Emission and Technology Pathways in the Shipping Sector

Thomas Eysseric-Cravinho, *Research Assistant*

Adrien Rose, *Research Assistant*

Dr. Gireesh Shrimali, *Head Transition Finance Research*

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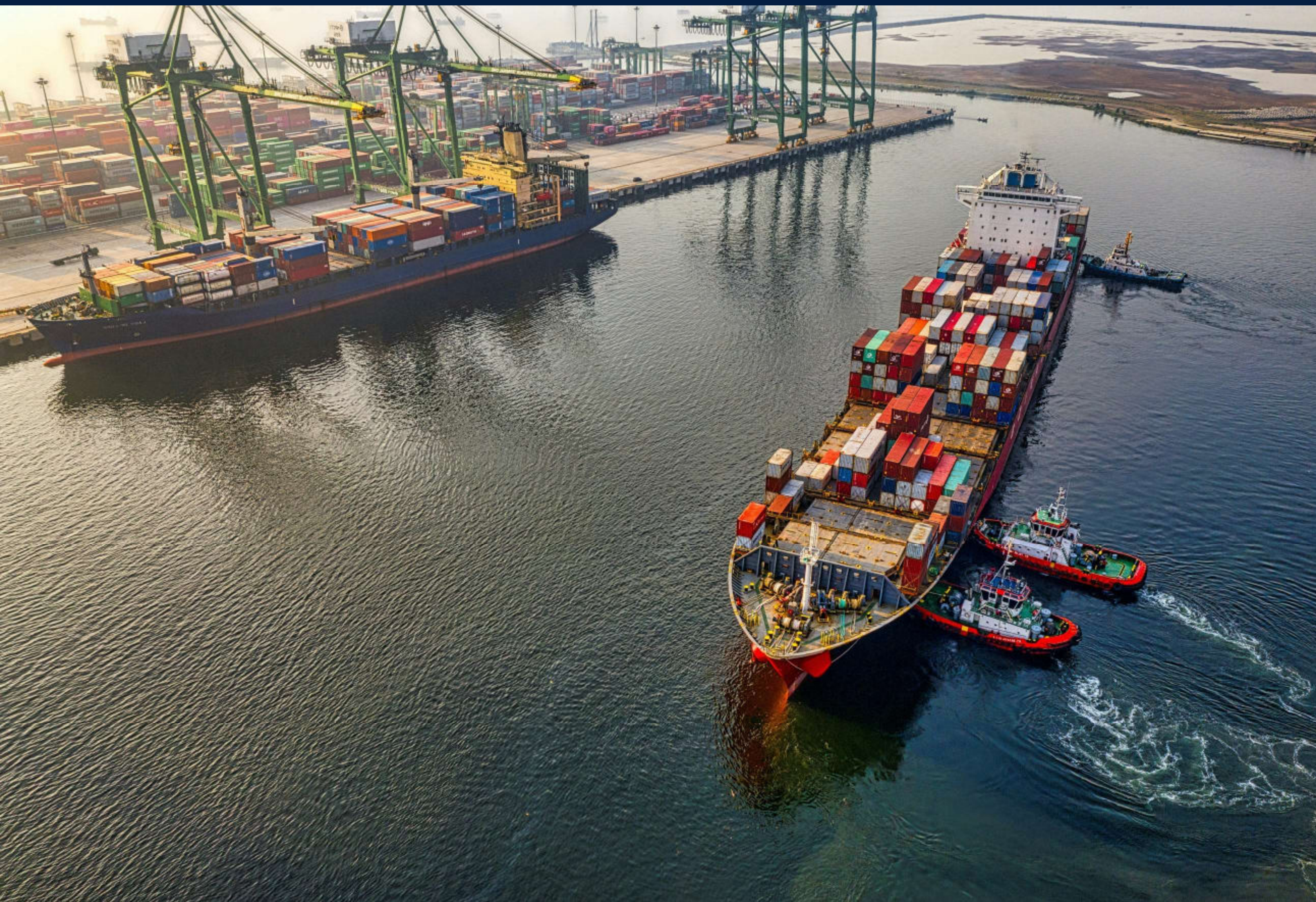

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Executive summary

Global shipping accounts for about 3% of global anthropogenic CO_2 emissions and, despite a recent relative decoupling of emissions from trade volumes, **sustained growth in maritime transport could further increase the sector's emissions by 90% to 130% by 2050 compared with 2008.** Decarbonizing shipping to achieve the Paris Agreement therefore poses a serious challenge to a sector characterized by slow turnovers of fleets, complex port-ship interfaces, and carbon-intensive activities due to the reliance on fossil fuels to power ships.

This paper compares four leading emission pathways for shipping and their underlying technology-policy mixes to identify benchmarks for the assessment of the credibility and feasibility of transition plans in the sector. While none of these pathways offers a sufficiently robust 1.5°C-aligned pathway, the International Energy Agency's Net Zero Emissions (IEA NZE) and the One Earth Climate Model 2.0 (OECM) pathways have noteworthy strengths since the latter is based on a 1.5°C-aligned carbon budget while the former provides the most robust and detailed technology-policy pathway.

The analysis also shows that technological solutions and operational measures exist or could emerge at the required scale with increased policy ambition and investments. The substitution of fossil fuels with low and zero-carbon marine fuels constitutes the main decarbonization lever in the medium and long term, although their deployment also requires the rollout of onboard technologies and port infrastructure investments, alongside significant energy efficiency operational measures and technological improvements, particularly in the short term. While findings indicate that there are few technical barriers to decarbonizing fuel mixes and reducing energy use from shipping, current policy and investment gaps are threatening the feasibility of short-term decarbonization targets.

Immediate action is therefore crucial to enable the decarbonization of global shipping in a manner that is mindful of just transition considerations and regional dynamics. Precisely, it requires decisive leadership from the International Maritime Organization (IMO) to facilitate the rollout of decarbonization measures and to ensure no country is left behind, as well as ambitious policy and investments from pioneering countries and companies to seize the opportunities brought by this transition.

1. Introduction

1.1 GHG emissions from shipping: Trends and drivers

With over 80% of global trade by volume in 2022 carried by sea, shipping plays a critical role in enabling growing flows of goods across the global economy (UNCTAD, 2022). During the past three decades, maritime transport grew at an average rate of 3.3% and enabled the increasing globalization of production and trade. Despite a slowdown in growth since 2017 and a contraction of trade in 2020 as the global economy was hit by the COVID-19 pandemic, shipping volumes are expected to continue to expand steadily, at an annual average rate of around 2.1% between 2024 and 2028 (UNCTAD, 2022, 2023). As maritime transport currently relies almost entirely on fossil fuels to power vessels and maritime operations, growth in seaborne trade over the past decades has also resulted in increasing greenhouse gas (GHG) emissions.

In 2018, shipping accounted for 2.89% of global anthropogenic CO_2 emissions. Globally, the sector was responsible for 1,076 Mt CO_2e of emissions, representing a 9.6% increase compared to 2012. International shipping was responsible for more than two thirds of the sector's global CO_2 emissions[1] (Faber et al., 2020). When measured using the 100-year global warming potential of GHG emissions, CO_2 accounts for 91% of emissions generated by international shipping. Black carbon, a soot-like and highly potent short-lived climate forcer, is responsible for most of the remaining global warming potential of shipping emissions. Methane emissions from ships have nonetheless also been increasing significantly – by 87% since 2012, due to the growing use of liquified natural gas (LNG) by LNG tankers.

