Pathways to low-carbon international transport: 
a comparison of shipping and aviation
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Abstract
Each year, the chance of avoiding ‘dangerous climate change' diminishes as CO2 emissions rise. While some sectors have started to implement measures aimed at curbing greenhouse gases, meaningful policies focused upon cutting emissions from international shipping and aviation remain inadequate. At a global scale, a similar policy approach to tackling these ‘international’ emissions has been taken, yet the strengths and weaknesses of these industries with regard to both mitigation and their globalised nature have important distinctions. For instance, the shipping sector has a plethora of low-carbon technology options available to it: sails, kites, Flettner rotors, a range of alternative fuels etc, while aviation does not. On the other hand, in aviation, engine efficiency already pushes the boundaries of engineering, while in shipping, the debate is currently less focused on efficiency and more concerned with the sulphur content of heavy fuel oil. Perhaps a more contentious difference, is that shipping serves global trade, while the majority of flights are taken for leisure. This work builds upon existing scenario analysis and technology roadmapping to demonstrate what 2°C means for mitigating greenhouse gases in international aviation and shipping. The paper discusses the implications of using technology, operational changes and demand management to deliver cuts commensurate with 2°C, highlighting where there are similarities and where there are differences between these two important sectors. Finally, the paper concludes that technology plays an important role in pathways towards low-carbon shipping, whereas in aviation, demand management is the key. However, the complexity of the shipping system is, and will likely continue to be, a significant barrier to implementation.

Keywords: Shipping; climate change; aviation; cumulative emissions; step-change

1. Introduction

The starting point of this paper is an assumption that the global community continues with its ambition to limit global temperature rises to 2°C above pre-industrial levels. Interpreting what a temperature goal means in terms of emissions budgets, targets and policies necessitates three key choices:

a) The probability of exceeding the 2°C threshold which thereafter provides a constraining global carbon budget (Anderson and Bows 2007; Meinshausen et al. 2009)

b) Consideration of when global emissions can reach a peak

c) A decision regarding how nations or sectors are apportioned responsibility for meeting the target.

Articulating 2°C in terms of emissions budgets (and ultimately emission pathways) is a first scientifically robust step towards quantifying the scale of the climate challenge for nations, sectors and regions. A valid criticism of stage 3, could, however, be that dictating a budget and/or emissions pathway to a sector does not allow for a more market-based approach to emission reductions, whereby sectors more able to reduce emissions than others, could participate in an emissions trading scheme, such as the one instigated by the EU, thereby removing a need to explicitly apportion responsibility. On the other hand, failure of the EU’s Emissions Trading Scheme (ETS) to date to provide an adequate mechanism for absolute emissions reductions, coupled with the cap being at odds with a reasonable probability of avoiding 2°C as well as the opportunity for leakage, leave it on the sidelines in
terms of meaningful mitigation policy commensurate with 2°C. Given this inadequacy at present, this paper presents a preliminary quantification of the scale of emission reductions required of both the international aviation and shipping sectors, assuming their emissions reduce in line with global average pathways commensurate with 2°C. The paper goes on to discuss the viability of meeting 2°C emission reductions when considering the specific natures of both the international aviation and shipping industries.

2. Methodology

The three choices outlined in the introduction provide the quantitative framing for delivering 40-year emission pathways for the international aviation and shipping sectors. These pathways bind the scale of the challenge from which emerges the discussion regarding the ability of either the aviation or shipping sectors to mitigate emissions to the appropriate level.

2.1 Probability of exceeding 2°C

The climate system is complex, which means that whilst overarching trends and directions of travel commensurate with future temperature outcomes are robustly described by climate modelling communities, there is a range of cumulative budgets commensurate with a global temperature rise of 2°C above pre-industrial levels. To put it another way, a particular cumulative carbon budget is associated with a range of probabilities of exceeding 2°C. Differences within studies depend on how sensitive the global climate model being used is to a change in greenhouse gas concentration (climate sensitivity), the starting conditions of any particular run of the climate model, differences between climate model parameterisations and so on. The most comprehensive scientific analysis of carbon budgets and associated probabilities is the work of Meinshausen et al., (Meinshausen et al. 2009). Informed by this work, here the constraining carbon budget chosen is 1578 GtCO₂ over the 21st century which has an approximate 50% chance of exceeding 2°C.

