternative fuel in the long run for most segments. According to the experts, one of the biggest challenges is that different fuels will be used at different times and in different markets. This situation is due to various aspects of the fuels, such as availability and lack of infrastructure. Moreover, whether there will be enough fuel for the shipping sector is uncertain if another sector or industry starts using the same alternative fuel. However, as one panellist commented, the offtake by another industry may benefit the maritime sector through spillover effects and economies of scale in fuel production.

Similarly, there is no silver bullet for applying alternative fuels in the ships, making the investors reluctant to decide which vessels to invest in. This reluctance can be a hurdle to reaching the targets set by IMO. Similarly, another uncertainty regarding alternative fuels is that the discrepancy between sulphur scrubber demand and installation capacity might increase the demand for alternative fuels. As LNG seems to be the

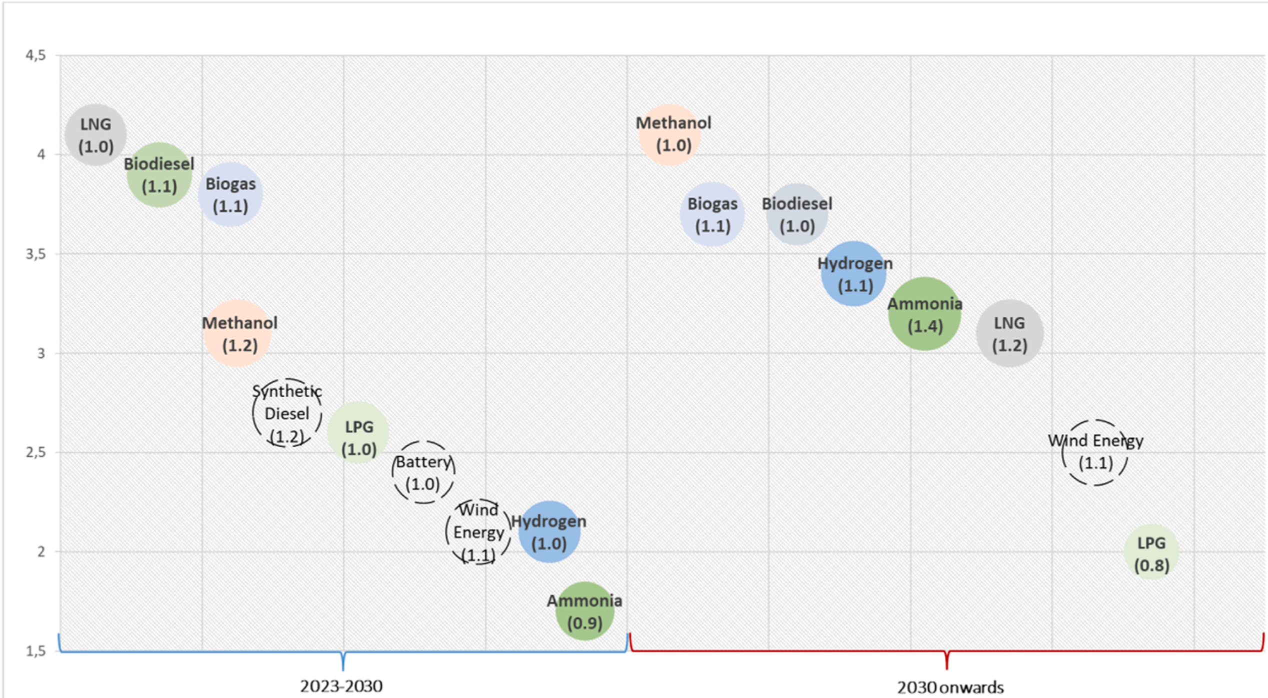

Fig. 4. The economic feasibility of the following fuels for decarbonising cruise vessels in the next decade (standard deviation in brackets).

