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Shifting waves of shipping: a review on global shipping projections and methodologies

Hesam Naghash[1*], Dingena Schott[1] and Jeroen Pruyn[1]

*Correspondence: H.Naghash@tudelft.nl

[1] TU Delft, Maritime and Transport Technology, Mekelweg 2, 2628CD Delft, The Netherlands

Abstract

As climate change continues to pose a significant threat to our planet, international maritime shipping plays a crucial role in mitigation efforts. Recognizing the urgency, the International Maritime Organization (IMO) has revised its targets, now aiming for full decarbonization by 2050. However, there is no established pathway to get to the target. To achieve this, there is a need for models depicting possible futures of the maritime sector, and finding feasible pathways. This research aims to find the most suitable way to develop models to find pathways toward decarbonization targets. This involves evaluating existing ranges and scenarios to understand current estimations and their underlying assumptions and assessing the most suitable modeling methods based on defined criteria. Considering the context, the most suitable models for this objective should perform on a global scale. They should include dynamics between shipping demand & supply as well as the derived fuel demand and supply and emissions; integrate the sector with other parts of the economy; incorporate various technologies into the framework; and span multiple scenarios. The study has two main parts. First, existing scenarios on the future of maritime shipping are analyzed to identify current estimations and assumptions impacting these estimations. Second, various modeling frameworks are assessed against the defined criteria to identify the most suitable modeling structure for achieving the decarbonization targets. Many projections do not meet the IMO's updated targets, highlighting the need for a paradigm shift in setting targets and finding feasible pathways rather than focusing solely on individual measures. Integrated Assessment Models (IAMs) have been identified as suitable for such projections and policy analysis, although international shipping is often underrepresented in current models. Future research should combine the insights of sectoral models in integrated frameworks such as IAMs to develop integrated strategies to investigate pathways to achieve zero-emission targets. The ultimate goal is to understand how to effectively reduce the sector's emissions and achieve more environmentally friendly international maritime shipping.

Keywords: International shipping, Climate change, IMO targets, CO_2 emissions, Alternative fuels, Integrated Assessment Model

Introduction

Climate change is one of the major and complex challenges that humans need to solve in the current era. The international body for assessing the science related to climate change -the Inter-governmental Panel on Climate Change (IPCC)- reports that an increase in temperature may cause irreversible damage in terms of rising sea levels, extreme weather events, loss of biodiversity, and ocean acidification. Greenhouse gases, with CO_2 being the most abundant, are responsible for this temperature rise (IPCC 2023). The transportation sector was responsible for about 15% of net global anthropogenic greenhouse gas (GHG) emissions in 2019 (Lee et al 2023). The international shipping sector is an important contributor to the emissions, accounting for approximately 1.06 $GtCO_2$/year. A substantial portion of this (0.74 $GtCO_2$/year) is related to international freight transport (IEA 2020; IMO 2020). This sector accounts for 80-90% of global trade, moving over 10 billion tonnes of containers, solid and liquid bulk cargo annually across the world's oceans (Walker et al 2019). Given the historically upward trend in shipping activities and the undeniable linkage between trade, shipping, and economic growth, these emissions are expected to increase. In 2019, world trade saw an 18% increase compared to 2016, further exacerbating the issue of emissions in the maritime shipping sector (WTO 2021). Also, the shipping sector, which was not initially included in the Paris Agreement, has been slower to adopt decarbonization measures than other sectors. As a result, the share of greenhouse gas emissions from shipping is expected to grow.

In 2018, the United Nations body responsible for environmental regulation of international shipping -the International Maritime Organization (IMO)- established a pilot strategy to reduce shipping-related GHG emissions. This strategy aims to achieve a pathway of GHG emissions consistent with the Paris Agreement temperature goals. This has been translated into the objective of limiting total emissions from international shipping in 2050 to 50 % of the emission amount in 2008 (IMO 2018). IMO's ultimate goal was to completely decarbonize the marine transportation sector Schnurr and Walker (2019); Walker et al (2019). Recently, IMO has adopted the updated 2023 Strategy to lower GHG emissions from ships, setting more ambitious goals for net-zero emissions by 2050 and boosting the use of zero and low-emission fuels by 2030 (IMO 2023). Operational measures, such as slow steaming and optimizing vessel speeds, can lead to enhanced fuel efficiency and reduced emissions. Slower speeds improve wind assistance and contribute to overall fuel savings. However, these impacts are limited (Balcombe et al 2019). The 4th IMO GHG study suggested that new energy carriers are required, as other measures will not be able to achieve the required reduction of GHG emissions (IMO 2018). Also, Psaraftis (2021) concludes that without including and adopting alternative fuels, it is unlikely that the shipping sector will be fully decarbonized.

Currently, green fuel production is very limited, and no clear best option is available, leading to a large set of fuels and converters applying for this role (IEA 2020). In short, While the target of achieving a zero-emission, sustainable shipping sector is clear, the specific pathways to reach this goal have not yet been defined. Also, we know that alternative fuels are needed, but we need to know the economic viability of these fuels under different circumstances. In that regard, it is essential to consider the interplay with other transport sectors, as they share a common fuel supply chain. This means that developments in sectors like aviation, road transport, and industry can significantly influence fuel availability, cost, and technological development in maritime shipping. Over time, many models have been developed with various scopes and objectives. However, a robust model with specific features is needed to identify pathways toward a zero-carbon international maritime shipping sector by mid-century. Models that integrate the sector with the broader economy, including supply and demand dynamics and technological options like alternative fuels, are required. These models should operate globally while also reflecting regional specifics and be capable of simulating diverse scenarios to evaluate the impacts of policies. Thus, five criteria for the models are defined, based on which the quality of existing studies will be assessed. This paper aims to find the most suitable way to develop models to find pathways toward decarbonization targets. This is done in two main parts. First, we look into existing ranges and scenarios to identify the current estimations and the assumptions impacting these estimations. Secondly, based on the defined criteria for the objective and context of this paper, the most suitable modeling method will be evaluated. Combining the insights obtained from valid assumptions and modeling methods, in line with a new philosophy of looking at the problem, leads to appropriate modeling direction.

Therefore, the main question to answer is: *"What are the projected trajectories & modeling methods for international shipping activity, fuel mix, and* CO_2 *emissions under future economic and regulatory scenarios?"* To address this question, it's crucial to recognize the central role of legislation as the primary driver for the shipping industry's transition to sustainability.

Section 2 discusses the five defined criteria, followed by the methodology for collecting and selecting the literature. Section 3 presents reviews of the selected literature, divided into subsections: shipping activity demand, efficiency, fuel supply, and emission. Section 4 analyzes the underlying assumptions and the suitability of modeling frameworks. Conclusions and recommendations for future studies are presented in Sect. 5.

Methodology

In the methodology section, we reviewed previous studies on the future outlook of international shipping. These studies were selected based on their relevance to the research question and goals. The search was conducted in the Scopus and Google Scholar databases using specific keywords, such as "International maritime shipping", "pathway", "future", "projection", "emission", "supply", and "demand." The selection of these keywords was deliberate. "International maritime shipping" was included as it is the primary focus of the research. Keywords like "emission", "supply", and "demand" were chosen for their direct relevance to the main components of the research. The terms "pathway" and "projection" were selected for their implications regarding the trajectory and potential scenarios that shipping may follow in the long term, offering insights into systematic changes. The term "future" was incorporated to ensure that the research covered forward-looking studies that extend beyond historical data, including trends, predictions, and strategic planning relevant to maritime shipping. Articles not in English were excluded from the search. The articles that did not align with the research based on their titles, summaries, and keywords were removed. Online tools were utilized to find additional relevant publications connected to existing literature to ensure comprehensive coverage of relevant literature.

In the process of this literature review, the Multi-Criteria Decision Analysis (MCDA) technique is employed to systematically rate and rank the selected papers. MCDA is a method used to analyze decision options and identify the most preferred values based on a set of criteria that determine their relevance to the problem (Wieckowski and Szyjewski 2022). Given the global nature of climate change and shipping and the complex interactions of the economy, five criteria for the models used in the literature are defined and justified in the following.

1. **Sectoral integration scope** Sectoral modeling primarily focuses on a specific sector, in this case, maritime shipping, to understand factors related exclusively to that sector in isolation. However, integrated approaches adopt a more holistic view, accounting for a myriad of factors, including economic, social, and environmental variables. This type of model considers multiple factors, such as energy use, population growth, and economic development, to create future scenarios. Integrated approaches combine energy technology models with economic and climate models to assess various pathways. Such a comprehensive evaluation allows for an assessment of the feasibility of achieving distinct climate change mitigation goals (Hare et al 2018). A crucial dimension that supports the case for an integrated approach is the phenomenon of intersectoral knowledge spillover. This refers to the transfer of knowledge and ideas across different sectors of the economy (De Vincenti 2007). Recognizing this effect augments the analysis by capturing technological knowledge influences that are not confined to a single sector (Murat and Pigliaru 1998). To illustrate, consider the potential of hydrogen utilization and production for light-duty vehicles & energy storage. As this production escalates, the ensuing economies of scale could drive down the marginal costs over the years. Consequently, the now cheaper hydrogen could become a feasible option for marine transportation. Such interconnected impacts remain elusive to single-sector approaches. So, while looking at the shipping industry can be useful for short-term questions, an integrated approach is better for understanding the bigger picture, especially when considering implications like climate change mitigation.
2. **Dimensionality:** Analyzing international maritime shipping through the lenses of demand, supply, and emissions offers a comprehensive perspective on the sector. Demand pinpoints the required shipping activity in tonne-nautical miles (ton.nm) or equivalent units, which subsequently informs the fuel demand side on how these needs can be met and by which fuels. The chosen supplying fuels, along with efficiencies, determine the emissions produced by the sector. Taking such an integrated approach provides a more accurate projection of future scenarios and improves the coherency among these different sides by ensuring consistent and aligned assumptions underlying the model. In the past, some studies, like Xing et al (2021) and Esmeijer et al (2020), have studied only one side, such as the supply side and emission side, respectively. In contrast, others, like Müller-Casseres et al (2021b), have embraced a wider perspective, addressing demand, emissions, and policy implications. The more sides of maritime shipping we incorporate, our understanding becomes clearer and more comprehensive. Figure 1 illustrates the integrated nature of international maritime shipping within the broader picture and its impact on cli-

mate change. Transportation as a whole contributes to emissions, with maritime shipping being a significant sub-sector. Maritime shipping is driven by international trade demand, which is influenced by economic growth and macroeconomic factors. These economic drivers affect shipping activity (demand side), which in turn influences the fuel supply and vessel types (supply side). These factors are regulated by specific policies, which determine the resulting emissions. These emissions contribute to overall greenhouse gas emissions, linking maritime shipping directly to climate trajectories. This chain underscores the role of international maritime shipping in the bigger puzzle.

3. **Technology Range:** The choice of either narrowing down on one or two technologies, fuels, and vessels or exploring a wider range of options largely depends on the research question and study objectives. A focused study on a single technology, fuel, or ship type can provide detailed insights into its advantages and drawbacks. However, expanding the study to include various options gives a wider perspective. This includes understanding trade-offs, synergies, and the interplay between different technologies, fuels, vessels, and associated policy implications. Also, Including technologies like BECCS (Bioenergy with Carbon Capture and Storage) and DAC (Direct Air Capture) in the study is crucial since they have undeniable effects on the strategy and cost-effectiveness of climate targets (Köberle 2019). Relying on a limited set of options might lead to projections that don't capture the full landscape. The rationale behind this is underscored by the notion that in a techno-economical study, incorporating all alternative fuels is pivotal for understanding the complementary role each can play in future energy frameworks (Stančin et al 2020). Illustrating this, studies like those by Elgohary et al (2015), Inal et al (2022), and Watanabe et al (2022) focused on specific fuels like LNG, hydrogen, and drop-in biofuels, respectively. Contrastingly, research undertakings by Xing et al (2021) and Ampah et al (2021) cast a wider net, investigating multiple alternative fuels.
4. **Geographical Scope:** The choice between a global or a region-specific study also depends on the research question and objectives. For this study, a global approach suits well because of the global nature of shipping and climate mitigation targets. A

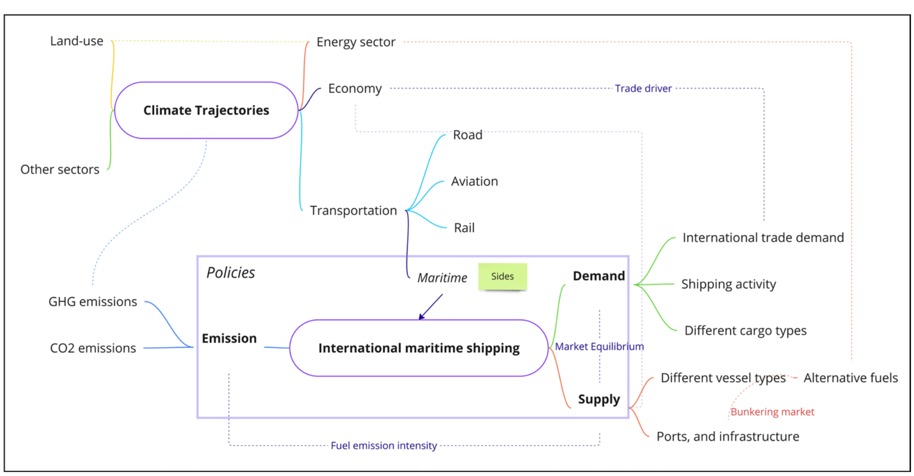


Fig. 1 The integrated nature of international shipping with other parts of the economy

global study offers a detailed analysis of possible strategies for cutting emissions in the shipping sector while also recognizing the trade-offs and synergies among different geographic regions and policy alternatives. One important factor to capture in the global approach is international spillovers. This is when something big that happens in one country's economy or technology sector affects another country. For example, if one country comes up with a new technology, another country might learn from it and boost its industry after a time lag (Kramel et al 2021). This shows why a global perspective is valuable. Also, a global study allows the inclusion of trade distances between bilateral regions, which is key to determining shipping demand activity. Supporting this stance, specific regional studies, such as those by Yang et al (2017) on China and Müller-Casseres et al (2021a) on Brazil, might illuminate regional intricacies but don't necessarily provide a comprehensive global snapshot.

