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A global review of marine air pollution policies, their scope and effectiveness

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ABSTRACT

Shipping is associated with various environmental impacts, such as pollutants discharged to air and sea. Much of this pollution appears to be unregulated, and global emissions from shipping are expected to more than triple between 2020 and 2050. This paper reviews global, national, regional and port-level legislative approaches that have been implemented to reduce emissions of carbon dioxide (CO_2), nitrous oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM). Policies are identified on the basis of a systematic review of the literature in combination with a detailed analysis of the respective global, national and local policy initiatives. Findings suggest that many policies are voluntary or, in ports, incentive-based; regulatory approaches are largely limited to Emission Control Areas. Policies also focus on efficiencies, they are not concerned with absolute pollutant and greenhouse gas levels. No policies incentivizing or forcing the transition to zero-carbon fuels were identified. As ports can define limits to pollution, for instance by demanding shore power use, they can significantly affect the clean development of the sector. Further legislation will be needed nationally to counterbalance the lack of supranational ambition on pollutants and climate change mitigation.

1. Introduction

Ships carry three-quarters of the world's freight (ITF 2019), along with very significant passenger numbers on ferries and cruise ships (Cruise Market Watch, 2021). Shipping causes emissions to air, including carbon dioxide (CO_2), nitrous oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter ($PM_{2.5}$, PM_{10}). These contribute to climate change and air pollution (Richter et al., 2004; Traut et al., 2018). NO_x and $PM_{2.5}$ in particular can have serious health impacts (e.g. Andersson et al., 2009; Corbett et al., 2007; Künzli et al., 2000; Marelle et al., 2016; Pandolfi et al., 2011), and populations living in proximity to ports have been found to be exposed to particularly high levels of air pollution (e.g. Merico et al., 2017; Saxe and Larsen 2004). CO_2 is the most important greenhouse gas, and even though shipping makes only a small contribution to global warming, the sector's expected growth will challenge a global economy seeking to decarbonize by mid-century (UNFCCC 2018).

There is a growing body of literature addressing pollutants and emissions from shipping and strategies to reduce these (Anderson and Bows 2012; Balcombe et al., 2019; Bows-Larkin 2015; Eide et al., 2013; Gilbert and Bows 2012; Traut et al., 2018; Wan et al., 2018). In the Fourth IMO GHG study, the International Maritime Organization (IMO) estimates that the contribution of shipping (international, domestic, fishing) to overall global emissions of greenhouse gases is 1076 Mt CO_2-equivalent, the major part of this attributed to CO_2 (1056 Mt), with the remainder falling on CH_4 (methane) and N_2O (nitrous oxide) (together: 20 Mt CO_2-equivalent; MEPC 2020). While the share of CO_2 emissions coming from shipping is still relatively low in comparison to other sectors - at 2.89% of total anthropogenic CO_2 emissions in 2018 (MEPC 2020) -, expected growth rates suggest that in a decarbonizing world, shipping's role will become increasingly relevant. This is illustrated in Fig. 1 for CO_2 from international marine bunkers, suggesting that shipping roughly doubled its contribution to climate change between 1971 and 2019. Continued growth is anticipated, and the IMO foresees an increase in emissions by 90–130% to 2050, notably in a scenario that considers efficiency gains (MEPC 2020). In absolute numbers, emissions may grow to 2.6 Gt CO_2 by 2050 (IMO 2020a; ITF 2019).

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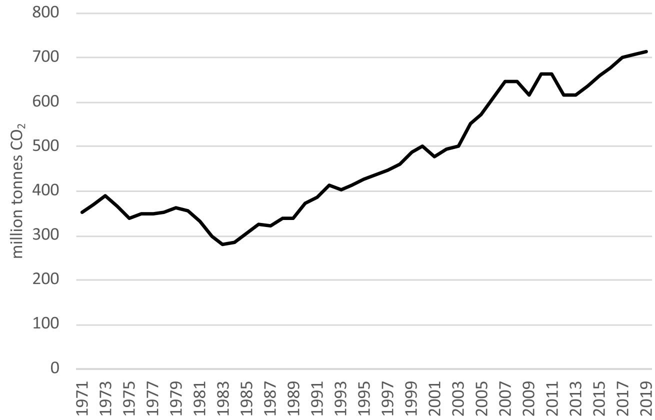


Fig. 1. CO_2 emissions from international marine bunkers, 1971–2019.
Source: IEA (2020)

