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CO₂ Targets, Trajectories and Trends for International Shipping

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1. Introduction

1.1. Shipping in Changing Climates

The Shipping in Changing Climates (SCC) project connects the latest climate change science with knowledge, understanding and models of the shipping sector in a whole systems approach. It seeks to explore the potential to cut CO₂ through the use of technical and operational changes in shipping and to understand how the sector might transition to a more resilient and low-carbon future; it also seeks to explore different climate change scenarios and related food and fuel security issues to gain an understanding of the direct and indirect impacts of climate change on the shipping sector. These scenarios can be used to build evidence and understanding around the range of potential future directions that the shipping industry may take.

The RCUK Energy funded project brings together researchers from UCL (Energy Institute, Mechanical Engineering and Laws), Manchester, Southampton, Newcastle and Strathclyde, in close collaboration with a core industry stakeholder group of Shell, Lloyd's Register, Rolls Royce, BMT and Maritime Strategies International, but drawing on the expertise and connections of over 35 companies and organisations worldwide. This paper is non-peer-reviewed and represents the collective opinions of the authors and should not be assumed to represent the views of all the researchers across the project or the project's industry partners and their organisations.

1.2. Context and objective of this paper

The Copenhagen Accord laid out an ambition to manage the risk of dangerous climate change by limiting the global mean temperature rise to no greater than 2°C above pre-industrial levels (Copenhagen Accord, 2009). Even with this level of warming, over time many low-lying nations could become uninhabitable due to sea level rise (Schaeffer et al. 2012). As a consequence, targeting just 1.5°C of warming continues to receive serious consideration from many parts of the world (Cancún Agreements, 2010; AOSIS, 2014). Both targets require an imminent peak in GHG emissions, followed by rapid and sustained emissions reductions across all sectors (UNEP, 2010).

Scenarios of future shipping GHG emissions, presented in the Third IMO GHG Study 2014, suggest that under current policy, shipping emissions are expected to rise significantly (by 50 to 250%). However, under both the 2°C and 1.5°C framing of climate change, and taking into account the latest IPCC and IMO studies, shipping emissions must be bounded by one of two alternative sets of conditions:

1. No further policy is applied to international shipping, leaving emissions on a business-as-usual growth trajectory. Under this option, the required cuts to greenhouse gas emissions from other sectors would need to go above and beyond the already significant reductions necessary to remain in line with the Copenhagen Accord and the Cancún Agreements.
2. Emissions from international shipping are limited and reduced to contribute a fair share to mitigation of global CO₂ consistent with the targeted maximum temperature rise (and associated probability).

With emphasis on the second set of boundary conditions, this paper considers the potential implications for international shipping by:

- Deriving two global CO₂ budgets that are consistent with a 50% chance of limiting global warming to 2°C and 1.5°C, respectively.
- Translating the global CO₂ budgets to CO₂ budgets for international shipping, assuming that a fair sharing of mitigation efforts suggests international shipping cut its emissions by the same proportion that is required for the global average¹.
- Exploring what reductions in the CO₂ intensity (and, in particular, shipping's Energy Efficiency Operational Indicator, EEOI) of maritime transport are needed to keep within these CO₂ budgets against the backdrop of continued growth in the shipping industry and projected rises in demand for sea transport.
- Reviewing the evidence from recent studies of the trends and drivers of trends in the shipping sector's CO₂ intensity (for 2007-12).

2. CO₂ budgets for shipping consistent with 1.5°C and 2°C

To derive CO₂ budgets² for the shipping sector that are consistent with limiting global warming to 2°C and 1.5°C, respectively, this study first considers global emissions budgets associated with such temperatures. In the Shipping in Changing Climates project, the climate model MAGICC (Meinshausen et al. 2011a&b) is used to calculate the climate's temperature response to emissions scenarios over the 21st century. In the 2°C reference scenario, which has a 50% chance of staying below 2°C of global warming, cumulative CO₂ emissions over the period 2011 to 2100 are estimated to be 1428GtCO₂.

In addition, a 1.5°C reference scenario is created³, yielding a 50% chance of limiting global warming to 1.5°C, in which case cumulative CO₂ emissions over the time period 2011-2100 are an estimated 773GtCO₂. It is noted that this number is significantly above the headline range given in the IPCC's AR5 Synthesis Report (IPCC, 2014).⁴

There may be reasons for increasing shipping's share of global CO₂ emissions. For example, it may be quicker or lower cost for other sectors to reduce their share of emissions. However, at present, whilst such reasons remain unsubstantiated and until another sector or region commits to reducing their share of emissions faster, to accommodate a growing emissions share from shipping, an appropriate assumption is that shipping's share will need to remain constant. This enables a cumulative CO₂ budget for international shipping to be derived from a global budget by assuming that shipping's budget should be in proportion to its current

¹ This is a strong assumption. For example, it could be argued from an analysis of process emissions from cement production and from deforestation are likely to reduce the budgets available from all other sectors.

