Decarbonizing the international shipping industry

solutions and policy recommendations

Author(s)

Wan, Zheng; el Makhoulfi, Abdel; Chen, Yang; Tang, Jiayuan

DOI

[10.1016/j.marpolbul.2017.11.064](https://doi.org/10.1016/j.marpolbul.2017.11.064)

Publication date

2018

Document Version

Proof

Published in

Marine Pollution Bulletin

[Link to publication](#)

Citation for published version (APA):

Wan, Z., el Makhoulfi, A., Chen, Y., & Tang, J. (2018). Decarbonizing the international shipping industry: solutions and policy recommendations. *Marine Pollution Bulletin*, 126(January), 428-435. <https://doi.org/10.1016/j.marpolbul.2017.11.064>

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please contact the library: <https://www.amsterdamuas.com/library/contact/questions>, or send a letter to: University Library (Library of the University of Amsterdam and Amsterdam University of Applied Sciences), Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

Amsterdam University of Applied Sciences

Decarbonizing the international shipping industry

el Makhloufi, A.; Zheng Wan & Jiayuan Tangd

Published in:
Marine Pollution Bulletin

[Link to publication](#)

Citation for published version (APA):
Zheng Wan & Jiayuan Tangd (2017). Decarbonizing the international shipping industry: solutions and policy recommendations. Marine Pollution Bulletin.

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please contact the library: <http://www.hva.nl/bibliotheek/contact/contactformulier/contact.html>, or send a letter to: University Library (Library of the University of Amsterdam and Amsterdam University of Applied Sciences), Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

Decarbonizing the international shipping industry: Solutions and policy recommendations

Zheng Wan^{a, b, *}, Abdel el Makhloufi^c, Yang Chen^a, Jiayuan Tang^d

^a College of Transport and Communications, Shanghai Maritime University, Shanghai 201306, China

^b Institute of Transportation Studies, University of California Davis, Davis, CA 95616, USA

^c Amsterdam University of Applied Sciences, 1097, DZ, Amsterdam, The Netherlands

^d Cass Business School, 106 Bunhill Row, London EC1Y 8TZ, United Kingdom

ARTICLE INFO

Keywords:

International shipping

Greenhouse gas

International maritime organization

Policy

Emissions trading scheme

ABSTRACT

Ship-source greenhouse gas (GHG) emissions could increase by up to 250% by 2050 from their 2012 levels, owing to increasing global freight volumes. Binding international legal agreements to regulate GHGs, however, are lacking as technical solutions remain expensive, and crucial industrial support is absent. In 2003, the International Maritime Organization adopted Resolution A.963 (23) to regulate shipping CO₂ emissions via technical, operational, and market-based routes. However, progress has been slow and uncertain; there is no concrete emission reduction target or definitive action plan. Yet, a full-fledged roadmap may not even emerge until 2023. In this policy analysis, we revisit the progress of technical, operational, and market-based routes and the associated controversies. We argue that 1) a performance-based index, though good-intentioned, has loopholes affecting meaningful CO₂ emission reductions driven by technical advancements; 2) using slow steaming to cut energy consumption stands out among all operational solutions thanks to its immediate and obvious results, but with the already slow speed in practice, this single source has limited emission reduction potential; 3) without a technology-savvy shipping industry, a market-based approach is essentially needed to address the environmental impact. To give shipping a 50:50 chance for contributing fairly and proportionately to keep global warming below 2 °C, deep emission reductions should occur soon.

1. Introduction

Ocean shipping, the most energy-efficient form of freight transport, is the backbone of global trade, but this sector heavily depends on fossil fuel. The lengthy debate on whether ship-source greenhouse gas (GHG) emissions are classified as marine pollution has delayed the international regulation and subsequent implementation to limit the carbon emissions from the shipping sector (Shi, 2016a).

Ship-source GHG emissions could increase by up to 250% by 2050 from 2012 levels, owing to increasing global freight volumes (Fig. 1). Unchecked, such emission levels are projected to constitute 17% of the global CO₂ emissions by 2050 from the current figure of approximately 2% (Cames et al., 2015). Yet, at the Paris Climate Agreement of 2015, the shipping industry was neither included in the global emissions reduction targets nor mentioned in the agreement (United Nations Framework Convention on Climate Change, 2015). Discussions regarding shipping emissions were simply left, like in the Kyoto agreement, to the International Maritime Organization (IMO), who is expected to develop regulations, set emission reduction targets, and determine measures to facilitate their practical implementation.

To satisfy the lofty goal of the Paris Agreement to limit global warming below 1.5 °C–2 °C, all sectors may be ultimately

* Corresponding author at: College of Transport and Communications, Shanghai Maritime University, Shanghai 201306, China.
Email address: mrwan@ucdavis.edu (Z. Wan)

Fig. 1. CO₂ emissions in the shipping sector. Illustration based on Buhaug et al. (2009), Smith et al. (2014), Anderson and Bows (2012), Lloyd's list of intelligence data, and OECD analysis. If shipping aims at delivering its fair and proportionate contribution at 50:50 chance to keep global warming well below 2 °C, a deep emission reduction up to 85% by 2050 compared with the 2010 baseline is needed. Existing technology and operational solutions are not enough.

mately required to produce zero emissions or develop tools to remove GHGs from the atmosphere (Williamson, 2016). Regarding shipping emissions, large shipping nations and the shipping industry are slow and sometimes reluctant to introduce appropriate measures aimed at reducing emissions and improve global rules for the industry (Upton, 2016).