Important air pollutants from shipping that have significant health impacts include NO_x and $PM_{2.5}$ (Künzli et al., 2000). Various studies have pointed at shipping as an emitter of 14–15% of all nitrogen from fossil fuel combustion (Corbett et al., 1999; Corbett and Koehler 2003; Endresen et al., 2003; Eyring et al., 2005). Current estimates are 20.9 Mt of NO_x in 2015, or 15% of the global total (Johansson et al., 2017). In the most recent assessment, the Fourth GHG Study (MEPC 2020: 144) concludes that NO_x emissions from shipping (international, domestic, fishing) reached 19.65 Mt in 2017. With regard to $PM_{2.5}$, Johansson et al. (2017) calculated shipping emissions in the order of 1.49 Mt of $PM_{2.5}$ in 2015. This figure is essentially confirmed in the Fourth GHG Study (MEPC 2020), at 1.43 Mt $PM_{2.5}$ in 2017. In comparison to an estimated overall global total of 78 Mt $PM_{2.5}$ in 2007 (Huang et al., 2014), shipping is responsible for about 2% of $PM_{2.5}$. Particulate matter contributes to cardiopulmonary and lung cancer (Corbett et al., 2007), with estimates of 14,500–37,500 premature deaths worldwide related to $PM_{2.5}$ (Liu et al., 2016). As ships often contribute to air pollution in port towns, the impact of NO_x and PM has been the focus of much research (Pandolfi et al., 2011; Saxe and Larsen 2004; Merico et al., 2017; Tichavska and Tovar 2015; Maragkogianni and Papaefthimiou, 2015; Papaefthimiou et al., 2016). Other important pollutants from shipping included, in 2017, SO_x (10.1 Mt), NMVOC (0.8 Mt), CO (0.8 Mt), and black carbon (80,000 t) (MEPC 2020).

As this overview indicates, shipping is a source of significant amounts of air pollutants and emissions, even though the sector's contribution to global totals is low. Shipping's relevance is thus twofold: First, in a world seeking to decarbonize, its contribution to global warming will grow in relative and absolute terms. This is a problem specifically in regard to shipping's non-inclusion in the Paris agreement (UNFCCC 2018) and the global community's zero-emission goals to 2050. Second, shipping is a major factor in local air pollution, affecting in particular port and coastal communities. In these environments, shipping is often the major source of air pollution.

To reduce air pollutants, various strategies have been discussed. For example, technology innovations reduce fuel use (e.g. hull designs), make fuels redundant (e.g. shore power), reduce carbon-intensities (e.g. LNG), replace fossil fuels (e.g. synthetic fuels), or introduce entirely new propulsion technologies (e.g. electric). Management strategies can include slow steaming or specific routing to reduce energy demand (Balcombe et al., 2019; Eide et al., 2013). There is however much agreement that this will require governance, i.e. policies to initiate change on the basis of voluntary, market-based, or regulatory approaches (Gilbert and Bows 2012; Larkin et al., 2017; Walsh et al., 2017; Wan et al., 2018).

While many papers have discussed technology options, management as well as policies, it is increasingly clear that these may have made shipping somewhat more efficient, but not changed overall air pollutant and emission growth trajectories. This is also evident in IMO's report on emissions from international shipping to the UNFCCC (IMO 2019), which does not focus on overall emission growth, rather than a host of strategies to improve the relative efficiency of ships. Many of the strategies have been outlined by the sector itself, including new power and propulsion systems and fuels (IMO 2019; MEPC 2020), but they are unlikely to be introduced without regulation or market-based measures, as they are too costly (Eide et al., 2009). There is thus a significant challenge to transform the sector, for instance in regard to Paris Agreement objectives (Traut et al., 2018). The ITF Transport Outlook (ITF 2019) concludes that "transport CO_2 emissions remain a major challenge", with calculations that the sector would have to reduce its GHG emissions by 85% by 2050 compared to 2010 in order to support the wider global decarbonization goals (Anderson and Bows 2012). Even under a scenario that considers all known opportunities to limit shipping emissions, this goal will be difficult to achieve (Wan et al., 2018).

Perhaps as a result, IMO's (2020a) emission reduction goal is more modest, and defined as a reduction in the absolute level of GHG emissions by at least 50% by 2050 in comparison to 2008 (Fig. 2). This proposition is somewhat confusing as it relies on the combined effect of design and technology, operations, and yet unknown "innovative measures, fuels and technologies". While there is limited evidence that known designs, technical and operational measures are on track to reduce the sector's emissions by the level proposed by IMO, it is even less clear how unknown innovations would contribute to decarbonization, notably in a scenario that suggests that reductions will be accelerating over time. Fig. 2 thus suggests that there is a growing "emissions gap", defined as the difference between anticipated emission trajectories and mitigation goals. This gap could amount to more than 1.5 Gt CO_2 annually by 2050, or about 1.5 times the current amount of emissions from shipping (IMO 2020a). Given the tight timeline for the transition to a zero-emission global economy, IMO's proposition for greenhouse gas emission reductions must be considered insufficient in both ambition and reliability (see also Acciaro et al., 2013).