² The focus is on CO₂ because it is the most important greenhouse gas, for two main reasons. Most of the radiative forcing from anthropogenic greenhouse gases is from cumulative CO₂ (Fuglestad et al. 2008); and a large fraction of the CO₂ emitted into the atmosphere will remain there for centuries to millennia (Archer et al. 2009).

³ Non-CO₂ emissions in the 2°C scenario are as in RCP4.5; non-CO₂ emissions in the 1.5°C scenario are as in RCP2.6 (Moss et al. 2010).

⁴ Due to differences in non-CO₂ emissions, path dependency, and other factors.

contribution to global emissions. The Third IMO GHG Study 2014 estimates CO₂ emissions from 2007 to 2012, amounting to 2.33% of global CO₂ emissions over that period. This results in a CO₂ budget of 33Gt over the time period from 2011-2100 for international shipping under the 2°C global warming scenario; and of 18Gt of CO₂ under the 1.5°C scenario.

Two stylised emissions trajectories corresponding with the two cumulative budgets, respectively, are shown in Figure 1. Many different trajectories of CO₂ emissions over time may correspond to the same budget (curves of different shape with the same area under the curve). But it is instructive to consider specific examples. To this end it is assumed that CO₂ emissions from international shipping follow the reference scenario from the Third IMO GHG Study 2014⁵ until 2020 and then a linear decrease over time. In the 2°C case, the cumulative budget is used up in 2079, when CO₂ emissions reach zero. In the 1.5°C case, emissions reach zero in 2044. Keeping within these carbon budgets must happen against the backdrop of continued growth in the shipping industry, which in the scenario considered here, is estimated to be four time greater by 2050 than in 2012, as discussed below.

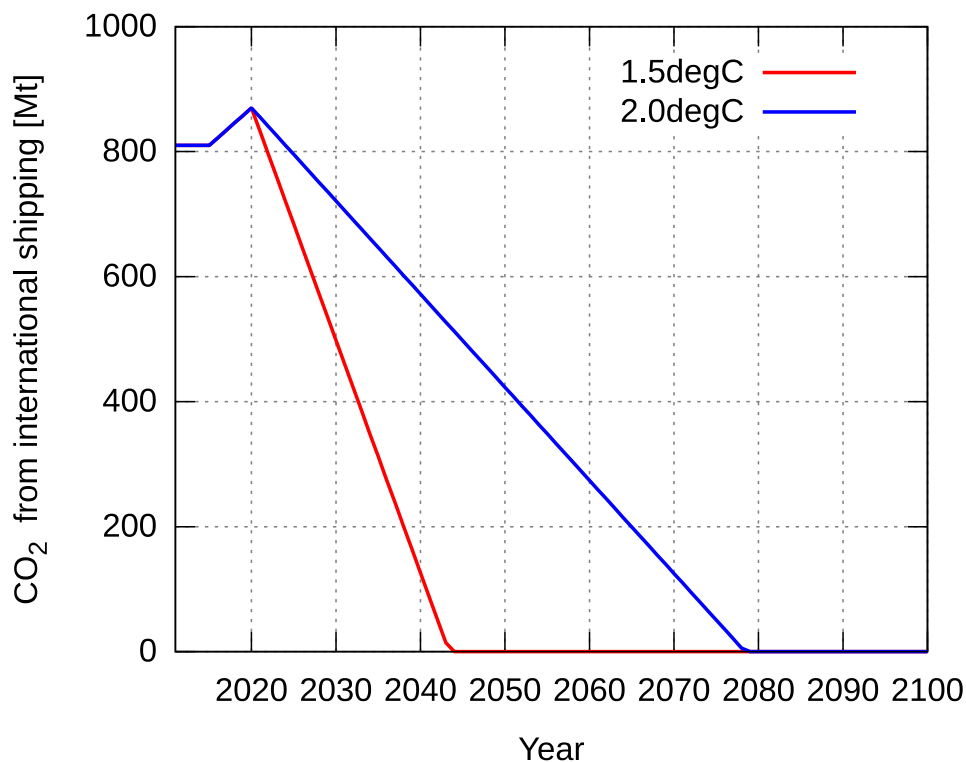


Figure 1, CO₂ emissions trajectories for international shipping consistent with a 2°C temperature rise (blue curve) and a 1.5°C temperature rise (red curve). The trajectories assume emissions as in the reference scenario from the Third IMO GHG Study 2014 to 2020, followed by constant reductions, with the year-on-year reduction determined by the remaining CO₂ emissions budget of 33Gt and 18Gt, respectively.

⁵Scenario 16, the BAU scenario based on RCP2.6.

Table 1, CO₂ emissions from international shipping in selected years, for 2°C and 1.5°C scenarios, respectively, as in Figure 1.