5. **Scenario Evaluation:** The scope and depth of policies and scenarios in the studies under review varied, with some offering a singular perspective while others presented multiple policies, regulations, or scenarios. Benchmarking multiple scenarios enriches the analytical depth, enabling a comparative evaluation of intervention effects. This range of scenarios allows us to explore different intervention and their impacts. Regulatory measures include emission price controls, which may manifest as taxes contingent on fuel's pollutant profile, emission quantity controls that set carbon budgets over time frames, and subsidies dispensed by authoritative bodies to enhance specific industry sectors (Less et al 2010; Nikolakaki 2013; Anderson et al 2017; Harrison et al 2005). Emissions Trading System (ETS) is a mechanism that operationalizes the "polluter-pays principle" and incentivizes stakeholders to curtail their emissions. The ETS operates on a cap-and-trade foundation, allocating emission allowances to regulated entities. Notably, on July 14, 2021, the maritime sector's GHG emissions were proposed to be encompassed within the EU ETS's purview (Lagouvardou et al 2022; Lagouvardou and Psaraftis 2022). Recently European Commission announced that Europe will include maritime emissions in its Emissions Trading System starting in 2024, covering emissions from large ships and incentivizing energy efficiency and low-carbon fuels to achieve climate neutrality by 2050 (European Commission 2023). Other strategies include the bunker levy, which has the potential to precipitate notable short-term emission reductions. Additionally, IMO has ratified measures such as the Energy Efficiency Design Index (EEDI), which mandates efficiency benchmarks for vessels post-2012, along with the Energy Efficiency Existing Ship Index (EEXI), the Ship Energy Efficiency Management Plan (SEEMP), and the Carbon Intensity Indicator (CII) (Transport and Environment 2018; DNV 2021). Integrating this discussion with the role of scenario benchmarking, it becomes clear that such an analytical tool is required for future planning, especially given the inherent uncertainties (Khosravi and Jha-Thakur 2019). Comparing scenarios and policies helps decision-makers understand various future outcomes, enabling them to make informed decisions.

Based on the outlined criteria that are depicted in Fig. 2, publications were evaluated on a scale from 0 to 10, with 2 points allocated for each criterion. Each criterion was assigned an equal weight. Regarding "Dimensionality", three sides of international maritime shipping-demand, supply, and emissions-are considered. For each side addressed, a score of 0.66 is awarded. For example, a study focusing solely on emissions receives a 0.66 score, whereas a study examining all three sides achieves the full 2 points. Concerning other criteria, scores are awarded as either 0 or 2. To be more clear, for the "sectoral integration", "technology range", "geographical scope", and "scenario evaluation" a score of 0 means that the study is sector-specific (not integrated), incorporates only one technology, is region-specific, and includes a single or no scenario for benchmarking. In contrast, a score of 2 signifies that the study integrates across sectors, includes multiple technologies, has a global focus, and evaluates multiple scenarios, respectively. Then, studies below 4 points have been eliminated. A more detailed scoring table with details of scores of each criterion is presented in the Appendix A. Our review focuses on studies that show what the future might look like for the international maritime sector. We specifically examined research that presents at least one detailed scenario. Initially, 179 papers were found, out of which 104 were deemed relevant through skimming and were selected for further review. Among these, 28 studies were rated sufficiently. Studies that obtained the score but do not depict a scenario of the future are used for qualitative assessment.

This approach is practical for selecting qualified publications for further analysis. We will now discuss the future predictions from the papers to better understand the outcomes and presented information. Then, the underlying assumptions will be evaluated.

Models and forecasts

As mentioned earlier, the main sides of international maritime shipping are listed as the demand side, supply side, and emissions. The results for each one will be discussed hereafter. The data gathered and presented in this section is important to understand the current ranges and most repeated estimations in the field and also to understand what

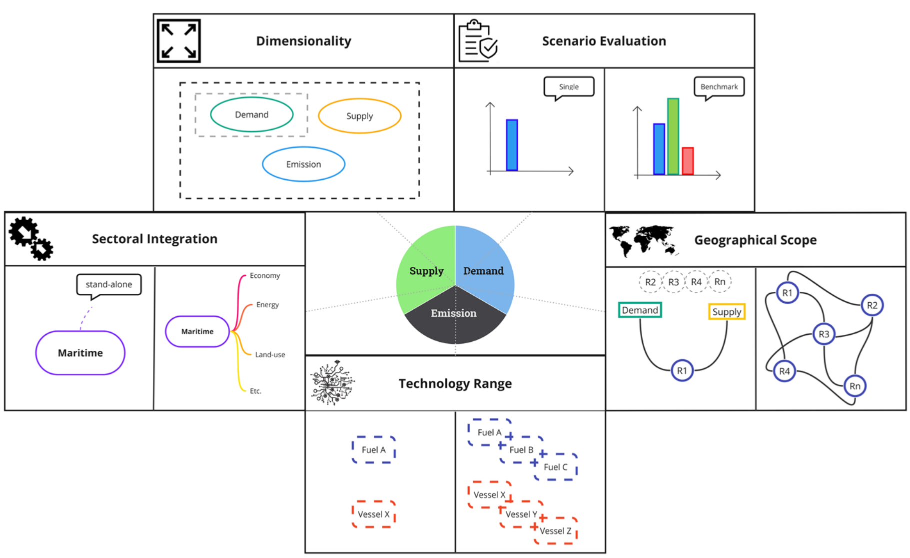


Fig. 2 Five defined criteria to match the study requirements for global carbon neutrality of international shipping context

variables and assumptions derive those estimates. Note that different studies cover different sides, and thus, not all will be referred to in each section.

Shipping activity demand

In this research, demand refers to shipping activity or transport work in [mass × distance] units. In 2021, the total volume of international maritime trade, including crude oil, tanker trade, and dry cargo, was 10.98 GTon/year of loaded goods, as reported by the United Nations Conference on Trade and Development (UNCTAD 2022). Ton-miles are estimated by Clarksons Research based on its data on seaborne trade and maritime distances as 58,988 billion ton-miles (Clarksons Research 2022). Various approaches have been employed to forecast demand. Traditionally, the relation between economic activity and freight transport is used to make forecasts of future aggregate freight flows and volumes (Meersman and Van de Voorde 2013). Given the role of maritime transport in linking global supply chains and supporting trade, the relationship between GDP and trade is fundamental to all forecasting methods. Some studies estimate the future amount of shipping demand in mass-based metrics. Considering the objective of emission estimation, this gives an incomplete picture. To be able to link the demand to supplying fuels and, thereafter, to emissions, the discussion of shipping distances is imperative.

Müller-Casseres et al (2021b) employed the "IMAGE" integrated assessment model (IAM) to study various socio-economic pathways. A framework has been established by the climate change research community known as the Shared Socioeconomic Pathways (SSPs). This framework facilitates the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The pathways were developed over the last years as a joint community effort and describe plausible major global developments that together would lead in the future to different challenges for mitigation and adaptation to climate change (Riahi et al 2017). The projections are based on a demand-driven approach using the IMAGE model. The model generates yearly mass-based trade matrices for each product, which are used to obtain long-term projections of global trade according to six scenarios. They considered proxy ports for each region to calculate the shipping distance and estimate the transport work requirement. Their projections vary significantly across scenarios. The 'SSP2-mit' scenario, based on global climate policy, forecasts a moderate increase in global maritime transport demand, 31% by 2035 and 127% by 2100. In contrast, the 'SSP5' scenario, which assumes fossil-fueled development and high economic growth, predicts much larger increases, 145% by 2035 and 388% by 2100. Such variations indicate the profound influence of economic conditions, policy considerations, and population growth patterns on maritime transport demand.

DNV (2018) utilized their proprietary model, projecting a 50% increase in global maritime shipping demand by 2035 and 2050, with no data available for 2100. The tool is a demand-driven model in which the main drivers of energy demand are energy efficiency, population, and GDP. The absence of longer-term predictions underscores the challenges in forecasting farther into the future.

Walsh et al (2019) leveraged the "TIAM" integrated assessment model for their projections. The methods used to forecast these scenarios are based on a combination of historical data analysis, expert input, and modeling. The authors used historical data on the production and trade of non-energy, non-containerized goods to estimate the relationship between changes in output and changes in trade. They then used this relationship to project future trade patterns based on scenario-specific adjustments. Their findings span a range of projected outcomes. From the 'MR2C' scenario, which anticipates a 26% increase of globally traded goods by 2035, to the 'GR' scenario, with a notable 63% rise by 2050, driven by high biomass and high CCS. On the other end of the spectrum, the 'HR' scenario, pivoting around a $4°C$ rise and low biomass use, predicts a 106% increase of traded goods by 2035 and an even more significant 191% increase by 2050. The discussion of shipping distances is missing in the study, and the lack of transport work remains a shortcoming. The variance in these projections shows the significant role of environmental considerations and the impact of technology assumptions such as CCS and biomass availability.

Halim et al (2018) adopted the International Freight Model (IFM) for their analysis. the modeling approach used in the study is a four-step freight transportation modeling approach, which takes the OECD trade projection as an input. The International Freight Model (IFM) is designed to estimate the weight of commodities traded between countries, the choice between modes and transport routes used to transport these commodities based on transport network characteristics, and relevant socioeconomic variables such as transport costs and time. The model consists of four components: trade flow disaggregation model, value-to-weight model, mode choice model, and route choice model. Their projections span from 'Scenario B', which anticipates a %40 global transport work demand increase by 2035, due to a 20% rise in intraregional trade combined with reduced fossil fuel commodity trade, to the 'Baseline' scenario projecting a %62 increase by 2035. These figures underscore the potential effects of regional trade dynamics.

Eyring et al (2005) utilized a straightforward linear Regression analysis with GDP as the only independent variable. Their projections start with the 'TS1' scenario, which assumes an annual GDP growth of 2.3%. Under this scenario, traded goods are expected to increase by 22% by 2035 and by 78% by 2050. On the other end, the 'TS4' scenario predicts a more robust annual GDP growth of 3.6%. According to this scenario, traded goods would see a 97% increase by 2035 and a 238% increase by 2050 in mass units. However, there is no discussion of shipping haul, and they only study the amount of traded goods on a mass basis. These figures demonstrate the direct correlation between GDP growth rates and the expansion of maritime transport demand.

A noteworthy contribution is by Michail (2020), who looked into the relationship of demand not just with GDP but also with the oil price. They employed a Vector Error Correction Model (VECM) to capture the long-run relationship of seaborne transport demand with world GDP and the price of oil, considering variations by countries' income. Although the study did not offer precise future demand values, its insights into the effects of oil price and income on maritime trade contribute to a better understanding of factors impacting future shipping demand.

(IMO (2020), pp. 345–366) combined Regression analysis with IAM for their predictions. The study forecasts future transport work using two main methods. The logistic analysis assumes that the relationship between transport work and its driver (total GDP) follows a logistic (S-curve) pattern. On the other hand, the gravity model assumes a linear relationship based on panel data of bilateral trade flows. Both methods base their projections on historical trends and data from the Shared Socio-Economic Pathways (SSPs). In total, 24 scenarios are created. For a focused analysis, and to align with the scope of other studies, we selected 8 representative scenarios from the complete set. This selection was curated to include the scenarios with the lowest and highest projected growth rates, the 'middle of the road' SSP2-based projections, and to capture variations across different SSPs, RCPs, and modeling methods. Their projections span a diverse set of outcomes. The 'SSP4-RCP26-G' scenario projects the smallest increase of 16% by 2035, and the 'SSP5-RCP60-L' scenario predicts the most substantial rise of global transport work (ton.nm) potentially to more than doubling by 2050, reflecting a 210% increase. Under the SSP2 pathway, the 'SSP2-RCP19-G' scenario anticipates a 20% increase in transport work by 2035, whereas the 'SSP2-RCP26-L' foresees a significant increase to 91% by 2050. These results vary depending on the long-term socio-economic and energy scenarios, and different methods to establish the relation between transport work and relevant drivers. The logistic model results generally show higher growth than the gravity one.

Insights driven by the demand results are listed below:

- **Growth Variability:** Maritime transport demand growth is susceptible to diverse factors, with projections varying significantly across studies and scenarios.
- **Economic Imperatives:** Regional and global economic growth emerges as a pivotal determinant. Higher GDP growth rates generally correlate with steeper demand increases.
- **Environmental and Policy Interventions:** Scenarios rooted in sustainability or global climate policy tend to project moderated growth, emphasizing the dampening potential of environmental considerations and policy measures.
- **Modeling Complexity:** The choice of forecasting models and tools can influence outcomes, reflecting the inherent complexities in modeling maritime demand.
- **Future Uncertainties:** Long-term projections, especially those for 2100, are sparse, underscoring the inherent challenges in forecasting farther into an uncertain future.

The data of all studies are gathered in Table 1 and Fig. 3. All in all they illustrate an obvious upward trend in the forecasted international shipping transport demand from 2035 to 2100. This trend, especially evident in the consistent growth rate between 2035 and 2050 and the increased variability in projections for 2050, underscores the expected progression of the sector. By 2100, the forecasts show less variation and seem more certain, but this is because there are fewer data points to consider. The wide range of forecasts for 2050 highlights the uncertainties or differing opinions on factors influencing transport demand during that period. Nonetheless, while the trajectory of maritime transport demand growth is upward, the magnitude and rate of this growth remain influenced by numerous socio-economic, policy, and environmental factors.