The discussion highlights two different roles for governance and policies in transforming shipping, i.e. the need to establish more ambitious decarbonization goals for the sector than currently set by IMO; and to implement policies that will bring shipping on a credible and reliable low-carbon trajectory. Without political interventions, the most likely scenario is that emissions will continue to rise. There is a related issue for NO_x, SO_x and PM, and the need to significantly reduce air pollution levels, specifically in proximity to coastal populations. This impasse been recognized at various political scales. For example, the UN (2019) has called for a "propulsion revolution" to avoid "environmental disaster", while the EU launched a monitoring, reporting and verification initiative for shipping (Council of the European Union 2015). Various port initiatives throughout the world have also sought to limit air pollution levels (López-Aparicio et al., 2017; Maragkogianni et al.,

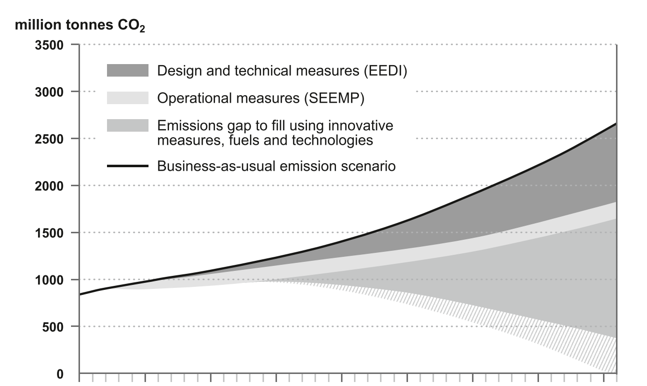


Fig. 2. IMO GHG reduction pathway.
Source: IMO (2020a).

2016; Papaefthimiou et al., 2017).

Overall, the global policy situation remains unclear and is the focus of this review, which investigates the scale, scope and effectiveness of existing marine policies to address greenhouse gas emissions and pollutants from shipping now and in the future. Policies are also evaluated in regard to legislative approaches, which may be voluntary, market-based (including incentives) or regulatory, as well as the policies' scope, which may be global, regional, national or at port level.

2. Materials and methods

A systematic review approach was applied to ensure replicability and literature quality (Bryman, 2016). This applied three review steps: (1) literature search with a set list of predefined relevant terms in order to capture global/regional, national, and local/port policies; (2) for each policy identified in the literature search, review of original source material detailing the policy (e.g., policymaking organizations, institutions, authorities); and (3) organizing summary of the identified policies by scope, implementation date, and policy type. Following the systematic review, policies were then critically evaluated against the marine transportation sector's goals for pollutant reduction and decarbonization.

To identify policies (step 1), Google Scholar was searched for the following keywords (December 2020), both as single terms as well as in combination: "marine policy", "regulation", "shipping", "cruise", "port", "municipality". This approach led to the initial identification of 137 papers, which were screened for relevance in regard to the research objective. During the process, 36 papers were removed from the collection. In a consecutive step, the remaining 101 papers were evaluated to extract and list all policies falling into this paper's boundaries, i.e. policies refereed to either CO_2 as the principle greenhouse gas or air pollutants NO_x, SO_x, and PM. The review considers regulation, agreements between governments/ports and the shipping industry, as well as initiatives by industry. It excludes discharge to sea. Articles cover two decades, i.e. the period 1999–2020.

In the second step, the exact scope of the policies was determined in a review of the original sources. Websites of the respective organizations, institutions and authorities were visited, and details on the policies collected. This included a comparison of statements made in papers, i.e. content was checked for accuracy, and the policies' scope noted in short summaries (Annex I). All policies are evaluated and listed by scale (global/national/port) as well as by policy type (voluntary, market-based or regulatory). Incentives are included as market-based policies. This approach is different from earlier publications that investigated management initiatives, distinguishing for instance physical, regulatory, economic, or educational strategies (Johnson 2002), or by category, geographical embedding, and legislative body (Christodoulou et al., 2019). In comparison, this paper is focused on policy types, their scope in regard to air pollutants, and their legal applicability by region. The overall goal is to illustrate the level at which legal initiatives have been implemented, and whether these are significant enough to reduce air pollutants from shipping.

3. Results

Identified marine policies are listed in Table 1, grouped by geographic scale (i.e., global/regional, national, local/port) and summarized by scope, enacted date, and policy type. Fig. 3 presents an overview in the form of a timeline, distinguishing policy types and geographical relevance.

