Emissions budgets for shipping in a 2°C global warming scenario, and implications for operational efficiency

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ABSTRACT
To achieve the widely accepted goal of keeping global temperature rise below 2°C above pre-industrial levels, greenhouse gas emissions must reduce drastically over the coming decades. Under this premise, the assumption that the shipping industry realises the same proportionate CO_2 emission reductions as all other sectors on average has strong implications. This paper begins by considering an appropriate global CO_2 emissions budget associated with a temperature rise of 2°C. Next, a range of future demand scenarios for international transport shipping are presented. Meeting the demand in any of the scenarios, while remaining within the emissions budget, requires stringent increases in overall operational efficiency. Different emissions and efficiency trajectories – with efficiency expressed in terms of the Energy Efficiency Operational Indicator (EEOI) – in line with the 2°C target are analysed. The potential short and long term levers of operational efficiency are explored.

Keywords: Carbon budgets, 2°C, operational efficiency, EEOI, emission pathways, ghg emissions

1. INTRODUCTION

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 CO_2 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 CO_2 budgets that are consistent with a 50% chance of limiting global warming to 2°C and 1.5°C, respectively.
- Translating the global CO_2 budgets to CO_2 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 average[1].
- Exploring what reductions in the CO_2 intensity (and, in particular, shipping's Energy Efficiency Operational Indicator, EEOI) of maritime transport are needed to keep within these CO_2 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 CO_2 intensity (for 2007-12).

[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. GLOBAL CO_2 BUDGETS

To derive CO_2 budgets[2] 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.

2.1 CO_2 BUDGETS FOR SHIPPING

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 CO_2 emissions over the period 2011 to 2100 are estimated to be 1428GtCO_2.

In addition, a 1.5°C reference scenario is created[3], yielding a 50% chance of limiting global warming to 1.5°C, in which case cumulative CO_2 emissions over the time period 2011-2100 are an estimated 773GtCO_2. 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 CO_2 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 CO_2 budget for international shipping to be derived from a global budget by assuming that shipping's budget should be in proportion to its current contribution to global emissions. The Third IMO GHG Study 2014 estimates CO_2 emissions from 2007 to 2012, amounting to 2.33% of global CO_2 emissions over that period. This results in a CO_2 budget of 33Gt over the time period from 2011-2100 for international shipping under the 2°C global warming scenario; and of 18Gt of CO_2 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 CO_2 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 CO_2 emissions from international shipping follow the reference scenario from the Third IMO GHG Study 2014[5] until 2020 and then a linear decrease over time. In the 2°C case, the cumulative budget is used up in 2079, when CO_2 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.

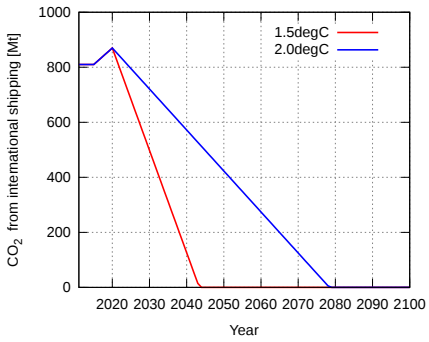

Figure 1: CO_2 emissions trajectories for international shipping consistent with a 2°C temperature rise (blue curve) and a 1.5°C temperature rise (red curve). The trajectories assume emissions as in the reference scenario from the Third IMO GHG Study 2014 to 2020, followed by constant reductions, with the year-on-year reduction determined by the remaining CO_2 emissions budget of 33Gt and 18Gt, respectively.

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[2] The focus is on CO_2 because it is the most important greenhouse gas, for two main reasons. Most of the radiative forcing from anthropogenic greenhouse gases is from cumulative CO_2 (Fuglestvedt et al. 2008); and a large fraction of the CO_2 emitted into the atmosphere will remain there for centuries to millennia (Archer et al. 2009).

[3] Non-CO_2 emissions in the 2°C scenario are as in RCP4.5; non-CO_2 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.