Year	2020	2030	2040	2050	2060
2°C scenario emissions (Mt CO ₂)	870	721	572	423	274
1.5°C scenario emissions (Mt CO ₂)	870	498	126	0	0

3. Interpreting CO₂ budgets for international shipping

Having derived a target CO₂ trajectory, the implications of this for shipping’s EEOI (operational CO₂ intensity) can be estimated, given an assumption about future transport demand. Furthermore, this operational CO₂ intensity can be interpreted as a technical CO₂ intensity trajectory, given certain assumptions about speed and utilization. The interconnection of these different components and how they contribute to determine shipping’s share of total anthropogenic CO₂ emissions is shown in Figure 2.

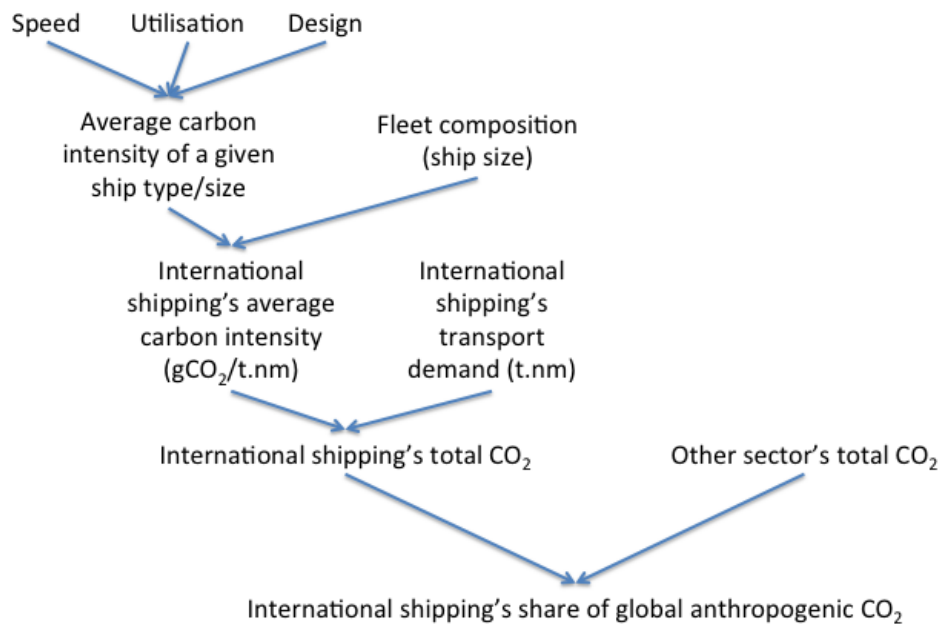


Figure 2, Diagram showing the interactions which contribute to shipping's CO₂ as a share of global anthropogenic CO₂

In 2012, international shipping comprised approximately 60,000 ships (Smith et al. 2014). Following the approach used in the Third IMO GHG study 2014 to provide descriptions at an appropriate level of detail for understanding the fleet, these ships can be grouped into fleets of similar ship types and sizes. This enables the differences in the technical and operational specifics of these fleets to be considered, as well as differences in the projections of each fleet’s transport demand. The following sections of this paper focus on understanding the implications of the target CO₂ trajectory for just three ship types: container ships, tankers and bulk carriers. In combination, these three ship types accounted for approximately 62% of international shipping’s CO₂ emissions in 2012.

1.3. Transport demand

In order for shipping emissions to remain within a given CO₂ budget under scenarios of increasing transport demand, the CO₂ intensity per unit of transport work will need to reduce. The demand for transport work, measured in tonne-nms, can be used to determine the CO₂ intensity, measured in CO₂ emissions per transport work, that shipping must achieve to stay below its CO₂ emissions target. For an individual ship, the CO₂ intensity is indicated by the Energy Efficiency Operational Indicator (EEOI).

To explore what changes in CO₂ intensity will be needed, we draw on one of the demand scenarios from the Third IMO GHG Study 2014. These scenarios are intended to explore plausible future developments (noting that different developments might come to pass), and the scenario is chosen to align appropriately with the broader climate change mitigation objectives. To consider then how demand for sea transport for various cargo and ship types might develop over the first half of the 21st century, the Study models the link between transport demand for that cargo type and an indicator variable, such as world GDP or global coal consumption. For example, non-bulk dry cargoes are linked to world GDP. The projected indicator variables are taken from the IPCC's reference scenarios: the Representative Concentration Pathways (RCP)(Moss et al. 2010), and the Shared Socioeconomic Pathways (SSP)(O'Neill et al. 2014).

In this study, the demand scenario for containerized shipping, dry bulk shipping and wet bulk shipping is taken from the Third IMO GHG Study 2014 based on RCP2.6 (van Vuuren et al. 2011), the only RCP scenario consistent with limiting global warming to below 2°C, and SSP4, is considered⁶. The scenarios involve narratives about the future, and aspects of those narratives are reflected in the quantitative analysis - most saliently in the different demand trajectories of wet and dry bulk, due to the expanding coal use in RCP2.6. But the scenarios are not predictions and as a consequence some of the quantitative details may depend on the specific scenario, while the conclusions hold more generally for a future of no more than 2°C or 1.5°C, respectively, of global warming. The demand trajectories are shown in Figure 3. Overall for the three ship types considered, demand grows by a factor of four between 2012 and 2050. There is a significant difference between ship types with the overall growth driven by container shipping (grows by a factor of eight from 2012 to 2050), whilst oil tankers see a decline in transport demand as globally, demand for fossil fuels is reduced and alternative sources of energy supply are sourced.