While emissions growth and international seaborne trade growth have historically been tightly linked, a relative decoupling has occurred in the past decade. Indeed, since the economic recession in 2009, the carbon intensity of shipping, measured in grams of CO_2 per ton per nautical mile, has decreased by 20 to 30% between 2008 and 2018, mainly because of energy efficiency gains.

Despite this trend, sustained growth in trade volumes has outpaced carbon intensity reductions and resulted in increases in GHG emissions from shipping in absolute. According to the IMO's latest GHG study, which is to date the most comprehensive inventory of emissions for the sector, global emissions from shipping in 2050 are projected to range

[1] International shipping emissions is accounted on a voyage-based allocation of emissions.

between 90% and 130% of 2008 emission levels if no additional measures are put in place[2] (Faber et al., 2020).

The main source of GHG emissions in the shipping sector is the use of fossil fuels for the propulsion and operation of ships. As a result, shipping-related emissions are mainly driven by global maritime trade volumes and distances travelled, as well as operating speeds. The latter are dependent on market forces and behaviour trends in the industry, rather than technical constraints or design specifications, as shipping operators modulate cruising speeds to optimize fuel consumption and travel times considering logistical constraints at ports.

On the other hand, the carbon intensity of shipping, which has decreased since new energy efficiency regulations entered force in 2008 at the international level, is driven by increases in ship size, design efficiency, slower operating speeds and payload fuel efficiency, which have all led to lower energy use per ton. Nonetheless, after rapidly decreasing between 2008 and 2012, the carbon intensity of maritime transport has since decreased at a slower annual pace of 1% to 2%.

Given the urgency and scale of decarbonization imperatives, IMO, the UN agency responsible for regulating international shipping to ensure safe, secure and efficient shipping, and prevent pollution from ships, **has in recent years ramped up its ambition to reduce GHG emissions from the sector.** In July 2023, it revised its Strategy on the Reduction of GHG Emissions from Ships, setting the target for international shipping to "reach net-zero GHG emissions by or around, i.e., close to, 2050, taking into account different national circumstances" (IMO, 2023, p. 6). This revised strategy constitutes a ratcheting up of ambition for international shipping decarbonization, up from the previous target of a 50% reduction of total annual GHG emissions by 2050 compared to 2008 (IMO, 2018).

This new strategy puts the shipping sector closer to a pathway consistent with limiting the global temperature increase to 1.5°C above pre-industrial levels, a global objective enshrined in the Paris Agreement (UNFCCC, 2015). According to the Intergovernmental Panel on Climate Change (IPCC), this global temperature goal requires roughly halving CO_2 emissions by 2030, at least reaching net-zero anthropogenic CO_2 emissions by 2050 and declining emissions in non-CO_2 radiative forcers that include methane and nitrous oxide (Skea et al., 2022; Fankhauser et al., 2022). Consequently, global emission pathways compatible with this goal, which we shall refer throughout this paper as 1.5°C-aligned pathways, imply still more ambitious GHG emission reductions in the shipping

[2] This range reflects differences in projection methods and socio-economic pathways.

sector, especially in the near term. Such pathways also need to account for interactions between shipping and other sectors, including risks of shifting emissions to other sectors, as achieving the Paris Agreement requires a systemic reduction of cumulative CO_2 emissions. At a global level, the latest IPCC carbon budgets (IPCC, 2021) provide scientifically rigorous conditions for limiting global temperature increases at a given level with a certain probability, which the shipping sector will need to abide by to achieve global climate targets.

1.2 Sector characteristics and GHG emissions

Although decarbonization is a systemic and global challenge, maritime transport faces challenges that are specific to the sector, due to the nature of shipping activities, assets and practices. **Firstly, ships are characterized by long lifetimes,** averaging between 25 and 30 years. Slow turnovers of fleets and the high costs associated with the early retirement of vessels limit the ability of shipping operators to rapidly reduce emissions generated by their fleet, resulting in the long-term lock-in of carbon emissions (Seto et al., 2016).

Secondly, the sector is comprised of diverse shipping activities, depending on the type of ships and transport distances, hence differences in the activities that generate emissions. For international shipping, six types of ships constitute over 86% of GHG emissions, namely container ships, bulk carriers, oil tankers, liquified gas tankers and general cargo, by decreasing order of importance.

Table 1 presents the breakdown of energy consumption between ship types for international shipping based on a voyage allocation and illustrates the predominance of container and bulk shipping among international maritime transport activities in terms of fuel consumption. All ship types are currently reliant on fossil fuels, especially heavy fuel oil (HFO) which represents close to 80% of total fuel consumption. Marine diesel oil (MDO) is the second most used fuel for international shipping and has been increasingly used across all ship types over the last decade. The use of LNG as a bunker fuel for liquified gas tankers has also grown and accounts for roughly half of fuel consumption for this ship type (Faber et al., 2020).

Table 1. Voyage-based allocation of energy consumption for international shipping

Vessel type	Share in energy consumption
Container	27%
Bulk carrier	23%
Oil tanker	15%
LNG tanker	8%
Chemical tanker	7%
General cargo	5%
Others	15%

Source: IRENA (2021), based on data from Faber et al., 2020.

Thirdly, the breakdown of GHG emissions across operational phases differs depending on the ship type. For instance, for chemical and oil tankers, 20% of emissions occur at or near the port or terminal, whereas that share drops to less than 10% for container ships. The nature of goods carried on board also affects emission trends, as container ships have been operating at slower speeds over the past decade, hence a lower use of fuel, whereas oil tankers have responded to higher demand with higher operating speeds. In addition, emissions from shipping are partly determined by port activities, hence the importance of considering the port-ship interface in assessing emission pathways. According to UNCTAD, the 20 largest ports handle over 50% of global cargo (IEA, 2021), and therefore are key nodes of transport that play a determining role in limiting port-related emissions from shipping.

Fourthly, it is important to note that like aviation, **GHG accounting for international shipping proves challenging** as emissions from international voyages are often excluded from the scope of countries' GHG emission budgets, targets, and nationally determined contributions (NDCs). As a result, the IMO plays a significant role in setting GHG emissions reduction targets and coordinating the implementation of decarbonization measures in the shipping industry (Bullock et al., 2022).

1.3 This paper

Shipping is considered a hard-to-abate sector by the IPCC and the IEA, given its critical role in global trade and the absence of clear feasible pathways to decarbonize shipping with current commercially viable technologies. However, this claim has been disputed, with Smith (2022) arguing that not all segments of shipping can be defined as critical to economic development (e.g., container shipping of high-value goods to high-income countries) and that decarbonization solutions exist, although a key question remains how to minimize their costs.

This paper assesses and compares four of the proposed sectoral emission pathways for shipping,[3] to provide a benchmark against which corporate transition pathways can be assessed in the shipping industry:

- The IMO's revised Strategy on the Reduction of GHG Emissions from Ships (IMO, 2023) and the associated emission and technology pathways.
- The IEA Net Zero Emissions pathway (IEA, 2021), complemented by its revised version in the IEA World Energy Outlook 2022 (IEA, 2022) and by the 2023 update of the IEA Net Zero Emissions pathway (IEA, 2023).
- The OECM pathway (Teske et al., 2020; Teske et al., 2022).
- The IRENA pathway to decarbonize the shipping sector (IRENA, 2021).