2.2 When global emissions reach a peak

Whilst Integrated Assessment Modelling studies (IAMs) provide suites of scenarios commensurate with avoiding a 2°C rise, the process of a ‘reality check’ on peak dates appears absent on a number of levels. In general the policymaking process is informed by highly optimistic, sometimes entirely unrealistic (past) peaking dates (Hansen et al. 2008; Nordhaus 2010; Raskin et al. 2010) and relatively low growth to the peak year (Baer and Mastrandrea 2006; Stern et al. 2006; Ranger et al. 2010; King et al. 2011). This leaves policymakers with the impression that climate change is a problem of long-term targets rather than short-term budgets. If instead, a more realistic appraisal of how soon emissions can reach a peak is taken, a quite different quantitative analysis emerges. This is illustrated in analysis by Anderson and Bows (2008) where they show how emission peaking dates of 2015, 2020 and 2025 influence emission pathways for the same carbon budget.

To remain within the budget, the later the emissions peak, the more rapid annual emission reductions are needed post-peak date, increasing by a few percent for each 5 year interval. Thus, the earlier the peak date is assumed, the more palatable the outcome in terms of mitigation policy. However, palatability should not be the aim of scientific analysis, therefore here it is assumed that a realistic emissions peak date is determined by a combination of constraining the analysis within the 2°C budget, whilst paying significant attention to the momentum of current energy systems around the world. Furthermore, non-OECD, or ‘non-Annex 1’ nations are now the larger share of annual global greenhouse gas emissions (under both territorial and consumption-based accounting approaches (Bows and Barrett 2010)), meaning that trends in non-Annex 1, rather than Annex 1 nations emissions largely dictate the global growth trend. Peak dates are therefore taken from Anderson and
Bows (2011), where consideration is given specifically to the rate and direction of travel within non-Annex 1 countries. Although within that paper it was assumed viable emissions could reach a peak by 2015, given four years have now passed since this analysis was undertaken with emissions continuing to rise unabated (Friedlingstein et al. 2010), this is no longer considered realistic, therefore peak dates post 2015 are assumed.

2.3 Apportioning responsibility

For many years, stakeholders representative of both the international aviation and shipping sectors have argued that their emissions should not be apportioned to individual nations, but rather treated at a global scale, as if they themselves are sovereign nations (Bows et al. 2009; Gilbert and Bows 2012). This is in part a legacy of their treatment in the Kyoto Protocol which excluded emissions produced within international waters and airspace from national emission reduction targets. Whilst the authors have explored the issue of apportionment of both aviation and shipping emissions to nations (Wood et al. 2010; Gilbert and Bows 2012), here a global perspective more closely aligned with the industry preference is taken. Furthermore, rather than making an assumption that aviation and shipping will mitigate more or less than other sectors, it is assumed these sectors will take a path proportionally in line with what is necessary from the global average rate of mitigation appropriate for the chosen probability (a) and pathway as determined by (b). One argument in support of this approach is that the emission pathway is already so stringent, that for any sector to do less than the average, an arguably unreasonable pressure will be placed on others to compensate (Calverley 2012). It is beyond the scope of this paper to analyse which sectors could, if necessary, deliver greater emission reductions than the average. However, the feasibility of international aviation and shipping being able to maintain such stringent mitigation pathways is discussed in section 4.

2.4 Building pathways to low carbon futures

Road-mapping and scenario development are used by a wide range of stakeholders to scope potential future emissions across sectors. Some analyses produce forecasts for levels of emissions underpinned by GDP growth projections, such as those that build upon the Special Report on Emission Scenarios (Eyring et al. 2005; Bows 2010). Others take the starting point as where in the future emissions ‘need’ to be to avoid particular levels of climate change. These are backcasting scenarios (for instance, Bows et al. 2009). Backcasting draws attention to the pathways to change, identifying milestones that can be technological, operational or related to changing patterns and levels of demand. Here, a range of ‘futures’ analyses published in the academic literature are compared with the 2°C emission pathways derived. Furthermore, participatory exercises that include industry and policy stakeholders add significant value to an understanding of the scope for change. Workshops and interviews hosted by the author and colleagues are drawn upon for particular insights into potential trends and new developments.