1.4. Target fleet CO₂ intensity / EEOI trajectories

Figure 3 highlights three interacting trajectories for the three ship types focused on in this study: the demand trajectories, the fleet's CO₂ trajectories and the operational CO₂ intensity (EEOI) trajectories. The trajectories are presented for both the 1.5°C and 2°C CO₂ budgets.

⁶The four RCP scenarios span a wide range of climate futures, including radiative forcing from anthropogenic greenhouse gases to be used in climate modelling studies. Their naming relates to the resulting radiative forcing, with RCP8.5 the scenario with the highest radiative forcing, and RCP2.6 the only scenario likely to stay below 2°C of global warming. The SSP scenarios represent different future socioeconomic scenarios and can be used in conjunction with the RCP scenarios (with different pairings possible) for integrated modelling studies.

The EEOI is presented as the required aggregate average EEOI inclusive of all sizes of ship within the ship type at a given point in time (including both the newbuild ships and the existing fleet). This allows for there to be a range of efficiencies of individual ships, varying according to the ship's age, size and specific design and operational specifications.

The EEOI and CO₂ trajectories are calculated through an accountancy process by assuming that:

- Demand is exogenous, that is to say there is no feedback between the level of decarbonisation, or change in operational CO₂ intensity, and demand
- From 2020, each ship type undertakes similar percentage improvements in operational CO₂ intensity over the period out to 2050. This is a simple starting assumption for illustrative purposes, and if it turns out that the cost-effectiveness of decarbonisation differs between ship types, then a differential in the rate of operational CO₂ intensity change may be preferable.
- The aggregate CO₂ trajectory of all three ship types is set to meet their share of the total budget identified in Table 1 (1.5°C case on the left, and 2°C case on the right in Figure 3).
- That the share of international shipping's emissions associated with containerized, dry bulk and wet bulk (tanker) shipping remains constant between 2012 and 2050 at 62% of international shipping's CO₂ emissions.