The earliest, global policies for international shipping were introduced in 1973, when IMO adopted the International Convention for the Prevention of Pollution from Ships (MARPOL) in response to various oil spills (IMO 2020b). In 1994, the Green Award represented the first global initiative at port level, offering discounts to ships going through voluntary certification. Some 1000 certified ships and 145 discount

Table 1
Overview of policies by jurisdiction and policy type.

Policy	Scope	Implementation	Policy Type
Global/regional			
Green Award	International	1994	Market-Based
EU Sulphur Directive	EU	1999	Regulatory
Operational Guidelines – Association of Arctic Expedition Cruise Operators (AECO)	Arctic areas	2003	Voluntary
MARPOL Annex VI sulphur limits	IMO	2005	Regulatory
Emission Control Areas (ECAs); MARPOL Annex VI	IMO	2005	Regulatory
Clean Shipping Index (CSI)	International	2007	Market-based
Energy Efficiency Operational Indicator (EEOI)	IMO	2009	Voluntary
Environmental Ship Index (ESI)	WPCI	2011	Market-based
Ship Energy Efficient Management Plan (SEEMP)	IMO	2011	Regulatory
Energy Efficiency Design Index for new ships (EEDI)	IMO	2011	Regulatory
Climate and Clean Air Coalition (CCAC)	International	2012	Voluntary
International Code for Ships Operating in Polar Water (Polar Code)	IMO	2014	Regulatory
Data Collection System (DSC)	IMO	2014	Regulatory
Monitoring, Reporting and Verification scheme (MRV)	EU	2015	Regulatory
World Ports Climate Action Program (WPCAP)	International	2018	Voluntary
National			
Commercial Passenger Vessel Environmental Compliance (Cruise Ship) Program	USA (Alaska)	2002	Regulatory
NOx tax/NOx fund and agreement	Norway	2007/2008	Market-based
Ocean-Going Vessel Fuel Regulation (OGVFR)	California	2008	Regulatory
Act to Prevent Pollution from Ships (APPS)	USA	2011	Regulatory
Maritime Singapore Green Initiative (MSGI)	Singapore	2011	Market-based
Ocean-Going Vessels at Berth Regulation (OGVBR)	USA (California)	2014	Regulatory
Sulphur Emission Control Area (SECA)	China	2016	Regulatory
Environmental differentiated fairway dues (EDFD)	Sweden	2018	Market-based
Clean maritime plan: Maritime 2050 environment route map (CMP 2050)	UK	2019	Voluntary
Port			
Los Angeles Port - Alternative Maritime Power (AMP) (2004) - Environmental Ship Index Program (2005) - Vessel Speed Reduction Incentive Program (VSRIP) (2008)	Port of Los Angeles	2004 2005 2008	Market-based & Regulatory
Green Port Policy - Port of Long Beach (GPP LB)		2005	Market-based

(continued on next page)

Table 1 (*continued*)

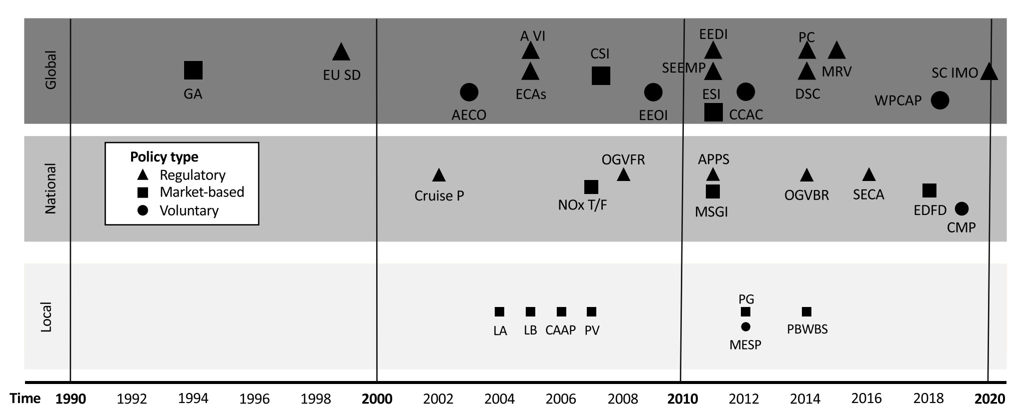
Policy	Scope	Implementation	Policy Type
- Green Ship Incentive Program - Green Ship Award Program - Alternative Maritime Power			
Clean Air Action Plan (CAAP)	Long Beach Los Angeles	2006	Market-based
Port of Vancouver (PV) - EcoAction Program (2007) - Blue Circle Award (2010)	Vancouver	2007 2010	Market-based
Sustainable Port (SP G)	Gothenburg	2012	Marked-Based
Managing the Environmental Sustainability of Ports for a Durable Development (MESP)	Mediterranean Ports	2012–2015	Voluntary
Vessel Speed Reduction – Protecting Blue Whales and Blue Skies (VSP)	Santa Barbara County	2014	Marked-Based