The IMO placed the climate impact of shipping in the agenda in 2003. On December 5 of the same year, the IMO adopted Resolution A.963 (23) requiring the Marine Environment Protection Committee (MPEC) to regulate shipping CO₂ emissions through technical, operational, and market-based routes (IMO, 2004). However, stakeholder values are diverse, leading to slow negotiations and no concrete emission reduction pathways or definitive action plan. A full-fledged roadmap may not even emerge until 2023 (Green4sea, 2016). Many widely discussed market tools, such as the cap and trade approach, implemented in other sectors are unlikely to be implemented in the shipping business soon because they are linked to a fuel data collection system that will start only in 2019 (Dufour, 2016).

In this policy analysis, we revisit the progress of technical, operational, and market-based instruments and their associated controversies. Based on existing evidence, we argue the following.

1) Many technical solutions remain too expensive, and crucial industrial support is absent. A performance-based index,

though good-intentioned, has loopholes leading to concerns on the meaningful effect on CO₂ emission reductions.

- 2) Using slow steaming to cut energy consumption is apparent among other operational solutions due to its immediate and obvious results, but with the already slow speed in practice, further emission reduction potential from this single source may be limited. On the other hand, ships could still adopt faster speed when the market and economic circumstances improve. A potential impact will be exerted on fuel use and associated emissions correspondingly. Other types of operational solutions must be incorporated into shipping companies' energy management strategies for extra reduction potential.
- 3) Without a technology-savvy shipping industry, a market-based approach is essentially needed to address the environmental impact. The core of the maritime emissions trading system (ETS) system lies in the "carbon emissions ceiling" and "trading process." However, the method of using benchmarking plus grandfathering rights adopted by the European Union (EU) aviation industry cannot simply be applied to the more complex international shipping industry.
- 4) If shipping has a 50% probability of delivering its fair and proportionate contribution to keep global warming well below 2 °C, a deep emission reduction should take place soon. Constructive regional actions must be recognized as they can be both responsive and cost effective.

2. Technical and operational solutions

2.1. Technical solutions

Technical solutions aim at using technical means to improve a ship's energy efficiency, thereby reducing the CO₂ impact per capacity mile (expressed in ton-mile) (IMO, 2012). The IMO has introduced the mandatory Energy Efficiency Design Index (EEDI) for newly built ships with the hope that such a measure will stimulate a series of technology and engineering innovations ranging from optimized hulls and propellers and improved engine performance to better waste heat recovery systems (MEPC, 2011). Most newly built ships only need to become 0%–10% (the actual number depends on the vessel type and size) more energy efficient between 2015 and 2020, but the index will be tightened incrementally every five years.

A performance-based index, though good-intentioned, has loopholes that led to concerns on the meaningful effect on the CO₂ emission reductions driven by technical advancing. In theory, the use of derated engines with less power can yield significant EEDI reductions at the expense of speed without extra technology improvements (Psaraftis and Kontovas, 2013). An empirical study found that regulations on EEDI would even result in slight increases in CO₂ emissions in large crude carriers because by limiting the installed power on board, vessels would be induced to operate on higher revolutions-per-minute engines that consume more fuel though the EEDI limit is met (Devanney, 2011). In practice, EEDI only reflects the efficiency of ship design but totally neglects the operational variations that determine the real energy efficiency (Cichowicz et al., 2015).

Moreover, increasing competition has led to ever increasingly larger ships with better fuel economy, which translates into a smaller EEDI (Ozaki et al., 2010), but uncertain demand could complicate the real performance—ships could consume more energy per goods transported if half loaded than fully loaded (Wan et al., 2016a). Increasingly larger ships can yield other unexpected side impacts from concentrated pollution at hub ports, such as Hong Kong and Shanghai, to under-regulated ship scrapping of smaller vessels in developing countries, such as Bangladesh and Pakistan. This may lead to public health disasters and biodiversity crises owing to the heavily polluting ship-breaking process.

An array of technical solutions to serve as alternative power have emerged, including fuel cells, waste heat recovery, solar or wind power, and shore-to-ship power (see Fig. 2 for detailed information and comments); however, they struggle to steer the shipping industry toward a low-carbon direction because they require not only engineering breakthroughs in an economically feasible way but also rapid and transformative adoption by an industry that is always slow to react. As shown in Fig. 3, many technical solutions carry a hefty price tag—the average CO₂ reduction cost ranges between 50 USD/ton and 200 USD/ton (Eide et al., 2011), which is far more expensive than the emission-trading price of \$5–\$15 per ton in the United States.

Technical solutions also include capital-intensive options to power vessels with cleaner fuels or even nonfossil fuels, but so far the responses are polarized. A theoretically sound technology to reduce CO₂ may be difficult to engineer and economically unfeasible in real-world settings. For example, converting a vessel to be propelled by liquefied natural gas (LNG) can significantly reduce airborne pollutants and GHG emissions, but this requires millions of U.S. dollars in investment, sacrificing

precious on-board storage space (Verbeek et al., 2011). Such converted ships also rely on a supporting LNG-charging infrastructure network that barely exists today.

2.2. Operational solutions

Operational solutions are usually implemented under the Ship Energy Efficiency Management Plan (SEEMP) targeting vessels greater than 400 GT for international voyage. Operational solutions are typically linked to the shipping companies' energy management strategies, including slow steaming, optimized ship trim, enhanced network routing, hull cleaning, and engine maintenance. In general, these measures require low operating costs and do not involve hefty initial investment but can achieve promising energy savings.