3. Analysis

3.2 Global trends vs trends in aviation and shipping

The resulting emission pathways at a global scale taken from Anderson and Bows (2011) are indexed to 1990 and translated for aviation and shipping using 1990 as a starting date (Figure 1). Data for the aviation and shipping emissions are taken from the International Energy Agency (IEA), and between 1990 and 2010, the global data is based on the Carbon Dioxide Information Analysis Centre (CDIAC). IEA estimates for the combined CO₂ from both aviation and shipping, in red, show a growth of approximately 78% by 2010 from
1990, while total global emissions grew by 42%. In other words, aviation and shipping emissions combined grew much more rapidly between 1990 and 2010 than the globally averaged empirical data across all sectors for the same period. Given it is cumulative emissions that dictate the impact on the climate, it is already clear from Figure 1 that the combined international aviation and shipping industry emissions have had a considerably higher climate impact between 1990 and 2010 than if they had followed the average growth for all sectors. Arguably then a more equitable analysis would remove the cumulative emissions already attributable to aviation and shipping from the remaining 2010-2050 budget, further limiting the emissions space for these sectors. However, such a quantitative assessment is beyond the scope of this early analysis.

![Figure 1: International aviation and shipping emissions indexed to 1990 based on two 2°C pathways taken from Anderson and Bows (2011) and Anderson and Bows (2012). Also, combined international aviation and shipping emission estimates for 1990 to 2010 based on IEA data.](image)

2.5 Comparison with existing scenarios/projections

Using the data presented in Figure 1, a series of metrics emerge that provide constraints or targets for the aviation and shipping industries commensurate with a 50:50 chance of avoiding 2°C. Firstly, by 2030, emissions from these sectors need to be back to 1990 levels or higher by less than 25%. Secondly, emissions in 2050 must be 71 to 76% lower than 1990. Thirdly, a rate of emission reduction from around 2025 onwards needs to be between 6 and 8% per year. It also illustrates that emissions need to reach a peak by between 2015 or 2020, depending on the ongoing growth rate. Making a comparison with both existing emission trends and analyses projecting future trends serves to illustrate the huge disjuncture between what is necessary and what is expected. For instance, within IMO projections (Anderson and Bows, 2012) emissions are projected to increase by 180% to 305% relative to 1990 levels by 2050 (102 to 193% if 2000 is the baseline). Similarly for aviation, a review by Gundmundsson and Anger, (2012) shows that aviation emissions are assumed to rise by as much as 515% between 2000 and 2050, although more commonly figures around 220% are projected, compared with a 75% to 78% reduction required to remain commensurate with the 2°C scenarios in Figure 1.

No doubt the reaction of the international aviation and shipping industries would be that such reductions are not feasible, and would result in economic damage. However, taking an ecological economics framing, where it is physical planetary limits that are of paramount importance, with society and economy residing within those boundaries, it is useful to explore how, from a technical, operational and demand perspective, opportunities that
could be exploited to achieve this significant task. This paper does not conduct an exhaustive review but draws on existing studies to consider the gap between the necessary mitigation and ‘expected’ development.

4. Options for decarbonising aviation

The decarbonisation focus across all sectors tends to consider in the first instance, new technologies and alternative fuels, and the aviation sector is no exception. Across all sectors, this narrow constraint has arguably led to an assumption that as long as the technologies are deployed by 2050, the 2°C target can be achieved, and existing behaviours, practices and even operational systems can be maintained. Unless technologies are ready to deliver change immediately, taking an often long-term technology-focused lens ignores the science underpinning the 2°C target – that it is curbing cumulative emissions over time as opposed to cutting emissions significantly in the long-term that matters. The absence of meaningful policies addressing all aspects of a system in order to deliver emission cuts in the short-to-medium-term is most acutely apparent in the levels of emissions and growth rates being maintained in the aviation sector. The combination of incremental technology change, marginal adjustments to operations, coupled with very high rates of growth in terms of passenger-km, combine to maintain global CO₂ growth rates in international aviation typically around 3% to 6% per annum. Even in nations where the aviation industry is considered to be ‘mature’, for instance the USA, CO₂ emissions from international flights to and from the USA have been rising at around 2.5% since 1990, an increase of 64% in twenty years. The outlook for CO₂ growth (or decline) is considered below by describing available technology, operational and demand-side measures that could feasibly mitigate rising levels of CO₂.