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

Table 1: CO_2 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

2.2. IMPLICATIONS FOR SHIPPING CO_2 INTENSITY

Having derived a target CO_2 trajectory, the implications of this for shipping's EEOI (operational CO_2 intensity) can be estimated, given an assumption about future transport demand. Furthermore, this operational CO_2 intensity can be interpreted as a technical CO_2 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 CO_2 emissions is shown in Figure 2.

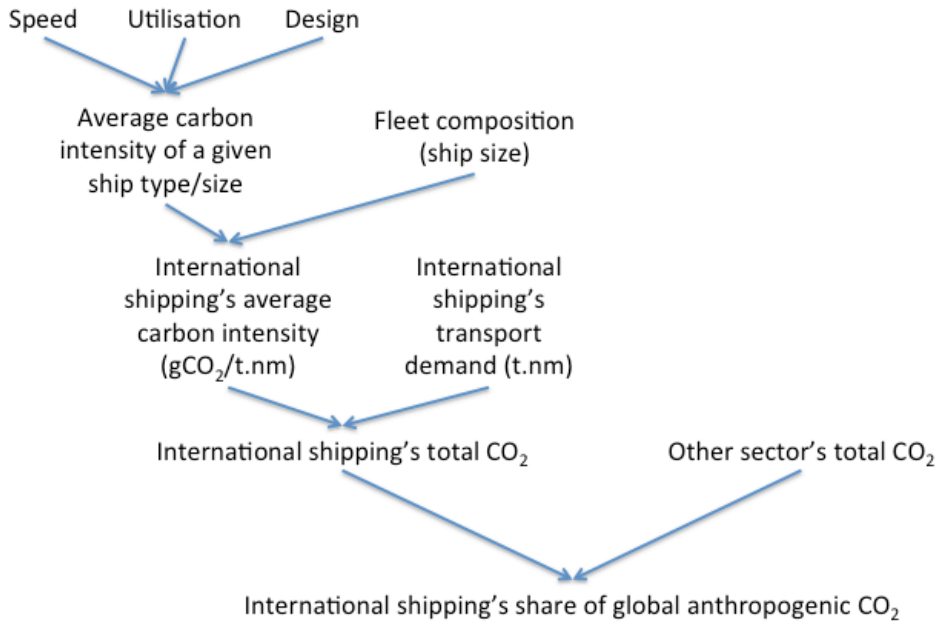

Figure 2: Diagram showing the interactions which contribute to shipping's CO_2 as a share of global anthropogenic CO_2

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 CO_2 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 CO_2 emissions in 2012.

2.3. IMPLICATIONS FOR TRANSPORT DEMAND

In order for shipping emissions to remain within a given CO_2 budget under scenarios of increasing transport demand, the CO_2 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 CO_2 intensity, measured in CO_2 emissions per transport work, that shipping must achieve to stay below its CO_2 emissions target. For an individual ship, the CO_2 intensity is indicated by the Energy Efficiency Operational Indicator (EEOI).

To explore what changes in CO_2 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 considered[6]. 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.

3. RESULTS

Figure 3 highlights three interacting trajectories for the three ship types focused on in this study: the demand trajectories, the fleet's CO_2 trajectories and the operational CO_2 intensity (EEOI) trajectories. The trajectories are presented for both the 1.5°C and 2°C CO_2 budgets. 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 a range of efficiencies of individual ships, varying according to the ship age, size and specific design and operational specifications.

3.1 EEOI & CO_2 TRAJECTORIES

The EEOI and CO_2 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 CO_2 intensity, and demand
- From 2020, each ship type undertakes similar percentage improvements in operational CO_2 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 CO_2 intensity change may be preferable.
- The aggregate CO_2 trajectory of all three ship types is set to meet the 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 CO_2 emissions.

[6]The 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.