Table 1 Summary of seaborne trade demand's evolution forecasts

Source	Tool	Units	Scenario	Description	Forecasted increase% (2020 baseline)		
					2035	**2050**	**2100**
Müller-Casseres et al (2021b)	IAM (IMAGE)	Ton-nm	SSP1	Sustainability - Rapid and sustainable economic growth, low inequality, and low population growth	63%	81%	81%
			SSP2	Middle of the Road - Moderate economic growth, medium inequality, and medium population growth	72%	109%	200%
			SSP2-mit	Climate policy scenario: This scenario assumes that a global climate policy is implemented	31%	54%	127%
			SSP3	Regional Rivalry - Uneven economic growth, high inequality, and declining population growth	45%	60%	154%
			SSP4	Inequality - High economic growth, high inequality, and declining population growth	54%	90%	100%
			SSP5	Fossil-fueled Development - High economic growth, high inequality, and high population growth	145%	228%	388%
Walsh et al (2019)	IAM (TIAM)	Ton	GR	2C scenario - RCP2.6 - SSP1 (Sustainability) - high biomass - high CCS	36%	63%	-
			HR	4C scenario - RCP8.5 - SSP5 (Fossil-fueled Development) - low biomass - low CCS	106%	191%	-
			MR2C	2C scenario - RCP2.6 - SSP2 (Middle of the Road) - moderate biomass - moderate CCS	26%	40%	-
			MR4C	4C scenario - RCP8.5 - SSP2 (Middle of the Road) - moderate biomass - moderate CCS	45%	82%	-

Table 1 (continued)

Source	Tool	Units	Scenario	Description	Forecasted increase% (2020 baseline)		
					2035	2050	2100
Halim et al (2018)	International Freight Model (IFM)	Ton-km	Baseline	No additional measures are taken beyond those already in place	62%	-	-
			Scenario A	20% rise in intraregional trade	50%	-	-
			Scenario B	20% rise in intraregional trade + reduction in trade of fossil fuel commodities	40%	-	-
Eyring et al (2005)	Regression analysis	Ton	TS1	Annual GDP growth of 2.3%	22%	78%	-
			TS2	Annual GDP growth of 2.8%	60%	150%	-
			TS3	Annual GDP growth of 3.1%	80%	180%	-
			TS4	Annual GDP growth of 3.6%	97%	238%	-
DNV (2018)	DNV model	Ton-nm	-	-	50%	50%	-
IMO (2020)	Regression analysis + IAM	Ton-nm	SSP2_RCP19_L	SSP2 (Middle of the Road) GDP projections, RCP 1.9, Logistics model	20%	34%	-
			SSP2_RCP26_G	SSP2 (Middle of the Road) GDP projections, RCP 2.6, Gravity model	46%	91%	-
			SSP4_RCP26_G	SSP4 (Inequality) GDP projections, RCP 2.6, Gravity model	16%	35%	-
			SSP4_RCP26_L	SSP4 (Inequality) GDP projections, RCP 2.6, Logistic model	44%	83%	-
			SSP5_RCP60_G	SSP5 (Fossil-fueled Development) GDP projections, RCP 6.0, Gravity model	56%	100%	-
			SSP5_RCP60_L	SSP5 (Fossil-fueled Development) GDP projections, RCP 6.0, Logistic model	91%	210%	-
			OECD_RCP26_L	OECD's GDP projections, RCP 2.6, Logistics model	24%	43%	-
			OECD_RCP26_G	OECD's GDP projections, RCP 2.6, Gravity model	37%	66%	-

Table 1 (continued)

Source	Tool	Units	Scenario	Description	Forecasted increase% (2020 baseline)		
					2035	**2050**	**2100**
Martinez et al (2014)	International Freight Model (IFM)	Ton-km	Baseline	Trade agreements remain unchanged until 2060	60%	202%	-
			Bilateral	Bilateral "Free Trade Agreement" between major regions, cutting 50% of tariffs by 2030, abolishing tariffs by 2060,	62%	220%	-
			Multi-lateral	Global tariffs and agricultural support in regions are halved by 2060, Regulatory barriers adjusted in the FTA	70%	245%	-

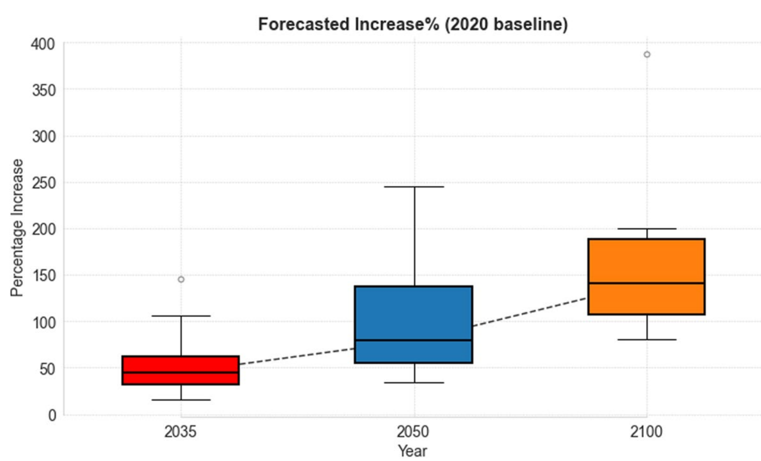


Fig. 3 Summary of global seaborne trade demand forecasts with uncertainties in 2035, 2050 and 2100

Energy efficiency

We need to consider the load factor and efficiency improvements to transition from transport demand in [mass × distance] units to the energy demand of ships in energy units. The load factor varies as some ships may travel fully loaded in one direction and return empty such as in the case of long-term contract oil carriers (Masten 2009). Also, not all vessels operate with full cargo, leading to more actual vessel usage and higher energy demand for a given transport demand. Efficiency improvements include technological, operational, and alternative energy sources. Technologically, optimizing the ship's hull design and applying specialized coatings can reduce water resistance and fuel consumption. Waste heat recovery systems utilize the engine's heat to enhance energy efficiency. Improving the ship's auxiliary systems, like lighting and air conditioning, reduces energy use, while exhaust treatment technologies lower emissions. Engine performance can be enhanced through design and material advancements, contributing to more efficient fuel use. Operationally, speed optimization, or slow steaming, reduces fuel consumption, while route optimization ensures travel efficiency and efficient cargo handling in ports and minimizes turnaround time. Regarding alternative energy sources, solar panels can provide auxiliary power, slightly reducing CO2 emissions, but their overall impact on the ship's power needs is limited. Wind assistance technologies like Flettner rotors and sails offer potential fuel savings, though adoption varies due to technological and industry factors (Balcombe et al 2019; IMO 2020). Wind propulsion, when paired with voyage optimization, can enhance carbon savings beyond 30% by leveraging wind conditions. Slower sailing speeds can further boost these savings, with potential overall reductions reaching up to 60%, showcasing the considerable CO2 reduction achievable with current technologies (Mason et al 2023).

The approach in studies varies. Some studies modeled efficiency improvement, and it comes as a result of the model, while others make assumptions on exogenous improvement values. Müller-Casseres et al (2021b) defines two efficiency scenarios. The 'incremental gain scenario', utilizing efficient hull design and energy efficiency policies, assumes 30% and 35% improvement by 2050 and 2100 with the year 2020 as a reference point. The 'high gain scenario', by considering auxiliary propulsion improvement and slow steaming, assumes 40% and 50% improvement instead. In the first scenario, the total energy demand from international shipping lies in the range of 12-25 EJ in 2050 and 18-46 EJ in 2100. With higher efficiency gains, the energy demand lies in the range of 9-17 EJ in 2050 and 13-32 EJ in 2100. The efficiency scenarios are exogenously assumed. Müller-Casseres et al (2021a) modeled efficiency gains to align with EEDI, resulting in a more efficient fleet by 20% and 30% by 2030 and 2050 with respect to 2010. DNV (2022) defines 5 distinct energy efficiency packages. Baseline Energy Efficiency (EE) covers vessels built before 2015, focusing on essential operational and maintenance practices such as hull cleaning and engine tuning. Basic EE applies to ships made between 2015 and 2020, featuring hull design enhancements and propulsion system improvements. Enhanced EE, for the 2020–2025 period, plans to integrate advanced energy systems, including batteries and waste-heat recovery. Looking ahead to 2025–2030, Advanced EE aims to implement renewable energy technologies like hard sails and solar panels. Beyond 2030, Cutting-edge EE is set to introduce innovative technologies, including digital twins and onboard wind turbines, representing the leading edge of maritime energy efficiency development. Their model also assesses speed reductions at levels from 0% to 50%, analyzing fuel savings using data from over 2,000 vessels. Greater power savings occur at 10% and 20% reductions than at higher reductions due to wind and wave resistance. Fuel consumption decreases by 30-35% at 20% speed reduction and 60-67% at 50%. However, speed reduction reduces transport capacity, necessitating more vessels and increasing costs due to longer transit times. In Horton et al (2022), three efficiency packages are assumed. Package 1 integrates medium energy efficiency measures with a 10% speed reduction and transitions to zero-carbon fuels by 2035. Package 2 continues medium efficiency improvements and a 20% speed reduction from 2025. Package 3 maximizes energy efficiency technologies and operational measures with a 30% speed reduction, introducing advanced decarbonization technologies and alternative fuels by 2035. This type of assumption could be valuable to understand the effects of different measures, but not necessarily reflect the real case scenarios. (IMO (2020), pp. 400–404) shows an average efficiency improvement of around 15% for both gravity and logistic models applied within the maritime sector. Specifically, bulk carriers exhibit the highest potential for efficiency gains, while passenger ships show the least improvement. The improvements are the results of the models. In Smith et al (2016) model runs across various scenarios and forecasts significant efficiency improvements for maritime vessels by 2050, using 2010 as the baseline. dry bulk carriers see enhancements ranging from 40% to 63%. Container ships have a projected improvement span of 10% to 36%, while tankers are expected to achieve efficiency gains between 21% and 50%. Esmeijer et al (2020) indicates that efficiency standards are often not captured adequately within IAMs, suggesting to improve the representation of efficiency improvements and standards.

Supplying fuels

In this research, supply refers to supplying fuels to the ships required to satisfy the demand for transport activity. The maritime sector currently depends almost entirely on oil-based, high-emitting fuels such as heavy fuel oil (HFO) and Marine Fuel Oil (MFO) (UNCTAD 2021). The sector must diversify its energy sources to transition towards a more sustainable future, moving away from solely oil-based options. The International Maritime Organization's (IMO) decarbonization target emphasizes the need for this shift, and the exploration of alternative carbon-neutral fuels has gained momentum Herdzik (2021); Law et al (2021); Xing et al (2021).

To comprehend the choices available, knowing the advantages and disadvantages of each potential fuel is vital. Ampah et al (2021) offers a detailed exploration of the pros and cons of each fuel option. In the evaluation of potential fuels for the maritime sector, each fuel brings its unique set of advantages and challenges. LNG stands out for its competitive pricing and the availability of supporting infrastructure and technologies. However, its storage requirements and inability to meet stringent CO_2 reduction targets pose concerns. LNG, often viewed as a transition fuel, also features prominently, reinforcing its bridging role as the industry moves toward a greener future Brauers et al (2021). The study in Bengtsson et al (2011) employs a life cycle assessment (LCA) to compare heavy fuel oil, marine gas oil, gas-to-liquid, and LNG, alongside exhaust treatments. They found that LNG significantly reduces acidification and eutrophication but has a minimal effect on global warming potential, achieving only an 8-20% reduction. Hydrogen offers a promising path to zero emissions, especially when combined with fuel cells, and its potential for on-site production near ports. Yet, its low energy density, high costs, and absence of infrastructure present significant obstacles. Ammonia, versatile in its usage in combustion engines and fuel cells, is limited by its toxicity, high operational costs, and current production's GHG emissions. Biofuels, including methanol and HVO, align well with the sector's carbon-neutral targets and compatibility with existing systems, but they grapple with high costs, limited production capacity, and variability in quality Van der Kroft and Pruyn (2021). Lastly, Electricity promises zero emissions with high efficiency, but its applicability remains confined to short-range, low-power vessels due to prohibitive capital costs and current battery technology limitations. The uncertainty surrounding the future usage of these alternative fuels in the maritime energy mix remains high. This is largely due to their current absence in the prevalent mix. The eventual types of fuels to be adopted in the future will be influenced by various factors, as observed in the following studies.

Table 2 lists the main advantages and disadvantages of alternative marine fuels, and Table 3 presents a comprehensive summary of maritime shipping's projected fuel mix for 2050, as indicated by various studies.

Using the Global Transport Model (GloTraM) as its foundation, the study presented in Register (2016) and Smith et al (2016) a detailed exploration of the maritime fuel landscape for 2050. GloTraM is a specialized simulation tool employed in the shipping industry to investigate future scenarios. This model is particularly adept at estimating CO_2 emissions by combining various modeling techniques, focusing on fleet evolution up to 2050. At its core, GloTraM operates by modeling the profit maximization of shipowners under macroeconomic, market, and regulatory scenarios. It uses a range of assumptions regarding the availability of different fuels, machinery, and technologies. The study spans various scenarios, from the "BAU" where traditional Oil-based fuels remain dominant at 75%, and LNG accounts for 22%, to "Scenario 3", which forecasts a significant shift with 58% Oil-based, 29% LNG, and an introduction of Biofuels at 13%. The study highlights how carbon budget, fuel viability, and biomass availability shape the maritime fuel mix. Another more recent study by Carlo et al (2020) used the GloTram model. Providing two scenarios of decarbonization by 2050 and decarbonization by 2070, they suggest that the fuel mix will be dominated by ammonia. Detailed assumptions of recent scenarios remain undisclosed.

Table 2 General advantages and disadvantages of alternative marine fuels

Fuel	Advantages	Dis-advantages
LNG	• Competitive fuel price • Available infrastructure and technologies	• Must be stored in insulated tanks • Cannot comply with huge CO_2 reduction
Hydrogen	• Enable zero-emission (with fuel-cell) • Can be produced from electrolysis near ports	• Low energy density (50% of LNG) and large storage tanks • Extensive flammability range imposes the need for safety mitigating measures at an added cost • Expensive CAPEX and OPEX are around three times greater than LNG and viable production likely decades away • Absence of supply, bulk storage, and bunkering infrastructure
Ammonia	• Can be used in various combustion engines as well as fuel cells • Can be stored at relatively low pressure and high temperature (liquefied ammonia)	• High toxicity imposes the need for safety mitigating measures at an added cost • Excessive high OPEX-green ammonia is up to 4x LNG cost • Absence of bunkering and bulk infrastructure along major cargo routes • Current production generates undesirable high GHG emissions.
Biofuel (Methanol, HVO, etc.)	• Can be carbon neutral • Compatible with existing infrastructure and engine systems	• Expensive • Extremely limited due to land competition for food • Production capacity and bunkering availability • Quality and consistency of production varies; lack of agreed fuel standards,• High NOx and Particulate Matter emissions
Electricity	• Enable zero-emission • High efficiency	• Prohibitive CAPEX costs; battery technology not practicable for large oceangoing ships, battery costs could exceed the new build cost of a vessel • Applicability - limited to short-range low-power coastal vessels

Table 3 Summary of maritime shipping's fuel mix forecasts in 2050

Source	Tool	Scenario	Description	Fuel mix of International maritime shipping in 2050					
				Oil-based	LNG	Biofuels	Ammonia/ Hydrogen	Methanol	Electricity
DNV (2022)	DNV model	A	IMO 2018 ambitions, low biofuels	32-38%	20-29%	33-43%	0-1%	1-2%	3-4%
		B	IMO 2018 ambitions, low efuels	34-39%	19-26%	0-38%	3-14%	0%	3-4%
		C	IMO 2018 ambitions, low fossil fuels	28-40%	22-38%	22-35%	2-15%	0%	3-4%
		D	Decarbonization by 2050, low biofuels	0%	0%	92-96%	0-1%	0-45%	3-4%
		E	Decarbonization by 2050, low efuels	0%	0%	34-70%	24-35%	0%	3-4%
		F	Decarbonization by 2050, low fossil fuels	0%	0%	41-80%	16-54%	0%	3-4%
DNV (2018)	DNV model	-	-	35%	20%	40%			5%
Horton et al (2022)	Global vessel fleet model	Package 1	SSP2, RCP2.6| Ammonia/ hydrogen from 2025, grey-green transition, 10% speed cut	12%	10%	0%	78%	0%	0%
		Package 2	SSP2, RCP2.6| Biofuels from 2025, 20% speed cut	1%	1%	98%	0%	0%	0%
		Package 3	SSP2, RCP2.6| High tech, ammonia/ methanol by 2035, 30% speed cut, carbon capture	10%	1%	49%	20%	20%	0%
Halim et al (2018) (for 2035)	ITF International freight model	-	80% carbon reduction factor, carbon pricing to reach 500 US$/tonne by 2035	2%	3%	25%	70%	0%	0%
ABS (2022)	-	-	-	28%	14%	0%	42%	26%	0%