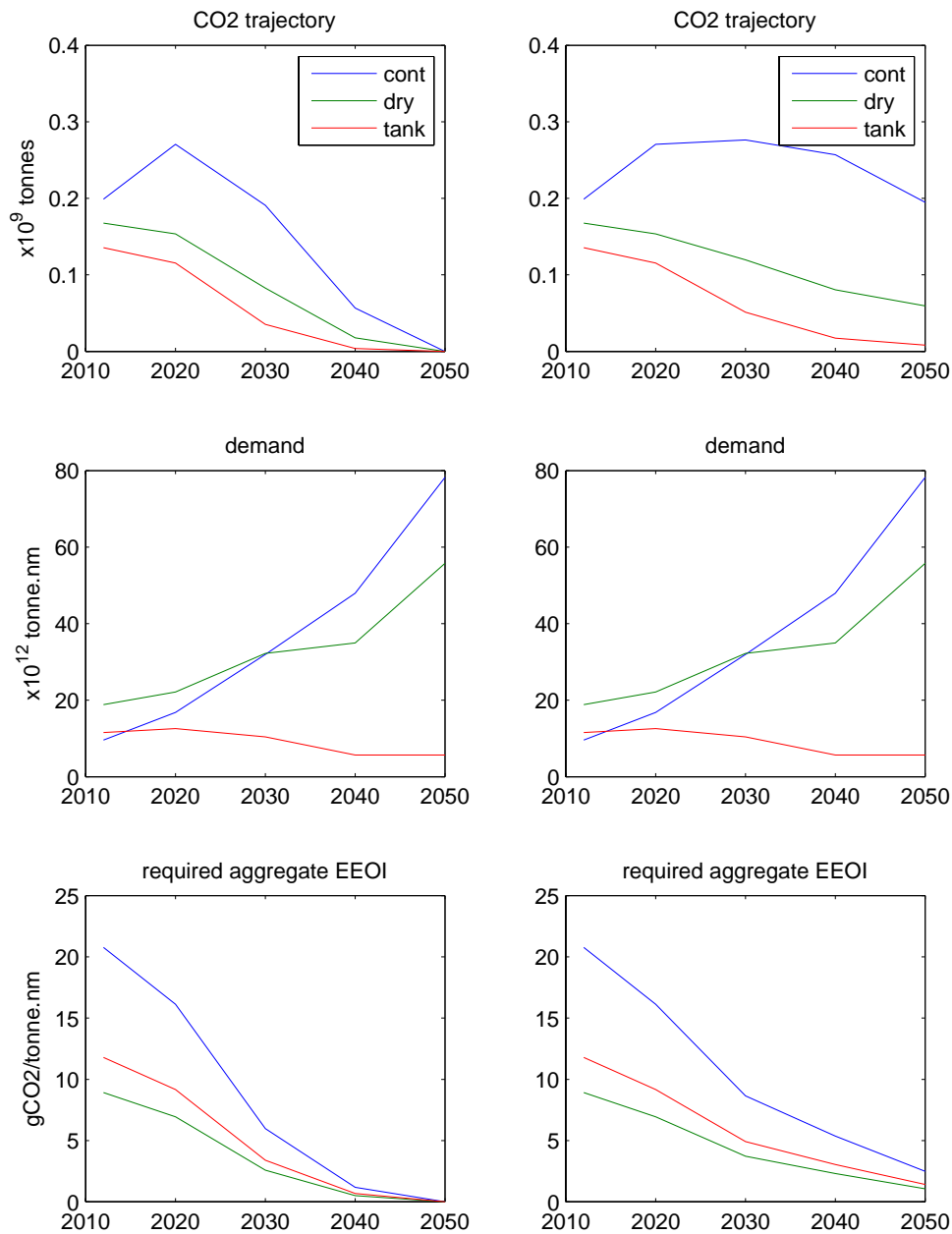


Figure 3: Estimation of trends in CO₂ trajectory and associated target operational CO₂ intensity trajectory consistent with 1.5°C (left hand side) and 2°C (right hand side)

1.5. Trends and drivers of fleet CO₂ intensity

Since the global financial crisis starting in 2008, shipping has already seen some changes to its operational CO₂ intensity (Smith et al. 2015). Some of the key trends in shipping during this period are described in the IMO Third GHG Study 2014, and include extensive take-up of slower speeds. Reducing speed creates reductions in fuel consumption, which, if all other influences of operational CO₂ intensity remain constant, can deliver significant improvements in a fleet's aggregate operational CO₂ intensity (even allowing for the additional numbers of ships required to meet the same level of overall transport demand, at least until very low operating speeds e.g. 5 knots and below).

In addition to changes in operating speed, utilisation (the total transport work as a % of total dwt-nm) can also vary over time, as can the composition of the fleet (e.g. the average size of ship), and the technical specification of ships (the use of energy efficiency technologies). The interaction of these drivers of fleet CO₂ intensity is discussed in more detail in Appendix A, with example values taken from recent analyses of the tanker, bulk carrier and containership fleets.

The data in Appendix A is used to derive ‘what if?’ scenarios for the future evolutions of the drivers of fleet CO₂ intensity, presented in Table 2. These are speculative because these drivers are in themselves affected by a number of market and regulatory forces which are currently unknown. The purpose of these scenarios is to test and illustrate the sensitivities of technical CO₂ intensity to imaginable future scenarios for the global fleet.

Table 2: Three different scenarios describing the future evolution of operational CO₂ intensity influences, speed and utilisation

Scenario	Speed	Utilisation
A	Steady decrease in operating speed of 10% per decade	Highest values during (2007-12)
B	Constant at 2012 level	Highest values during (2007-12)
C	Constant at 2007 levels	Lowest values during (2007-12)

The operating speed and utilisation resulting from the assumptions in Table 2 are shown over the time period 2012-2050 in appendix B.

4. Technical CO₂ intensity trajectories

Insight into the future requirements for ship design can be obtained from combining the required aggregate EEOI trajectories with the assumptions in Table 2. The results in terms of EETI (see Appendix A) can be seen in Figure 4, Figure 5 and Figure 6. EETI is a proxy for technical CO₂ intensity (sometimes referred to as technical efficiency) in gCO₂/t.nm representing the average ship’s performance when fully loaded and at its reference (e.g. design) speed. It is similar to EEDI (Energy Efficiency Design Index), but includes in-service impacts on fuel consumption created by hull fouling, engine and machinery wear, and weather.

The required aggregate EETI by 2050 in the 2°C scenarios ranges from 25% of the 2012 value (Scenario A) to approximately 10% of the 2012 value (Scenario C). The 1.5°C scenarios all require a more rapid rate of change, reducing to 50% to 25% of the 2012 values of EETI by 2030, depending on the specifics of speed and utilisation.

The sensitivity of the required EETI to the operational assumptions (speed and utilization) can also be clearly seen by contrasting the EETI in the different scenarios in the year 2020.

The difference between the scenarios being that the aggregate EETI can be either increasing or approximately staying constant (Scenario A), or it will need to undergo rapid reduction (Scenario C) – in other words if speeds return to 2007 levels and utilization remains low, a much greater reduction is required in the EETI to compensate.