4.1 Technology

Fuel costs have become increasingly important for the aviation sector, given the very energy-intensive nature of flight. Even when kerosene could be purchased at a much lower price, minimising fuel consumption through improving fuel efficiency has always been a concern. This has resulted in engineers developing extremely efficient high bypass, high pressure-ratio gas turbine engines that now dominate the fleet (Bows et al. 2008). Unsurprisingly, opportunities for making ongoing improvements to these engines diminish over time, and reside typically at 1% per year in terms of fuel combusted per passenger-km. To achieve significantly more than this, a fundamental shift in aero-engine design penetrating rapidly across the fleet is needed. Open-rotor engines offer some scope for moderate level improvements, but they have limited application given higher noise levels than a turbo-fan. Thus at present, engine developments are likely to continue to offer marginal CO₂ improvements.

Airframe design, including the materials used to construct the aircraft, is another area where improvements can deliver better fuel efficiency. The latest aircraft increasingly incorporate composite materials, with newer designs from both Boeing and Airbus replacing 50% of the aluminium with composite materials. These materials are around 20% lighter, thereby improving fuel efficiency. This technological development is playing an important role, however, it is only as these newer aircraft replace the existing fleet, assuming the older aircraft are retired, that the real benefits can be gained. Combining the latest technological developments, fuel efficiency is still only improving at a marginal 1 to 2% per year. One of the reasons is that a large proportion of the improvements cannot be retrofitted to an existing aircraft. Therefore improvements gained are hampered by the time it takes for new technology to penetrate the global fleet.

The same problem arises when considering alternative fuels or completely different airframe designs, for instance the Blended Wing Body aircraft or hydrogen propulsion systems. For hydrogen to radically decarbonise aviation, designs need to be modified to incorporate a much larger fuel tank, given hydrogen’s lower energy density. It would take decades before new and radically different designs penetrated the fleet significantly, given the conservative nature of the industry as well as the large amount of infrastructure world-wide requiring modification to service a hydrogen-fuelled or Blended Wing Body fleet.
To curb the rate of growth in CO\textsubscript{2} in the short-term through technology change points instead to something that can be retrofitted to the existing fleet in some way. Producing kerosene-grade fuel from biomass is one such option. Research into this is ongoing, but will need to overcome a range of broader concerns including the needs of other industries for the same biomass, as well as issues over its sustainable production given concerns over potential displacement much-needed food production (Bows-Larkin and Anderson 2013). Taking all of the options and issues together, over the coming decades technology improvements offer only ongoing marginal change to fuel consumption and carbon intensity. Thus other options require consideration to fit with the reductions presented in Figure 1.

4.2 Operational change

For many years discussions surround the emissions savings to be made through improving congestion around airspace for instance to avoid circling and delays when taxiing, have been taking place. Within the EU, having ‘One European Sky’ in terms of airspace control was being put forward as an idea around the start of the millennium, with projected improvements of 4 to 6% in terms of fuel burnt per passenger km suggested. However, as of 2013, while some progress has been made between the UK and Ireland to establish joint airspace control, such a mode of operation is still under discussion while skies over the EU become increasingly busy. Moreover, even if the operational improvements could deliver this scale of change, a one-off saving would be made that could not be repeated. Finally, and possibly most significantly, improvements made in terms of congestion that facilitate a greater rate of take-off and landing serve to support aviation growth. So, whilst temporarily reducing the fuel consumed per passenger-km, these improvements will very rapidly likely to be offset by growth in numbers of flights and passengers. It is here that arguments around airport expansion, for instance around Heathrow, revolve. On the one hand, additional runways would ease congestion, and lead to less fuel burnt during circling. On the other, they facilitate a greater use of the airport over time. Only if the rates of growth are lower than the improvements to be gained through both operational change and technology improvement, will CO\textsubscript{2} growth be curbed, and ultimately reduce.