Table 3 (continued)

Source	Tool	Scenario	Description	Fuel mix of International maritime shipping in 2050					
				Oil-based	**LNG**	**Biofuels**	**Ammonia/ Hydrogen**	**Methanol**	**Electricity**
Register (2016) & Smith et al (2016)	GloTraM model	BAU	No carbon budget, RCP2.6, SSP3, all fuels excluding hydrogen	75%	22%	3%	0%	0%	0%
		Scenario 1	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 20% out-sector offsets, low bio	38%	16%	3%	43%	0%	0%
		Scenario 2	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 20% out-sector offsets, high-bio	38%	6%	21%	35%	0%	0%
		Scenario 3	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 50% out-sector offsets, high bio	58%	29%	13%	0%	0%	0%
Franz et al (2022)	SEAMAPS model	A	200 $/tCO2eq, 30% fuel saving assumption	3%	4%	0%	89%	4%	0%
		B	480 $/tCO2eq, 30% fuel saving assumption	0%	0%	0%	92%	8%	0%
		C	780 $/tCO2eq, 70% fuel saving assumption	0%	0%	0%	98%	2%	0%
Muller-Casseres et al (2023)	IAM - COFFEE	NDC,C1000,C600	Ranges of scenarios: Nationally Determined Contributions (NDC), 1000 and 600 GtonCO2 carbon budget until 2100	48-61%	1-52%	0-29%	0-11%	0%	0%
	IAM - IMACLIM-R			52-75%	0%	25-45%	0-3%	0%	0%
	IAM - IMAGE			72-89%	0%	11-28%	0%	0%	0%
	IAM - PROMETHEUS			13-89%	4-6%	6-58%	0-11%	0-12%	0-2%
	IAM - TIAM-UCL			41-91%	9-41%	0-3%	0-15%	0%	0%
	IAM - WITCH			88-96%	0%	3-5%	3-7%	0%	0%

DNV (2018)'s projection, sketched a potential fuel mix for maritime shipping by 2050. However, the backdrop or narratives guiding these projections remain undisclosed. As per this forecast, biofuels emerge as significant players, constituting 40% of the fuel mix. Oil-based fuels and LNG are projected to contribute 35% and 20%, respectively. DNV's 2018 outlook underlines the maritime industry's inclination towards biofuels while still retaining a significant dependency on established fuels.

In DNV (2022), they delved into the potential maritime fuel mix using their model. The study presented 24 scenarios, which were grouped into six primary sets, each illustrating a unique fuel mix outlook for 2050. Scenarios "A", "B", and "C" align with the previous targets set by the IMO in 2018. Specifically, "Scenario A" assumes a low cost for biofuels, projecting oil-based fuels to constitute between 32% and 38%, LNG ranging from 20% to 29%, and biofuels capturing 33% to 43% of the mix. Other fuels such as ammonia, hydrogen, methanol, and electricity have minor roles, with their contributions hovering between a negligible amount and a modest 4%. "Scenario B", which assumes a low cost for electro-fuels, foresees a diverse fuel mix. In this scenario, oil-based fuels are projected to account for 34-39%, LNG for 19-26%, and biofuels could vary dramatically from 0% up to 38%. Ammonia and hydrogen also hold a presence, ranging from 3% to 14%. "Scenario C", emphasizing a low cost for blue ammonia, offers a different trajectory, with specific details reflecting its unique assumptions. Conversely, Scenarios "D", "E", and "F" pivot towards the ambitious goal of full sector decarbonization by 2050. "Scenario D", echoing the assumptions of "Scenario A", anticipates a low cost for biofuels. Similarly, "Scenario E" mirrors "B" but places its bet on the low cost of electro-fuels, and "Scenario F" parallels "C", spotlighting the low cost of blue ammonia. DNV's insights from 2022 illuminate the maritime industry's capacity for adaptability, with each scenario underscoring the different avenues the sector could take.

Horton et al (2022) used the Global vessel fleet model, which proposes a range of scenarios for the maritime fuel mix by 2050. Horton's methodology incorporated base year inputs from Clarkson and MRV, deploying three demand scenarios as defined by the IMO to model changes in the fleet, emission impacts, and cost implications. However, the specifics of the modeling approach and framework remain undisclosed. A feature of the "Package 1" scenario is its substantial reliance on ammonia and hydrogen, contributing a dominant 78% to the mix. In contrast, "Package 2" foresees a maritime industry powered by biofuels at 98%. Meanwhile, "Package 3" provides a more diversified outlook, showing significant contributions from biofuels, oil-based fuels, and a combination of ammonia and methanol. Gareth Horton's projections reveal the maritime industry's potential tilt towards alternative fuels, influenced by varying technology assumptions.

Franz et al (2022) utilizes a least-cost optimization model (SEAMAPS model) to evaluate the maritime industry's transition with different carbon tax scenarios. It integrates detailed fuel emission profiles, green fuel production costs, production capacity scaling, biomass availability, and climate action measures like carbon pricing and fuel demand reduction. The research identifies methanol and ammonia, produced via green hydrogen, as key to the sector's green transition, contingent on substantial upscaling of electrolyzer capacities. The analysis, based on well-to-wake emissions and including life-cycle fuel production costs, reveals the potential for significant emission reductions through adopting green fuels, particularly green ammonia, under high carbon pricing scenarios. The study's main limitations are the pure assumptions on fuel cost trajectories, biomass resource availability, and the pace of technological advancements.

The 2022 projections by the ABS (2022), albeit lacking detailed scenario narratives, suggest a maritime fuel landscape by 2050 where ammonia and methanol scale up as the primary contributors.

Muller-Casseres et al (2023) gathers 6 different IAMs, to run three sets of scenarios ranging from Nationally Determined Contributions (NDC) scenarios to carbon budget scenarios that limit global carbon emission by 1000 and 600 GTonCO_2 until the end of the century. The paper uses the strength of a multi-IAM analysis of international shipping, showing different scenarios as a result of models. Despite a shared goal, models show variability in predicting the energy future of shipping, influenced by different fuel options and structural trends, such as the shift towards electrification. The study suggests that a diverse portfolio of alternative fuels is crucial for developing green corridors. However, Electricity and methanol are not included in the predicted fuel mix across all models and scenarios, except for the Prometheus model. Additionally, oil persists as a part of the mix even in mitigated scenarios, with the extent of its use depending on each model's structure, where models allow carbon capture technologies to offset the predicted emissions of shipping.

From the knowledge gained from projections (Fig. 4), electricity, despite its sustainable appeal, is not projected to be a primary fuel source for maritime shipping. This is mainly due to energy density and the battery-powered vessels'range limitation. Energy density constraints and refueling considerations impact the feasibility of battery-powered vessels for long-haul shipping (Stolz et al 2022). The projections for hydrogen, ammonia, and biofuels exhibit high variability, emphasizing the existing uncertainty surrounding their adoption. Also, oil-based fuels seem to be present in most of the results, emphasizing the challenge of complete elimination of them. Interestingly, none of the reviewed reports or studies provided regional breakdowns for their fuel mix projections. Those that did offer predictions often lacked robust backing for their estimates, with results mainly driven by predefined scenarios such as high biofuel, low biofuel, low electro, etc.

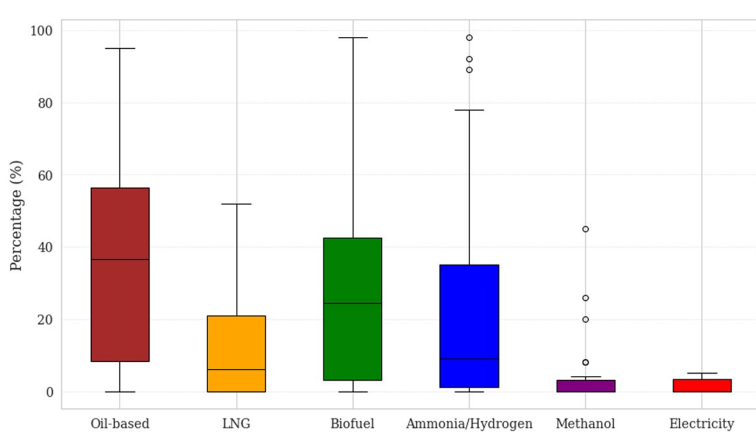


Fig. 4 Summary of global fuel share of different types of marine fuels with uncertainties in 2050

Emission side

Projected emissions are mostly derived from demand and supply forecasts, where demand drivers and the models estimate future demand which has to be met by fuel supply, and the resulting fuel mix, combined with emission intensities and energy efficiency, determines sector-specific emissions. The maritime sector is changing its approach to emissions, influenced by the IMO's new target. The IMO's revised ambitions are clear: a reduction in sector emissions by 20% (with aspirations of reaching a 30% cut) by 2030, culminating in full decarbonization by 2050. These goals stand in contrast to the earlier IMO target, which aimed for a halving of emissions, targeting a value of less than 0.40 Gt CO_2eq/year by 2050.

Table 4 presents and summarizes the estimated CO_2 emissions for the years 2030 and 2050. It also contains scenarios depicting those values with the corresponding description.

The research by Müller-Casseres et al (2021b) utilizes the IAM (IMAGE) tool to forecast CO_2 emissions by 2050 across various SSPs, which have been explained earlier. For the SSP1 scenario, CO_2 emissions are projected to be in the range of 1.2 to 1.6 GtCO_2/year by 2050. The SSP2 scenario anticipates emissions between 1.2 and 1.7 GtCO_2/year. The SSP2-mit scenario, emphasizing global cooperation to achieve the Paris Agreement's objectives, projects a more optimistic range of emissions between 1 and 1.4 GtCO_2/year. In contrast, the SSP3 scenario expects emissions between 0.8 and 1.2 GtCO_2/year, while the SSP4 scenario projects emissions between 1.2 and 1.6 GtCO_2/year. The SSP5 scenario is the most concerning, forecasting the highest emissions between 2 and 2.6 GtCO_2/year. The variance in projected emissions across these scenarios highlights the significant impact of socioeconomic factors, policy decisions, and technological pathways on the future of marine-related CO_2 emissions.

In a detailed study by Horton et al (2022), various potential futures for marine CO_2 emissions were presented using the Global vessel fleet model. Horton grouped his predictions into three main categories. The first set of predictions highlights a move from using grey to green hydrogen, with an introduction of ammonia and hydrogen as marine fuels starting in 2025. Additionally, this group anticipates electric ships for shorter routes by 2045. The second group centers on using biofuels from 2025 and suggests ships could reduce their speed by 20% to cut emissions. The third category, termed the "high-tech" approach, expects ships to start using ammonia and methanol by 2025, with a gradual switch from grey to green hydrogen after 2040. Importantly, Horton's data indicates that early use of alternative fuels and electrification can lead to the lowest emissions, with figures dropping to as low as 0.18 GtCO_2/year by 2050 in some scenarios. On the other hand, scenarios heavily reliant on biofuels without additional changes could result in the highest emissions, reaching up to 1.1 GtCO_2/year by 2050. This study underscores the significant impact of our fuel choices and technological shifts on future marine emissions. One shortcoming is that most of the influential parameters are fixed exogenously throughout the estimations.

In the study by Halim et al (2018), the potential futures of marine CO_2 emissions were explored using the ITF International freight model. The scenarios presented span a spectrum of interventions, from maintaining the status quo to aggressive emission reduction strategies. The "Baseline" scenario, which lacks additional measures, projects CO_2

Table 4 Summary of maritime shipping's emission forecasts in future

Source	Tool	Scenario	Description	Forecasted CO_2 emission ($GtCO_2$ /year)	
				2030	2050
Müller-Casseres et al. (2021b)	IAM (IMAGE)	SSP1	Sustainability - Rapid and sustainable economic growth, low inequality, and low population growth	–	1.2 - 1.6
		SSP2	Middle of the Road - Moderate economic growth, medium inequality, and medium population growth	–	1.2 - 1.7
		SSP2-mit	Climate policy scenario: This scenario assumes that a global climate policy is implemented	–	1 - 1.4
		SSP3	Regional Rivalry - Uneven economic growth, high inequality, and declining population growth	–	0.8 - 1.2
		SSP4	Inequality - High economic growth, high inequality, and declining population growth	–	1.2 - 1.6
		SSP5	Fossil-fueled Development - High economic growth, high inequality, and high population growth	–	2 - 2.6
Horton et al.(2022)	Global vessel fleet model (Sectoral)	Package 1, low	SSP4, RCP6.0| Ammonia/hydrogen from 2025, grey-green transition, 10% speed cut	0.5	0.18
		Package 1, central	SSP2, RCP2.6| Ammonia/hydrogen from 2025, grey-green transition, 10% speed cut	0.58	0.19
		Package 1, high	SSP1, RCP4.5| Ammonia/hydrogen from 2025, grey-green transition, 10% speed cut	0.6	0.2
		Package 2, low	SSP4, RCP6.0| Biofuels from 2025, 20% speed cut	0.62	0.6
		Package 2, central	SSP2, RCP2.6| Biofuels from 2025, 20% speed cut	0.79	0.81
		Package 2, high	SSP1, RCP4.5| Biofuels from 2025, 20% speed cut	0.82	1.1
		Package 3, low	SSP4, RCP6.0| High tech, ammonia/methanol by 2035, 30% speed cut, carbon capture	0.5	0.2
		Package 3, central	SSP2, RCP2.6| High tech, ammonia/methanol by 2035, 30% speed cut, carbon capture	0.59	0.3
		Package 3, high	SSP1, RCP4.5| High tech, ammonia/methanol by 2035, 30% speed cut, carbon capture	0.61	0.48

Table 4 (continued)