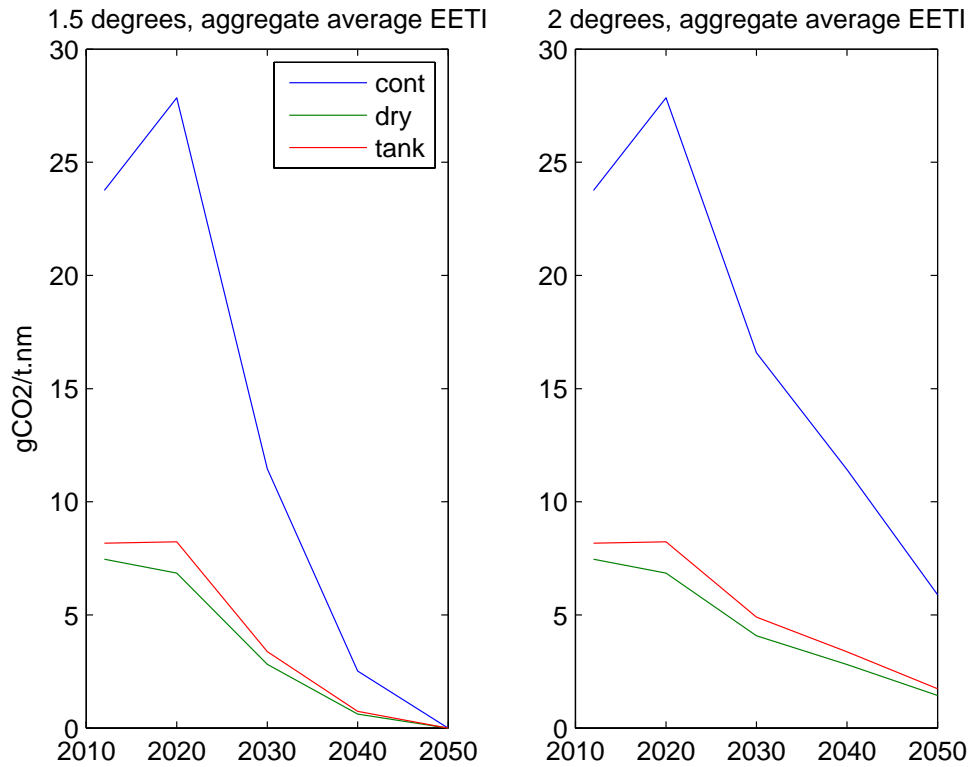


Figure 4: Required aggregate average EETI trajectories, Scenario A

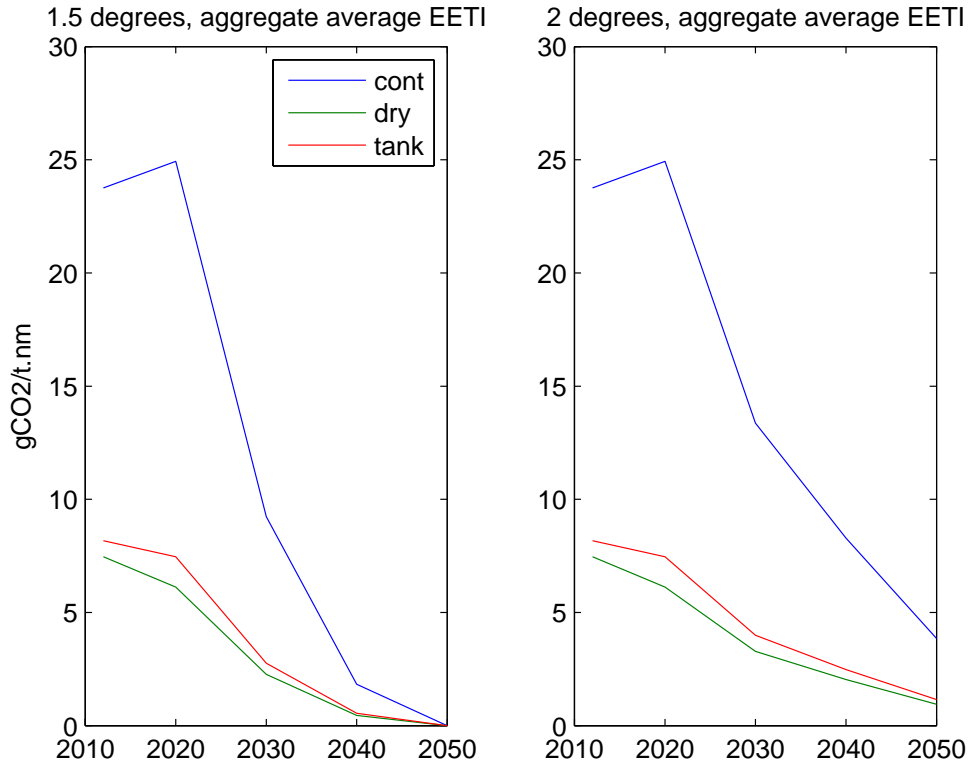


Figure 5: Required aggregate average EETI trajectories, Scenario B

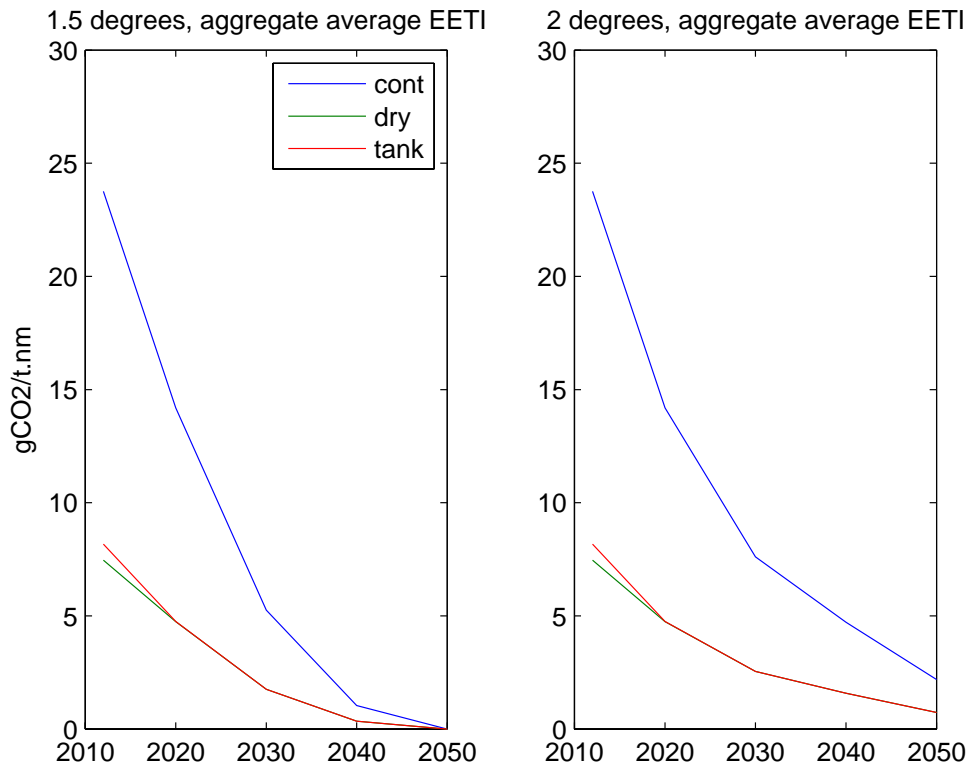


Figure 6: Required aggregate average EETI trajectories, Scenario C

5. Concluding remarks and further work

International shipping has a significant story evolving in relation to its CO₂ emissions:

- Evidence of some decoupling of emissions from tonne-nm: falling CO₂ emissions occurring at the same time as growth in trade during the period 2007-12 (Smith et al. 2014)
- Recent implementation of new regulations on energy efficiency and emissions intensity: EEDI and SEEMP
- Rapid technological developments: In many cases, recent ship designs have exceeded their required EEDIs

However, like all other sectors, international shipping requires a CO₂ target. This is because:

1) Even allowing for the positive developments described, there remains a discrepancy between global climate change targets and international shipping's ability to deliver a proportionate contribution to that objective (Bows-Larkin 2015).

2) Even allowing for debate on precisely what shipping's 'fair' contribution is, the scale of the discrepancy between targets commensurate with global climate change objectives and the industry's projected emissions scenarios is so large, and the risk of negative consequences of failing to avoid dangerous climate change so great, that clear and careful management of the required transition requires urgent attention (Anderson and Bows, 2012).