4.3 Demand management

Given the evidence suggesting that reductions in CO\textsubscript{2} through technological and operational change are likely to be up to 2% per annum, subsequently off-set by growth rates, it is useful to consider what typical growth rates are ‘allowable’ given the constraints of the 2°C target. For the C+4 scenario presented in Figure 1, global international aviation growth rates in terms of passenger-km would need to reduce to zero from 2020, falling to around a 4% reduction per annum by 2025. For the C+5 scenario, zero growth is needed by 2025, then reductions of around 6% per year by 2033. Whilst constraining aviation demand is not a popular policy measure, a gradual reduction from the typical 3% per annum growth seen since 1990 to zero by 2020 to 2025 is more physically feasible than expecting large-scale role out of emerging technologies. New research would be needed to consider where passenger-km could be cut in absolute terms through provision of, for instance, long-distance, low-carbon rail travel, so as to compensate for regions where flying per capita as well as absolute emissions are still extremely low (such as China), while at the same time growth rates are high.

5. Options for decarbonising shipping

Taking now the shipping sector in contrast, this section explores the opportunities in terms of technology, operations and issues of demand relevant for decarbonising shipping at the same rate as that for aviation. However, it is worth noting that both sectors make arguments for why they play such a pivotal role in economic
growth that they should be, to some extent, protected from making stringent cuts to their emissions. Yet these two industries are vastly different. One is largely driven by leisure travel and passengers, while the other by trade and freight. One stakeholder suggested that grounding all of the aircraft tomorrow will cause some disgruntlement, while preventing shipping and trade would leave supermarket shelves empty within days. This suggests that demand management is even less politically appealing within shipping than aviation, but are there other reasons for why demand-side intervention may play an important role in shipping mitigation, as discussed in section 5.3.

5.1 Technology

Fuel efficiency has not been such a significant driver within shipping as in aviation, and in fact, the shipping sector uses oil products that are at the bottom of the fuel hierarchy – heavy fuel oil. This is for a number of reasons. Firstly, the energy required to move a tonne of goods by ship is considerably lower than the equivalent energy required for flight, therefore monetary savings gained by improving engines and ship designs are less pronounced. Secondly, the many different actors within the shipping system means that the ship operator or charterer may not own the fuel, therefore incentivising fuel-saving measures is diluted through the system’s players. This is not to say that the engines within ships are not extremely efficient however, but rather that the fuel cost driver is weaker. As a result, a wide range of incremental technologies, many of which could be retrofitted to existing ships, are still yet to be widely exploited globally. These include micro-bubbles to reduce friction around the hull, counter rotating propellers to capture energy lost in the wake or waste heat recovery systems, although these are currently not an option for retrofit.

With a range of technologies offering incremental improvements, there are also technologies that could, if combined with improved operational systems, deliver more significant change. Exploiting wind propulsion for shipping may at first sight appear a step backwards, yet innovative technological designs have emerged and have the potential to offer fuel savings as high as 50% depending on ship type, route and speed (Traut et al. 2013) as well as reducing the need for using heavy fuel oil for auxiliary power; these include Flettner Rotors, kites and fixed or rigid sails. Flettner Rotors harness the Magnus effect for propulsion and the technology was first proven in 1924. Retrofitting Flettner Rotors to existing vessels larger than 10,000 dwt is considered feasible although the use of deck space for different ship types is a key consideration. Kites can attach to the bow of the vessel and controlled from deck to operate at high altitudes to maximise wind speeds. Sails have demonstrable impact on a bulk carrier run by the Modern Merchant Sailing Vessel (MMSC), with other examples including sail-assisted cargo ships (Gilbert et al. 2014). Many such technologies also have the advantage that they can be retrofit onto vessels in the short-term.

