Climate Policy

ISSN: 1469-3062 (Print) 1752-7457 (Online) Journal homepage: https://www.tandfonline.com/loi/tcpo20

CO_2 abatement goals for international shipping

Michael Traut, Alice Larkin, Kevin Anderson, Christophe McGlade, Maria Sharmina & Tristan Smith

To cite this article: Michael Traut, Alice Larkin, Kevin Anderson, Christophe McGlade, Maria Sharmina & Tristan Smith (2018) CO_2 abatement goals for international shipping, Climate Policy, 18:8, 1066-1075, DOI: 10.1080/14693062.2018.1461059

To link to this article: https://doi.org/10.1080/14693062.2018.1461059

Published online: 19 Apr 2018.

CLIMATE POLICY
2018, VOL. 18, NO. 8, 1066–1075
https://doi.org/10.1080/14693062.2018.1461059

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS Check for updates

CO_2 abatement goals for international shipping

Michael Traut [a], Alice Larkin [a], Kevin Anderson[a], Christophe McGlade[b], Maria Sharmina [a] and Tristan Smith[b]

[a]Tyndall for Climate Change Research, University of Manchester, Manchester, UK; [b]UCL Energy Institute, London, UK

ABSTRACT

The Paris Agreement, which entered into force in 2016, sets the ambitious climate change mitigation goal of limiting the global temperature increase to below 2°C and ideally 1.5°C. This puts a severe constraint on the remaining global GHG emissions budget. While international shipping is also a contributor to anthropogenic GHG emissions, and CO_2 in particular, it is not included in the Paris Agreement. This article discusses how a share of a global CO_2 budget over the twenty-first century could be apportioned to international shipping, and, using a range of future trade scenarios, explores the requisite cuts to the CO_2 intensity of shipping. The results demonstrate that, under a wide range of assumptions, existing short-term levers of efficiency must be urgently exploited to achieve mitigation commensurate with that required from the rest of the economy, with virtually full decarbonization of international shipping required as early as before mid-century.

Key policy insights

- Regulatory action is key to ensuring the international shipping sector's long-term sustainability.
- For the shipping industry to deliver mitigation in line with the Paris Agreement, virtually full decarbonization needs to be achieved.
- In the near term, immediate and rapid exploitation of available mitigation measures is of critical importance.
- Any delay in the transition will increase the risk of stranded assets, or diminish the chances of meeting the Paris Agreement's temperature commitments.

ARTICLE HISTORY
Received 23 August 2017
Accepted 30 March 2018

KEYWORDS
CO_2 budgets; International shipping; Paris Agreement

1. Introduction

While the Paris Agreement has entered into force, international shipping emissions are notably absent from it. The half-century prior to the financial recession of 2007–2008 was a time of unprecedented growth in international trade, in terms of both value and volume, outstripping growth in global production of goods, gross domestic product (GDP) and emissions (Le Quéré et al., 2017; World Bank, 2016; WTO, 2015). Reflecting increases in shipping efficiency, CO_2 emissions from international shipping have grown more slowly than trade, broadly in line with global emissions, reaching 800 Mt in 2012, about 2.2% of the global total (Smith, Jalkanen et al., 2015), and remaining roughly constant in subsequent years 2013 to 2015 (Olmer, Comer, Roy, Mao, & Rutherford, 2017). Forecasts project a further increase in both seaborne trade and CO_2 emissions. Yet, besides an efficiency standard for new-build ships, there is presently no global mechanism to control the sector's CO_2 emissions. This raises the question of how emissions from international shipping can be reduced in line with the remaining global CO_2 budgets associated with the Paris Agreement's goals of 'Holding the increase in the global

CONTACT Michael Traut michael.traut@manchester.ac.uk Tyndall for Climate Change Research, University of Manchester, Pariser Building, Manchester M13 9PL, UK

average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C' (Paris Agreement, 2015; Article 2.1(a)).

Following a review of global, cumulative CO_2 budgets associated with temperature outcomes (Section 2), the article discusses how a global CO_2 budget over the twenty-first century could be apportioned to international shipping (Section 3). Using a range of future trade scenarios (presented in Section 4), we explore the requisite cuts to the CO_2 intensity of shipping (Section 5). A discussion is given in Section 6 and conclusions are presented in Section 7.

2. Global, cumulative CO_2 budgets

There is a near-linear relationship between cumulative CO_2 emissions and the global temperature response by the end of the century (Collins et al., 2013). Following the method outlined by Jones et al. (2013), the IPCC's Fifth Assessment Report has estimated remaining global CO_2 emissions budgets from 2011 to 2100 commensurate with a range of future temperature outcomes (Collins et al., 2013), using Representative Concentration Pathway (RCP) scenario runs from 20 models: 15 from CMIP5, and 5 EMICs (Stocker et al., 2013). Emission budgets since pre-industrial times are calculated for a given probability of staying below a given temperature goal, with the probability defined as the fraction of models with a temperature rise below the goal at the time the budget is used up; budgets from 2011 onwards are then calculated by subtracting the estimated emissions since pre-industrial times until the beginning of 2011. Further subtracting historical emissions from 2011–2016 (Le Quéré et al., 2017), yields remaining budgets from 2017 onwards.