Source	Tool	Scenario	Description	Forecasted CO_2 emission ($GtCO_2$ /year)	
				2030	2050
Halim et al.(2018)	International freight model (IFM)	Baseline	No additional measures beyond current	1.1	–
		Adjusted demand	50% coal trade reduction, 33% oil trade reduction	0.85	–
		Ultra-slow operation	Maximum speed reduction and technical measures.	0.18	-
		Low-carbon technology	Technical measures and low-carbon fuels	0.14	–
		Zero-carbon technology	Moderate speed reduction, technical measures, electric ships	0.07	–
		Maximum intervention	Max speed reduction, technical/operational measures, zero-carbon fuels	0.05	–
Eyring et al.(2005)	Regression analysis	TS1	Very low emissions, low sulfur, aggressive NOx cut, advanced tech, 90% NOx reduction by 2050	1.1	1.1
		TS2	Moderate emissions, low sulfur, moderate NOx cut, partial tech adoption	1.15	1.2
		TS3	Complies with IMO, high sulfur, standard NOx cuts, current tech standards	1.3	1.4
		TS4	Maintains current standard, high sulfur, standard NOx cuts, no shift to alternative fuels	1.4	1.5
IRENA (2021)	Sectoral gravity model	BES	Base Energy Scenario (BES): continuation of current energy policies, a 2050 energy demand of 12.4 EJ	0.82	0.92
		PES	Planned Energy Scenario (PES): nations' current energy plans, Paris Agreement NDCs, 2050 energy demand of 11.8 EJ	0.75	0.75
		TES	Transforming Energy Scenario (TES): more ambitious energy policies with a shift towards renewables, 2050 energy demand of 9.5EJ	0.62	0.38
		IRENA 1.5C	IRENA 1.5° C Scenario Paris Agreement's 1.5° C goal, a comprehensive energy shift, 2050 energy demand of 7.9EJ	0.55	0.14
DNV (2023)	DNV model	Scenario 1	No policies lead to 2050 gains offset by shifted emissions, echoing fossil fuels.	1	0.83
		Scenario 2	GHG standards usher in carbon-neutral shipping, aiming beyond 80% emission reduction.	0.98	0.2

Table 4 (continued)

DNV (2022)	DNV model	IMO ambition (old)	ETS allowance 22 to 135 $/t$CO_2$, CII and EEXI requirement: 40% to 75% reduction (2030 and 2050)	0.78	0.42
		Decarbonization2050	ETS allowance 14 to 250 $/t$CO_2$, CII and EEXI requirement: 40% to 100% reduction (2030 and 2050)	0.78	0
IEA (2020)	IEA pathways	Technology Scenario	Focuses on tech solutions for energy demand and decarbonization	1	1.42
		2DS	Aims for a max 2° C global temperature rise by 2100 through energy system overhauls and increased renewables	0.8	0.64
		WB2DS	Targets temperatures Well Below 2° C, urging aggressive measures, rapid sector transitions, and robust policies	0.76	0.4
IMO (2020)	IAMs + Regression analysis	SSP2_RCP1.9_G	GDP and population projections based on SSP2, RCP2.6, Gravity model coupled with IAM	1.04	1.05
		SSP2_RCP2.6_L	GDP and population projections based on SSP2, RCP2.6, logistic model coupled with IAM	1.15	1.46
		SSP4_RCP2.6_G	GDP and population projections based on SSP4, RCP2.6, Gravity model coupled with IAM	1.03	1.04
		SSP4_RCP2.6_L	GDP and population projections based on SSP4, RCP2.6, logistic model coupled with IAM	1.19	1.47
		SSP5_RCP6.0_G	GDP and population projections based on SSP5, RCP6.0, Gravity model coupled with IAM	1.19	1.47
		SSP5_RCP6.0_L	GDP and population projections based on SSP5, RCP6.0, logistic model coupled with IAM	1.38	2.34
		OECD_RCP4.5_G	GDP and population projections based on OECD, RCP4.5, Gravity model coupled with IAM	1	1.14
		OECD_RCP4.5_L	GDP and population projections based on OECD, RCP4.5, logistic model coupled with IAM	1.12	1.37
Eide et al.(2013)	Monte Carlo simulation technique (Sectoral)	Gray	Baseline scenario	1.6	2
		Blue	Incorporating nuclear, biofuel, LNG, and technical/operational measures	0.9	0.6
		Yellow	CO_2 reduction potential is like the blue line but excludes nuclear	1.1	0.9

Table 4 (continued)

Register (2016) & Smith et al (2016)	GloTraM model (Sectoral)	BAU	No carbon budget, RCP2.6, SSP3, all fuels excluding hydrogen	1.05	1.4
		Scenario 1	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 20% out-sector offsets, low bio	1	0.7
		Scenario 2	Carbon budget 33Gt, RCP2.6, SSP3, all fuels, 20% out-sector offsets, high-bio	0.9	0.59
		Scenario 3	Carbon budget 33Gt, RCP2.6, SSP3, all fuels excluding hydrogen, 50% out-sector offsets, high bio	0.85	1
Esmeijer et al (2020)	IAM (IMAGE)	BAU	Baseline scenario	0.75	0.8
	IAM (IMAGE)	Mitigated	2C degree by 2100 scenario	0.62	0.35
	IAM (POLES)	BAU	Baseline scenario	1.2	1.5
	IAM (POLES)	Mitigated	2C degree by 2100 scenario	0.75	0.48
	IAM (MESSAGE)	BAU	Baseline scenario	1.2	1.5
	IAM (MESSAGE)	Mitigated	2C degree by 2100 scenario	0.75	0.48
Wang and Lutsey (2013)	Shipping fleet turnover model	Baseline with EEDI standards	Improves new ship efficiency by 15% by 2015, 20% by 2020, and 30% by 2025 from their 2005 levels	1.15	1.45
		Additional technology	Technology 20% co2 reduction (1.5%/year) from 2025 through 2040	1.1	1.3
		Operational and new ship technology efficiency	Technology 20% co2 reduction (1.5%/year) from 2025 through 2040 operational 20% co2 reduction (1.1%/year) 2015 through 2035	0.9	0.9
		Top 5% industry efficiency leader	Fleet-wide 54% gco2-per-tonne-nm intensity reduction from 2015 to 2035 (3.8%/year) to match 5% highest efficiency cargo-hauling ships in 2011	0.8	0.82

emissions at 1.1 $GtCO_2$/year by 2050. The "Adjusted demand" scenario, which factors in reductions in coal and oil trade, predicts a slightly lower emission of 0.85 $GtCO_2$/year. The introduction of ultra-slow operations and low-carbon technologies further reduces the projected emissions to 0.18 and 0.14 $GtCO_2$/year, respectively. Notably, the "Zero-carbon technology" scenario, which merges speed reduction and alternative fuels, forecasts a substantial drop to 0.07 $GtCO_2$/year. The most assertive approach, the "Maximum intervention" scenario, anticipates the lowest emissions at 0.05 $GtCO_2$/year. This research underscores the significance of technological and operational shifts in reducing marine CO_2 emissions and emphasizes the potential of aggressive interventions.

In the work by Eyring et al (2005), marine CO_2 emissions were forecasted using a linear regression analysis approach, leading to four distinct scenarios. The TS1 scenario, characterized by very low emissions and aggressive controls on nitrogen oxides (NOx), projects emissions to remain stable at 1.1 $GtCO_2$/year from 2030 to 2050. TS2, which assumes moderate emissions and NOx controls, anticipates a slight increase from 1.15 $GtCO_2$/year in 2030 to 1.2 $GtCO_2$/year by 2050. The TS3 scenario, aligned with the old IMO efficiency standards, forecasts emissions to rise from 1.3 $GtCO_2$/year in 2030 to 1.4

GtCO$_2$/year in 2050. Lastly, the TS4 scenario, which retains current emission standards, predicts a steady ascent from 1.4 GtCO$_2$/year in 2030 to 1.5 GtCO$_2$/year by 2050. The projections serve as a reminder of the environmental implications of regulatory choices and emphasize the need for stricter emission controls.

In the detailed analysis by IRENA (2021) using the Sectoral model, a variety of scenarios were presented, each reflecting a different trajectory of marine CO_2 emissions. The Base Energy Scenario (BES) portrays a future where current trends persist, leading to emissions of 0.92 GtCO$_2$/year by 2050. The Planned Energy Scenario (PES), in contrast, embodies the current energy and climate commitments of nations, predicting a stabilization of emissions at 0.75 GtCO$_2$/year by 2050. The Transforming Energy Scenario (TES) offers a more optimistic outlook, emphasizing a shift towards a sustainable energy future and forecasting a reduction to 0.38 GtCO$_2$/year by 2050. Perhaps the most ambitious of all, the IRENA $1.5^\circ C$ Scenario is geared towards meeting the Paris Agreement's stringent $1.5^\circ C$. This scenario projects a significant reduction in marine CO_2 emissions to 0.14 GtCO$_2$/year by 2050. IRENA's 2021 findings underscore the potential of policy decisions and energy transformations in reducing marine CO_2 emissions.

In the DNV (2022), two groups of scenarios are presented. The "IMO ambition (old)" scenario, which considers a range of ETS allowances and the implementation of CII and EEXI regulations, forecasts a CO_2 emission reduction to 0.42 GtCO$_2$/year by 2050. The "Decarbonization2050" scenario embraces a more aggressive ETS allowance range and the same regulations. This scenario is geared towards the new IMO target, aiming for a complete decarbonization of the maritime sector by 2050. The predicted emissions are zero by 2050, showcasing the sector's potential to fully align with global climate goals. DNV's findings offer a compelling case for aggressive policy interventions and technological innovations.

By looking closer at requirements leading to the full-decarbonized projections of DNV (2022) suggest a dominant role for biofuels, spanning 32% to 96% of the fuel mix, with blue and green ammonia contributing up to 65% and 55% respectively. Electric propulsion, though still emergent, is anticipated to account for 3-4% of the mix. To actualize these configurations, significant financial commitments are necessary, with vessel-specific capex for biofuels, e-fuels, and blue ammonia estimated between \$0.25-\$0.7 trillion and onshore requirements reaching up to \$2.5 trillion. Regulatory standards, such as the EEDI's ambitious 90% reduction target by 2040 and the ETS's escalating allowance prices. These requirements are shown in Fig. 5. The approach to locking in the target and finding requirements to reach it is highly commendable. However, among these projections lies a high degree of uncertainty, exacerbated by the inherent limitations of sectoral modeling and its vulnerability to externalities. Notably, the specific assumptions driving DNV's model remain undisclosed, masking key variables and considerations.

A more recent study by DNV, DNV (2023), presents two contrasting scenarios for marine CO_2 emissions. These scenarios are not new but are reruns of two individual scenarios DNV previously published in 2022. The first scenario predicts a future where the absence of new policies leads to a modest reduction in emissions by 2050, dropping to 0.83 GtCO$_2$/year. This reduction is largely offset by a shift towards higher-emission fuels. In contrast, "Scenario 2" envisions a world where stringent greenhouse gas standards facilitate the transition to carbon-neutral shipping. This transition results in a reduction in CO_2 emissions, dropping to a mere 0.2 GtCO$_2$/year by 2050.

IEA (2020) offers a comprehensive look into the future of marine CO_2 emissions through various scenarios. The "Technology Scenario" emphasizes technological solutions, projecting emissions of 1.42 $GtCO_2$/year by 2050. The "2 Degree Scenario (2DS)" outlines a future where global warming is limited to 2°C, with CO_2 emissions decreasing to 0.64 $GtCO_2$/year by 2050. The most assertive of the three, the "Well Below 2 Degree Scenario (WB2DS)", envisions a future where global temperatures are kept well below a $2^\circ C$ rise, resulting in a more significant reduction in emissions to 0.4 $GtCO_2$/year by 2050. The projections from IEA 2017 illuminate the role of technological innovations and aggressive policy interventions in curbing marine CO_2 emissions.

In (IMO (2020), p. 236), a range of scenarios were presented to provide insights into the potential trajectories of marine CO_2 emissions. These scenarios, developed using integrated assessment models combined with gravity and logistic curves, capture different outcomes based on SSPs and Representative Concentration Pathways (RCPs). Among 24 scenarios produced by the study, 8 of them were chosen. The rationale behind it was explained earlier in the demand section. The SSP-based scenarios project emissions ranging from 1.04 to 2.34 $GtCO_2$/year by 2050, while the OECD-focused scenarios anticipate figures between 1.14 and 1.37 $GtCO_2$/year for the same year. The variations in emission forecasts stem from differing projections of transport work. These variations are, in turn, a result of different socio-economic projections and distinct methods used to determine the relationship between transport work and independent factors such as per capita GDP, population, and primary energy demand. This analysis by the IMO provides a deep understanding of the maritime sector's potential CO_2 emissions in Business-as-usual scenarios, emphasizing the importance of socioeconomic trajectories in shaping the sector's future. The variance in results is also partially due to the modeling approach.

Eide et al (2013) study delivers a variety of scenarios, each showcasing unique marine CO_2 emission trajectories. These scenarios are devised using the Monte Carlo simulation, a computational method that employs random sampling to model intricate systems. By generating numerous random samples based on input variable probability distributions, it estimates the output variable's probable distribution. This technique is prevalent in multiple domains, like finance and engineering, especially when modeling complex systems. The "Gray" variant serves as the baseline, depicting the highest emissions of 2 $GtCO_2$/year by 2050. In contrast, the "Blue" scenario, emphasizing technological innovations and a shift towards alternative fuels like nuclear, biofuel, and LNG, forecasts significantly lower emissions of 0.6 $GtCO_2$/year by 2050. The "Yellow" scenario offers a similar CO_2 reduction potential to the "Blue" one, albeit through different strategies, and predicts emissions of 0.9 $GtCO_2$/year by 2050. These scenarios underscore the significant variability in potential future emissions, hinging on technological, policy, and strategic choices. The study reinforces the message that proactive measures can lead to substantial emission reductions, while inaction could result in the opposite.

Utilizing a global fleet turnover model, Wang and Lutsey (2013) estimates shipping emissions by assessing the impact of enhanced efficiency from 2020 to 2050, considering factors such as fleet characteristics and operational data. They calibrated ship population against IMO projections and examined the influence of vessel age, size, and technology on carbon intensity. The scenarios include a baseline with EEDI standards, further technological enhancements (EEDI+), and industry-leading efficiency practices, each providing a differing scale of emission reductions. By 2030, adopting top efficiency practices could significantly reduce CO2 emissions and oil consumption. By 2050, the model suggests that emissions could stabilize at current levels despite increased activity, underscoring the effectiveness of operational improvements and advanced technologies in mitigating shipping's carbon footprint. The study provides a detailed analysis of potential reductions in carbon emissions in the maritime sector, demonstrating the substantial benefits of efficiency measures while also implicitly acknowledging the challenges of implementing such changes industry-wide. The study's assumptions might not accurately reflect fluctuations in scrappage rates and shipping activity while downplaying the socio-economic, regulatory, and geopolitical factors affecting shipping efficiency. Economic considerations, such as costs and investments for efficiency improvements, are not fully addressed, and the projections may be overly optimistic about the industry's readiness to embrace new technologies.