An extensive review shows that slow steaming is the most significant reduction strategy among all major optimization initiatives (Armstrong, 2013). Fuel consumption is directly linked with engine power impacted by operational speed. A medium-sized containership that reduces speed by 30% could use 55% less fuel (Cariou, 2011). Thanks to the widespread adoption of slow steaming in response to industrial overcapacity after the financial crisis, CO₂ emissions from international shipping fell by around 10% during 2007–2012 (Smith et al., 2014). However, slower speed will inevitably increase transit time and other operating costs (e.g., on-board labor costs) and reduce on-time performance possibly interrupting logistics reliability. Given that many oceangoing vessels already operate at the speed of 15–18 knots, further fuel savings and emission reduction potential from slow steaming alone may be limited (Woo and Moon, 2014). Even incorporating slow steaming into future forecasts, only two scenarios out of sixteen have CO₂ emissions declining to nearly 2012 levels by 2050, with the rest continuing to grow (Bows-Larkin et al., 2015). Another concern is that when the transport market reverts to booming, shipping companies tend to revert to faster steaming speeds to improve vessel utilization, posing a doubt whether this option can last long.

Other operational solutions have received less industrial attention because they often require a skilled crew to respond quickly to a rapidly changing, and often sophisticated, environment rather than a conventional “follow the protocol” approach on board. For example, optimizing the trim of the ship can lead to 0.5% and 2.3% fuel savings (Coraddu et al., 2018); however, this has to be done using complicated data analysis techniques. Not done properly, it will endanger navigational safety.

3. Market-based solutions

3.1. The surging of market-based solutions

Indeed, if it works as planned, the combination of EEDI and SEEMP can substantially reduce business-as-usual CO₂ emissions; however, increasing trade volume on a global scale would still bring total emissions in 2050 at twice the 2007 level (Bazari and Longva, 2011). If shipping aims at delivering its fair and proportionate contribution at a 50:50 chance to keep global warming well below 2 °C, a deep emission reduction up to 85% by 2050 compared with the 2010 baseline is needed (Anderson and Bows, 2012). We believe that technical and operational measures alone will not suffice.

Increasing calls for market-based measures have been emerging (Shi, 2016b). The IMO received several proposals

Fig. 2. Potential CO₂ reduction potential from an array of technical and operational solutions. Extracted data (Bouman et al., 2017) from 60 quantitative studies on the CO₂ emissions reduction potential based on the array of technical and operational solutions listed in the figure. Owing to data scarcity, it is unlikely to make a meaningful meta-analysis to reveal statistical inference. The solid bar denotes the whole range of potential CO₂ reduction, but the widest range (i.e., the highest and lowest reported reduction potential) in each solution suggests poor agreement in the literature on the reduction potential. Such a high degree of uncertainty is due to 1) some studies being limited to a certain type of vessel, meaning that the conclusions cannot be applied to the entire industry and 2) some studies being based on different model assumptions. Applying all these types of technical and operational solutions could yield a high CO₂ reduction potential of 78% or a much lower CO₂ reduction potential of 29%. Such a high degree of performance uncertainty combined with costly investments lead to lethargic industry action.

from its member states (mostly advanced industrialized nations) on possible emission-trading systems to tackle CO₂. Representative proposals include MEPC/60/4/22 by Norway, MEPC/60/4/26 by the United Kingdom, MEPC/60/4/41 by France, and MEPC 60/4/54 by Germany (their features will be mentioned later). At the MEPC 63rd session, measures to reduce GHG emissions by market mechanisms have received widespread attention and were discussed; however, opinions differed widely between developed and developing countries, with the latter worrying about the unknown economic impact and the ripple effect on the export sector. Some member states emphasized that “the necessary financial, technological and capacity-building support for developing countries by developed countries,” “the principles of common but differentiated responsibilities” must be incorporated into a future resolution (MEPC, 2012).

In subsequent MEPC sessions, the IMO members finally agreed to apply a “three-step approach.” (Report of the Marine Environment Protection Committee on Its Sixty-Eighth Session, 2015) This approach comprises 1) collection of global data for

the fuel consumption of ships, 2) data analysis, and 3) decision making on possible resources. The shipping industry expects that it will take many years before the first collected global data will be analyzed. Measures such as carbon pricing will take a long time before implementation owing to the three-step approach agreement, e.g., no decision making can take place before data collection and analysis.

The MEPC agreed to propose an initial GHG reduction roadmap covering the 2017–2023 period, and a sketchy mitigation strategy is expected to be announced in 2018 (Green4sea, 2016). However, as mentioned earlier, many widely discussed market tools that have been implemented in other sectors are unlikely to be applied to the shipping business soon because they are linked to an IMO-led fuel data collection system that will start only in 2019. Industry analysts believe that a full-fledged plan may only emerge in 2023 with actual implementation schedules many years later (Merk, 2017). Having said that, it could take another six years, with a list with recommended options, and mandatory requirements could take another ten years to come into effect.

Fig. 3. Average marginal CO₂ reduction cost per option. Figure adapted from the study by Eide et al. (2011). Cost-effective solutions are mainly operational ones, such as slow steaming and weather routing. In contrast, many technical solutions carry a hefty price tag that offers no incentive to the industry to invest—the average CO₂ reduction cost is 50–200 USD/ton, which is far more expensive than the emission-trading price of \$5–15/ton in the United States. Carbon trading is favored by many economists and industry because it will lower the compliance cost while meeting the emission reduction target.