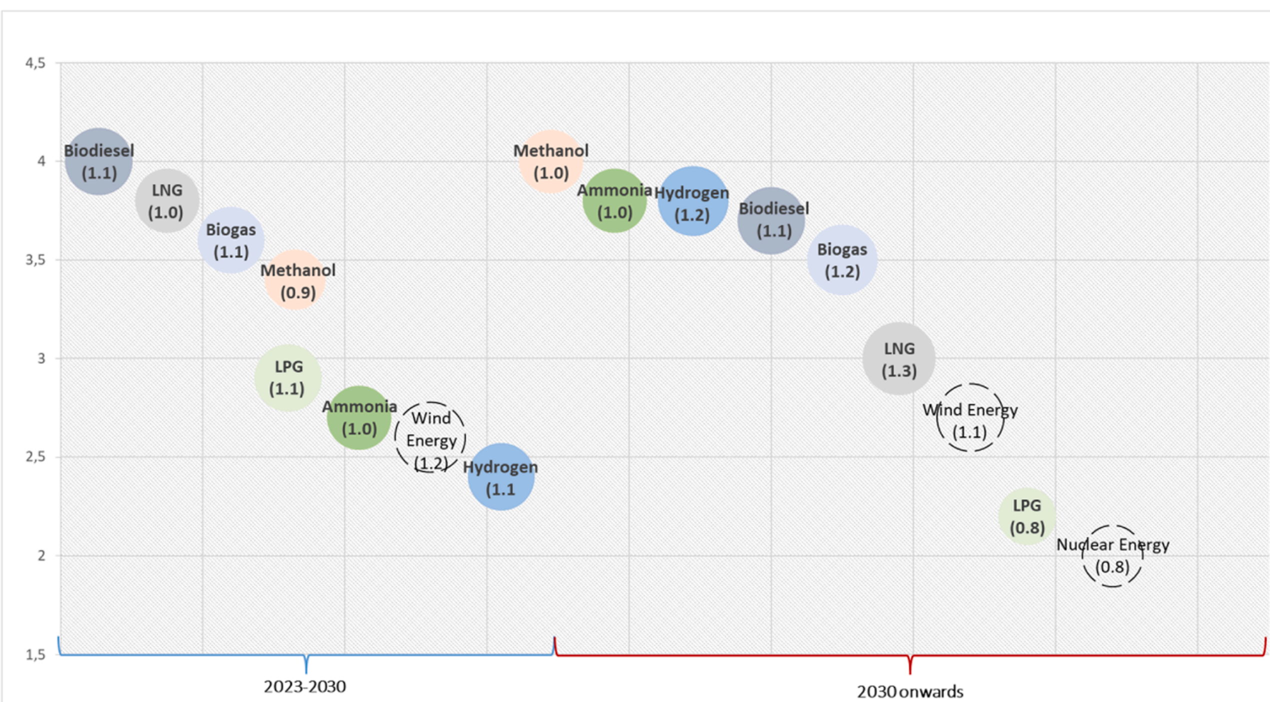

Fig. 5. The economic feasibility of the following fuels for decarbonising short-sea cargo (feeders, bulkers) (standard deviation in brackets).

most feasible alternative fuel, it can be used in the shorter term, providing the problem of reinvesting in the ship because a vessel's average life is between 25 and 30 years. Moreover, owners and operators can hesitate to invest in upgrading and retrofitting later because modifications are costly.

Furthermore, the availability of alternative fuels is a big concern that can impact their use. Regulations are essential in using and applying alternative fuels. Table 3 shows the list of uncertainties explored and their ranking.

5. Discussion and conclusions

5.1. Contribution

As earlier studies [28,5] indicate, a big leap will be taken using alternative fuels. According to the Delphi panellists, LNG/LPG,

Table 3
Uncertainties regarding alternative fuels.

Uncertainty	Average	SD
Different fuels will be used in long- and short-distance shipping.	4.3	0.7
The fuel selected and implemented by other industries will help its application in the maritime industry (through spillover effect and economies of scale).	4.0	1.0
After investing in specific fuel technology, stakeholders may be reluctant to switch to another fuel, which can be a hurdle in reaching the targets set by IMO.	3.9	0.8
LNG or LPG is good for the short term, which will phase out mid-century, after which additional investment will be required by the ships to operate on other alternative fuels.	3.3	1.4
Regulations will limit the options for alternative fuels, even leading to a situation where better alternatives are discarded.	3.2	1.2
A discrepancy between sulphur scrubber demand and installation capacity may present an opportunity for alternative fuels to gain market share.	3.1	1.1
The future supply of alternative fuels will suffice for the shipping industry's needs.	3.0	1.3
Wind-powered container ships can also be a solution for energy transformation of the shipping industry if Flettner rotors are installed on the ships.	3.0	1.3
99% of voyages on a particular China–United States shipping route could be done by hydrogen-powered vessels if used in fuel cells or combusted in engines, like heavy oil today (with certain modifications).	3.0	1.5
Minimising local emissions outweighs minimising GHG emissions.	2.3	1.0
Battery-powered container ships could serve the transatlantic trade if the shipping speed is low and the batteries are charged at different ports.	2.1	1.3

biodiesel, and biogas are stronger contestants among all alternative fuel options during the next decade. The higher availability of these fuels and established technologies for their use on ships explain this outcome. In the long term, synthetic fuels, hydrogen, and batteries are expected to become more prevalent as the technologies mature and fuel availability increases. According to our results, LNG will likely lose its position as one of the most feasible fuels but is likelier to be seen as a transition period fuel (as other studies indicate). However, our panellists expect LNG to remain an alternative in the long run (considering the current fleet and ordered vessels). Differences in the long-term options for alternative fuels exist depending on the shipping sector:

- Methanol has been mentioned as the most feasible future fuel in all segments, likely due to its higher energy density and easier logistics (including storage) compared to ammonia and hydrogen.
- Ammonia is unlikely to be used in cruise and RoPax/RoRo shipping due to the potential passenger hazard.
- Hydrogen is seen as a potential fuel only for short-sea shipping. The result can be explained by its low energy density and, thus, the need for significant storage space, which will be challenging to implement on vessels in deep-sea shipping.
- Batteries (electricity) are believed to be feasible only for short distances (e.g., ferries) due to the weight and volume of the needed battery capacity for deep-sea traffic or high charging frequency.

Table 4
Feasibility of different alternative fuels in various shipping segments (in prioritised order).