This work provides an overview of the main challenges to decarbonize the shipping industry and how decarbonization pathways from prominent organizations converge or differ. It does not directly address how corporate or national transition plans in the shipping industry should be assessed. However, reviewing credible pathways to decarbonize the shipping industry is a stepping stone to identifying benchmarks for the assessment of the credibility and feasibility of transition plans in the sector.

The paper is structured as follows: section 2 reviews the main characteristics of the four pathways, focusing on emissions pathways (2.1), the decarbonization levers to achieve these emissions reductions (2.2), and the associated technology pathways; then section 3 discusses the credibility of the four pathways to identify key factors affecting the feasibility of pathways.

[3] These four emission pathways are compared for the period until 2050, which corresponds to the reference year of most long-term emission targets at global, national and corporate levels.

2 Pathways to net-zero

This section discusses four pathways to achieving net-zero emissions in the shipping industry, comparing and contrasting their decarbonization strategies while highlighting areas of consensus and divergence among the proposed approaches. Sub-section 2.1 evaluates the divergent emission trajectories, carbon budgeting approaches and their congruence with the Paris Agreement across the four pathways. Sub-section 2.2 delves into the decarbonization levers crucial for transitioning the sector, while sub-section 2.3 focuses on the technological pathways that underpin these emission reduction strategies.

2.1 Emission pathways

Although it is widely acknowledged that limiting global warming to 1.5°C will require a significant reduction in GHG emissions from shipping by 2050, there has been disagreement on the extent and speed of decarbonisation efforts needed in the sector.

The four pathways reviewed claim to be aligned with the Paris Agreement, and except for IMO's pathway as outlined in its revised strategy, they claim to be consistent with the 1.5°C goal. However, the OECM pathway is the only one that provides an overall carbon budget that is explicitly compatible with a 67% probability of limiting global warming to 1.5°C above pre-industrial levels with no or low overshoot (400 Gt CO_2 between 2020-2050). Precisely, the OECM allocates a carbon budget of 12 Gt for the shipping sector, which corresponds to a proportional share of CO_2 emissions compared to current emissions by sector.

As illustrated by Table 2, the four pathways differ in the proposed emission trajectories and targets by 2050 for shipping. It is important to note that both the IMO and IRENA pathways are limited to international shipping whereas the IEA and OECM pathways cover all shipping activities, hence the difference in baseline emissions at the start of the period. It is also worth noting that the Getting to Zero Coalition (GZC) articulates three additional transition pathways for shipping, which are nonetheless qualitative scenarios that are not explicitly underpinned by emission trajectories. GZC's scenarios are discussed below but given the absence of quantitative data, are not directly compared to the four pathways above. Table 2 compares these four selected pathways based on their emission reduction pathways.

Table 2. Comparison of emission pathways for the shipping sector.

	IEA	OECM	IMO	IRENA
Coverage	Global*	Global*	International	International
Target baseline year**	2022	2019	2008	2018
Emissions reductions by 2030	19%	16%	20-30%**	-
Emissions reductions by 2040	63%	-	70-80%**	-
Emissions reductions by 2050	87%	100%	Net Zero	80%
2050 GHG emissions	0.11 Gt	0 Gt	-	0.144 Gt
Carbon budget (2020-2050)	-	48 Gt	-	-
Reliance on CC(U)S	Yes	No	Yes	Yes
Claimed temperature alignment	1.5˚C	1.5˚C	1.5 – 2˚C***	1.5°C

Sources : IRENA, 2021 ; IEA, 2023 ; Teske et al., 2020 ; IMO, 2023.

** Global means that both domestic and international shipping are covered.*
*** Baselines vary across scenarios which impacts the ambition of emissions reduction targets. Emissions in 2018 amount to around 90% of emissions in 2008, making the IMO target less ambitious between 2022 and 2030 than the IEA and OECM targets for 2030.*
**** IMO pathway claims to be consistent with the temperature goal set out in Article 2 of the Paris Agreement, i.e., "well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C" (UNFCCC, 2015, p. 3).*

2.1.1 IMO GHG emission pathway

The IMO pathway for international shipping is based on the agency's strategy for the reduction of GHG emissions from ships revised in 2023, which provides absolute and relative emission targets for 2030, 2040 and 2050. IMO aims to peak absolute GHG emissions as soon as possible and reach net-zero GHG emissions "by or around 2050" for international shipping. By 2030, it aims to achieve at least a 20% reduction in total GHG emissions compared to 2008, while striving for 30%. Similarly, it seeks to reduce emissions by 70 to 80% by 2040 (IMO, 2023). It is worth noting that contrary to all other selected pathways, IMO's is the only one that covers all GHG emissions. These emission targets are based on a 'well-to-wake' accounting approach, cognizant of the risk of emission leakage to other sectors (Ricardo Energy & Environment, 2021).

However, in its current articulation, **the IMO pathway does not appear to be 1.5°C aligned due to the slack interim GHG targets,** as this temperature goal requires halving CO2 emissions by 2030. Indeed, the gradual reduction in GHG emissions associated with this pathway without significant reductions in the near term would lead to a carbon budget for international shipping that would likely exceed its proportional share under this temperature goal. Moreover, the lack of clarity regarding the timing of the net-zero GHG emissions targets as well as the provision of ranges for interim targets are a source of ambiguity that could undermine the integrity of the IMO pathway. Finally, IMO's net-zero target does not state the amount of gross GHG emissions remaining in 2050 and, as noted by Smith (2022), the shipping industry has limited capacity for in-setting.

2.1.2 EA Net Zero Emissions pathway

The IEA NZE pathway for shipping is part of the IEA's Net Zero by 2050 Roadmap for the Global Energy Sector that aims to achieve net-zero energy-related and industrial-process CO_2 emissions by 2050 and minimize methane emissions from the energy sector. **It has a probability of at least 50% to limit the global temperature increase to 1.5°C.** The IEA NZE accounts for both domestic and international navigation and focuses on CO_2 emission reductions. It envisions that by 2050, annual emissions from shipping will reach 112 Mt CO_2 (IEA, 2021; IEA, 2023), representing an 87% reduction in emissions from their level in 2022. Achieving this target requires a 7% annual reduction in emissions on average throughout the projected period.

In this pathway, the shipping sector therefore does not reach net zero. As a result, shipping is considered in this pathway as a hard-to-abate sector, for which residual emissions will need to be offset through CO_2 removals.

2.1.3 OECM pathway

The OECM is a high technical resolution energy scenario model with detailed industry-specific demand and supply parameters that can be modelled and that provides industry-specific KPIs for the financial sector. It includes a transport scenario model with high technical resolution and provides a specific pathway for the shipping sector. To enable its use by the financial sector, the OECM pathway is compatible with different Scope 1, 2 and 3 GHG accounting methods, including the 'production-centric' approach which accounts for embedded emissions for all passenger-kilometres and freight-kilometres in Scope 1 rather than Scope 3.

The OECM 1.5°C scenario has a 67% chance of a 2100 temperature below 1.5°C, though after a slight overshoot, but contrary to the IEA Net Zero scenario, the OECM pathway does not use any Carbon Capture and Storage (CCUS) technologies, nor bioenergy with carbon capture and storage (BECCS). Instead, the OECM pathway assumes a sharper decline in emissions and relies significantly on reforestation and forest restoration. As noted previously, the OECM pathway for global (international and domestic) shipping is constrained by a 48.1 Gt carbon budget.