3.2. EU's pioneering response

As early as 2004, the EU Commission Decision 2004/156 was adopted and guidelines for monitoring and reporting CO₂ emissions were established during the first phase of the implementation of the European Union Emission Trading Scheme—the world's first and largest international carbon emission-trading market (Ellerman and Buchner, 2007). However, the shipping industry was not included in these guidelines because the shipping community believes that the IMO is the recognized international entity to act. Frustrated at the slow progress in achieving international commitment, the EU was determined to act on its own first. In 2015, the EU adopted the MRV system for the shipping industry; it stipulated that all vessels over 5000 gross tonnage calling EU ports should monitor, report, and verify the CO₂ emissions from 2018 on per voyage basis (Verifavia-shipping, 2015).

In a recent update, the EU's environment committee issued a statement on December 16, 2016, vowing to bring shipping into the EU-ETS system from 2023 unless the IMO has adopted a comparable scheme by 2021. European parliament adopted the proposal with a few rhetoric modifications (Spurrier, 2017). Ships that may call at the EU ports are now officially counting down to embrace market instruments aiming to curb the intensive emission growth.

Constructive regional actions such as EU's MRV system, a prerequisite for including shipping into the current carbon emissions trading market, play a vital and catalytic role in promoting global policy action. In fact, the EU's strategy echoes many proposals (e.g., Norway, the United Kingdom, France, and Germany) submitted to the IMO. They share the following highlights.

- (1) Under the total amount control strategy, set a carbon emissions ceiling for a period of time.
- (2) "Ships" are objects subject to regulation. Ship operators, flag states, and port states should jointly validate or supervise the real energy performance of ships.
- (3) During the initial implementation phase, relevant parties in the carbon emission-trading market can freely gain or purchase quotas in the primary market corresponding to their bunker consumption share. They can then trade the quota in the secondary market or access emission allowances from other sectors to offset carbon emissions. Ships must ensure that their possessed emission quotas can cover the actual emissions during the period; otherwise, they will incur a penalty.
- (4) The auction of these emission allowances shall be organized by a recognized national or international entity.
- (5) The revenues generated by the initial auction of the emission allowances are used for climate change funds to support mitigation and adaption efforts.

3.3. Maritime ETS system

In our view, the core of the maritime ETS system lies in the "carbon emissions ceiling" and "trading process." Setting a reduction target is vital to the success of the scheme. We argue that the uncertainty of emission allowances trading under a floating limit is less than that under the fixed one (see Appendix for proof). Setting a reasonable floating limit on carbon emissions can encompass the uncertainties in the future maritime trade volumes, thereby reducing the impact from dramatic emission quota price volatility.

Notably, building consensus over the allocation method of the shipping carbon emissions is challenging. The method of using benchmarking plus grandfathering rights (González, 2006), adopted by the EU aviation industry cannot be applied to the more complex international shipping industry. Cargo ships have a high degree of customization; various types and sizes could yield a combination of hundreds of emission levels per unit good transported. If a benchmarking method similar to that used in aviation is adopted, the emission levels of each shipping company will then simply be decided by multiplying a fixed emission performance indicator, freight turnover, and length of voyage (see https://ec.europa.eu/clima/policies/ets/allowances/aviation_en for detailed explanations). This is problematic. According to the IMO's third GHG research report (Smith et al., 2014), dry bulk carriers emit 8.4 g carbon dioxide per km ton, whereas refrigerated ships emit 80.4 g per km ton, a difference of almost 10 times. Developing the quota system without distinguishing the ship types and sizes is definitely unfair.

Grandfathering means that shipping companies with high historical emissions will have more free or discounted quotas for present use, which is contrary to the common but differentiated principle. Such a quota system would reward companies whose prior emissions were high and made reverse incentives to enterprises that took pioneering action to reduce emissions. In addition, unlike land assets, ships are mobile around the world, which will affect the applicable area of quotas. For example, Region A integrates the shipping industry into its local ETS. A ship carried out transport activities in Region A, and its route was changed into Region B without ETS. Then, according to the historical emissions method, this particular ship can still receive free or discounted carbon quotas from Region A in the next trading cycle, which could affect the carbon emission-trading market of Region A.

Some currently notable carbon trading markets include the EU's ETS, the California and Quebec shared carbon market, and China's pilot ETS (Xiong et al., 2017). Other nations have stated that they are planning or considering carbon pricing under their own jurisdiction but none includes shipping. The environmental committee of the European Parliament has proposed to include shipping in the EU's ETS that would apply to all ships calling at the EU ports irrespective of origin. However, other nations following the EU's proposal would induce economical complications as well as political resistance because all ports within different jurisdictions can demand carbon tax even for a single voyage. Such a proposal is doomed to be unwelcome, as evidenced by the widespread boycott of the EU's aviation carbon tax scheme (Liang and Zhang, 2014). We believe that integrating the fragmented carbon trading systems, at least for some global business operating with great mobility (in our case, the shipping industry), should be carefully evaluated to close the loopholes and minimize business complications.

4. Policy implications

4.1. Limitations of technical solutions

EEDI has pros and cons and is a flawed proxy to be relied upon to regulate emissions reduction. The focus should be on real-world operation performance rather than this theoretical number for characterizing ship design. Decreasing the EEDI number does not automatically translate into equally lower energy consumption in real-world operations.

In certain circum-

stances, the pursuit of lower EEDI number will sacrifice navigational safety under extreme weather and sea conditions due to the derated engine power.