To articulate the scale of the discrepancy, this paper outlines how the latest IPCC reports provide a clear constraint on the total CO₂ emissions that can be emitted, if international shipping's share of global anthropogenic emissions remains at current levels. This illustrates that total emissions must peak soon and then undergo a rapid and sustained decline. The 2°C target requires at least a halving of international shipping's CO₂ emissions on 2012 levels by 2050, and to have zero carbon emissions by 2080. A more stringent 1.5°C target requires a halving of emissions by 2035, and carbon neutrality by 2045.

The scale of the challenge and the clarifying benefits of setting a constraint on CO₂ are further demonstrated by analysing the trajectories of EEOI and EETI in the context of 1.5°C and 2°C targets. Trajectories for three ship types that contribute the majority (62%) of international shipping's CO₂ emissions: tankers, bulk carriers and container ships, are assessed. Due to expectations of rising transport demand, the 2°C target implies that the fleet aggregate average EEOI will need to be approximately 50% of 2012 levels by 2030 and 10% of 2012 levels by 2050. The 1.5 degree scenario requires aggregate average EEOI to be 25% of 2012 levels by 2030, just 15 years from now. This is significantly more stringent than currently discussed levels (Smith et al. 2014).

For fleet aggregate average technical CO₂ intensity, there are further uncertainties around how operational CO₂ intensity influences (e.g. speed and utilization) might evolve over time. Three scenarios are considered and these show significant variability in the scale of the technical challenge. For example, for the 2°C target, in 2030, the required EETI would need to be 75% of 2012 level in Scenario A or 33% of 2012 level in Scenario C. Temporarily putting aside the question of what combination of technology, fuel and ship size could most cost-effectively achieve these different levels of emissions reduction, it is clear that the scale of

required technical CO₂ intensity improvement is highly dependent on the evolution of operational CO₂ intensity (speed and utilization).