For a 66% probability (as defined above, capturing only the variability within the set of climate models) of not exceeding a 2°C increase of average global surface temperature above pre-industrial levels, the cumulative CO_2 emissions budget from 2017 onwards is 750 $GtCO_2$, for a 50% probability it is 1050 $GtCO_2$, and for a 33% probability it is 1250 $GtCO_2$ (Table 1).

By 2018 the world had already warmed by about 1°C (Morice, Kennedy, Rayner, & Jones, 2012[1]); therefore, the remaining budget for 1.5°C is much closer to the margin of the associated all time emissions budget. For a 66% probability of not exceeding a 1.5°C temperature increase, the cumulative CO_2 emissions budget from 2017 onwards is 150 $GtCO_2$, for a 50% probability it is 300 $GtCO_2$, and for a 33% probability it is 600 $GtCO_2$ (Table 1).

Beyond the uncertainty captured by the variation between models in the ensemble, these numbers depend on the definition of global average surface temperature (e.g. using either sea surface temperature or surface air temperature over the oceans), and they are threshold exceedance budgets (TEB) rather than threshold avoidance budgets (TAB).[2] They also depend on assumptions about emissions of non-CO_2 GHG, although Collins et al. (2013) show that this dependence is small across the range of RCP scenarios. The numbers are also subject to uncertainty in the observed temperature increase serving as the reference point. Arguing that the temperature anomaly to date, as defined in and calculated by the models, is higher than the observed temperature anomaly, and that the models have underestimated emissions to date, Millar et al. (2017) calculate larger remaining budgets, for instance. At the other extreme, it is possible that GHG emissions to date have already locked in warming beyond 1.5°C.

The budgets compare with current annual global CO_2 emissions of around 41 Gt and include emissions from deforestation and industrial processes. The following analysis is based on the budgets for a 50% probability of not exceeding 2°C or 1.5°C, respectively. A higher probability would be preferable, in terms of avoiding climate

Table 1. Cumulative global CO_2 budgets associated with a 2°C and 1.5°C temperature increase, respectively, from (including) 2017; global CO_2 emissions in 2015 from fossil fuels and industrial processes (ffi), and land use (lu).

Global remaining CO_2 budget from 2017 onwards [$GtCO_2$]			
Temperature rise	Probability of staying below temperature rise		
	66%	50%	33%
1.5°C	150	300	600
2°C	750	1050	1250
	Annual global CO_2 emissions (2016)		
Incl. ffi & lu		41	

risk; and it would further constrain the remaining budget, as indicated by the large uncertainty in specifying a CO_2 budget for a particular temperature rise.

3. CO_2 emissions share for international shipping

Despite emissions from international shipping not being included explicitly within the Paris Agreement, the Agreement's temperature goals imply that total emissions from all sources, including international shipping, need to reduce. Consequently, higher emissions from shipping imply deeper reductions from all other sectors. Therefore, what role international shipping could play in the global mitigation challenge, and what share of a global CO_2 budget it could take up, are important questions (Anderson & Bows, 2012).

With international shipping activity occurring in international waters, it is difficult, both in principle and practice, to apportion shipping emissions to individual nations (Gilbert & Bows, 2012). To overcome this issue, emissions from international shipping and aviation are not included in countries' inventories but reported as additional memos; and the Kyoto Protocol mandated its parties to work through the International Maritime Organization (IMO) to reduce emissions from international shipping, and through the International Civil Aviation Organization (ICAO) to reduce emissions from international aviation (Kyoto Protocol, 1997; Article 2.2). In order to avoid the difficulties of applying mitigation measures to the two major international transport sectors, international shipping and aviation have not been explicitly included in the Paris Agreement. However, the question of who is responsible for emissions is more complicated still for shipping than for aviation. In the latter case, emissions from a flight may be split between the country of origin and the country of destination, and the aviation sector's GHG strategy, agreed at ICAO in 2016, discriminates between routes in order to apply the principle of *Common but Differentiated Responsibilities and Respective Capabilities* (ICAO, 2016).

For comparison, however, consider the example of a container vessel owned by a Danish company, flying a Marshallese flag, chartered by a French shipping company, crewed mainly by Russians and Malaysians, that loads containers in Shanghai, offloading and then loading containers in Singapore, as well as in ports in many countries in Northern Europe, making it difficult to apportion emissions from the voyage. Thus, a major barrier to progress at the IMO has been the conflict between the principle of *No More Favourable Treatment*, which holds that all ships be treated the same way regardless of their flag state, and the concept of *Common but Differentiated Responsibilities and Respective Capabilities* maintained in the UN Framework Convention on Climate Change (UNFCCC) and subsequently the Paris Agreement (Kågeson, 2009). The international and mobile nature of international shipping speaks for a global-level constraint on emissions, which is explicitly preferred by the industry (ICS, 2014). Despite the merits of a global approach, there may still be scope for complementary action on the regional or national level (Bows-Larkin, 2015; Doudnikoff, 2013; Gilbert & Bows, 2012); for example, France has enacted regulation that requires ships transporting cargo or passengers to or from French ports to disclose their fuel consumption and associated CO_2 emissions (Ministry of Ecology, Sustainable Development, Transport and Housing, 2011). Subsequently, the EU has legislated a Monitoring, Reporting and Verification (MRV) scheme, which requires ships calling on EU ports to report their CO_2 emissions for the full year (EU, 2015). In proposing the scheme, the EU expressed its preference for a global scheme, but in the absence of one, moved ahead unilaterally (EC, 2013).