As illustrated earlier in Table 1, **the OECM pathway involves the steepest decline in CO_2 emissions in the 2030s compared to other pathways,** following a peaking of emissions in 2026**.** It is the only pathway aiming to reach zero energy-related CO_2 emissions by 2050 for the shipping sector.

2.1.4 IRENA 1.5°C pathway

IRENA's 1.5°C scenario for shipping is based on the IPCC's RCP 1.9-SSP1 scenario and claims to "enable the limitation of global temperature rise to 1.5°C and bring CO2 emissions closer to net zero by mid-century" (IRENA, 2021). Like the IMO pathway, it focuses on international shipping, but only provides a pathway for CO2 emissions.

This pathway sets the least ambitious targets among the compared pathways, leading to higher cumulative emissions, **which undermines the credibility of the claim that it is 1.5°C aligned.** Based on this emissions pathway, annual CO2 emissions from international shipping fall to 144 Mt by 2050, corresponding to an 80% reduction in CO2 emissions by 2050 compared to 2018 levels which implies that this pathway does not reach net-zero CO2 emissions by 2050. Moreover, interim targets under this scenario fall short of the 1.5°C-aligned trajectories outlined by the IPCC, since emissions from international shipping by 2030 only represent a reduction of around 25% compared to their level in 2018. According to IRENA, this pathway leads to a 12.5 Gt reduction in CO2 emissions between 2020-50 compared to its base energy scenario.

2.2 Decarbonisation levers

Given the scale and urgency of the decarbonization challenge, any 1.5°C-aligned emission pathway for shipping is necessarily underpinned by a deep and rapid transition of the sector. Precisely, the credibility of emission pathways is based on the underlying set of technological pathways and policies they leverage to cut emissions at sufficient scale and speed.

Four main decarbonization levers can be identified based on the latest study conducted for the IMO reviewing the readiness and availability of low and zero-carbon ship technology and marine fuels (DNV – Ricardo Energy & Environment, 2023). These levers are **(a) energy efficiency measures, (b) low and zero-carbon marine fuels, (c) low and zero-carbon technologies, and (d) enabling port infrastructure to decarbonize shipping activities.** While the expected implementation sequence of measures varies depending on the chosen pathway, these levers seem to play a significant role from now and toward 2050 and therefore require both actions in the short-term and long-term planning. They are presented in further detail in this section, which serves as a basis for the assessment and comparison of the technology-policy mixes underpinning the reviewed emission pathways. To assess the economic viability of technological pathways for the shipping sector, the key criteria we consider are the maturity and scalability of key technologies, their cost competitiveness over time and their energy efficiency (Englert et al., 2021).

Alongside these four technological levers, it is important to stress that **demand management,** through a restructuring of supply chains and reduced reliance on maritime trade, can also crucially contribute to reduced emissions from shipping. Indeed, demand management is responsible for 17% of the cumulative emissions reduction by 2050 in the IRENA pathway. However, unlike the other four levers, reducing emissions through a decrease in demand for shipping affects more fundamental economic dimensions. It therefore involves a more systemic transition that goes beyond sectoral action from the shipping industry. Consequently, although demand management constitutes a powerful lever, actioning it requires policies that are outside the scope of this paper, which is why it is not further developed below.

2.2.1 Energy efficiency measures

First, vessel design and operational energy efficiency measures play a crucial role in decreasing emissions through reduced fuel consumption. This is especially the case in the short term, as candidate fuels progress to commercial readiness and reach maturity. Several technologies that reduce fuel consumption are already mature or expected to reach maturity before the 2030s but will require high rates of adoption to accelerate energy efficiency gains, driven by more stringent regulatory requirements. These technologies improve the vessel design to increase energy efficiency, and include hull and structural optimisation that saves weight, optimised bow design and advanced hull coatings to reduce water resistance, as well as wave power bow foils that use wave motion to assist propulsion. Wind assistance technologies such as towing kites and rigid and soft sails can also reduce fuel use for propulsion, although they are still at the prototype stage and both their commercialisation and fuel-saving potential remain unclear.

Nonetheless, it is important to note that these technologies are not all suited to all types of vessels. Their adoption can be constrained by the low replacement rate of vessels and depends on the additional capital costs they require, their implications for operations and maintenance, and the safety challenges they raise.

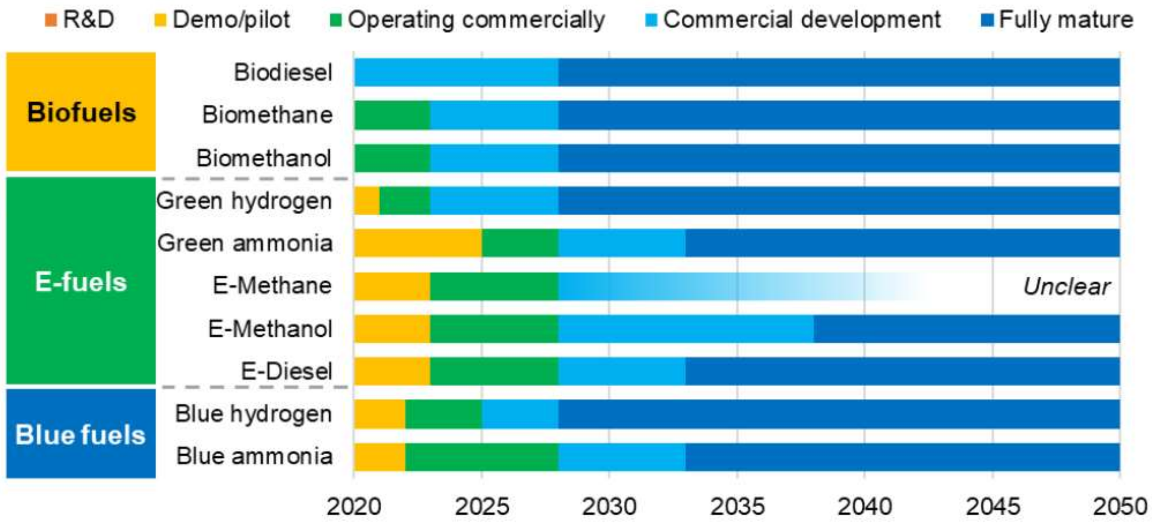
Operational efficiency measures can also be leveraged to reduce energy use. Slow steaming, i.e., reduced operating speeds, is already widely used to reduce fuel consumption per voyage, although there are concerns that the lower speed per voyage could result in the use of more vessels to address growing maritime transport demand. Likewise, the use of advanced autopilots for voyage optimisation and just-in-time arrivals could also reach maturity by 2030 and contribute to energy efficiency gains and reduced GHG emissions from international shipping.

2.2.2 Low and zero-carbon fuels

Second, since the propulsion of ships using fossil fuels is the main source of GHG emissions in the sector, it is widely acknowledged that **a transition to low or zero-carbon fuels is not only unavoidable but also the most important decarbonization lever.** While fossil fuels (HFO and MDO) currently dominate the marine fuel mix, several low and zero-carbon fuels have been identified as candidate fuels to decarbonize shipping. Based on lifecycle accounting that captures emissions from the sourcing of inputs to the final use of fuel, measured as well-to-wake (WtW) emissions, these candidate fuels either emit no CO_2 (zero-carbon fuels) or compensate tank-to-wake (TtW) emissions from onboard combustion with carbon sequestration upstream in their production phase (net-zero carbon fuels). Candidate fuels can be grouped into three broad categories based on the feedstock and technologies they rely on for their production: advanced biofuels, e-fuels and blue fuels.