providers (see Annex) have taken part in the scheme. The first policy with significant relevance for air pollution levels was the EU Sulphur Directive (1999), which limited oil sulphur content to 0.1% in the EU member states. This was, in 2005, reciprocated in the MARPOL Annex VI on sulphur limits, at 0.1% mass by mass in Emission Control Areas (ECA). A global limit of 0.5% outside ECAs was introduced in 2020 (see Annex for details). Environmental guidelines referring to polar areas were introduced in 2003 by industry (AECO) and in 2014 by IMO. Measures to increase the energy efficiency of ships at the global scale were introduced in 2009–2011, including the Energy Efficiency Design Index (EEDI; introduced in 2009) that is mandatory for new ships, and the Ship Energy Efficiency Management Plan (SEEMP; introduced in 2013). EU and IMO also made emission data collection mandatory in 2014/2015. All of these measures helped to better understand contributions to climate change and air pollution, to raise awareness, and to put emphasis on the importance of energy efficiency aspects in the design of new ships and ship operations. Other global incentive-based programs include the Environmental Ship Index, a worldwide reward initiative introduced in 2011 that now includes more than 8400 vessels documenting energy efficiencies and shore power capability. A global initiative directed at ports is the World Ports Climate Action Programme, established in 2018. The scheme is voluntary, and brings together ports looking into electrification infrastructure, currently including Antwerp, Barcelona, Gothenburg, Hamburg, Le Havre, Long Beach, Los Angeles, New York and New Jersey, Rotterdam, Vancouver, and Yokohama.

National policies were introduced in the USA, Norway, Sweden, UK, China and Singapore. Regulatory or market based, most national approaches sought to make pollution costlier, or to provide incentives for less polluting ships. A more recent regulatory policy is represented by Sulphur Emission Control Areas in China, limiting sulphur content to 0.1%. The Clean Maritime Plan presented in 2019 in the UK contains opportunities for funding and awards, though its targets are voluntary.

Port-level initiatives were introduced on different levels. Further initiatives were introduced in Los Angeles and Long Beach (California, USA) in the 2000s, and subsequently expanded. For example, the Port of Los Angeles introduced the Alternative Maritime Power programme in 2004, requiring auxiliary diesel engines to be shut down at-berth, and the Vessel Speed Reduction Incentive Program in 2008, asking ships to reduce speeds as they approach the port. Similar programs have been implemented by Long Beach, Gothenburg and Mediterranean Ports, usually on a voluntary or incentive basis.

The timeline of policy introductions (Fig. 3) in combination with the analysis of scale and policy type adds some insights. Regulatory policy types were introduced mostly on global and regional, as well as national levels. The designation of ECAs in the mid-2000s, as well as the EEDI and the SEEMP in 2011 perhaps constitute the most far-reaching policies at the global/regional scale. Most recently, the IMO's new fuel oil sulphur content limit (in 2020), in a tightening of the 2005 MARPOL Annex VI sulphur limits regulation from 3.5% mass by mass to 0.5%, makes a



AECO	Operational Guidelines – Association of Arctic Expedition Cruise Operators	EDFD	Environmental differentiated fairway dues (Sweden)	OGVBR	Ocean-Going Vessels At Berth Regulation (California)
APPS	Act to Prevent Pollution from Ships (USA)	EEOI	Energy Efficiency Operational Indicator (IMO)	OGVFR	Ocean-Going Vessel Fuel Regulation (California)
A VI	Annex VI of the International Convention for the Prevention of Pollution from Ships	ESI	Environmental Ship Index	PBWBS	Protecting Blue Whales and Blue Skies (Santa Barbara Channel)
CAAP	Clean Air Action Plan (San Pedro Bay Ports)	EU SD	Sulphur Directive 1999/32/EC (EU)	PC	Int. Code for Ships Operating in Polar Waters
CCAC	Climate & Clean Air Coalition	GA	Green Award	PG	Port of Gothenburg
CIS	Clean Shipping Index	LB	Port of Long Beach	PV	Port of Vancouver
CMP	Clean Maritime Plan (UK)	LA	Los Angeles Port	SC IMO	IMO low sulphur fuel cap
Cruise P	Commercial Passenger Vessel Environmental Compliance Program (Alaska)	MESP	Managing the Environ. Sustainability of Ports for a durable development (Mediterranean Sea Basin)	SECA	Sulphur Emission Control Areas (China)
DSC	Fuel Oil Data Collection System (IMO)	MRV	Monitoring, Reporting and Verification (EU)	SEEMP	Ship Energy Efficiency Management Plan (IMO)
ECA	Emission Control Areas (MARPOL Annex VI)	MSGI	Maritime Singapore Green Initiative	WPCAP	World Ports Climate Action Program
EDDI	Energy Efficiency Design Index (IMO)	NOx F	NOx Tax/Fund (Norway)		