In April 2016, at the 69th meeting of the IMO's Marine Environment Protection Committee (MEPC), the International Chamber of Shipping (ICS) argued for an 'Intended IMO Determined Contribution', in analogy to the Nationally Determined Contributions (NDCs) in the Paris Agreement (ICS, 2016). Addressing the same issue, some IMO member states have called on the IMO to define a 'fair share' for the international shipping sector to contribute to GHG mitigation efforts (Belgium et al., 2016). At MEPC 70 in October 2016, the IMO approved a roadmap for developing an 'IMO strategy' for GHG reductions with a view to adoption in 2023 (IMO, 2016). The wide range of positions on the issue submitted to MEPC 71 and 72 shows how difficult it will be to find agreement on the right 'level of ambition'. A number of considerations may play into the debate. For instance, the Paris Agreement holds that countries set their mitigation ambition according to their 'common but differentiated responsibilities and respective capabilities, in the light of different national circumstances'; parts of the shipping industry have argued for the sector's limited responsibility and capabilities, claiming, with respect to the concept of responsibility, a 'vital role' for shipping in serving developing economies and, with respect to capability, that shipping has less access to decarbonization measures than other sectors (ICS, 2016).

Ultimately, any consensus to emerge will have to result from a political process, negotiating between the interests of all the stakeholders involved. Politics is often called the art of the possible. This article does not pre-empt the political process, or anticipate what may be possible, but informs the debate with a complementary, and crucially important perspective.

The following analysis is based on the assumption that the international shipping share of the remaining CO_2 budget is proportionate to the sector's current share of global emissions of 2.2%. There are uncertainties associated with both estimates of global and international shipping emissions. Perhaps more importantly, there are arguments on both sides – for shipping to claim a higher or a lower share of the remaining emissions budget, respectively. Higher emissions from the sector would imply that international shipping increases its share of global emissions, with other sectors achieving relatively deeper cuts to their emissions, or a higher global temperature increase.

4. Future demand for sea transport

The level of mitigation that shipping must undergo to keep its emissions within a given budget is subject, in large part, to assumptions about how demand for sea transport will develop in the future. Therefore, to describe how CO_2 intensity may need to reduce in line with holding the global temperature increase below 2°C and 1.5°C, assumptions about future demand for sea transport, in terms of transport work in tonne-kilometres, are required.

Forecasts based on rigorous economic models often have short time horizons of a few years. The longest forecasts based on economic modelling for the shipping sector, ranging from 2018 to 2030 or 2035, are produced by market intelligence companies.

Projections and scenarios with a longer time horizon, and of relevance to the shipping sector, can be found in the fields of energy and climate change. For example, the International Energy Agency's 2015 World Energy Outlook extends to 2040 (IEA, 2015). Applying the IPCC's Special Report on Emission Scenarios (SRES) (Nakićenović et al., 2000), Eyring, Köhler, Lauer, and Lemper (2005) used a linear fit to establish the relationship between world waterborne trade and world GDP to calculate a set of four future trade scenarios based on constant future GDP growth rates. Mangset, Acciaro, and Eide (2011) took this approach one step further by using regional projections of GDP growth from the SRES scenarios and employing an economic model to map regionally differentiated economic growth to patterns of trade (in 2020 and 2030). Finally, in a study to estimate the fleet-wide emissions reduction potential (as a function of cost per tonne of CO_2 emitted), a heuristic approach[3] to forecasting fleet growth over a 20-year horizon was taken (Eide, Longva, Hoffmann, Endresen, & Dalsøren, 2011).

This article uses a range of demand scenarios from the 3rd IMO GHG Study (Smith, Jalkanen et al., 2015) based on the Representative Concentration Pathways (RCP), which provide a range of radiative forcing trajectories over the twenty-first century (van Vuuren et al., 2011), and the complementary Shared Socio-Economic Pathways (SSP), that form a set of five contrasting narratives of future global socio-economic development (O'Neill et al., 2015). Using variables from combinations of the RCPs and the SSPs, the 3rd IMO GHG Study created a range of future demand scenarios for shipping (Smith, Jalkanen et al., 2015). These cover the long timeframes relevant to climate change, and a range broadly in line with other publicly available scenarios or forecasts (cf. Figure 1).

In 2012, the three cargo types considered – container, wet and dry bulk – accounted for 69% of total emissions from international shipping (Smith, Jalkanen et al., 2015). Containers have relatively high emissions in terms of CO_2 per tonne-kilometre and are forecasted to experience higher growth rates than the bulk markets. While the three cargo types do not cover all international shipping activity, they are suited to explore future growth in sea transport, and the dynamics between different ship types in relation to the emissions reduction challenge.