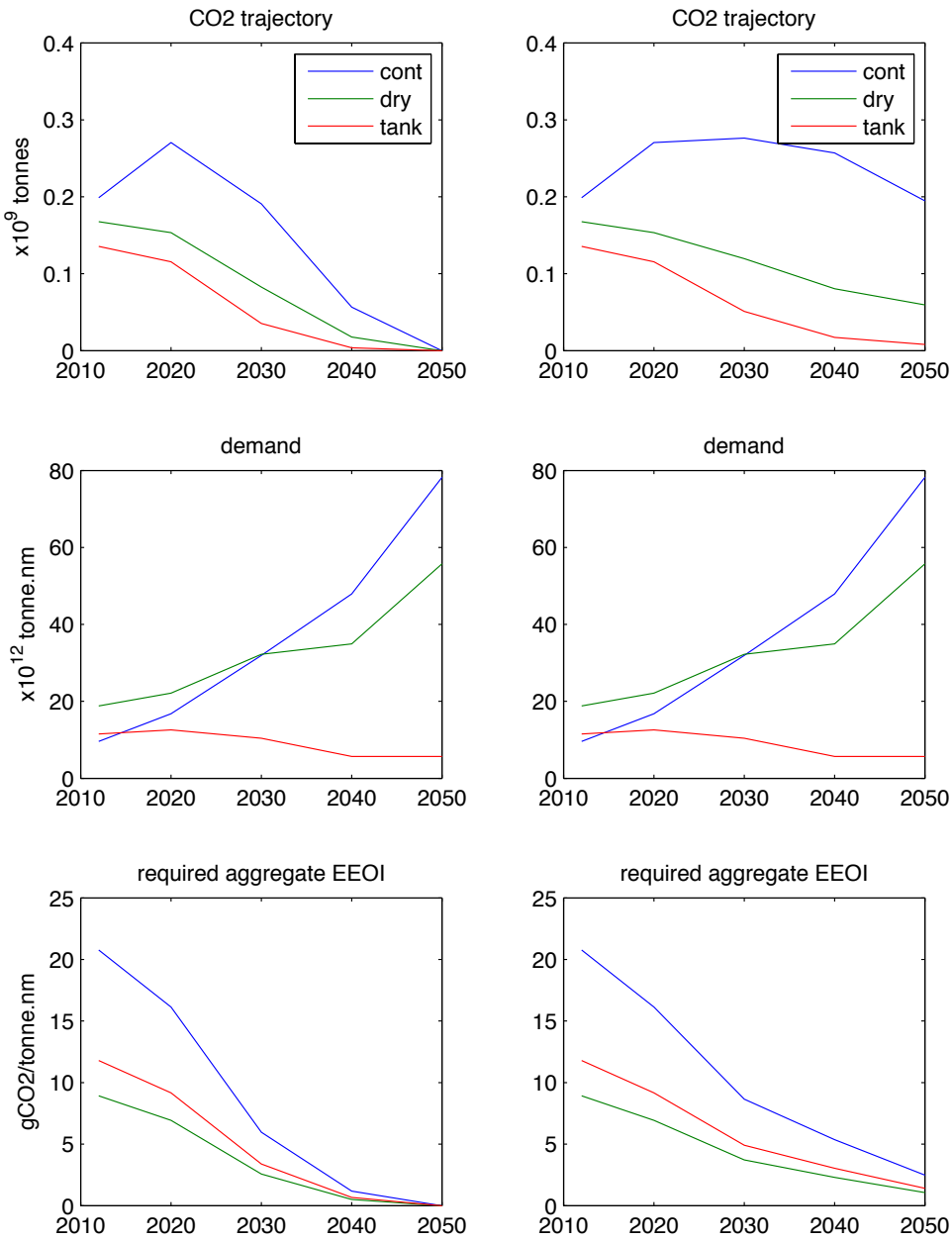

Figure 3: Estimation of trends in CO_2 trajectory and associated target operational CO_2 intensity trajectory consistent with 1.5°C (left hand side) and 2°C (right hand side)

3.2. TRENDS AND DRIVERS OF FLEET CO_2 INTENSITY

Since the global financial crisis starting in 2008, shipping has already seen some changes to its operational CO_2 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 CO_2 intensity remain constant, can deliver significant improvements in a fleet's aggregate operational CO_2 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 CO_2 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 CO_2 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 CO_2 intensity to imaginable future scenarios for the global fleet.