Figure 1 presents the expected readiness of production pathways for the ten most promising candidate fuels according to a study commissioned by the IMO. The potential of candidate fuel pathways depends on several factors throughout the fuel supply chain. The key factors are the sourcing of inputs, the technical readiness of production processes, the availability of distribution and storage networks, and the technical characteristics of these fuels for their use for propulsion.

Figure 1. Readiness of candidate marine fuels. Extract from the Report on the study on the readiness and availability of low- and zero-carbon ship technology and marine fuels (Ricardo Energy & Environment, 2023)



Source: (DNV – Ricardo Energy & Environment, 2023).

Advanced biofuels are net-zero carbon fuels that use second and third-generation feedstocks such as waste and algae as inputs for fuel production, thereby sequestering biogenic carbon during production that compensates carbon emissions from onboard fuel combustion. Biomethane, bio-methanol and biodiesel are the main candidate biofuels for marine transport given their technical readiness. They are expected to reach maturity before 2030 and could therefore contribute to decarbonizing marine fuel in the short term. However, the commercialization at scale of these biofuels is expected to be constrained by the limited availability of feedstock and competition for their use for other activities, including road transport. These availability constraints imply that they are not likely to dominate future fuel pathways.

On the other hand, e-fuels are hydrogen-based fuels that are produced through chemical processes that fully rely on renewable electricity for their production. Since their cost decreases with cumulative demand as opposed to biofuels that rely on a limited supply of feedstocks, e-fuels are better positioned to scale up. These fuels include green hydrogen, green ammonia, e-methanol, e-methane and e-diesel. Green hydrogen is produced through electrolysis using electricity from renewable sources. Green hydrogen production pathways are in commercial development and are expected to reach full maturity by 2030.

It can be directly used as a zero-carbon marine fuel, although it faces storage constraints due to its low volumetric density. Likewise, green hydrogen can be used to produce other candidate e-fuels.

Green ammonia is produced with green hydrogen and nitrogen and qualifies as a zero-carbon alternative fuel. As a result, green ammonia faces similar production constraints as green hydrogen, but its use at scale has greater potential as it is much easier to store and has a well-established transport network, although it is a highly toxic fuel that can cause serious environmental challenges if spilled (Wolfram et al., 2022). With a similar energy density as ammonia, methanol is also considered as a candidate fuel with high potential thanks to its ease of storage and the very low retrofitting costs its use requires for existing vessels. However, TtW emissions from the use of e-methanol are the same as methanol derived from natural gas. To qualify as a net-zero fuel, the production of e-methanol therefore requires the use, as inputs, of green hydrogen and CO_2 captured through biogenic processes or direct air capture using renewable power. E-methanol production pathways are therefore highly energy intensive and involve numerous steps, resulting in cost competitiveness and scalability challenges for its sourcing despite low barriers for its use in shipping operations (Martin, 2021). Due to their reliance on production processes involving green hydrogen and carbon capture, e-methane production pathways face equivalent challenges, despite the potential use of e-methane as a replacement fuel for LNG-fuelled tankers considering its compatibility with existing natural gas infrastructure and propulsion engines.

Unlike biofuels and e-fuels that either capture CO_2 as an input for fuel production or do not emit CO_2 in operations, blue fuels rely on carbon capture and storage (CCS) to eliminate emissions caused by fuel production processes which usually rely on natural gas. Two blue fuels qualify as candidate net-zero fuels, namely blue hydrogen and blue ammonia. While blue hydrogen could reach maturity before 2030, blue ammonia production pathways are expected to be fully mature in the 2030s, roughly at the same time as green ammonia. In both cases, these fuels use natural gas and depend on the efficiency of CCS processes to ensure they are effectively net-zero carbon. Moreover, their economic viability depends largely on their cost competitiveness compared to their green equivalents.

Finally, it is worth noting that nuclear energy can also qualify as a low-carbon candidate energy source. However, and although nuclear reactors take less space on board than alternative fuel systems, have low bunkering costs and result in no direct GHG emissions, the management of radioactive waste and perceived safety and environmental risks are considered as major barriers to their adoption (Lloyd’s Register).

2.2.3 Onboard powertrain and CCS technologies

Third, widespread adoption of candidate fuels also requires the development of onboard technology that enables their safe and efficient use at scale. Adapting powertrain technologies to enable low GHG emissions from propulsion therefore constitutes another key decarbonization lever. As the dominant powertrain for large vessels, internal combustion engines (ICE) are expected to continue to play a key role in vessel propulsion, with ICEs adapted to candidate fuels expected to reach commercial operation by 2030. Bio- and e-diesel as well as bio- and e-methanol can be used in existing ICE, although the latter require larger bunker tank capacity compared to fuel oil. Ammonia-fuelled engines are still at the laboratory stage and could reach commercial readiness by 2030, although their use on retrofitted oil-fuelled vessels is expected to be more complex than on LNG-fuelled tankers. However, commercial readiness of these technologies could be accelerated by higher demand and stronger policy ambition, given the relatively small technical barriers they face.

Although they are expected to improve, battery technologies are not viable for the propulsion of vessels on international shipping routes. On the other hand, fuel cells that produce electricity on board by oxidizing hydrogen, have a higher efficiency than combustion engines and can use candidate fuels including methane, methanol and ammonia as a direct fuel to produce hydrogen. However, retrofitting ships with fuel cells is more complex than the conversion of ICE to candidate fuels, hence the likely use of fuel cells for auxiliary power in combination with an ICE for propulsion. Nonetheless, this use for auxiliary power could enable later development at scale of fuel cells for propulsion, with facilitated vessel retrofitting through flexible design that leverages electric powertrains to enable the adoption of future breakthroughs in propulsion technologies.

To address the challenge of retrofitting current oil-fuelled vessels, another option is onboard CCS with high capture rates. However, the complexity of onboard storage of captured CO_2 and the high energy intensity of CCS processes are sources of concern regarding the feasibility and viability of this option compared to other retrofitting solutions, hence the uncertainty regarding the readiness of onboard CCS.

2.2.4 Port infrastructure

Fourth, port infrastructure, both for the supply and bunkering of candidate fuels and for the provision of shore power, **plays an enabling role** in the adoption of zero-carbon marine fuel and reducing GHG emissions from operations at berth. Given the pivotal role of certain ports in global shipping, especially the port of Singapore which handles 23% of global bunker volumes, decarbonizing shipping activities will require strategic infrastructure investment and regulation in key ports to lead the transition.

Shore power, also known as 'cold ironing', is expected to reduce fuel consumption of vessels at berth through the provision of renewable electricity for auxiliary power. The large electrical demand of large ships (up to 10 MW) is considered a barrier to the adoption of cold ironing, despite emerging commercial development. To overcome the high capital costs of shore power installation and the high costs of cold ironing compared to running on vessel fuel, more favourable policies and investment incentives will be needed.

Regarding bunkering infrastructure, the existing orderbook for hydrogen and methanol is expected to drive demand for bunker facilities, including through investments in green shipping corridors. As summarized in Figure 2, methanol, ammonia and hydrogen will require additional bunkering infrastructure, while for methanol and ammonia, existing distribution and storage infrastructure reduce barriers to the rollout of these fuels.