5. Requisite cuts to CO_2 intensity

Together, a demand scenario and a cumulative CO_2 budget define the challenge for the international shipping sector under Paris-based mitigation constraints. To explore the required changes in CO_2 intensity (measured as

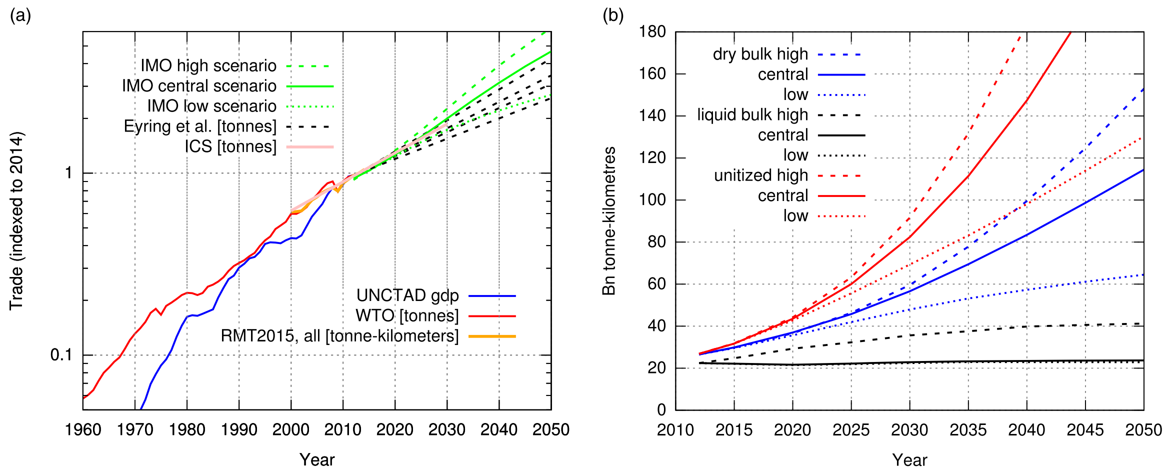

Figure 1. Scenarios of future demand for sea transport. Left: High, central, and low demand scenarios (Smith, Jalkanen et al., 2015); historical data of transport demand in tonne-kilometres (UNCTAD, 2015), international trade in tonnes (data from (WTO, 2015)), and GDP (data: UNCTAD, 2016, gross domestic product: total, constant (2005) prices, annual, 1970–2014); a market forecast of transport demand in tonne-kilometres [data: International Chamber of Shipping: Shipping, World Trade and the Reduction of CO_2 Emissions], and a suite of future scenarios of transport demand in tonnes from the climate change literature (Eyring et al., 2005). Right: Demand for dry bulk, wet bulk, and unitized cargo in high, central, and low growth scenarios (Smith, Jalkanen et al., 2015).

the amount of CO_2 emitted per unit of transport work) and the consequent timeframe for a transition away from carbon-intensive fuels, the analysis assumes, in the first instance, a constant year-on-year CO_2 intensity improvement. In practice, the specific pathway will depend on the mix of mitigation measures. For example, fleet-wide savings from low carbon new-builds will depend on the fleet replacement rate whereas retrofit or operational measures, such as slow steaming, can deliver their impact in the very near term. In calculating the annual reduction rate for the budgets outlined earlier, demand for sea transport is assumed to remain constant from 2050 onwards. This assumption is justified by the tightly constrained emissions space: other trajectories are possible in principle but do not significantly change the conclusions.

The CO_2 emission reduction rate r required to lower total emissions so as to stay within budget may be determined by setting $\sum E_n$ equal to the remaining budget, where $E_n = W_n \cdot EEOI_n$, with E_n the CO_2 emissions from international shipping in year n, and W_n the total demand for transport work; $EEOI_n = EEOI_{\text{baseline}} \cdot (1 - r)^{n-2019}$ is the average CO_2 intensity, determined by its baseline value and the reduction rate r. (On the ship level, the industry refers to the Energy Efficiency Operational Indicator, EEOI, a measure of CO_2 intensity. The term is used more broadly in this article to denote average CO_2 intensity.) Figure 2 shows the CO_2 intensity of international shipping as it reduces from 2020 onwards, for the range of demand scenarios, under the central budget for 1.5°C and 2°C, respectively. For comparison, CO_2 intensity is also shown in the case of no demand growth.

If the shipping sector is to achieve the same proportional reductions as all other sectors on average, the CO_2 intensity reduction rate is 8.0% p.a., in the 2°C case, for the central demand scenario (6.7% and 8.8% in the low and high demand scenarios, respectively). For a global temperature increase of 1.5°C the reduction rate rises to 23.5% p.a. (with a range of 22.5–24.3%).

However, without a measure to control and reduce emissions from international shipping, it appears plausible that stringent reductions in CO_2 intensity are only realized later. For the central demand scenario, Figure 3 shows the respective trajectories for start dates 2023, in which case the average CO_2 intensity is $EEOI_n = EEOI_{\text{baseline}} \cdot (1 - r)^{n-2022}$, and 2030, with $EEOI_n = EEOI_{\text{baseline}} \cdot (1 - r)^{n-2029}$. By the latter date, the budget for 1.5°C is already exhausted.