The Register (2016) and Smith et al (2016) studies, employing the GloTraM model, offer a series of scenarios with varied perspectives on the potential marine CO_2 emissions. The "Business As Usual (BAU)" scenario, which does not restrict the carbon budget and excludes hydrogen from its fuel mix, anticipates emissions of 1.4 $GtCO_2$/year by 2050. "Scenario 1" and "Scenario 2" share similar carbon budget and temperature rise assumptions yet differ slightly in their projections, with emissions forecasted at 0.7 and 0.59 $GtCO_2$/year, respectively, by 2050. "Scenario 3", although aligned with the carbon budget and pathway of the previous two, includes a huge out-of-sector offsetting potential with the exclusion of hydrogen, resulting in an emission projection of 1 $GtCO_2$ /year by 2050. This range of scenarios emphasizes the sensitivity of marine CO_2 emission projections to fuel choices and out-of-sector offsetting potential.

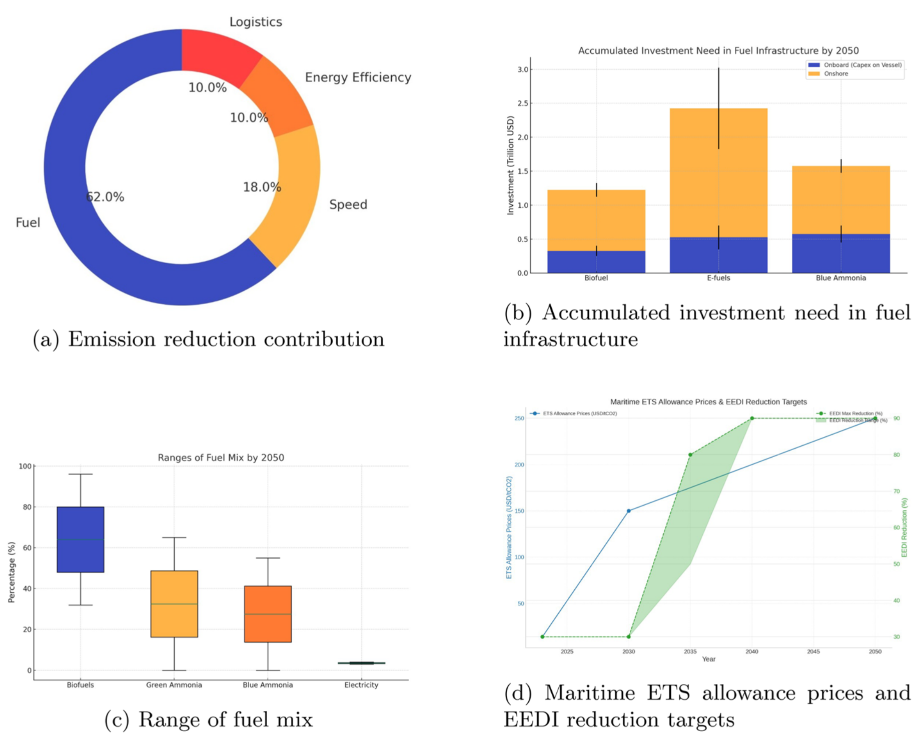
Esmeijer et al (2020) is a report by the PBL Netherlands Environmental Assessment Agency, which collects a series of Integrated Assessment Models (IAMs) to project potential marine CO_2 emissions. Three distinct models - IMAGE, POLES, and MESSAGE - are utilized, with each model having unique structures and underlying assumptions. These models each offer two scenarios: a baseline (BAU) and a mitigated scenario aiming for a 2°C temperature rise cap by 2100. The BAU scenarios present forecasts ranging from 0.8 to 1.5 $GtCO_2$/year by 2050. In contrast, the mitigated scenarios, aligned with global climate targets, anticipate CO_2 emissions between 0.35 and 0.48 $GtCO_2$/year by 2050. The variance in projections between the models is largely attributed to their distinct structures and the assumptions they're based upon. The study also emphasizes the importance of understanding the distinctions and complexities of different modeling approaches when interpreting and comparing results.

Figure 6 illustrates the emissions projections for international shipping in 2030 and 2050, with each point representing a scenario of each study's findings. In 2030, projections tend to converge below the 1 $GtCO_2$/year mark, with multiple scenarios reaching the targets. However, the new IMO target for 2050 proposes a more ambitious reduction than most studies currently predict. By 2050, the dispersion of data points indicates even greater uncertainty, with the new IMO target appearing as an outlier well below the bulk of projections, reflecting a target that may be difficult to achieve under current trajectories. Therefore a change in the philosophy of looking at the problem is required. Instead of estimating the effects of individual measures and policies, we should set the target as clear as it is and find feasible pathways toward reaching it. An extensive approach is needed that combines modeling techniques, socioeconomic trends, fuel and tech shifts, regulations, and economic factors, ensuring alignment with global climate targets and contributing to climate action under Sustainable Development Goal 13 (UN 2019).

Assumptions overview

Before discussing the types of models, the key assumptions behind the presented output are reviewed. From this overview, it becomes clear that many were relevant but were taken over by events, and a more robust approach may be required in this respect as well. In general, some assumptions are still valid, some are no longer valid, and others need a dynamic update before being used in a new model.

- Regarding the shipping demand:
  - The continuation of using historical trends for predicting the future by assuming the same trends as a predictor is being used by many studies. There is no better alternative, and this assumption would be maintained for now. This is done by most referenced studies. However, learning from recent disruptions such as the financial crisis of 2008/09, the COVID-19 pandemic, and recent geopolitical trends improves the accuracy of future predictions by accounting for potential volatility.
  - Pure assumptions about demand or fleet growth without empirical support possibly lead to lower reliability. Instead, models that incorporate a variety of



(a) Emission reduction contribution

(b) Accumulated investment need in fuel infrastructure

(c) Range of fuel mix

(d) Maritime ETS allowance prices and EEDI reduction targets

Fig. 5 Conditions under which full decarbonization is reached based on DNV2022 scenarios

economic and technical indicators to predict the trend of transport demand offers a more accurate approach. This could be enhanced further by various Machine-Learning (ML) techniques.
  - The assumption that energy trade outcomes result merely from cost optimization overlooks the complexities of global trade flows.
  - Relying on a limited set of variables for demand prediction, such as GDP or consumption only, simplifies the prediction model. Using more predicting variables increases the reliability of the model.
  - Using proxy ports to estimate regional distances has its merits. However, this approach requires regular updates to reflect the changing landscape of global shipping hubs. This will ensure capturing the most accurate average shipping haul between regions.
  - Models that incorporate exogenous factors or constraints on trade in a baseline without a detailed analytical foundation, such as a fossil fuel trade ban, could lead to less reliable results. These scenarios could be useful for assessing the extreme cases.
  - Assumptions regarding shipping demand reduction measures such as speed reduction and efficiency improvement are valid and provide insights into potential emissions reductions. However, they should be grounded in recent trends rather than speculations.

- Regarding the supplying fuel mix:

  - Assumptions regarding the availability of biomass and carbon capture and storage (CCS) adoption rates are seen as reasonable. Due to the existing high uncertainty, sensitivity analysis on them is valuable.
  - Predictions on fuel prices and capacities need to be grounded in recent data and trends, moving away from pure assumptions.
  - Pushing for or limiting a specific alternative fuel can be useful for sensitivity analysis. These assumptions should reflect ongoing technological and market developments.

- Regarding the policy implications:

  - Assumptions based on outdated IMO ambitions are not valid anymore. Updated targets should be used.
  - National policies, regulations, and trade agreements require updates to align with the latest targets and commitments.
  - Carbon pricing mechanisms (such as carbon pricing and carbon budget) and emissions trading systems should reflect current policy landscapes and economic conditions.

Finally, the utilization of Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) scenarios offers a valid framework for modeling future pathways. However, these scenarios must be periodically updated to incorporate the latest scientific understanding and policy directions. IAMC (2023) indicates an upcoming update on SSPs.

Comparative analysis of methodologies

Based on the projections of various studies and methodologies, there is a wide variety of projections and outcomes. Now, the general frameworks used to obtain those scenarios will be discussed to find the most qualified modeling framework for the context of this study. The studies and models reviewed in this paper can be categorized into five types: integrated modeling, sectoral modeling, regression analysis, life-cycle assessment, and undisclosed models in reports.

Integrated modeling takes a holistic approach, modeling interactions between various components, such as policy, technology, climate, and market forces. It helps understand complex interactions that affect emissions and explore different policy and technology options. Integrated assessment models (IAMs) have been widely used to explore the consequences of different long-term climate change mitigation strategies. These models provide a detailed representation of the world's energy, land use, agricultural, and climate systems, as well as their inter-linkages, cross-sectoral, and cross-regional connections over time. However, the level of uncertainty is high, and the results rely heavily on assumptions. The general limitation of integrated models is that they often operate at a high level of aggregation, which can mask sector-specific details such as the shipping sector. Two recent exceptions are Müller-Casseres et al (2021b) and Walsh et al (2019), which expanded the maritime sector into the IMAGE and TIAM models, respectively. *Sectoral modeling* looks at the shipping sector, examining the interactions between different sub-sectors to identify factors. They can dive into deeper details of operational measures such as speed optimization, engine efficiency improvement, hauling and waiting time, and port management. However, they don't capture the whole economy and miss some crucial factors such as inter-sectoral and inter-regional spillovers. *Regression analysis* is a statistical method used to establish relationships between variables, like the impact of fuel prices and economic growth on shipping transport work demand. Its primary limitation is not capturing the inherent complexities of the system, and its application remains limited to shipping demand projection. Regression analysis can be coupled with other modeling techniques to make the study more consolidated like the work done by IMO fourth report that is referenced by many studies. *Life-cycle assessment* quantifies the environmental impacts of a product or system from production to disposal. It helps understand the full environmental impact of shipping, including indirect emissions from fuel and other inputs used in the sector. However, most of these assessments focus on one specific option's perspective, and most applications are on supplying the fuel side only. *Reports* are produced by specific organizations or institutions to summarize their findings on a particular topic. Reports are undisclosed, so the reliability of the results from an academic point of view remains unknown. However, given the reputation of the organizations behind the report, they are referenced by the sector's policymakers. Therefore, they are valuable despite the lack of knowledge of the underlying assumptions.

The quality of a model is its suitability for its purpose and objective. Each model is designed with a specific objective and purpose. Sectoral models focus on detailed analysis within a narrow domain, while integrated holistic models offer broader coverage but may lack depth in specific areas. According to the objectives and context of this study, we look for models that go into more depth on the shipping side but still take a holistic approach. To find the quality of existing literature in the context, five relevant criteria

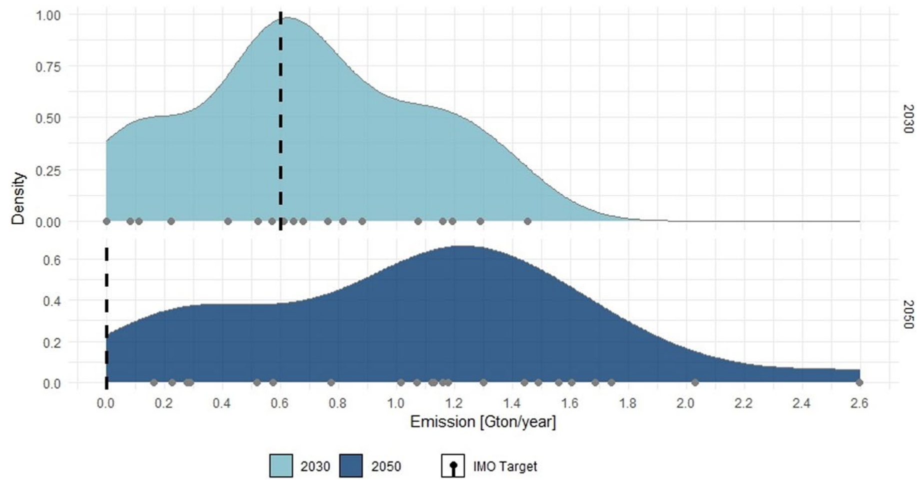


Fig. 6 Maritime shipping's CO_2 emission forecasts in 2030 and 2050 and the comparison to IMO's current target

are defined and justified in the Sect. 2. Table 5 shows the final average scores of each literature with its corresponding modeling method. A more detailed scoring table is also presented in the Appendix A. The insights provided by Table 5 can help to select the model direction for further research. Most of the studies are conducted by using a sectoral model. It also shows that integrated modeling has the highest average rate of 8.89, followed by undisclosed models within reports at 7.16. Both sectoral modeling and regression analysis have a rate of 7, while life-cycle assessment stands at 5.43. Figure 7 presents the number of studies analyzed with their corresponding average MCDA score. Therefore, due to having the required features, integrated modeling emerges as the most promising starting point for modeling international shipping pathways.

Integrated assessment models (IAMs) -the main integrated tools- are often used to develop and assess pathways in which greenhouse gas emissions are reduced, aiming to limit warming to specific temperature targets at the lowest overall cost (Rogelj et al 2011). Sectoral emission projections from these pathways can help policymakers in shaping their countries'climate targets. IAMs combine detailed models of energy system technologies with simplified economic and climate science models to evaluate different population, economic, and technological pathways. They enable an assessment of the feasibility of achieving specific climate change mitigation goals using different scenarios based on SSPs. These SSPs form the basis of key projections such as population, economies, and technology improvement rates developed by the International Institute for Applied Systems Analysis (IIASA) (Riahi et al 2017).

However, it's important to note that running scenarios in IAMs comes with the cost of time and complexity. Also, there are still gaps in IAMs, including the low level of representation of shipping. At the moment, international shipping is mostly underrepresented in most IAMs. Improving the representation of international transport would provide better insight into its potential contribution to global mitigation (Esmeijer et al 2020; Muller-Casseres et al 2023). Despite some recent improvements done by Müller-Casseres et al (2021b), Walsh et al (2019), and Müller-Casseres et al (2021a), most of the models typically treat shipping demand as an exogenous variable and do not necessarily capture connections to other aspects of the global economy. Now we will take a closer look at the underlying assumptions and the capacity for improvement of studies that used IAMs.

Walsh et al (2019) used the TIAM-UCL model to present world maritime trade scenarios in a 4°C future and a 2°C future. The article gives a good representation of the evolution of disaggregated trade demand in response to global climate change mitigation efforts. The paper also discusses the potential trade-offs that may arise as the shipping industry adapts to changing climates. However, the study focused only on the demand side and did not represent possible alternative fuels and their potential in the fuel mix. Also, the same neglection of cross-trade of energy commodities exists. Trade flow projections for these commodities are derived using the TIAM-UCL global energy system model. While optimization offers valuable insights, it also introduces a limitation by favoring future technological solutions rather than immediate demand-side changes. Additionally, despite the global scope of the study, the discussion of shipping distance is missing, and therefore, the trade demand remains in mass-based units rather than [mass × distance].