Technological advances have long been hailed as promising solutions to fight climate change but do not count on them to transform the shipping emissions in the near future. The early adoption phase in the shipping industry can be very expensive and requires significant premium from early adopters with unguaranteed investment returns. The cost would eventually relay to shippers, and consequently, clients will shift to other low-cost carriers. Subsidies or tax rebates from governments could help, but they can create allocative inefficiencies during the process and impose huge financial burden on governments (Chen et al., 2017). Some technological advancements could alter the ship design and reconfigure the ship-building process, but duplicating lab results in massive ship-building projects will require excessive patience and risk taking that most ship builders would not want to exercise rapidly; they would rather adopt a "wait-and-see" approach until a technology pathway is confirmed.

In many cases, economic sustainability is achieved at the cost of environmental sustainability. For example, economic gains lead to environmental damage and societal effects at city and regional levels. Ship demolition markets are a good example that shows the difficulty in balancing economic benefits (such as employment, incomes, and taxation) and environmental and societal effects (such as pollution, contamination of water resources, and health risks). New vessels are built, and the old ones are taken apart in areas that are ecologically vulnerable (Choi et al., 2016). Therefore, regulatory actions should be designed appropriately on the basis of full benefit and cost analyses to understand the best policy strategy. It is necessary to balance the interests and ensure that mitigation strategies adopted by the shipping industry are sustainable, not at the expense of other, particularly less-developed, economies.

4.2. Expansion of operational solutions

Using slow steaming to cut energy consumption stands out among all operational solutions due to its immediate and obvious results; however, with the already slow speed in practice, further emission reduction potential from this single source is limited. Other types of operational solutions should not be neglected as they can provide opportunities for extra reduction at a low cost.

Operational solutions such as ship trimming require sophisticated data-based optimization. Casual relationships between each type of operation and subsequent energy performance need to be carefully evaluated using real-time data analytics. While sensor technologies generate vast quantities of information, they are usually difficult for researchers outside the company to access for fear that commercial confidentiality is compromised. It is possible to develop a protocol for pooling and utilizing vessel performance data with the research community without compromising business secrets. Doing so would open up more fuel saving potentials with additional analysis that can yield important operational insights (Poulsen and Johnson, 2016). A good practice in this respect is the US-based smart manufacturing leadership coalition and Germany's platform industries 4.0 initiative for researchers to overcome barriers to discovery and access and use factory-level data to make manufacturing processes more energy efficient, profitable, and sustainable (Kusiak, 2017).

4.3. Introduction of maritime carbon trading

Without a technology-savvy shipping industry, a market-based approach is essentially needed to address the environmental impact. Some regional carbon trading markets are functioning well and are evolving to meet targets (Keohane and Morehouse, 2017). Including shipping in the scheme is necessary.

Carbon trading is favored by many economists and industries because it lowers the compliance cost while meeting the emission reduction targets. Much can be learned from decarbonizing the automobile industry in California, with an array of policy and market tools to address climate change. Based on the Air Resources Board cost and benefits analysis (California Air Resources Board, 2015), \$83.4 million rebates for “clean vehicles” (such as electric vehicles) resulted in 2.2 million tons of carbon reduction for a cost per ton over \$37 (three times more costly than the carbon trading). Investment in a hybrid and zero-emission truck and bus program is even worse, with a cost per ton of \$139 (11 times most costly than the carbon trade). Emission reductions under technology advancement in the transport sector alone are costing 3–11 times more than those under carbon trading, yet electric vehicles are only able to capture approximately 2% of the market share in California—the largest “clean vehicles” sales market in the United States. Carbon trading has been applauded as the best approach to achieving cost-effective CO₂ reductions (Stavins and Schatzki, 2014). Adding a high carbon tax (15USD/ton) for the shipping industry will only raise the commodity price by less than 1% (MEPC, 2010)—unlikely impact the global trade given that all other transportation modes are subjected to additional regulations.

4.4. Regional actions and global cooperation

Historically, there is a big gap between pledges and actions in the shipping community regarding environmental regulations (Tan, 2005). The endeavor to tackle a single maritime pollution could take dozens of years from initial discussion to action because the agenda of the IMO conventions is largely impacted by the regions where the ships are registered—typically with lax environmental and financial regulations (Wan et al., 2016b) (Fig. 4).

Rather than solely relying on universal or majority consensus (top-down approach) to regulate seaborne pollution, the IMO should recognize and encourage constructive regional actions (patchwork approach) to address GHG mitigation issues. Regional actions should not be equated to illegitimate unilateralism; rather, they can play a vital catalytic role in promoting global policy action (Shaffer and Bodansky, 2012). Appropriately designed and administered regional actions—for example, the EU and California's climate policy for transportation—can be both responsive and cost effective and of potentially great value to the world by more directly engaging various stakeholders and raising environmental awareness (Sperling and Eggert, 2014). Patchwork approaches can sometimes be superior because they advance the regions beyond the current status quo of policy inaction. More importantly, they may allow the rest of the world to explore the dynamic process of policy action and industrial reaction; therefore, future large-scale policy diffusion could be more data-driven and evidence-based.

Fig. 4. Top 15 ship-owning countries and their flag configuration. Data from the UNCTAD (2016) review of maritime transport. The 2016 UN statistics suggested that the top 15 ship-owning countries register the majority of their capacity under foreign flag, which often lack incentive to embrace environmental conventions. It could take a number of years for complex negotiations among nations to develop a new convention, and it will have taken many more years for the convention to enter into force.