Figure 3 also shows two alternative scenarios, one in which short term efficiency levers are exploited alongside other abatement measures from 2023, to effect an immediate reduction in emissions by 25%, subsequently allowing for slower progress towards decarbonization while remaining within the same budget; and in the other, CO_2 intensity reduces linearly over time. This means that emissions reduce slower initially but reductions

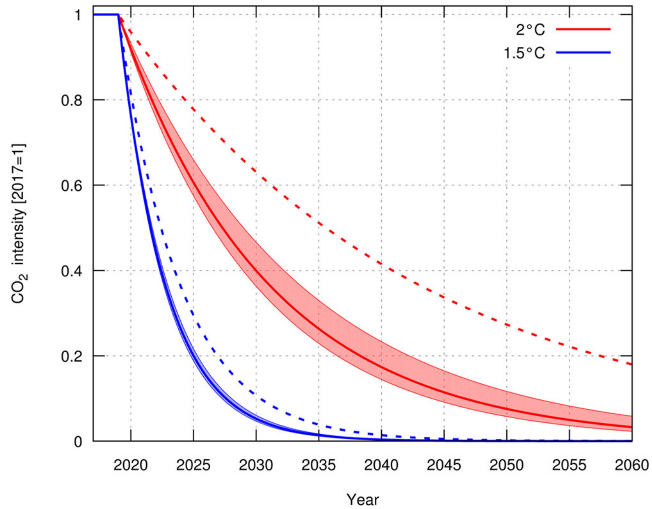

Figure 2. Average CO_2 intensity, reducing by constant year-on-year factor, from 2020 onwards, in 2°C scenario (less steep) and 1.5°C (steeper reductions). Shaded areas cover range from low to high demand growth scenario, with central demand scenarios shown as solid lines. Dotted lines show case of zero demand growth.

in absolute terms do not slow down over time, with emissions reaching absolute zero in 2045 (2°C) or almost immediately, in 2025 (1.5°C), respectively.

Following the logic of the IMO demand scenarios and disaggregating into unitized, dry, and wet bulk cargoes only (Figure 1), the challenge is greater still. Future demand growth is anticipated to be largest for unitized cargo, the sector currently with the highest CO_2 intensity. The average EEOI in 2012 is estimated as 12.1 gCO_2/tonne-kilometre for unitized cargo; 5.6 gCO_2/tonne-kilometre for dry bulk; and 5.8 gCO_2/tonne-kilometre for wet bulk. In this case $E_n = \sum W_{n,i} \cdot EEOI_{n,i}$, summing over years n and cargo categories i. These baseline (year 2012) values of EEOI are the ratio of: CO_2 emissions in 2012 (for containers, oil tankers, and dry and refrigerated bulkers) (Smith, Jalkanen et al., 2015); and the transport work supplied in 2012, by the same ship types

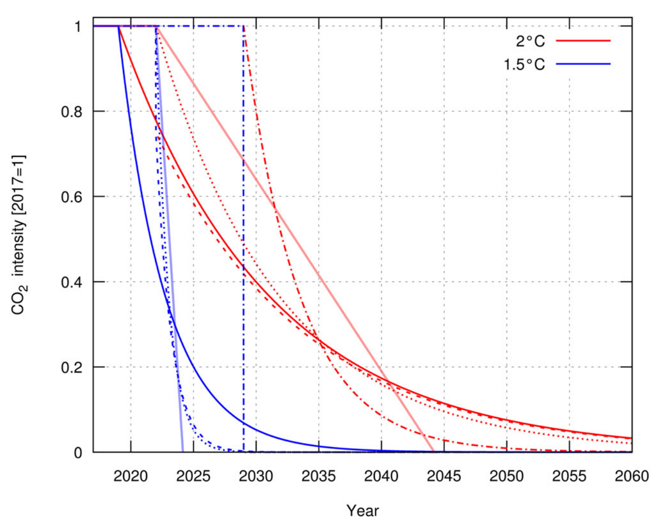

Figure 3. Average CO_2 intensity, in 2°C scenario (less steep) and 1.5°C (steeper reductions), for central demand scenario. Emissions reduce by constant year-on-year factor, from 2020, 2023, or 2030 onwards. In the fourth case, there is an additional, immediate one-time reduction of CO_2 intensity by 25% in 2023. Finally, shaded lines show a scenario of CO_2 reducing linearly over time, amounting to comparatively lower reduction rates earlier, and higher reduction rates later. Each set of five cases amounts to the same total budget from 2017 onwards, with the exception of mitigation from 2030, by when the budget for 1.5°C will already be exhausted.

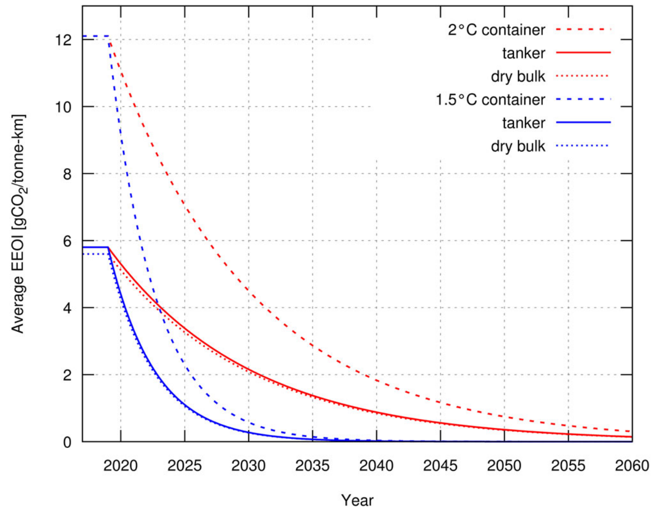

Figure 4. Average CO_2 emissions per unit of transport work, by ship type, in 2°C scenario (red) and 1.5°C (blue), under central demand growth scenario.