Alongside these high capital expenditure measures, low-cost operational measures can contribute to decarbonizing activities at the ship-port interface by contributing to short-term efficiency gains. These include the facilitation of immobilization and simultaneous operations in ports, and improved ship/berth compatibility and deadweight optimization through improved port master data (IMO-Norway GreenVoyage2050 Project and members of the GIA, 2021).

Figure 2. Readiness of distribution, bunkering and storage infrastructure. Extract from the Report on the study on the readiness and availability of low- and zero-carbon ship technology and marine fuels (Ricardo Energy & Environment, 2023)

Fuel types	Distribution and storage	Bunkering infrastructure
Fuel oils (e-diesel, bio-diesel)	Can use existing distribution and storage facilities for conventional fuel	Can use existing bunkering infrastructure
Gaseous fuels (e-methane, bio-methane)	Can use existing distribution and storage facilities for LNG	Can use existing LNG infrastructure
Methanol (e-methanol, bio-methanol)	Existing storage and distribution infrastructure: methanol terminals, already traded by ships	Successful demonstration bunkering operations, ship-to-ship bunkering possible. Partially developed bunkering infrastructure.
Ammonia (e-ammonia, blue ammonia)	Existing storage and distribution infrastructure: ammonia terminals, already traded by ships	No bunkering infrastructure today, and no bunkering operations demonstrated. Barriers remaining to be solved.
Hydrogen (e-hydrogen, blue hydrogen)	No existing distribution infrastructure	No existing bunkering infrastructure Local bunkering demonstrated. Barriers remaining to be solved.

Source: (DNV – Ricardo Energy & Environment, 2023).

2.3 Technology pathways

This broad landscape of decarbonization technologies and measures provides a basis to assess and compare the technological pathways that underpin emission pathways for the sector. Precisely, the technical and commercial readiness timelines of technologies impose constraints on the composition and evolution of technology-policy mixes to achieve interim and mid-century emission targets. The credibility of proposed emission pathways can therefore be assessed considering levels of readiness and economic viability of measures they leverage, as well as the integrity and consistency of the underlying technology-policy mixes.

Switching to net-zero carbon fuels is expected to play a major role in decarbonizing the shipping industry in the four pathways. However, as shown in Table 3, **only the IEA and the IRENA pathways provide a breakdown by fuel type of the evolution of the fuels used in the shipping industry.** This breakdown is key to understanding the technological and policy implications of scaling rapidly net-zero carbon fuels.

This element is therefore essential to assess the credibility and feasibility of a scenario, but it is not provided by the OECM pathway nor the IMO strategy.

Table 3. Evolution of the fuel mix for the four pathways

	2030				2050			
	IMO	IEA	OECM	IRENA	IMO	IEA	OECM	IRENA
Ammonia	-	6%	-	6%	-	44%	-	43%
Hydrogen	-	4%	-	0%	-	19%	-	7%
Biofuels	-	8%	-	7%	-	19%	-	10%
Methanol	-	1%	-	0%	-	3%	-	10%
Share of renewable fuels	**5-10%***	**19%**	**33%**	**13%**	**-**	**85%**	**100%**	**70%**

Sources : IRENA, 2021 ; IEA, 2023 ; Teske et al., 2020 ; IMO, 2023.

** The IMO targets to have zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10% of the energy used by international shipping. The scope is therefore slightly different than the one in other pathways.*

2.3.1 IMO pathway

Like in the pathway outlined in its initial strategy (IMO, 2018), **energy efficiency gains are expected to be the predominant lever to reduce the carbon intensity of shipping in the short term, (i.e., before 2028).** In the medium term, the IMO pathway is underpinned by both technical and economic measures, which are planned to be adopted by 2025 and enter into force by 2027. These measures include the establishment of a goal-based marine fuel standard to regulate the phased reduction in GHG emissions, as well as a maritime GHG emissions pricing mechanism. By 2030, it envisions that 5% to 10% of energy used should be zero or near-zero GHG emissions, contributing to the reduction of emissions by at least 20% in the same timeframe. In the long term, decarbonization is expected to be driven by the global introduction of low-carbon technologies, alternative fuels and energy sources, although the strategy does not provide any details on the composition and evolution of this long-term technology mix. Instead, the IMO has a roadmap to develop new medium- and long-term measures in 2028 for agreement beyond 2030.

On the other hand, it is worth noting that IMO stresses the need for a just transition, reflecting the consensus basis of this revised strategy. In particular, the strategy calls for greater consideration of the impact of decarbonization measures on states, including developing countries and especially least developed countries (LICs) and small island developing states (SIDS). While it critically emphasises the vulnerability of certain countries to the rapid transition to net-zero shipping, this statement could nonetheless result in contradictory trends. Indeed, it could either undermine the credibility of this pathway by enabling countries to leverage just transition considerations to justify the prioritization of development over the implementation of decarbonization measures, or it could support the calls of SIDS to raise ambition focused on strictly limiting global warming to 1.5°C, beyond which the future of many insular states is severely compromised (Allen et al., 2018).

2.3.2 IEA NZE pathway

The IEA NZE also **assumes that energy efficiency improvements will drive short-term emission reductions.** By 2030, oil will still account for about 80% of energy consumption for shipping, but slow steaming and wind assistance technologies are expected to lead to energy efficiency gains for this period. Precisely, a 30% speed reduction and the implementation of all energy efficiency measures could reduce energy demand by 15% to 27%, according to DNV – Ricardo Energy & Environment (2023). Nevertheless, the reliance of this pathway on wind assistance for short-term reductions could be a source of concern given the uncertainty regarding the technical readiness of these technologies.

In the medium and long term, the IEA NZE is underpinned by the global transition to low-carbon fuels, especially hydrogen, biofuels and, most notably, hydrogen-based fuels. It is two to four times more ambitious in the uptake rate of zero and near-zero emission fuels by 2030 compared to the IMO pathway, and more generally, the IEA NZE is underpinned by much more detailed trajectories in the composition of the future fuel mix. Ammonia accounts for 44% of global energy demand for shipping in 2050 under the IEA’s scenario, while hydrogen and bioenergy each account for 19%. This represents a significant shift in the global fuel mix for the sector, given that in 2030, these three alternative fuels have a combined share of just 18% under this pathway (Table 4). Moreover, the IEA pathway assumes a very limited role for electrification, although its potential for short-distance shipping is recognized.

Table 4. Evolution of the fuel mix for the IEA NZE pathway

	2022	2030	2035	2050
Ammonia	0%	6%	15%	44%
Hydrogen	0%	4%	7%	19%
Biofuels	0%	8%	13%	19%
Methanol	0%	1%	1%	3%
Share of renewable fuels	**0%**	**19%**	**36%**	**85%**

Source: IEA (2023)

This long-term technological pathway is consistent with the identified high potential of green ammonia to replace fossil fuel-based propulsion. Under this pathway, the switch to low-carbon fuels is expected to have little impact on vessel design but requires significant investments in bunkering and storage infrastructure alongside new safety standards.

However, by 2050, oil still accounts for 15% of shipping fuel demand in this pathway, due the vessels' long lifetimes. Residual emissions due to carbon lock-in in the fleet and port infrastructure in the IEA NZE highlight the need for considerable rates of retrofitting. According to GZC's strategy for the transition to net-zero shipping, retrofitting of existing ships and the construction of new ships for zero-emission fuels will be needed in similar magnitudes, unless an important share of fossil-fuel-based vessels are retired earlier than their expected end-of-life (Smith et al., 2021).