Fig. 3. Timeline of policy introductions.

significant contribution to limiting emissions of SO_x, also illustrating the viability of regulatory policy approaches. Market-based policies have been mostly implemented at port level, and in the form of incentives for 'greener' ships. This highlights a role for port-level legislation in supporting wider national or regional policies. The timeline of policy introductions suggests that no new initiatives at port level were taken in recent years, however, and that the number of ports participating in these initiatives is small. The most recent schemes, i.e. the World Ports Climate Action Program as well as the Clean Maritime Plan in the UK are mostly in the future and voluntary in character.

4. Discussion

4.1. Relative and absolute goals for pollution

The review of shipping air pollution policies provides a number of relevant insights. Results show that even though most policies are regulatory or market-based, none are designed to address growth and to systematically reduce total amounts of pollutants and greenhouse gases. Of the 32 policy initiatives identified, six are voluntary, 12 market-based and 14 regulatory. Many will raise awareness, while others are focused on data collection; yet none is designed to limit overall emissions, for instance through cap & trade schemes (CO_2). All approaches to reducing pollutants and greenhouse gases are thus relative, limiting emissions to specific levels and making operations more efficient, but leaving future total emission trajectories uncertain. This is perhaps most clearly evident in the IMO GHG reduction pathway (Fig. 2), which highlights an "emission gap", in which unspecified "innovative measures, fuels and technologies" are expected to make significant contributions to reducing absolute emission levels in the immediate future.

This is equally true for air pollutants. For example, even though the sulphur cap implemented by IMO in 2020 limits fuel oil sulphur content to 0.5% mass by mass, it remains unclear whether this is significant enough to satisfy health concerns, specifically if the sector continues to use growing amounts of fuel (IEA 2020a). The inherent conflict of efficiency gain approaches to emissions in comparison to absolute reduction needs is also evident at the port level. Globally, only a limited number of ports offer financial incentives in exchange for reducing speeds, use of shore power, or superior NO_x and PM emission performance. For ports with stable call numbers, this may help to reduce air pollution levels over time, though globally, pollutant amounts are likely to increase with growing trade volumes and ship traffic.

With regard to climate change, the most relevant initiative at the global level is the energy efficiency design index for new ships, which the IMO (2019) expects to reduce specific CO_2 emissions by 19–26% in comparison to a business-as-usual scenario. However, given the sector's continued growth, total emissions will continue to rise (Fig. 2). Even though a new reference level for the EEDI will be set every five years (IMO 2019), technologies also approach physical limits over time, which will subsequently lead to a decline in annual efficiency gains. This has for example been documented for aviation (Peeters et al., 2016). Yet, IMO (2020) anticipates *accelerating* progress on overall emission reductions (Fig. 2), which under any transport growth scenario means that efficiency gains have to be higher than the aspirational 1.5% per year set by the EEDI for 2015–2025, and combined with various other measures, such as reduced (design) speeds and the widespread adoption of low-carbon fuels (IEA 2020a). Likewise, the Fourth IMO GHG Study lists energy saving technologies, use of renewable energy and use of alternative fuels as strategies (MEPC 2020), all without any discussion of the necessary changes in regulatory and market-based policies that will govern the introduction of these technologies. The discussion highlights that there is a need to combine efficiency gain perspectives with modelling studies that determine their contribution to absolute reductions in greenhouse gases to near net-zero in 2050. Likewise, levels of air pollutants posing no health threats for coastal populations need to be defined and set. For any of these changes to happen, policy environments setting and mandating targets will be required.

4.2. The role of policies in technology innovation

The IEA (2020a) concludes that even just halving emissions from shipping by 50% (2050 compared to 2010) will not be achieved by efficiency measures alone, and that "policy action is needed to encourage the advancement of emerging technologies and fuels". Notably, a net-zero trajectory to 2050 is equivalent to a >3% annual adoption rate of zero-carbon fuels on the basis of a drop-in/blend-in approach that leads to the subsequent conversion to sustainable fuels, along with significant efforts to reduce overall fuel needs to offset growth rates. Even though MEPC (2020) presents potential abatement technologies and proposes new fuels, it remains unclear how these, in various combinations, will support zero-carbon goals (Table 2). Specifically, there are no markets for low-carbon or zero-carbon fuels, and hence no industries pursing research & development, nor any upscaling of production in significant ways. Many of the strategies proposed also remain technologically challenging, or uncertified for safe use. Clearly, technical barriers will remain very significant for decades to come, demanding an upscaling of efforts in research and development.