In Müller-Casseres et al (2021b), huge breakthroughs had been made to deepen the incorporation of shipping in IMAGE IAM. They look at shipping activity demand in high global climate mitigation scenarios. The discussion of distances between regions is evident, and the effect of different SSPs on shipping demand and renewable energy requirements is investigated. However, the article does not address alternative fuel mix and focuses only on the demand side. Additionally, the IMAGE model is a partial equilibrium simulation model with fewer macroeconomic details in the short term. Also, the trade of energy commodities such as oil, gas, and coal is a result of energy balance and the least-cost choice of the IAM itself. This could lead to neglection of the cross-trade in which a region can be an exporter and importer in the same year, leading to underestimating the actual physical flow of trade.

Müller-Casseres et al (2021a) used the IAM BLUES model[1] to develop scenarios considering different fuel alternatives, demand assumptions, and national mitigation targets, but the study only investigated Brazil and not global shipping. There is potential to expand the scope of research to include international and global maritime shipping. Also, the demand for transport activity is given exogenously.

In the most recent work, Muller-Casseres et al (2023), researchers from multiple institutes gather multiple IAMs to perform the first multi-IAM on the future of shipping in an integrated perspective. The study uses the current version of scenarios by COFFEE,[2] IMACLIM-R,[3] IMAGE,[4] PROMETHEUS,[5] TIAM-UCL,[6] and WITCH[7] models. Effective models highlight the importance of diverse fuel alternatives and the influence of models' structure and underlying constraints to obtain results. The authors conclude that the study is limited by an oversimplified view of shipping demand. These models

[1] Rochedo et al (2018)

[2] Rochedo (2016)

[3] Waisman et al (2012)

[4] Van Vuuren et al (2015); Stehfest et al (2014)

[5] E3 Modelling (2018)

[6] Pye et al (2020)

[7] Bosetti et al (2007); Emmerling et al (2016)

often overlook significant factors like the influence of imperfect markets and rising geopolitical tensions, which can substantially affect global shipping dynamics and demand. Future studies could benefit from incorporating economic analyses, particularly regarding the impact of a carbon tax on international shipping.

Apart from the mentioned articles, two reports also took advantage of IAMs in their overview.

Esmeijer et al (2020) is a report by PBL Netherlands Environmental Assessment Agency. They leverage the results of IAMs such as POLES, MESSAGE, and IMAGE. The report gives valuable insight by using different models. The report recommends distinguishing between international and domestic shipping emissions, incorporating diverse fuels and efficiency standards, and offering distinct emissions reporting for the shipping sector as the direction of improving IAMs. Additionally, integrating sector-specific models with IAMs could improve the depiction of technological options within the shipping domain. According to the report, IAMs show potential in modeling international shipping emissions, yet there's a notable gap in the detail and prioritization of such reporting. While models like POLES demonstrate a detailed approach by integrating trade flows and efficiency metrics, others like MESSAGE, WITCH, and REMIND offer less detail, focusing merely on energy demand and emission factors. A multi-IAM analysis boosts the reliability of climate policy advice by contrasting model outcomes to highlight trends and differences. Given each model's different structures and assumptions, it assesses uncertainties and model sensitivities. Furthermore, multi-IAM analysis broadens scenario and policy option exploration, supporting stronger climate policy decisions. This will need enhancement of shipping representation in multiple IAMs.

In (IMO (2020), pp. 345–378) the methodology for projecting shipping emissions involves six steps: First, it projects transport work for non-energy products by linking historical maritime transport data to economic indicators like GDP and population, then forecasts future transport based on these relationships. Second, it estimates transport work for energy products using two regression models and coupling to multiple IAMs. Third, the study analyzes the 2018 fleet and its emissions by ship category. Fourth, it forecasts future fleet composition through literature review and stakeholder feedback. Fifth, it projects ships' future energy efficiency considering regulatory and market changes. Finally, it combines these elements to project shipping emissions. They investigate 24 scenarios in total, including high mitigation scenarios aligned with the Paris Agreement. Although the methodology of creating regression models and coupling them to IAMs for policy assessment is rigorous and innovative, there is room for improvement, especially in the energy commodities (oil, gas, and coal) trade. Two regression models are the non-linear logistic regression and the augmented gravity model with fixed effects. In the logistic model, the only variable used to predict the trade of energy cargo trade is the global consumption of that product. The second model, an augmented gravity model, provides an interesting approach but is constrained by its exclusive focus on GDP and population as predicting parameters and aggregating trade demand by ship types rather than specific cargoes. Adding more influential parameters such as regional consumption and production of both importer & exporter regions, and fuel price could improve the reliability of the model.

Table 5 Publications and their average MCDA ratings

N	Method	Documents	Average MCDA rate
6	Integrated modeling	Müller-Casseres et al (2021a), Walsh et al (2019), Müller-Casseres et al (2021b) Muller-Casseres et al (2023), Esmeijer et al (2020), IMO (2020)	8.89
10	Sectoral modeling	Yang et al (2017), DNV (2022), DNV (2023), DNV (2018), Eide et al (2013), Register (2016) Smith et al (2016), Halim et al (2018), Horton et al (2022), Franz et al (2022), Martinez et al (2014)	7
2	Regression analysis	Michail (2020), Eyring et al (2005),	7
6	Life-cycle assessment	Xing et al (2021), Balcombe et al (2019), Van der Kroft and Pruyn (2021), Bengtsson et al (2011), Law et al (2021), Inal et al (2022)	5.43
4	Undisclosed	IRENA (2021), IEA (2020), ABS (2022) ,Wang and Lutsey (2013)	7.16

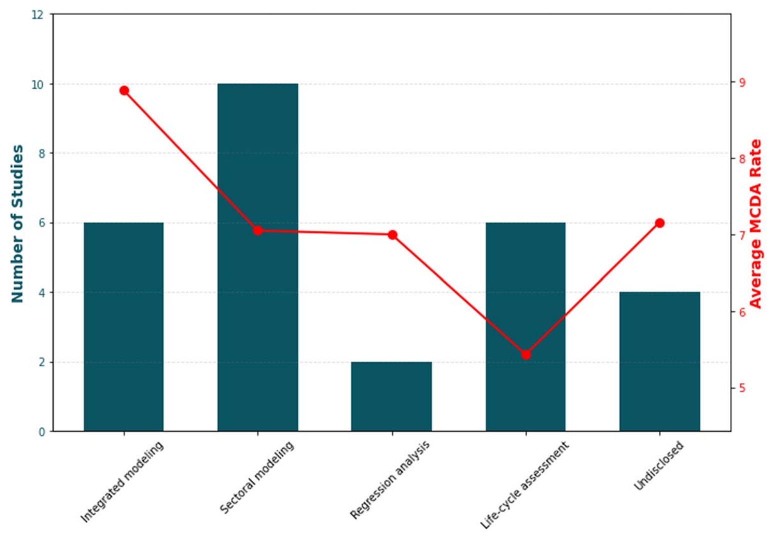


Fig. 7 Publications review: Number of studies vs Average MCDA rating

Modeling framework overview

In the quest to identify the most appropriate modeling framework for charting a path to zero emissions in the international shipping sector by 2050, it's imperative to adopt a holistic approach that synergizes the strengths of various models while addressing their limitations. A list of the pros and cons of each model, considering the aim of this paper, is shown in Table 6.

Integrated Assessment Models (IAMs) are pivotal for their broad analysis of global energy, land use, and climate systems, facilitating an understanding of long-term climate change mitigation strategies across sectors and regions. However, IAMs' expansive scope often leads to a generalized treatment of the shipping sector, missing the intricate details of maritime operations and technologies. This high-level perspective is IAMs' primary drawback, as it overlooks the detailed specifics crucial for shipping. To counteract this shortfall, sectoral models are valuable to infuse the required granularity into the analysis. These models excel in detailing the operational

Table 6 General Pros and Cons of each modeling framework

Method	Pros	Cons
Integrated modeling	Holistic approach; Long-term assessment; Policy analysis; Inter-sectoral and global integration	Lack of sector-specific detail; Sensitive to assumptions; High uncertainty
Sectoral modeling	Detailed sector-specific analysis; High specialization in operational measures, efficiency improvement, speed reduction measures, etc.	Limited scope beyond the sector; Integration with broader assessments is complex.
Regression analysis	Identifies trends/correlations; Provides predictive insights based on historical data.	Limited in capturing policy dimensions; Data-intensive; Risk of oversimplification
Life-cycle assessment	Comprehensive environmental impact assessment; Details on a specific fuel pathway	Mostly focusing on one specific option's perspective; No long-term assessment

aspects and technological details of the shipping industry, which IAMs gloss over. By integrating insights from sectoral models, the framework achieves a more comprehensive understanding of shipping dynamics, from fuel efficiency measures to vessel characteristics. Nevertheless, sectoral models typically focus on narrower aspects and might not fully capture the environmental impacts and specifics of various fuels over time-a gap effectively bridged by Life Cycle Assessment (LCA) methods. LCAs offer a detailed evaluation of fuel options' environmental footprint. However, they are limited by a singular focus on individual fuels without considering broader temporal dynamics. This is where the holistic view of IAMs complements LCAs by integrating these detailed environmental assessments into a broader temporal and systemic context. Regression models further enhance the framework by providing dynamic demand projections. They could incorporate a wide array of variables such as economic growth, population, shipping distances, fuel price, consumption, and production of cargo to predict trade flows. To increase the accuracy of such predictions, these predictions should be done bilaterally between regions and disaggregated for each cargo type. This approach will capture particular dynamics of each pair of importer-exporter regions, and each cargo type. However, regression models, with their focus on quantitative data, may overlook the qualitative aspects of policy impacts and market forces, elements that IAMs and sectoral models can capture.

This integrated approach of using IAMs for connecting sectors & regions and policy evaluations, sectoral models for detailed operational measures, LCAs for studying fuel impacts, and regression models for predicting demand mitigates the limitations of individual models and creates a robust, detailed, and coherent strategy that strengthens industry discussions and expert propositions. There are similarities and synergies between shipping and the aviation sector, and the same progress of integration perspective is taking place in the aviation sector (Muller-Casseres et al 2022; Wise et al 2017).

Conclusion

Climate change represents a critical global challenge, and international maritime shipping plays an undeniable role. Despite the sector's high ambition to achieve full decarbonization by mid-century, there is no established pathway. Currently, several modeling techniques and literature are examining the sector's future. This paper aimed *to find a suitable way of modeling to assess feasible pathways to the zero-emission shipping sector*. This is done in two main steps. Firstly, by evaluating the existing projections of future international maritime shipping, including transport activity demand, efficiency improvement, fuel supply mix, and emissions, to identify the most probable ranges and the underlying assumptions leading to this uncertainty and scenario. Secondly, the paper assessed the quality of the literature based on five criteria: sectoral integration scope, dimensionality, technology range, geographical scope, and scenario evaluation. Based on these criteria, an integrated, all-sides-encompassing, multi-technology, global, and multi-scenario model is essential for exploring pathways to decarbonize international maritime shipping by 2050.

International shipping transport demand is projected to significantly increase, expected to rise by 50% by 2030 and 100-150% by 2050. This necessitates a critical shift in the sector's energy matrix, where the use of electricity is constrained by energy density issues and the limited operational range of battery-powered vessels. The adoption rates of hydrogen, ammonia, and biofuels are marked by considerable uncertainty, reflecting the variability in future utilization scenarios. Projections for CO_2 emissions reveal a wide range of outcomes, with estimates around 1 $GtCO_2$/year by 2030, diverging significantly to span from zero to 2.6 $GtCO_2$/year by 2050, thereby highlighting the sector's challenge in aligning with new International Maritime Organization (IMO) targets.

The examination of emission projections, as shown in Fig. 6, revealed that a significant number of projections do not align with International Maritime Organization (IMO) targets. The suggestion of authors is a paradigm shift; to set the target and find pathways to achieve these goals, rather than focusing solely on the impacts of individual measures. This change in approach supports a more directed effort in modeling and policy development to ensure the maritime sector contributes effectively to global decarbonization objectives by achieving climate mitigation targets.

The evaluation of modeling assumptions for existing scenarios by 2050 shows a mix of valid and outdated assumptions alongside those needing updates. Relying on historical trends in demand projection remains a rough but valid assumption. Most referenced studies use it. Evaluating wider economic and sector-specific data to find historical trends improves the reliability and accuracy of this assumption. Assumptions regarding the supply of technologies like biomass availability and CCS adoption rates are seen as reasonable but require up-to-date insights to reflect technological and market realities. Policy assumptions, particularly regarding IMO targets and carbon pricing, must be revised to align with the latest international standards. The paper highlights the critical role of updated SSP and RCP scenarios in ensuring models are grounded in current scientific and policy contexts.

Regarding the modeling framework, lessons should be learned from previous efforts. The robust approach of coupling econometric regression models with Integrated Assessment Models (IAMs) as demonstrated by IMO (2020) is noteworthy, though the range of predicting variables is limited. Esmeijer et al (2020) and Muller-Casseres et al (2023) highlight the potential of IAMs and the importance of multi-IAM analysis, despite the scarcity of detailed shipping information in most IAMs. Müller-Casseres et al (2021b) and Walsh et al (2019) stand out for incorporating a more detailed representation of shipping into the IMAGE and TIAM-UCL models, respectively. However, the modeling of energy trade in these works, being the outcome of energy optimization, might underestimate scenarios where a region can be both an importer and exporter of cargo within the same period. Additionally, the discussion on potential fuel mixes is absent in these studies. Thus, the future direction for modeling suggests enhancing econometric models for energy commodities and other cargo shipping demands by incorporating a broader set of predicting variables. A disaggregated approach to regions and cargo types increases the accuracy of outcomes. It is recommended to utilize insights from sectoral models to represent improvements in efficiency, capital expenditures (CAPEX), operational expenditures (OPEX), and performance of vessels and ports, along with speed reduction and other operational measures. Insights from Life Cycle Assessment (LCA) studies of alternative fuels should be used to model their production pathways, learning curves, and environmental impacts. These elements should then be implemented in multiple IAMs and synthesized with expert opinions, such as those from DNV (2023), to improve informed decision-making in the sector. The limitations of such an approach would be high computing power and a high need for accessible and detailed data.