2.3.3 OECM pathway

For the OECM pathway, **the achievement of net-zero emissions by 2050 for maritime transport is largely driven by the transition to net-zero carbon marine fuels.** This pathway projects that the share of renewable and synthetic fuels in the global marine fuel mix grows to 33% by 2030, which is close to twice as much as the share projected in the IEA NZE. By 2040, this share reaches 87% in the OECM pathway, while by 2050, renewable and synthetic fuels represent 100% of the marine fuel mix, resulting in a total elimination of emissions from maritime transport (Teske et al., 2022). Nevertheless, **the OECM does not provide further details on the net-zero carbon fuels it relies on,** although the exclusion of CCUS from the analysis due to the lack of evidence of their commercial viability indicates that synthetic hydrocarbons, fuels whose production processes require CO2 like e-methanol, and blue hydrogen are not considered as candidate fuels.

Regarding energy efficiency gains, the OECM pathway projects only a 10% decrease in the energy intensity of freight transport by 2050 compared to 2019. Although the rate of energy efficiency gains is not specified, the small overall decrease over the period implies that unlike other pathways, this lever plays a minor role under the OECM pathway. On the other hand, changes in demand for domestic navigation are partly included in the OECM. Indeed, it assumes that by 2050, transport mode shifts will result in a 25% decrease in freight shipping demand compared to 2019, although it does not specify the impact of this modal shift on aggregate emissions for shipping.

This technological pathway appears to be consistent with the associated emission pathway which relies on deep emission cuts in the 2030s, driven by a rapid transition to alternative fuels. This indicates that the OECM assumes that emission reductions are largely contingent on the readiness of these fuels, with a limited role of other technological levers. Nevertheless, the lack of granularity on the composition of the marine fuel mix and required investments and policies to enable this transition does not allow to robustly establish its feasibility.

2.3.4 IRENA 1.5°C pathway

Like the other three pathways, the IRENA pathway relies mostly on energy efficiency, design and operations measures in the short term to reduce CO2 emission intensity per ton-kilometre. By 2050, improved energy efficiency is expected to account for 20% of cumulative reductions. Likewise, medium-term reductions under this pathway are achieved through the substitution of fossil fuels with 'renewable' biofuels and e-fuels. However, advanced biofuels (e.g., hydrotreated vegetable oils) are expected to be only a short-term option for fuel blends with at most a 20% to 30% biofuel input, since the competition for viable feedstocks with other sectors will likely lead to cost increases that limit the scalability of this fuel option. On the other hand, e-methanol and e-ammonia, two hydrogen-based alternative fuels, are identified as viable candidate fuels under this pathway. While e-methanol has the advantage of requiring little to no engine modifications, its reliance on CCUS to ensure that it results in zero or near-zero WtW emissions is expected to constrain its viability at the required scale under this pathway. Given its non-carbon content, e-ammonia is therefore identified as the backbone of international shipping decarbonization by IRENA. By 2050, renewable fuels represent 70% of the fuel mix, with e-ammonia making up to 43% of the fuel mix by 2050 (Table 5). Nonetheless, the IRENA pathway still relies significantly on LNG by mid-century.

Table 5. Evolution of the fuel mix for the IRENA pathway

	2022	2030	2040	2050
Ammonia	0%	6%	25%	43%
Hydrogen	0%	0%	4%	7%
Biofuels	0%	7%	8%	10%
Methanol	0%	0%	4%	10%
Share of renewable fuels	**0%**	**13%**	**41%**	**70%**

Source: IEA (2023)

Moreover, the IRENA pathway is based on four main enabling actions to raise decarbonization ambitions: (a) collaboration in the shipping sector and cross-stakeholder synergies for power fuels, (b) policy-driven actions including a realistic carbon levy, (c) R&D and innovation, and (d) investment in renewables and energy efficiency. Lastly, this pathway leverages measures to decarbonize port activities, which include cold ironing, adapting bunkering infrastructure, and decarbonizing activities of port vessels and auxiliary port infrastructure.

3 Credibility of pathways: A discussion

This section evaluates the feasibility and consistency of net-zero emission pathways in the shipping industry, highlighting commonalities such as the importance of energy efficiency gains in the short term and differences in fuel transition strategies, while underscoring key considerations such as just transition issues or the critical role of policy, technology and investment in bridging the gaps between scenarios to meet the 1.5°C temperature goal.

Considering the lack of currently mature candidate fuels and the significant lead times of enabling infrastructure and technologies their development at scale relies on, most pathways agree that sustained energy efficiency gains will be the key lever for short-term emission reductions. Consequently, achieving interim targets in 2025 and 2030 heavily depends on efficiency improvements coupled with greater policy stringency. The widespread rollout of operational measures such as slow steaming, voyage optimization and emission standards appears essential to reduce emissions in the short term.

Nonetheless, all pathways recognize that several decarbonization levers need to be actioned to hit the successive milestones for the sector's transition. Indeed, although energy efficiency gains could contribute up to 30% in reduction in emissions by 2050 according to IMO in maximum efficiency scenarios (Faber et al., 2020), this lever alone is not sufficient for 1.5°C alignment (Smith et al., 2021).

However, even with increased policy ambition, there are major feasibility gaps identified for the achievement of 2030 targets that are consistent with the 1.5°C temperature goal (DNV – Ricardo Energy & Environment, 2023). For instance, in the IMO pathway, which provides the most detailed short-term measures, the implementation timeline of technical and economic measures to incentivize emission reductions does not appear to be compatible with 1.5°C-aligned 2030 targets. More widely, none of the four pathways assume that emissions can be halved by 2030, therefore implying even greater cuts in the 2030s and 2040s to remain within carbon budgets compatible with the Paris Agreement. Consequently, credible net-zero pathways for the shipping sector must include immediate and massive action not only to reach 2030 emission reduction targets, but also to enable key technologies and fuels to rapidly reach maturity for their rollout at scale in the medium and long term.

Since most emissions from shipping are due to onboard fuel consumption, decarbonizing the marine fuel mix is considered the central lever for all four pathways. However, the composition and speed of change of the fuel mix varies from one pathway to another. While fossil fuels maintain a residual share in the marine fuel mix of 2050 for the IEA NZE and IRENA pathways, they are completely replaced by net-zero carbon fuels in the OECM pathway. On this point, the ambition of the latter therefore appears to be the most consistent with the Paris Agreement, although its credibility is undermined by the lack of granular data on the marine fuel mix which prevents the assessment of the underlying technological, economic and regulatory dynamics.

According to recent estimates, **zero-carbon fuel production must on average grow at an annual rate of 6% to 12% from 2030 onwards to reach full decarbonization by 2050** (DNV – Ricardo Energy & Environment, 2023). In most pathways, green ammonia is considered the most viable candidate fuel, complemented by green hydrogen, advanced biofuels and e-methanol. It appears that all pathways agree that the future fuel mix will likely be more diverse, relying on several renewable and synthetic fuels rather than on one or two dominant fuels as is currently the case (Ricardo Energy & Environment, 2021). The composition of the fuel mix is also likely to evolve throughout the next decades to adapt to different levels of commercial readiness of candidate fuels. Indeed, advanced biofuels could be used in the short term as they are expected to rapidly reach maturity, before being overtaken by e-fuels in the 2030s, which have greater potential to scale up and match global marine fuel demand.