Table 2. CO_2 intensity reduction rates required to reconcile demand for sea transport with climate-constrained emissions budgets, and benchmark values of CO_2 emissions per unit of transport work, by ship type, for central demand scenario.

	To avoid 1.5°C warming			To avoid 2°C warming		
Average gCO_2/t-km by ship type	Reduction rate p.a. from 2020	2030	2050	Reduction rate p.a. from 2020	2030	2050
Container Carrier		4.5	0.7		0.6	0.0
Dry bulk Carrier	8.6%	2.1	0.3	24.2%	0.3	0.0
Wet Bulk Carrier		2.2	0.4		0.3	0.0

(Smith, Prakash, Aldous, & Krammer, 2015). Here, too, uncertainties apply that are hard to quantify. Nonetheless, explicit numbers, in terms of gCO_2 emitted per tonne-kilometre, are instructive. The results, however, rest on the relative reduction rates, which are not subject to these uncertainties (except for the uncertainty in the ratios between the average EEOI values for the three respective cargo categories). Looking forward from 2020, if all ship types achieve the same proportional reductions, in the central demand scenario, the CO_2 intensity of the sector must reduce each year by 8.6% in the 2°C case, and 24.2% in the 1.5°C case. By 2030, this analysis suggests the average EEOI falls to 4.5 gCO_2/tonne-kilometre for container carriers, 2.1 gCO_2/tonne-kilometre for dry bulk carriers, and 2.2 gCO_2/tonne-kilometre for wet bulk carriers in the 2°C scenario (0.6, 0.3, and 0.3 gCO_2/tonne-kilometre, respectively, in the 1.5°C scenario), as shown in Figure 4.

Table 2 presents corresponding numbers in the year 2050. Even under the least challenging assumptions considered, required cuts to CO_2 intensity are deeper than the future potential envisioned by the industry. The 2nd IMO GHG Study estimates the potential for improvement at 2.1–3.3% p.a. between 2009–2050 (Buhaug et al., 2009); the 3rd IMO GHG Study estimates 2.5% p.a., excluding speed effects and alternative fuels (Smith, Jalkanen et al., 2015); and a study explicitly considering alternative fuels estimates up to 4.3% under the most optimistic set of assumptions (Eide, Chryssakis, & Endresen, 2013). Over the timeframe of decades, the 2nd IMO GHG Study has estimated historical reduction rates of up to 2–3% p.a. (Buhaug et al., 2009), though in the recent past larger reductions in CO_2 intensity have been reported in parts of the container market (Acciaro & McKinnon, 2015).

6. Discussion

Greenhouse gas emissions from shipping can be cut by reducing either shipping activity (i.e. demand), or its CO_2 intensity. Clearly, the latter can be considered preferable from the industry's perspective. Therefore, this study focuses on CO_2 intensity while noting that demand may also be affected by measures aimed at reducing CO_2 intensity, or even actively targeted in order to reduce total emissions.

To achieve the deep intensity cuts that the preceding analysis shows are necessary for the sector to align with the Paris Agreement clearly amounts to a formidable task. There exist short-term levers of CO_2 intensity that may be exploited, including changes to speed, ship size and utilization, available retro-fit technologies, and other efficiency measures (Eide et al., 2013; Eide, Endresen, Skjong, Longva, & Alvik, 2009). In the longer term, virtually full decarbonization is needed (cf. Figure 4), requiring fleet-wide deployment of near-zero carbon ships. This implies a fundamental change to the system in a very short timeframe, including a switch from fossil fuels to alternative energy sources.

While some solutions exist in niche markets, there are no technological solutions readily available to be implemented economically, and at scale. Many alternative fuels may be nearly CO_2 emission free in principle but in practice need to overcome a number of barriers, often upstream in their life-cycle, to fulfil this potential (Gilbert et al., 2018). Wind propulsion, making use of an emission free, and freely available energy source, has been identified as one potential piece of the puzzle (Eide et al., 2011; Traut et al., 2014), and in fact was shown to deliver savings during the 1980s oil crisis (MacAlister, 1985), but has seen only few more recent demonstration projects, leaving a key barrier to wide-spread uptake in place (Rehmatulla, Parker, Smith, & Stulgis, 2017). It is difficult, if not impossible, to anticipate which solutions will prove most fruitful. Set against the scale of the mitigation challenge and fledgling development of truly zero or very low carbon alternatives for the sector, serious RD&D efforts are of critical importance. Given the long lifetimes and cost of both ships and the wider marine fuel infrastructure, any delay in implementing low carbon technologies will increase the risk of stranded assets, or diminish the chances of meeting the Paris Agreement's 2°C and 1.5°C commitments.

7. Conclusion

As the international shipping sector is negotiating its GHG strategy at the IMO, what 'level of ambition' to include in the strategy to be finalised in 2023 is one of the main topics of debate. The preceding analysis reveals the scale of reductions in CO_2 intensity implied by the headline commitments of the Paris Agreement if the sector aspires to achieve the same emission reduction rates as all other sectors on average.