Appendix 1: study rating

Here the details of the Study rating are shown in Table 7

Table 7 Details of MCDA ratings

Average Rate	Method	Study	Dimensionality	Technology Range	Integration Scope	Geographical scope	Scenario Evaluation	Total score
8.89	Integrated modeling	Müller-Casseres et al (2021b)	1.33	2	2	2	2	9.33
		Walsh et al (2019)	1.33	2	2	2	2	9.33
		Müller-Casseres et al (2021a)	2	2	2	0	2	8
		Esmeijer et al (2020)	0.66	2	2	2	2	8.66
		IMO (2020)	1.33	2	2	2	2	9.33
		Muller-Casseres et al (2023)	0.66	2	2	2	2	8.66
7	Sectoral modeling	Yang et al (2017)	1.33	2	0	0	2	5.33
		DNV (2018)	1.33	2	0	2	2	7.33
		DNV (2022)	1.33	2	0	2	2	7.33
		DNV (2023)	1.33	2	0	2	2	7.33
		Eide et al (2013)	0.66	2	0	2	2	6.66
		Register (2016)	2	2	0	2	2	8
		Halim et al (2018)	2	2	0	2	2	8
		Horton et al (2022)	1.33	2	0	2	2	7.33
		Martinez et al (2014)	1.33	0	0	2	2	5.33
		Franz et al (2022)	1.33	2	0	2	2	7.33
7	Regression Analysis	Michail (2020)	0.66	2	0	2	2	6.66
		Eyring et al (2005)	1.33	2	0	2	2	7.33
5.43	Life-cycle assessment	Xing et al (2021)	0.66	2	0	2	0	4.66
		Balcombe et al (2019)	1.33	2	0	2	2	7.33
		Van der Kroft and Pruyn (2021)	0.66	0	0	2	2	4.66
		Law et al (2021)	0.66	2	0	2	0	4.66
		Inal et al (2022)	0.66	0	0	2	2	4.66
		Bengtsson et al (2011)	0.66	2	0	2	2	6.66
7.16	Undisclosed (Reports)	IRENA (2021)	1.33	2	0	2	2	7.33
		IEA (2020)	1.33	2	0	2	2	7.33
		ABS (2022)	1.33	2	0	2	2	7.33
		Wang and Lutsey (2013)	0.66	2	0	2	2	6.66

Abbreviations

BAU	Business As Usual
BECCS	Bioenergy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CII	Carbon Intensity Indicator
CEPII	Centre d'Études Prospectives et d'Informations Internationales
DAC	Direct Air Capture
DNV	Det Norske Veritas (Norwegian classification society)
EE	Energy Efficiency
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ETS	Emissions Trading System
FTA	Free Trade Agreement
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLOTRAM	Global Trade Analysis Model
HFO	Heavy Fuel Oil
HVO	Hydrogenated Vegetable Oil
IAM	Integrated Assessment Model
IEA	International Energy Agency
IFM	International Freight Model
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
MCDA	Multi-Criteria Decision Analysis
MFO	Marine Fuel Oil
ML	Machine Learning
MRV	Monitoring, Reporting and Verification
OECD	Organisation for Economic Co-operation and Development
OPEX	Operating expense
PBL	Netherlands Environmental Assessment Agency (Planbureau voor de Leefomgeving)
SEEMP	Ship Energy Efficiency Management Plan
SSP	Shared Socioeconomic Pathways
VECM	Vector Error Correction Model

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Author contributions
HN was the primary contributor, responsible for most of the research work and analysis. JP guided the formation of the paper and contributed significantly to the manuscript narrative. DS supervised the project and provided critical feedback. All authors, HN, JP, and DS, have read and approved the final version of the manuscript.

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Availability of data and materials
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Declarations

Competing of interests
The authors declare that they have no Conflict of interest.

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References

ABS (2022) Setting the course to lowcarbon shipping: Zero carbon outlook. https://ww2.eagle.org/en/publication-flip/zero-carbon-outlook.html

Ampah JD, Yusuf AA, Afrane S et al (2021) Reviewing two decades of cleaner alternative marine fuels: towards imo's decarbonization of the maritime transport sector. J Cleaner Prod 320:128871

Anderson K, Stoddard I, Schrage J (2017) Carbon budget and pathways to a fossil-free future in järfälla municipality
Balcombe P, Brierley J, Lewis C et al (2019) How to decarbonize international shipping: options for fuels, technologies, and policies. Energy Convers Manag 182:72–88
Bengtsson S, Andersson K, Fridell E (2011) A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. Proc Inst Mech Eng Part J Eng Marit Environ 225(2):97–110
Bosetti V, Massetti E, Tavoni M (2007) The witch model: structure, baseline, solutions
Brauers H, Braunger I, Jewell J (2021) Liquefied natural gas expansion plans in germany: the risk of gas lock-in under energy transitions. Energy Res Soc Sci 76:1024
Carlo R, Marc BJ, de la Fuente Santiago S et al (2020) Aggregate investment for the decarbonization of the shipping industry. UMAS, London, UK
Clarksons Research (2022) World seaborne trade tables. https://sin.clarksons.net, accessed: 2023-07-01
De Vincenti C (2007) Baumol's disease production externalities and productivity effects of intersectoral transfers. Metroeconomica 58(3):396–412
DNV (2018) Maritime forecast to 2050. Report, DNV
DNV (2021) Maritime forecast to 2050. Report, DNV
DNV (2022) Maritime forecast to 2050. Report, https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html
DNV (2023) Maritime forecast to 2050. Report, DNV
E3 Modelling (2018) Prometheus model documentation. https://e3modelling.com/modelling-tools/prometheus/
Eide MS, Chryssakis C, Endresen Ø (2013) Co2 abatement potential towards 2050 for shipping, including alternative fuels. Carbon Manag 4(3):275–289
Elgohary MM, Seddiek IS, Salem AM (2015) Overview of alternative fuels with emphasis on the potential of liquefied natural gas as future marine fuel. Proc Inst Mech Eng Part M J Eng Marit Environ 229(4):365–375
Emmerling J, Drouet L, Reis L, et al (2016) The witch 2016 model-documentation and implementation of the shared socioeconomic pathways
Esmeijer K, den Elzen M, van Soest H (2020) Analysing international shipping and aviation emission projections. PBL Publication (4076)
European Commission (2023) Reducing emissions from the shipping sector. https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en
Eyring V, Köhler H, Lauer A et al (2005) Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. J Geophys Res Atmosph 110(17):20
Franz S, Campion N, Shapiro-Bengtsen S et al (2022) Requirements for a maritime transition in line with the paris agreement. Iscience 25(12):112
Halim RA, Kirstein L, Merk O et al (2018) Decarbonization pathways for international maritime transport: a model-based policy impact assessment. Sustainability 10(7):2243
Hare B, Brecha R, Schaeffer M (2018) Integrated assessment models: What are they and how do they arrive at their conclusions. Clim Anal pp 1–12
Harrison D, Radov D, Patchett J et al (2005) Economic instruments for reducing ship emissions in the european union. NERA Economic Consulting, London, UK, p 30
Herdzik J (2021) Decarbonization of marine fuels-the future of shipping. Energies 14(14):4311
Horton G, Finney H, Fischer S, et al (2022) Technological, operational and energy pathways for maritime transport to reduce emissions towards 2050. Report, Ricardo Energy & Environment
IAMC (2023) Shared socio-economic pathways (ssp) update: take part in the review process. https://www.iamconsortium.org/news-from-the-community/news-f-the-community/shared-socio-economic-pathways-ssp-update-take-part-in-the-review-process/, accessed: 2023-02-09
IEA (2020) International shipping. Report, International Energy Agency, https://www.iea.org/reports/international-shipping
IMO (2018) Adoption of the initial imo strategy on reduction of ghg emissions from ships and existing imo activity related to reducing ghg emissions in the shipping sector
IMO (2020) Fourth imo ghg study 2020
IMO (2023) Revised ghg reduction strategy for global shipping adopted. https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx
Inal OB, Zincir B, Deniz C (2022) Investigation on the decarbonization of shipping: an approach to hydrogen and ammonia. Int J Hydr Energy 47(45):19888–19900
IPCC (2023) Sections. in: Climate change 2023: Synthesis report. contribution of working groups i, ii and iii to the sixth assessment report. https://doi.org/10.59327/IPCC/AR6-9789291691647
IRENA (2021) A pathway to decarbonize the shipping sector by 2050. Tech. rep, International Renewable Energy Agency, Abu Dhabi
Khosravi F, Jha-Thakur U (2019) Managing uncertainties through scenario analysis in strategic environmental assessment. J Environ Plann Manag 62(6):979–1000
Köberle AC (2019) The value of beccs in iams: a review. Curr Sustain Renew Energy Rep 6:107–115
Kramel D, Muri H, Kim Y et al (2021) Global shipping emissions from a well-to-wake perspective: the mariteam model. Environ Sci Technol 55(22):15040–15050
Van der Kroft DF, Pruyn JF (2021) A study into the availability, costs and ghg reduction in drop-in biofuels for shipping under different regimes between 2020 and 2050. Sustainability 13(17):9900
Lagouvardou S, Psaraftis HN (2022) Implications of the eu emissions trading system (ets) on european container routes: a carbon leakage case study. Marit Transp Res 3:100059
Lagouvardou S, Psaraftis HN, Zis T (2022) Impacts of a bunker levy on decarbonizing shipping: a tanker case study. Transp Res Part D Transp Environ 106:103257
Law LC, Foscoli B, Mastorakos E et al (2021) A comparison of alternative fuels for shipping in terms of lifecycle energy and cost. Energies 14(24):8502

Lee H, Romero J, et al (2023) Climate change 2023: Synthesis report. A Report of the Intergovernmental Panel on Climate Change Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

Less S, McIlveen R, Helm D (2010) Greener, cheaper. Policy Exchange, London

Martinez L, Kauppila J, Castaing M (2014) International freight and related co2 emissions by 2050: a new modelling tool. International Transport Forum Discussion Paper

Mason J, Larkin A, Bullock S et al (2023) Quantifying voyage optimisation with wind propulsion for short-term co2 mitigation in shipping. Ocean Eng 289:116065

Masten SE (2009) Long-term contracts and short-term commitment: price determination for heterogeneous freight transactions. Am Law Econom Rev 11(1):79–111

Meersman H, Van de Voorde E (2013) The relationship between economic activity and freight transport. In: Freight transport modelling. Emerald Group Publishing Limited, p 15–43

Michail NA (2020) World economic growth and seaborne trade volume: quantifying the relationship. Transp Res Interd Perspect 4:100108

Müller-Casseres E, Szklo A, Fonte C et al (2022) Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of brazil. Iscience 25(10):124

Müller-Casseres E, Leblanc F, van den Berg M, et al (2023) International shipping in a world below 2c. Nature Climate Change

Murat M, Pigliaru F (1998) International trade and uneven growth: a model with intersectoral spillovers of knowledge. J Int Trade Econom Develop 7(2):221–236

Müller-Casseres E, Carvalho F, Nogueira T et al (2021) Production of alternative marine fuels in brazil: an integrated assessment perspective. Energy 219:119444

Müller-Casseres E, Edelenbosch OY, Szklo A et al (2021) Global futures of trade impacting the challenge to decarbonize the international shipping sector. Energy 237:121547

Nikolakaki G (2013) Economic incentives for maritime shipping relating to climate protection. WMU J Marit Affairs 12(1):17–39

Psaraftis HN (2021) The future of maritime transport. International Encyclopedia of Transportation; Elsevier: Amsterdam, The Netherlands pp 535–539

Pye S, Butnar I, Cronin J, et al (2020) The tiam-ucl model (version 4.1.1) documentation. Technical Report Version 4.1.1, UCL Energy Institute

Register L (2016) Low carbon pathways 2050. Sustainability, Editor

Riahi K, Van Vuuren DP, Kriegler E et al (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ Change 42:153–168

Rochedo PR, Soares-Filho B, Schaeffer R et al (2018) The threat of political bargaining to climate mitigation in brazil. Nature Climate Change 8(8):695–698

Rochedo PRR (2016) Development of a global integrated energy model to evaluate the brazilian role in climate change mitigation scenarios. DS Thesis, Universidade Federal do Rio de Janeiro, Brazil

Rogelj J, Hare W, Lowe J et al (2011) Emission pathways consistent with a 2 c global temperature limit. Nature Climate Change 1(8):413–418

Schnurr R, Walker TR (2019) Marine transportation and energy use. Reference Module in Earth Systems and Environmental Sciences; Elsevier: Amsterdam, The Netherlands pp 1–9

Smith T, Raucci C, Hosseinloo SH et al (2016) Co2 emissions from international shipping: Possible reduction targets and their associated pathways. London, UK, UMAS

Stančin H, Mikulčić H, Wang X et al (2020) A review on alternative fuels in future energy system. Renew Sustain Energy Reviews 128:109927

Stehfest E, van Vuuren D, Kram T, et al (2014) Integrated assessment of global environmental change with image 3.0. model description and policy applications. Technical report, PBL Netherlands Environmental Assessment Agency

Stolz B, Held M, Georges G et al (2022) Techno-economic analysis of renewable fuels for ships carrying bulk cargo in europe. Nature Energy 7(2):203–212

Transport, Environment (2018) Statistical analysis of the energy efficiency performance (eedi) of new ships built in 2013-2017

UN (2019) Sdg 13 issue brief: Sustainable development goal 13 (sdg 13) - promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing states, including focusing on women, youth and local and marginalized communities. https://wedocs.unep.org/20.500.11822/28448

UNCTAD (2021) Review of maritime transport. United Nations Publications, New York

UNCTAD (2022) Review of maritime transport. United Nations Publications, New York

Van Vuuren DP, Kok M, Lucas PL et al (2015) Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the image integrated assessment model. Technol Forecast Soc Change 98:303–323

Waisman H, Guivarch C, Grazi F et al (2012) The i maclim-r model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. Climatic Change 114:101–120

Walker TR, Adebambo O, Del Aguila Feijoo MC, et al (2019) Environmental effects of marine transportation. World Seas: an Environmental Evaluation

Walsh C, Lazarou NJ, Traut M et al (2019) Trade and trade-offs: Shipping in changing climates. Marine Policy 106:103537

Wang H, Lutsey N (2013) Long-term potential for increased shipping efficiency through the adoption of industry-leading practices. The International Council on Clean Transportation 65

Watanabe MDB, Cherubini F, Cavalett O (2022) Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment. J Cleaner Prod 364:132662

Wieckowski J, Szyjewski Z (2022) Practical study of selected multi-criteria methods comparison. Proced Comput Sci 207:4565–4573

Wise M, Muratori M, Kyle P (2017) Biojet fuels and emissions mitigation in aviation: an integrated assessment modeling analysis. Transp Res Part D Transp Environ 52:244–253

WTO WTO (2021) International trade statistics. https://data.wto.org

Xing H, Stuart C, Spence S et al (2021) Alternative fuel options for low carbon maritime transportation: pathways to 2050. J Cleaner Prod 297:126651

Yang H, Ma X, Xing Y (2017) Trends in co2 emissions from china-oriented international marine transportation activities and policy implications. Energies 10(7):980

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