On the other hand, **the future marine fuel mix will crucially depend on the evolution of comparative costs for candidate fuels.** According to the latest study for IMO on the readiness of candidate fuels, carbon-based synthetic and biofuels such as bio and e-methanol are expected to be more expensive than green ammonia and green hydrogen in the long term. Nevertheless, this cost gap also depends on economic policies, and could be narrowed down if a carbon tax was imposed, thereby levelling the playing field for candidate fuels (Englert et al., 2021). The competitiveness of each fuel is also contingent on the levels of investments required for associated distribution and bunkering infrastructure, vessel construction and retrofitting, and the technical requirements for their onboard use for propulsion. Consequently, both stronger policies and higher levels of investment are needed to enable a fuel transition at the required scale and must therefore be reflected in technology-policy mixes underpinning emission pathways. According to the GZC pathway, global capital investments need to be in the range of US$ 1.2 to 1.7 trillion to allow the decarbonization of shipping activities (Smith et al., 2021). They could even reach US$1.9 trillion in aggregate for the period 2030-2050, representing over US$ 90 billion in annual investments (Krantz et al., 2020). This is assuming that ammonia becomes the primary fuel in the future marine fuel mix, although a different mix of zero-carbon fuels would result in investments in the same magnitude.

Importantly, **technical and commercial readiness is not expected to be a barrier to the rollout of technologies for energy demand reduction, fuel production and onboard fuel use.** A clear demand signal coupled with stronger policy ambition is the key to a rapid fuel transition of the required magnitude. Indeed, if the demand signal is clear, the price differential of candidate fuels is not expected to constrain their uptake by the shipping industry. It is rather the current uncertainty regarding the speed of price decreases that constitutes the main barrier. Likewise, the increased capital costs of vessels using candidate fuels are not expected to limit their uptake, while high capital costs for onboard CCS systems are anticipated to be a barrier to the adoption of this technology. Notably, the recent expansion of LNG as a bunker fuel for tankers shows that the rapid adoption of new fuels is possible and provides lessons to enable the uptake of alternative fuels (Lloyd's Register, 2019).

Consequently, 2040 and 2050 targets remain technically feasible, but will require greater investment levels and policy ambition to provide long-term clarity and enable an orderly transition (DNV – Ricardo Energy & Environment, 2023). Their achievement can also be accelerated by stronger international cooperation. The importance of this additional lever is stressed by the IEA NZE, the GZC pathway, the IRENA 1.5°C scenario as well as the IMO strategy.

Coordination between states and maritime organizations is critically needed to immediately tighten energy efficiency regulation, invest in port infrastructure that reduces emissions at the ship-port interface, and establish a carbon levy on shipping to facilitate the uptake of emerging zero-carbon fuels (IMO, 2019; IRENA, 2021). Imposing a carbon levy could allow to raise resources to support fleet upgrades and port infrastructure investment, and distribute it to the most vulnerable countries, especially LICs and SIDS. As a result, this redistribution mechanism would not only incentivize the adoption of marine fuels but also limit the impact of this transition on the final cost of shipped goods through reinvestment in port infrastructure (Dominioni et al., 2023).

Considerations of regional dynamics in the pace of decarbonization must also be accounted for when assessing the credibility of emission and technology pathways for maritime transport. The “common but differentiated responsibilities” principle enshrined in the UNFCCC implies that, for the shipping sector, companies operating on shipping routes servicing developed countries, especially in Europe and North America, could be required to reach net-zero emissions on a WtW basis by 2040 (UNFCCC, 1992; Smith, 2022). Consequently, depending on the level of international coordination of decarbonization policies, different rates of decarbonization and diverse levels of ambition could result in challenges for companies operating across jurisdictions and incentivize their alignment with the most ambitious pathways to ensure compliance, thereby requiring an even faster transition of their activities than that envisioned by global emission pathways.

The decarbonization of marine fuels also provides a unique economic opportunity for countries positioned on key maritime routes and with large renewable resources to position themselves as leading producers of zero-carbon marine fuels. Inclusive fuel production pathways could enable developing and emerging countries, such as Egypt, Morocco, Malaysia and India, to play a leading role in marine fuel production and provision (Englert et al., 2021). This potential distribution of production and implications for the availability of zero-carbon marine fuels must therefore be factored into the operational strategies of shipping companies.

Finally, although pathways consider demand management as a key decarbonization lever, the effectiveness of this lever is contingent on factors that go beyond the shipping sector, encompassing wider economic and geopolitical dynamics. As a result, demand management faces important feasibility barriers, hence its limited inclusion in the reviewed pathways (Smith et al., 2021).

4 Conclusion

With over 1 Gt CO2e generated annually by global maritime transport, reaching net-zero emissions by 2050 in the shipping sector requires immediate, deep and sustained cuts in emissions. This implies massive efforts to reduce energy consumption, decarbonize marine fuel and adapt port infrastructure, vessels and operations to low-carbon technologies and fuels. To address this challenge, several emission pathways have emerged to guide the sector's decarbonization. The comparison of four emission pathways for international and global shipping shows that the degree of ambition and alignment with the 1.5°C temperature goal varies, with only one pathway effectively reaching net-zero emissions by 2050 and sticking to a clear carbon budget for the sector.

This diversity in emission pathways is reflected in the technology-policy pathways that underpin them, although there is convergence to a certain extent on the main levers and the timing of action. In the short term, energy efficiency gains, sustainable fuel requirements and investment partnerships are urgently required to reach near-term emissions reduction targets and accelerate the uptake of alternative marine fuels. In the medium and long term, these pathways are centred around the rapid transition to zero-carbon fuels, especially ammonia, despite variations in the likely composition of the future marine fuel mix. While technical and commercial readiness are not expected to be a barrier to the uptake of zero-carbon fuels, greater policy ambition and a clear demand signal are essential to ensure their rapid uptake at scale and are needed immediately.

Coordinated and massive investments in port infrastructure, fleet renewals and retrofitting, and fuel supply networks will be key to decarbonizing shipping activities. Economic measures, such as a global carbon levy, could prove instrumental in accelerating this transition by providing incentives to reduce the carbon intensity of shipping activities, while its fair redistribution could ensure that vulnerable countries are not penalized and can exploit the new economic opportunities that emerge.

By comparing the main global emission pathways for shipping through the analysis of underlying technology-policy mixes and the landscape of available technologies and measures, **this paper therefore provides a benchmark against which transition plans in the shipping sector can be assessed.**

Precisely, the IEA NZE provides the most credible pathway for shipping based on a detailed technology-policy mix, although its ambition appears to fall short of a strict 1.5°C alignment.

Conversely, the OECM pathway provides a complementary alternative with a stringent carbon budget that is consistent with the 1.5°C goal.

Based on the comparative analysis of pathways, this paper therefore lays the foundation to establish specific criteria for the assessment of the credibility and integrity of transition plans of companies involved in maritime transport.

To build on this paper, **future work could focus on analyzing the consistency of National Action Plans** for the shipping sector with global sectoral emission pathways, to identify possible discrepancies between levels of ambition across scales as well as potential avenues for cooperation and coordination (GreenVoyage2050, 2022; IMO 2022). To assess action at the corporate level, the comparative analysis of existing sector-specific metrics, disclosure frameworks and transition plan credibility frameworks such as those proposed by SBTi (WWF-SBTi, 2023) would then allow the establishment of criteria to assess the integrity of corporate transition plans and targets in the sector.

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