While it is conceivable that shipping be allocated (or assume in practice) an increasing share of global emissions, it is worth noting that other sectors' 'levels of ambition' are generally not on track for keeping the global temperature increase below 2°C, let alone 1.5°C (Kuramochi et al., 2018), as is also indicated by countries' published NDCs (Rogelj et al., 2016). Moreover, the international aviation sector's strategy foresees its emissions continuing to increase (ICAO, 2016). Ultimately, apportioning a 'fair' share of the global mitigation burden to international shipping (or other sectors) inevitably relies on subjective judgements, and the outcome can only be determined by a political process involving the various stakeholders. The mitigation rates implied by the Paris Agreement are subject to uncertainty in, for example, the observed global temperature increase since pre-industrial times, the temperature response to future GHG emissions, and future growth in demand. However, and not withstanding these uncertainties, the core conclusions drawn here for international shipping remain essentially unchanged.

For the shipping industry to deliver mitigation in line with the Paris Agreement, virtually full decarbonization needs to be achieved. In the near term, immediate and rapid exploitation of available mitigation measures is of critical importance, as any delay in the transition will make the challenge much harder and, with a view to the Paris Agreement's ambitious temperature goals, potentially infeasible.

Clearly, any regulatory and/or financial action to pursue mitigation will have to adjudicate between a range of interests, with the mitigation challenge posing both risks and opportunities. It is therefore paramount to begin in earnest a debate on how to shape the best possible response. However, the time for such debate is short, and ways towards meaningful, absolute and sustained emissions reductions need to be found soon, in the interest of both the shipping industry's sustainability and our chances of achieving the commitments enshrined in the Paris Agreement.

Notes

1. Data from https://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html, downloaded 28 January 2018.
2. A threshold exceedance budget (TEB) is defined as the amount of cumulative emissions until the time when the temperature response reaches a given threshold, with a given probability. A threshold avoidance budget (TAB) is defined as the amount of cumulative emissions of a scenario that stays below the threshold, with a given probability. To calculate a TAB, a timeframe needs to be defined. If, for example, the timeframe is the time until peak warming, then both are the same. But in contrast with a TAB, a TEB can also be calculated from a scenario that exceeds the given temperature threshold.
3. Based on expert judgment and information about order books and the general economic outlook, growth rates are modelled to first decline and then return to a historical 'normal'.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/K039253/1.

ORCID

Michael Traut http://orcid.org/0000-0002-0689-9171
Alice Larkin http://orcid.org/0000-0003-4551-1608
Maria Sharmina http://orcid.org/0000-0002-5521-700X

References

Acciaro, M., & McKinnon, A. (2015). Carbon emissions from container shipping: An analysis of new empirical evidence. *International Journal of Transport Economics*, *42*(2), 211–228. Retrieved from scopus.com

Anderson, K., & Bows, A. (2012). Executing a Scharnow turn: Reconciling shipping emissions with international commitments on climate change. *Carbon Management*, *3*(6), 615–628.

Belgium, France, Germany, The Marshall Islands, Morocco, & Solomon Islands. (2016). International shipping's share in international efforts to limit the rise of global average temperature. *MEPC 69*, *7*(2), Retrieved from imo.org

Bows-Larkin, A. (2015). All adrift: Aviation, shipping, and climate change policy. *Climate Policy*, *15*(6), 681–702.

Buhaug, Ø, Corbett, J., Endresen, Ø, Eyring, V., Faber, J., & Hanayama, S. … Nilsen, J. (2009). *Second IMO GHG study 2009*. London: International Maritime Organization (IMO).

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., … Wehner, M. (2013). Long-term climate change: Projections, commitments and irreversibility. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 1029–1136). Cambridge: Cambridge University Press.

Doudnikoff, M. (2013). *Governance issues in the regulation of greenhouse gas emissions from maritime transport*. Ecological Economics and Institutional Dynamics, 10th International Conference of the European Society for Ecological Economics.

EC. (2013). *Proposal for a regulation of the European parliament and of the council on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport and amending regulation* (EU) no 525/2013. COM(2013) 480 final.

Eide, M. S., Chryssakis, C., & Endresen, Ø. (2013). CO_2 abatement potential towards 2050 for shipping, including alternative fuels. *Carbon Management*, *4*(3), 275–289. doi:10.4155/cmt.13.27

Eide, M. S., Endresen, Ø, Skjong, R., Longva, T., & Alvik, S. (2009). Cost-effectiveness assessment of CO_2 reducing measures in shipping. *Maritime Policy & Management*, *36*(4), 367–384. doi:10.1080/03088830903057031

Eide, M. S., Longva, T., Hoffmann, P., Endresen, Ø, & Dalsøren, S. B. (2011). Future cost scenarios for reduction of ship CO_2 emissions. *Maritime Policy & Management*, *38*(1), 11–37. doi:10.1080/03088839.2010.533711

EU. (2015). Regulation (EU) 2015/757 of the European parliament and of the council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC. *Official Journal of the European Union*, *58*, L123/55–76.

Eyring, V., Köhler, H., Lauer, A., & Lemper, B. (2005). Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. *Journal of Geophysical Research: Atmospheres*, *110*(D17). doi:10.1029/2004JD005619

Gilbert, P., & Bows, A. (2012). Exploring the scope for complementary sub-global policy to mitigate CO_2 from shipping. *Energy Policy*, *50*, 613–622. doi:10.1016/j.enpol.2012.08.002

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., & Murphy, A. (2018). Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, *172*, 855–866.