If these rates of change are put in the context of currently available technology, and combined with expectations of continued increases in ship size, achieving the *least* constrained EETI trajectory to 2030 may be challenging but feasible. However, regardless of whether 1.5°C or 2°C, Scenario A, B or C, the levels of aggregate average EETI improvement by 2050 are well beyond those currently being debated. As such, they will require careful targeting, planning and coordination of a global industry, and with just 35 years to reach the goal, coupled with the constraints placed by a CO₂ budget, rather than long-term end-point framing, and a ship's service life currently a similar length of time, this planning and coordination cannot start soon enough.

1.6. Areas of ongoing and further work

This paper is, by design, a simplified representation of a complicated topic developed using the current state of the art knowledge on the climate, transport demand and the shipping system. Besides the uncertainties in the estimation of CO₂ budgets, there are uncertainties both in the trends and trajectories of international shipping's transport demand, as well as operational and technical CO₂ intensity. Research can help both by simplifying and articulating the challenge associated with decarbonisation of shipping, as well as providing more detail, explanation and justification of assumptions made in simplified analysis such as is presented in this paper. Along with many other research groups and initiatives, the Shipping in Changing Climates project aims to contribute on the following topics:

- Detailed analysis (costs and benefits) of the different ship design solutions that could meet different targets
- Understanding of interaction between the design and operation of ships, and optimal solutions for ship owners and operators
- Understanding of recent trends in the industry and what these can tell us about future trajectories
- Understanding the risks of unintended consequences, for example the impacts of changes in transport cost on transport demand, or increases in GHG created through life cycle emissions or through other impinging air pollution regulation
- Understanding the drivers of shipping's transport demand and foreseeable scenarios for its evolution over the next 40 years
- Understanding the impacts of climate change on the shipping industry (both 2°C and 4°C scenarios)
- Understanding the impacts of different mitigation policies on the shipping industry

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7. Appendix A—decomposing EEOI into technical and operational parameters

The operational CO₂ intensity is a combination of both the technical CO₂ intensity of a ship in a reference condition (e.g. fully loaded and at a reference speed such as its design speed), and a number of operational parameters including the speed the ship is operated at and the utilisation (Smith et al. 2013). A ship's utilisation reflects both the number of loaded voyages performed relative to ballast voyages, and the average mass of cargo carried when loaded. Using the performance model deployed in the IMO Third GHG Study, which found that a cubic relationship between speed and fuel consumption correlated well with empirical data from ship operators, the relationship between technical CO₂ intensity (in this instance represented as an Energy Efficiency Technical Indicator (EETI)), operating speed and utilisation can be approximated using Equation 1.

$$EEOI = EETI \cdot \frac{(v_{op}/v_{ref})^2}{\eta_u} \quad \text{Equation 1}$$

In order to provide further detail on the implications of the target EEOI trajectories shown in Figure 3, estimates of the consequent trajectories of EETI, given assumptions of operating speed and utilisation, can be made. Table 3 details the average aggregate EEOI, utilisation and operating speed for the three ship types focused on in this study. These are aggregated averages for all sizes and ages of ship operating within that ship type in the specified year. The overall ship type's average EEOI is calculated by dividing the ship type's total CO₂ emissions by the ship type's total transport work done (tonne-nm). Both are calculated using data from the IMO Third GHG Study 2014 and described both in that document and in MEPC 68 Inf. 24. The aggregate average utilisation and operating speed are found from calculating the weighted average of these parameters across all ship sizes within the ship type, weighted according to the total transport work performed by the given ship size category. The utilisation data for 2007 is sourced originally from the Second IMO GHG Study 2009 (the 2007 cargo mass was not re-estimated in MEPC 68 Inf. 24), whereas all other data is sourced from the Third IMO GHG Study 2014.

Two developments can be seen from Table 3; the first is that operating speeds have decreased across all ship types – reflecting the slow-steaming trend already referred to. The second is that there are variations in the utilisation for each ship type between 2007 and 2012. The explanation for the variation is made more difficult because the source of the data is not the same for both years and some of the variation may be influenced by methodological differences. Nevertheless, the results presented in MEPC 68 Inf. 24 imply that, as well as incentivizing slow steaming, another consequence of the financial crisis and its effects on international shipping has been a reduction in average cargo mass carried and therefore utilisation (driven by overcapacity in the fleets).

Table 3, Summary of aggregate average EEOIs and the influences of EEOI, in 2007 and 2012

ship type	year	EEOI	utilisation	operating speed
		gCO ₂ /t.nm	%	kt
container ships	2007	26.9	67%	17.7
	2012	21.4	50%	15.6
dry bulk	2007	9.2	53%	12.7
	2012	8.8	50%	11.8
tanker	2007	10.0	48%	13.8
	2012	10.8	41%	12.0

8. Appendix B—description of evolution of operational CO₂ intensity influences 2012-2050