Segments	2022–2030	2030–2050
Short-sea shipping (RoRo, RoPax, ferry)	LNG, biodiesel, and biogas	Methanol, hydrogen, and battery
Deep-sea shipping (tankers, bulkers, container vessels)	LNG, biodiesel, and biogas	Methanol, ammonia, and biogas
Cruise shipping	LNG, biodiesel, and biogas	Methanol, biogas, and biodiesel
Short-sea cargo shipping (feeders, bulkers)	Biodiesel, LNG, and biogas	Methanol, ammonia, and hydrogen

Table 4 summarises the results from the panel per shipping segment and period.

Our study contributes to understanding the emerging expert consensus opinions on the complex issues of CO_2 emission abatement in shipping. While the study does not provide an absolute answer, it complements a wide range of reviews on the choices of measures for decreasing greenhouse gas emissions from shipping (Bouman et al., 2018) and especially the future choice of ship fuels [2,20]. Previous studies typically address cost [10,32,9], profitability [31], availability [7], or safety as the critical decision criterion. The Delphi study's advantage is that it can account for at least some other criteria a ship owner or operator must consider when deciding on a new investment. These include, for example, the current fleet, expectations regarding transitioning the shipping industry to new fuels, and the search for regulatory compliance. While the effect of these considerations is not explicit in a Delphi study, we enrich the understanding of the future of alternative fuels with the review of 11 critical uncertainties regarding adopting alternative fuels in shipping (see Section 4.6).

5.2. Implications

Some implications, mainly policy implications, are derived from this study. First, given that investments in ship propulsion have a long-time horizon, there is a need for agile and rapid policy and regulatory frameworks concerning future alternative fuels, allowing the various stakeholders to make decisions quickly and with the most significant possible degree of certainty. In this regard, our study provides some ideas regarding the preferred choices in the short and long terms. Given the short- and long-term targets by IMO and the EU, various regulatory measures can be compared with those choices. A challenge for policymakers is balancing and bridging the short- and long-term targets and regulations. Whereas the industry may well achieve the transition in 30 years (with all the technological development infrastructure, construction, and new builds it will take), reaching the short-term goals may be more difficult.

Second, closely linked to the above, different regulations are in force and under discussion (e.g., EU and IMO), which do not always contain convergent elements and incentives. Our study showed that this circumstance undoubtedly represents limitations and adds to the uncertainty regarding investment decisions. It is essential to align regulatory incentives to avoid endangering the long-term industry transition targets for 2050.

Third, our study indicates that no universally suitable fuel for all shipping segments exists. This multi-option future of marine fuels differs significantly from the current situation when only a few fuel alternatives are used and available globally. This underlines the need for continued technology-neutral policymaking and ensures that incentives for increasing the uptake of alternative marine fuels do not create barriers for those fuel options most suitable for specific shipping segments.

The study also gives ship owners and designers preliminary ideas for navigating a sea of uncertain alternatives. However, the final decision to invest in a vessel (or technology) requires case-specific investigations.

5.3. Limitations

Like any study, this article has limitations. First, there are many ways to continue choosing emission abatement measures in shipping. For instance, a finer-grained segmentation of the shipping market could provide more concrete results for a similar panel study. Second, as the complexity and uncertainty of choice are so high (as our research also indicated), case studies in well-specified contexts could uncover contextual factors and uncertainties when deciding on an abatement measure or a new ship project. Third, our study indicates that fuel blends will be a viable solution in the short, medium and long term. While we addressed the feasibility of different types of alternative marine fuels in detail, more research is needed into the feasibility and suitability of the variety of fuel mixes.

Finally, we recognise that the success of the Delphi approach is highly dependent on the panel's composition and that the reached consensus must be seen against it. In this regard, we especially note that our results may be strongly biased toward ongoing European discussions among certain industry players and researchers. In this sense, understanding the situation in other geographic areas and other players (like authorities) would provide significant value in understanding the future use of alternative fuels in the shipping industry globally.

6. Conclusions

As much uncertainty exists around how to reach the climate targets in shipping best, we performed a Delphi panel study to see what kind of consensus an expert panel would develop around the issue. Our analysis also shows no clear answer, but many solutions will likely be needed. In the long run, alternative fuels are believed to be the most effective way to reduce emissions. Different fuels will be used for various market segments based on fuel availability, price, safety considerations, fleet, and infrastructure development. The fuel of the future is an intricate one that challenges decision-makers. Achieving short- and long-term targets requires special attention regarding technology-neutral bridging policies. We have pointed out certain weaknesses with the chosen method (Delphi study) and our specific approach, providing avenues for further research on the crucial topic. Albeit consensus is not always necessary for a transition, it is undoubtedly valuable in maritime transport, a truly global business that requires significant coordinated investments to make the transition come true.

CRediT authorship contribution statement

Rabetino Rodrigo: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Tsvetkova Anastasia:** Writing – original draft, Writing – review & editing. **Schwartz Henry:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Hammad Ul Haq Syed:** Formal analysis, Investigation, Methodology, Writing – original draft. **Hellström Magnus:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare no conflicting interests.

Data Availability

Data will be made available on request.

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