The need for global cooperation to tackle shipping emissions is difficult because of the diversity in institutional framework and arrangements for environmental and marine pollution that involve many different agendas, strategies, ambitions, and goals (industry, states, nonstates, and global and regional organizations) (Roe, 2012). In this respect, improving multilateral cooperation and technical assistance among countries is crucial. This is because many developing countries lack the (economic and organizational) resources and technical capacity to fully participate in international conventions and implement the obligations and regulations effectively.

5. Conclusions

Global antimarine pollution efforts led by the IMO emerged in the 1970s, and some vessel-source pollutants have been gradually regulated since the 1980s. Binding international legal agreements to regulate GHGs, however, are evolving slowly, as technical solutions remain expensive, and crucial industrial support is absent.

Though being the most energy-efficient form of freight transport, the shipping industry is not immune from the global efforts to decarbonize economic growth. A pathway goal for the shipping industry is prominently needed to ensure projected reductions. A laissez-faire approach or slow mitigation efforts will have long-lasting transboundary effects. Overcoming the barriers of mitigation currently in place throughout the shipping industry should be of high priority. Current and possible future mitigation strategies commendably include transdisciplinary solutions covering technical, operational, and market

aspects; however, widespread application requires them to be evidence-based and economically viable. Their success also hinges on the continuous assessment and refinement in real-world applications. Synergies, led by the top maritime commander, the IMO, must speed up cooperation in the global shipping community, linking scientists, engineers, businesses, and policymakers to honor the centuries-old industry in the “spirit of Paris.”

Acknowledgement

We would like to thank the reviewers and editor for their insightful comments to improve this article. We also thank Dr. Mo Zhu for her careful fact checking. Z.W. is supported by National Natural Science Foundation of China (71704103 and 71402096), Y.C. is supported by National Natural Science Foundation of China (71402093).

Appendix A.

The cointegration analysis by Xu et al. (2014) suggests that the world's maritime freight turnovers are positively linked to the global shipping CO₂ emissions. Specifically, when the world's maritime transaction volume changes by 1%, the international shipping carbon emissions will correspondingly change by 0.85%. Inspired by Jotzo and Pezzey (2007), it can be proven that a floating limit on the total amount of CO₂ emissions has fewer uncertainties compared with a fixed quota system. Setting a reasonable floating limit on the total amount of CO₂ emissions considers the uncertainties in future maritime trade volumes, thereby reducing the uncertainty of carbon trading and making the target reflect actual conditions better. Consequently, the supply of carbon quotas can be adjusted according to their demands, and carbon prices can be stabilized.

First, assume that when there is no restrictive policy to control the CO₂ emissions, the fluctuations in maritime trade correspond to fluctuations in carbon emissions

$$\tilde{E}_C = E_C (1 + \varepsilon_Y) \quad (1)$$

where $\tilde{E}_C$ is the observed value of CO₂ emissions when there is no restrictive policy; E_C is the expected value of CO₂ emission when there is no restrictive policy, and ε_Y is the prediction error of maritime freight turnover.

Assume that ε_Y represents random error and obeys the normal distribution. The above terms are independent of each other and we get

$$E[\varepsilon_Y] = 0 \quad (2)$$

$$E[\varepsilon_Y^2] = \sigma_Y^2 \quad (3)$$

The upper emissions limit is set based on the amount of carbon emissions generated when no restrictive policy is implemented, specifically shown in the following function:

$$\tilde{X} = \mu E_C (1 + \beta \varepsilon_Y) \quad (4)$$

$$\mu = \frac{X}{E_C} \quad (5)$$

where $\tilde{X}$ is the observed upper limit of floating CO₂ emissions; X is the expected upper limit of floating CO₂ emissions;

μ is the ratio of the upper limit of carbon emissions under the business-as-usual situations (i.e., without restrictive policy). The stricter the policy, the smaller is μ and the less are the total allowable emissions ($0 \leq \mu \leq 1$). β is the floating degree of the upper limit of CO₂ emissions ($0 \leq \beta \leq 1$).

The correlation between the upper limit of CO₂ emissions and freight turnover depends on β , particularly when $\beta = 0$, the upper limit of CO₂ emissions, is fixed and has nothing to do with the freight turnover, so that

$$X_0 = \mu E_C \quad (6)$$

where X_0 is the fixed upper limit of CO₂ emissions.

Based on Eqs. (1) and (4), the difference between the total amount of CO₂ emissions and its limit is obtained—the emissions reduction $\tilde{Q}$ is

$$\tilde{Q} = \tilde{E}_C - \tilde{X} = E_C - X + \tilde{N} \quad (7)$$

$$\tilde{N} = (\tilde{E}_C - \tilde{X}) - (E_C - X) = E_C [(1 - \beta\mu) \varepsilon_Y] \quad (8)$$

where $\tilde{N}$ denotes the difference between the observed and expected values of the emissions reduction considering all the uncertainties under the floating CO₂ emissions quota.