Table 2: Three different scenarios describing the future evolution of operational CO_2 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.

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 CO_2 intensity (sometimes referred to as technical efficiency) in gCO_2/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.

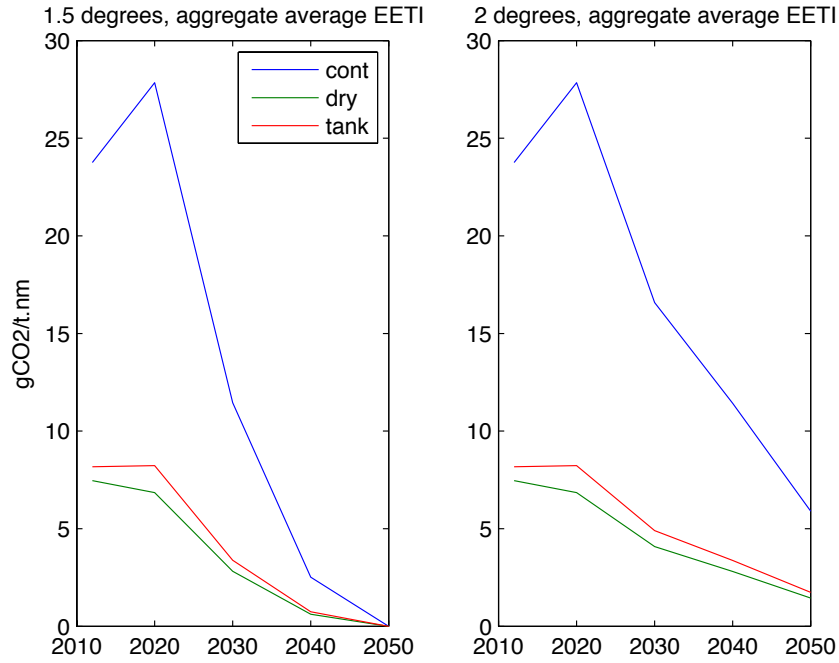

Figure 4: Required aggregate average EETI trajectories, Scenario A

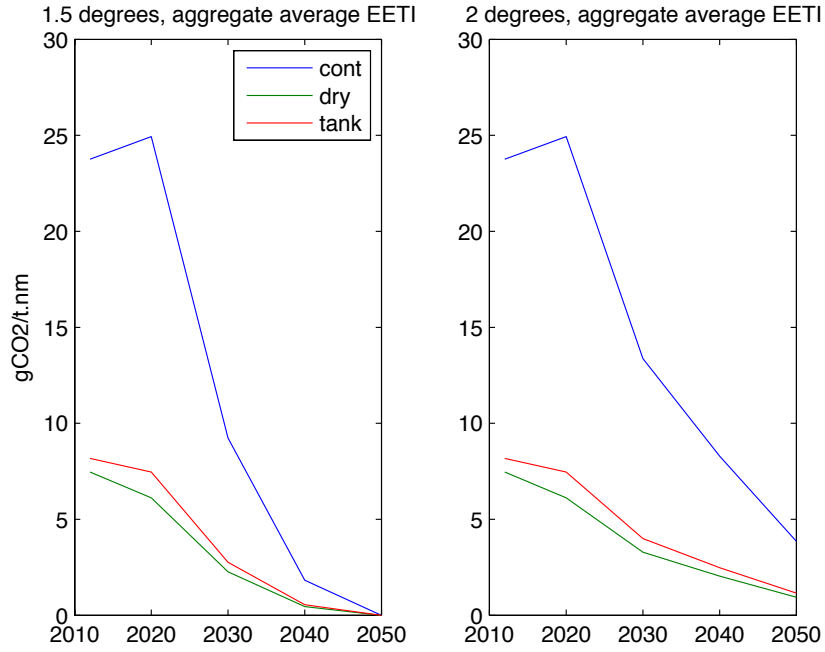

Figure 5: Required aggregate average EETI trajectories, Scenario B

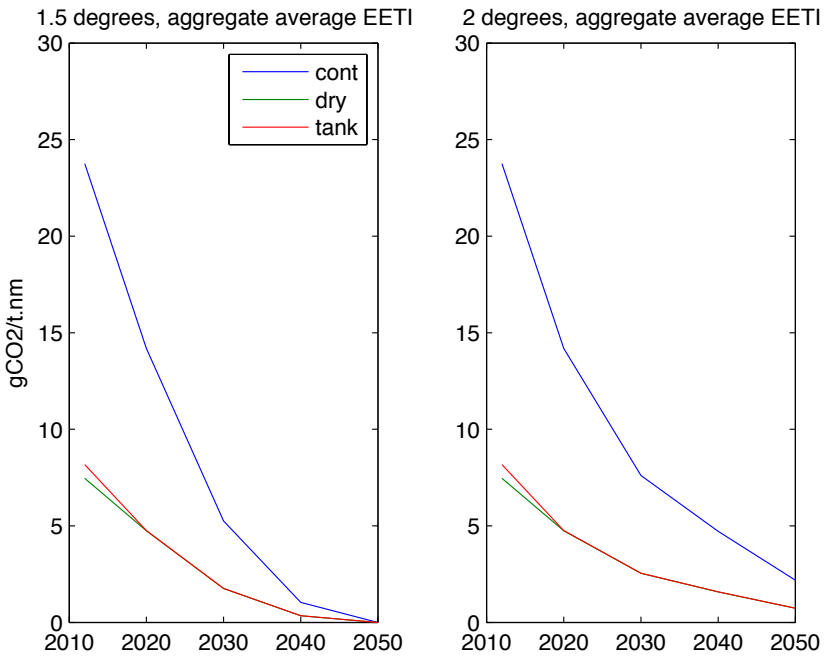

Figure 6: Required aggregate average EETI trajectories, Scenario C

4. CONCLUSIONS

Like all other sectors, international shipping will need to significantly curb its CO_2 emissions if the global target of avoiding a 2°C temperature rise is to remain viable. Some progress towards curbing CO_2 from this sector, but not in all instances driven by climate policy, has recently emerged. For instance, there is evidence of some decoupling of emissions growth from demand growth as CO_2 emissions have reduced at the same time as growth in trade during the period 2007-12 (Smith et al. 2014). There has been the recent implementation of new regulations on energy efficiency and emissions intensity: EEDI and SEEMP. Finally, there have also been some rapid technological developments where new ship designs have exceeded their requirements under the EEDI. Nevertheless, 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). Moreover, 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).

This analysis outlines how the latest IPCC reports provide a clear constraint on the total CO_2 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 in the next few years, and then undergo a rapid and sustained decline. The 2°C target requires at least a halving of international shipping's CO_2 emissions on 2012 levels by 2050, and to have zero carbon emissions by 2080.

The scale of the challenge and the clarifying benefits of setting a constraint on CO_2 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 CO_2 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 CO_2 intensity, there are further uncertainties around how operational CO_2 intensity influences (e.g. speed and utilization) might evolve over time. Three scenarios are considered showing 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 between 75% and 33% of 2012 levels. 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 CO_2 intensity improvement is highly dependent on the evolution of operational CO_2 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, under a 2°C target in all scenarios, 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 CO_2 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.

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Appendix A–decomposing EEOI into technical and operational parameters

The operational CO_2 intensity is a combination of both the technical CO_2 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 CO_2 intensity (in this instance represented as an Energy Efficiency Technical Indicator (EETI)), operating speed and utilisation can be approximated using Equation 1.

$$EEOI = EETI.\frac{(V_{op}/V_{ref})^2}{\eta_u} \qquad \text{Equation 1}$$

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 CO_2 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

Appendix B–description of evolution of operational CO2 intensity influences 2012-2050