This dilemma has in principle been acknowledged by supranational

Table 2
IMO view of abatement technologies and alternative fuel options.

1. Energy-saving technologies	
Group 1 Main engine improvements	• Main Engine Tuning • Common-rail • Electronic engine control
Group 2 Auxiliary systems	• Frequency converters • Speed control of pumps and fans
Group 3 Steam plant improvements	• Steam plant operation improvements
Group 4 Waste heat recovery	• Waste heat recovery • Exhaust gas boilers on auxiliary engines
Group 5 Propeller improvements	• Propeller-rudder upgrade • Propeller upgrade (nozzle, tip winglet) • Propeller boss cap fins • Contra-rotating propeller
Group 6 Propeller maintenance	• Propeller performance monitoring • Propeller polishing
Group 7 Air lubrication	• Air lubrication
Group 8 Hull coating	• Low-friction hull coating
Group 9 Hull maintenance	• Hull performance monitoring • Hull brushing • Hull hydro-blasting • Dry-dock full blast
Group 10 Optimization of water flow hull openings	• Optimization water flow hull openings
Group 11 Super light ship	• Super light ship
2. Use of renewable energy	
Group 12 Reduced auxiliary power demand	• Reduced auxiliary power demand (low energy lighting etc.)
Group 13 Wind power	• Towing kite • Wind power (fixed sails or wings) • Wind engine (Flettner rotor)
Group 14 Solar panels	• Solar panels
Group 15A Use of alternative fuel with carbons	• LNG + ICE or FC
3. Use of alternative fuels	
Group 15B Use of alternative fuel without carbons	• Hydrogen + ICE or FC • Ammonia + ICE or FC • Synthetic methane + ICE or FC • Biomass methane + ICE or FC • Synthetic methanol + ICE • Biomass methanol + ICE • Synthetic ethanol + ICE • Biomass ethanol + ICE
4. Speed reduction	
Group 16 Speed reduction	• Speed reduction by 10%

Source: MEPC 2020

organizations from the IEA (2020a) to the OECD (2017), which have highlighted the necessity of regulatory policy schemes, mandatory efficiency design standards, and zero-carbon fuel introductions. While some scenarios indicate the magnitude of the challenge of even achieving a 30% low-/zero carbon fuel uptake by 2050 (IEA 2020b), there is a void of decarbonization and de-pollution scenarios, including their cost and technological feasibility. IMO's (2020a) own scenario of decarbonization is neither ambitious nor reliable in regard to global mitigation ambitions.

Given the central role of zero-carbon fuels in the transition to sustainable shipping, a major focus of decarbonization policies will have to be their development and market introduction. Sustainable biofuels have limits in available biomass, drop-in non-biogenic synthetic fuels require vast amounts of renewable energy for their production, and hence also significantly more costly than conventional fuel. A general advantage for the maritime sector is that LPG can replace, on shorter distances, marine oil and diesel, while synthetic fuels can replace LPG and oil/diesel. This is easier and cheaper to achieve for synthetic gas; an option that is not available to the aviation sector and its high-density, low-volume energy requirements on longer routes. Yet, even for shipping, there are expectations on future propulsion that will be difficult to meet (Gray et al., 2021: 5):

- High energy density (MJ/L) and specific energy density (MJ/kg) to minimize fuel volume and mass and allow for long-distance travel;
- Low levels of local emissions (SO_x, NO_x and PM) to ensure compliance with IMO ECA regulations;
- Low energy costs (€/MWh), to ensure cost competitiveness with low-quality residual fossil fuels;
- Low lifecycle GHG emissions (gCO_2 e/MJ), to meet the IMO goal of reducing emissions from shipping by 50% by 2050;
- Scalability, to ensure that large volumes of fuel are available at the quantities required of the shipping sector;
- Widespread bunkering infrastructure, to ensure vessels are able to refuel at ports around the world;
- Compatibility with existing infrastructure, to allow for decarbonization of current vessels and future potential retrofit projects.