The variance of $\tilde{N}$ is

$$D(\tilde{N}) = E[\tilde{N}^2] - E[\tilde{N}]^2 = E_C^2 (1 - \beta\mu)^2 \sigma_Y^2 \quad (9)$$

Similarly, according to Eqs. (6)–(8), the variance of $\tilde{N}_0$ under a fixed CO₂ emissions reduction quota is

$$D(\tilde{N}_0) = E_C^2 \sigma_Y^2 \quad (10)$$

and because $\beta\mu \geq 0$, so

$$(1 - \beta\mu)^2 < 1 \quad (11)$$

From Eqs. (9)–(11), the following relation is obtained:

$$D(\tilde{N}) < D(\tilde{N}_0) \quad (12)$$

References

- Adoption of the Paris Agreement FCCC/CP/2015/L.9/Rev1, 2015. United Nations Framework Convention on Climate Change.
- Anderson, K., Bows, A., 2012. Lloyd's list intelligence. Executing a Scharnow turn: Reconciling shipping emissions with international commitments on climate change. *Cardiol. Manag.* 3, 615–628.
- Armstrong, V.N., 2013. Vessel optimisation for low carbon shipping. *Ocean Eng.* 73, 195–207.
- Bazari, Z., Longva, T., 2011. Assessment of IMO Mandated Energy Efficiency Measures for International Shipping: Estimated CO₂ Emissions Reduction from Introduction of Mandatory Technical and Operational Energy Efficiency Measures for Ships. International Maritime Organization, London, UK.
- Bouman, E.A., Lindstad, E., Riialand, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping—a review. *Transp. Res. Part D: Transp. Environ.* 52, 408–421.
- Bows-Larkin, A., Anderson, K., Mander, S., Traut, M., Walsh, C., 2015. Shipping charts a high carbon course. *Nat. Clim. Chang.* 5, 293–295.
- Buhaug, J., Corbett, J., Winebrake, J., Mjelde, A., Lee, D., Hanayama, S., ... Yoshida, K., 2009. Second IMO GHG Study 2009 Update of the 2000 GHG Study: Final Report Covering Phrases 1 and Phrases 2. IMO, London.