ICAO. (2016). *Environmental Report 2016 – Aviation and climate change*. ICAO, 2016.

ICS. (2014). *Shipping, world trade and the reduction of CO_2 emissions*. Retrieved from http://www.ics-shipping.org/docs/default-source/resources/policy-tools/shipping-world-trade-and-the-reduction-of-co2-emissionsEE36BCFD2279.pdf?sfvrsn=20

ICS. (2016). Proposal to develop an 'intended IMO determined contribution' on CO_2 reduction for international shipping. *MEPC 69*, *7*(1), Retrieved from imo.org

IEA. (2015). *World energy outlook 2015*. Paris: Author.

IMO. (2016). *Working group on reduction of GHG emissions from ships*. 70th meeting of the International Maritime Organization's Marine Environment Protection Committee, MEPC70, 24–28 October, IMO Headquarters, London.

Jones, C., Robertson, E., Arora, V., Friedlingstein, P., Shevliakova, E., & Bopp, L., … Tjiputra, J. (2013). Twenty-first-century compatible CO_2 emissions and airborne fraction simulated by CMIP5 earth system models under four representative concentration pathways. *Journal of Climate*, *26*(13), 4398–4413. doi:10.1175/JCLI-D-12-00554.1

Kågeson, P. (2009). *Transport for a global economy – Challenges and opportunities in the downturn*. Leipzig: International Transport Forum.

Kuramochi, T., Höhne, N., Schaeffer, M., Cantzler, J., Hare, B., Deng, Y., … Blok, K. (2018). Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, *18*(3), 287–305. doi:10.1080/14693062.2017.1397495

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., … Becker, M. (2017). Global carbon budget 2017. *Earth System Science Data Discussions*. doi:10.5194/essdd-2017-123

MacAlister, R. (1985). Sail retrofit on an inter-island vessel in Fiji. *Windship Technology*, *19*(1–3), 157–186. doi:10.1016/B978-0-444-42531-7.50012-9.

Mangset, L. E., Acciaro, M., & Eide, M. S. (2011). *A global seaborne trade pattern forecasting method for shipping emissions modeling*. International Association of Maritime Economists Conference, 25–28 October, IAME, Santiago De Chile.

Millar, R. J., Fuglestvedt, J. S., Friedlingstein, P., Rogelj, J., Grubb, M. J., Matthews, H. D., … Allen, M. R. (2017). Emission budgets and pathways consistent with limiting warming to 1.5 C. *Nature Geoscience*, *10*(10), 741–7747.

Ministry of Ecology, Sustainable Development, Transport and Housing. (2011). *Information on the quantity of carbon dioxide emitted during transport*. French Ministry of Ecology, Sustainable Development, Transport and Housing: Decree n. 2011-1336.

Morice, C. P., Kennedy, J. J., Rayner, N. A., & Jones, P. D. (2012). Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research: Atmospheres*, *117*(D8), doi:10.1029/2011JD017187

Nakićenović, N., Alcamo, J., Davis, G., Vries, B. d., Fenhann, J., Gaffin, S., & Dadi, Z. (2000). *Special report on emissions scenarios: A special report of working group III of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.

Olmer, N., Comer, B., Roy, B., Mao, X., & Rutherford, D. (2017). Greenhouse gas emissions from global shipping 2013–2015. *The International Council on Clean Transportation*. https://www.theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., & Rothman, D. S., … Solecki, W. (2015). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*. doi:j.gloenvcha.2015.01.004

Rehmatulla, N., Parker, S., Smith, T., & Stulgis, V. (2017). Wind technologies: Opportunities and barriers to a low carbon shipping industry. *Marine Policy*, *75*, 217–226.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., … Meinshausen, M. (2016). Paris agreement climate proposals need a boost to keep warming well below 2 C. *Nature*, *534*(7609), 631–639.

Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., … Pandey, A. (2015). *Third IMO GHG study 2014*. London: International Maritime Organization (IMO).

Smith, T. W. P., Prakash, V., Aldous, L., & Krammer, P. (2015). The existing shipping fleet's CO_2 efficiency. *MEPC 68, INF*, *24*, Retrieved from imo.org

Stocker, T. F., Qin, D., Plattner, G.-K., Alexander, L. V., Allen, S. K., Bindoff, N. L., … Xie, S.-P. (2013). Technical summary supplementary material. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 1–17). IPCC. Retrieved from www.climatechange2013.org and www.ipcc.ch.

Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., … Wood, R. (2014). Propulsive power contribution of a kite and a flettner rotor on selected shipping routes. *Applied Energy*, *113*, 362–372.

UNCTAD. (2015). *Review of maritime transport 2015*. Geneva: United Nations.

UNCTAD. (2016). *Review of maritime transport 2016*. Geneva: United Nations.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., & Hibbard, K., … . Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1-2), 5–31. doi:10.1007/s10584-011-0148-z

World Bank. (2016). *World Bank national accounts data, and OECD national accounts data files*.

WTO. (2015). *International trade statistics 2015, appendix: historical trends, table A-1*. World Trade Organization (WTO).