4.3. Governance: how to address the future?

Results show that only few countries and regions have stringent pollution control mechanisms, while there is no global decarbonization strategy based on a reliable net-zero emission strategy to mid-century. Paradoxically, this research has found that it is ports that often set the stage for allowable pollution and emissions by offering incentives for pollutant abatement and shore power installations. IMO as the supranational organization tasked with decarbonization thus faces the challenge of implementing world regulations that will be necessary for the future development of global trade under net-zero scenarios. The notable absence of discussions on global governance needs and the resulting policy gap also highlights the importance of national, regional and port-specific policy initiatives. Even though geographically limited, these can influence the shipping industry's development. For example, shore power requirements, shipping indices classifying ships by environmental performance, and associated incentives awarded to cleaner ships are promising avenues for an upscaling of policies: Bonus systems, for example, can be combined with malus approaches that have worked well for cars (d'Haultfoeuille et al., 2014).

Port-level pollutant levels can be toughened much faster than national or global limits, and increase pressure on shipping companies to phase out old ships, or to more carefully consider the design and technologies of new ones. Notably, for some ship types such as cruise ships, auxiliary and heat energy demand is approximately equivalent to total propulsion energy demand (MEPC 2020), indicating a significant potential for pollutant and emission reductions. For the global fleet of vessels, most energy and associated emissions are caused during cruising and slow transit, reflecting on the need for policies to cover voyages in their entirety, by replacing fossil fuels. Regional initiatives to strengthen legislation are thus specifically relevant in regard to climate change. For instance, jurisdictions such as the European Union may mandate a feed-in quota for renewable fuels that forces the sector on a low-carbon trajectory.

In the future, the range of policies may be developed. For example, an investigation of the Norwegian coastal administration into duties to accept ships in time of COVID revealed that environmental risks, which includes air pollution, represent reason to prevent ships from calling in ports (Kystverket 2020). This may provide a legal basis for rejecting highly polluting ships, in an analogue to EU-legislation for vehicles.

Overall, this review underlines that the major barrier to the transformation of the sector is the absence of policy environments that will push the transition towards low-pollution shipping. It can be expected that ship owners and traders relying on shipping will not be supportive of any changes that increase the cost of freight or passenger transport. Yet, these are needed in order to make technology solutions and sustainable alternative fuels economically viable. To harmonize the planning for economically viable, low-pollution, zero-carbon shipping requires longer-term policy visions sending reliable price signals to the shipping industry. Norway, for example, has proposed a continuously increasing CO_2 price to 2030 in order to create a stable basis for industry to plan investments (Regjeringen 2021). This policy blueprint may also be applied to bunker fuels.

5. Conclusions

Shipping contributes to a small, but growing share of greenhouse gas emissions as well as pollutants including NO_x, SO_x and PM that affect the health of coastal populations. There is a broad scientific and political consensus that the sector's emissions need to be reduced. A wide range of propositions have been made in this regard, focused on designs, technical and operational measures, as well as low- and zero carbon fuels that in their combination are supposed to bring shipping on a low-pollution trajectory. A largely undebated question concerns the policy environment needed to achieve this.

Findings as presented in this research confirm that there is no agreement on how the transition would be achieved politically: there is no market case nor significant political pressure for a transformative shift in the adoption of new technologies or the introduction of low-carbon fuels, both of which would have to be upscaled rapidly if global low-pollution and net-zero carbon goals are to be achieved. There are no models to determine timelines for transitions, nor are there assessments of the cost this would imply. Currently, it is not even clear whether any low-carbon, low-pollution trajectory is even technically feasible within the timeline of 30 years, the global decarbonization goal by mid-century. In many areas, air pollution levels would need to be reduced even earlier in order to adequately protect the health of coastal populations.

The review of global marine policies makes the case that current and ongoing policy initiatives are not significant enough. Organizations such as IMO, OECD or IEA have regularly presented scenarios of emission growth, but there are no models to determine how any mix of measures will lead to declining trajectories, and at which cost. Even if such models existed, it would be even more complex to then translate these into policies at global scale. In the current policy climate, results of this paper suggest that it is ports that have the greatest potential to affect global shipping, as they can influence call conditions in comparably fast decision processes. These conditions may exempt certain types of ships from calling, for instance if these are found to be excessively polluting, charge inefficient ships higher fees, and continue to award those with clean technologies. Ports can send powerful signals to industry that can also have relevance for at sea operations, provided they significantly expand and substantiate existing policies. For this to happen, far more ports would have to implement such policies. Progressive regions such as the

EU also gain importance in mandating change, for instance by legislating a renewable bunker fuel quota. A global transition of the shipping sector to meet desired low air pollution and zero-carbon emission targets will require the IMO to significantly toughen regulatory policies, and for regions, nations, and ports to make additional contributions to increasing the interest for ship owners to invest in new technologies while reconsidering operational strategies.

Declaration of competing interest

The authors declare no conflict of interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2021.105824.

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