- California Air Resources Board, 2015. Greenhouse gas quantification methodology for the air resources board low carbon transportation program. In: <https://www.arb.ca.gov/cc/capandtrade/auctionproceeds/arbldprogramsqm.pdf>.
- Cames, M., Graichen, J., Siemons, A., Cook, V., 2015. Emission reduction targets for international aviation and shipping, available at [http://www.europarl.europa.eu/RegData/etudes/STUD/2015/569964/IPOL_STU\(2015\)569964_EN.pdf](http://www.europarl.europa.eu/RegData/etudes/STUD/2015/569964/IPOL_STU(2015)569964_EN.pdf).
- Cariou, P., 2011. Is slow steaming a sustainable means of reducing CO₂ emissions from container shipping? *Transp. Res. Part D: Transp. Environ.* 16, 260–264.
- Chen, C.W., Hu, W.M., Knittel, C.R., 2017. Subsidizing Fuel Efficient Cars: Evidence from China's Automobile Industry (No. w23045). National Bureau of Economic Research.
- Choi, J.K., Kelley, D., Murphy, S., Thangamani, D., 2016. Economic and environmental perspectives of end-of-life ship management. *Resour. Conserv. Recycl.* 107, 82–91.
- Cichowicz, J., Theotokatos, G., Vassalos, D., 2015. Dynamic energy modelling for ship life-cycle performance assessment. *Ocean Eng.* 110, 49–61.
- Coraddu, A., Oneto, L., Baldi, F., Anguita, D., 2018. Vessels fuel consumption: A data analytics perspective to sustainability. In: *Soft Computing for Sustainability Science*. Springer, Cham, pp. 11–48.
- Devanney, J., 2011. The impact of the energy efficiency design index on very large crude carrier design and CO₂ emissions. *Ships Offshore Struct.* 6, 355–368.
- Dufour, J., 2016. EU MRV vs. IMO fuel consumption data collection system. In: <https://www.green4sea.com/eu-mrv-vs-imo-fuel-consumption-data-collection-system/>, (access on Nov 7, 2017).
- Eide, M.S., Longva, T., Hoffmann, P., Endresen, S.B., 2011. Future cost scenarios for reduction of ship CO₂ emissions. *Marit. Policy Manag.* 38, 11–37.
- Ellerman, A.D., Buchner, B.K., 2007. The European Union emissions trading scheme: origins, allocation, and early results. *Rev. Environ. Econ. Policy* 1 (1), 66–87.
- González, P.D.R., 2006. Harmonization versus decentralization in the EU ETS: an economic analysis. *Clim. Pol.* 6 (4), 457–475.
- Green4sea, 2016. Green4sea, Industry stakeholders react on the EU ETS decision, in: <https://www.green4sea.com/industry-stakeholders-react-on-the-eu-ets-decision/>, 2016, (access on Nov 7, 2017).
- IMO, 2004. Resolution A.963(23) Adopted on 5 December 2003, (Agenda item 19). In: IMO Policies and Practices Related to the Reduction of Greenhouse Gas Emissions From Ships. [http://www.imo.org/blast/blastDataHelper.asp?data_id=26597&filename=A963\(23\).pdf](http://www.imo.org/blast/blastDataHelper.asp?data_id=26597&filename=A963(23).pdf) Accessed 7 November 2017.
- IMO, 2012. EEDI - rational, safe and effective. In: <http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/EEDI.aspx>, (access on Nov 7, 2017).
- Jotzo, F., Pezzey, J.C., 2007. Optimal intensity targets for greenhouse gas emissions trading under uncertainty. *Environ. Resour. Econ.* 38, 259–284.
- Keohane, N., Morehouse, E., 2017. Carbon markets: Extend, don't limit. *Nature* 544, 297.
- Kusiak, A., 2017. Smart manufacturing. *Int. J. Prod. Res.* 1–10. <https://doi.org/10.1080/00207543.2017.1351644>.
- Liang, W., Zhang, L., 2014. Legal issues concerning the EU unilateral aviation ETS: a Chinese perspective. *SCJ Int. L. & Bus.* 11, 1.
- MEPC, 2010. Report of the Marine Environment Protection Committee on its 60th Session, MEPC 60/4/54, London, UK.
- MEPC, 2011. Report of the Marine Environment Protection Committee on its 62nd Session, MEPC 62/24, London, UK.
- Merk, O., 2017. Shipping and emissions trading: in or out? In: http://shippingtoday.eu/shipping_emissions_trading/, (access on Sep. 1, 2017).
- MPEC, 2012. Report of the marine environment protection committee on its 63rd session. In: <http://www.dco.uscg.mil/Portals/9/DCO%20Documents/5p/5ps/International%20Maritime%20Organization/MEPC/mepc63-report.pdf?ver=2017-06-29-130038-667>, (access on Nov 7, 2017).
- Ozaki, Y., Larkin, J., Tikka, K., Michel, K., 2010. An evaluation of the Energy Efficiency Design Index (EEDI) baseline for tankers, containerships and LNG carriers. In: *Climate Change and Sips: Increasing Energy Efficiency a SNAME and Marine Board Symposium, USA*.
- Poulsen, R.T., Johnson, H., 2016. The logic of business vs. the logic of energy management practice: understanding the choices and effects of energy consumption monitoring systems in shipping companies. *J. Clean. Prod.* 112, 3785–3797.
- Psarafitis, H.N., Kontovas, C.A., 2013. Speed models for energy-efficient maritime transportation: a taxonomy and survey. *Transp. Res. Part C Emerg. Technol.* 26, 331–351.
- Report of the Marine Environment Protection Committee on Its Sixty-Eighth Session, 2015. MEPC 68th Session, Agenda Item 21, IMO Doc MEPC 68/21, (29 May 2015).
- Roe, M., 2012. Maritime governance and policy-making, (SSBM).
- Shaffer, G., Bodansky, D., 2012. Transnationalism, unilateralism and international law. *TEL* 1, 31–41.
- Shi, Y., 2016. Are greenhouse gas emissions from international shipping a type of marine pollution? *Mar. Pollut. Bull.* 113 (1), 187–192.
- Shi, Y., 2016. Reducing greenhouse gas emissions from international shipping: is it time to consider market-based measures? *Mar. Policy* 64, 123–134.
- Smith, T.W.P., et al., 2014. Third IMO Greenhouse Gas Study 2014 (International Maritime Organization).
- Sperling, D., Eggert, A., 2014. California's climate and energy policy for transportation. *Energy Strat. Rev.* 5, 88–94.
- Spurrier, A., 2017. European Parliament votes to bring shipping into EU emissions trading scheme. In: <https://fairplay.ihs.com/safety-regulation/article/4282156/european-parliament-votes-to-bring-shipping-into-eu-emissions-trading-scheme>, (access on Nov 7, 2017).
- Stavins, R., Schatzki, T., 2014. Beyond AB 32: Post-2020 climate policy for California. In: http://www.analysisgroup.com/uploadedfiles/content/insights/publishing/post_2020_ca_ghg%20policy.pdf, Accessed 15 July 2017.
- Tan, A.K.J., 2005. Vessel-source Marine Pollution: the Law and Politics of International Regulation. Vol. 45, Cambridge University Press.
- Upton, J., 2016. Shipping industry mulls modest steps to slow warming. In: <http://www.climatecentral.org/news/shipping-industry-modest-response-to-climate-change-20811>, (access on Nov 7, 2017).
- Verbeek, R.P., Kadijk, G., van Mensch, P., Wulfers, C., van den Beemt, B., Fraga, F., Aalbers, A.D.A., 2011. Environmental and Economic Aspects of Using LNG as a Fuel for Shipping in The Netherlands. TNO, Delft.
- Verifavia-shipping, 2015. As a first step towards cutting greenhouse gas emissions from maritime transport, the EU requires operators of ships exceeding 5,000 GT to monitor and report their carbon emissions and transport work on all voyages to, from, and between the EU ports. In: <http://www.verifavia-shipping.com/shipping-carbon-emissions-verification/shipping-mrv-regulation-overview-6.php>, Accessed 7 November 2017.
- Wan, Z., Zhu, M., Chen, S., Sperling, D., 2016. Three steps to a green shipping industry. *Nature* 530, (275–227).
- Wan, Z., Chen, J., Makhoulouf, A.E., Sperling, D., Chen, Y., 2016. Four routes to better maritime governance. *Nature* 540, 27–29.
- Williamson, P., 2016. Emissions reduction: scrutinize CO₂ removal methods. *Nature* 530, 153–155.
- Woo, J.K., Moon, D.S.H., 2014. The effects of slow steaming on the environmental performance in liner shipping. *Marit. Policy Manag.* 41, 176–191.
- Xiong, L., Shen, B., Qi, S., Price, L., Ye, B., 2017. The allowance mechanism of China's carbon trading pilots: a comparative analysis with schemes in EU and California. *Appl. Energy* 185, 1849–1859.
- Xu, H., Liu, W., Xu, M., 2014. Study on the relationship among carbon emission from international shipping. In: *World Seaborne Trade Amounts and Global Economic Activity*. 13, Science and Technology Management Research, pp. 219–223.