Aside from the renewable technology options, technologies to improve energy storage and make use of fuel cells are also feasible. Electric drive using lithium-ion batteries is being considered, and storage technologies include super-conductors and flywheels. The electric motor would likely favour ferries and cruise vessels given their frequent load changes. Fuel cells such as solid oxide fuel cells are appropriate for application in marine propulsion, while Proton Exchange Membrane devices are more suitable for auxiliary engines.

If fuel for propulsion is the focus, here too there are a range of options that are feasible, some of which are already being exploited. Liquefied natural gas (LNG) offers CO₂ emissions savings in the short-term, although given it is still a fossil fuel, a wholesale switch to LNG will not be sufficient to deliver the scale of necessary decarbonisation. Biogas, biofuels and micro-algae are also feasible, but suffer the same sustainability concerns as they do for other sectors such as aviation. Nuclear ships are also worth considering and already used in the military. Public perceptions of such a technology are crucial but in terms of engineering, and if appropriate markets are identified, nuclear ships could offer significant cuts to CO₂ from trade.

Opportunities for decarbonising the shipping sector through technological intervention are manifold, but similar to decarbonising stationery sources, it is likely that there will be a portfolio of solutions that depend on the particular end-use and need. Moreover, some of these technologies, particularly renewable interventions, have
more scope for decarbonising a voyage if the ship speed is reduced, so what is the scope for changing operations in shipping?

5.2 Operations

Following the global economic downturn of 2008, many ship operators sought measures to reduce fuel costs. One of the most significant of these was slow-steaming. As fuel consumption has a cubed relationship to ship speed, slow-steaming offers very significant opportunities for reducing CO$_2$—with cuts of up to 80% per voyage achievable (estimated using the ASK-ships model using data from Buhang et al., (2009)). Depending on ship market, ships can often wait for many days outside ports, either due to congestion or waiting for the price of bunker fuel to change. It is therefore not always the case that the arrival time of a ship is crucial. Slow-steaming could however, have an impact on flows of trade, which at present rely heavily on ‘just-in-time’ policies (particularly perishable goods). Moreover, having slower ships serving trade could lead to an incentive to build more ships, in order that freight flows are not reduced. Nevertheless, slow-steaming, and designing ships to be optimised for slower speeds in future reduces the overall propulsive power required, and provides a greater incentive to incorporate renewable technologies that could further cut CO$_2$.

5.3 Demand management

With a much more optimistic outlook in terms of technology and operations than in the aviation sector, coupled with the ‘need’ for trade, the issue of demand management could appear to have less relevance. However, despite the very significant potential for decarbonisation in shipping, there are few incentives for mitigating emissions significantly, and only very niche markets at present for some of the more significant interventions. Unlike the aviation sector, most ship building occurs in nations without climate change objectives, and a great number of manufacturers, operators, charterers, owners and other interested stakeholders that serves to maintain the status quo. Influencing change in this sector is therefore extremely challenging, and arguably most effectively encouraged at port-state level (Gilbert and Bows 2012; Doudnikoff 2013). Nevertheless, with the appropriate incentives, regions of an EU scale, could lead the way in supporting change.

One other key aspect of the demand side to consider is how demand for goods may alter over time, and how this may impact on the shipping system. UK and EU policy on climate change has led to measures that aim to decarbonise energy systems. At present, 50% of tonnes imported and exported to and from the UK related to fossil fuels, coal, oil and gas. Depending on the decarbonisation path chosen, shifts in the consumption of fossil fuels, and the potential growth in biomass/biofuels, will significantly alter the shipping landscape (Mander et al. 2012). This is one area where there will likely be significant change, but others include the strain on global resources of ores and minerals, as well as the climate impacts on the production of key food commodities worldwide. This issue of resource use and the limits to it could feasibly raise the debate around levels and types of consumption, which again could impact on the demand for shipped goods. So, whilst there is little appetite to manage demand in shipping at present, there are certainly good reasons to think that demand will likely shift significantly in future.

6. Discussion and conclusion

International shipping and aviation are frequently coupled in the same breath when discussing climate change mitigation. Like all other sectors, aviation and shipping face a significant challenge in achieving decarbonisation at a level commensurate with 2°C. What makes them distinct to some extent, is that as ‘international’ sectors, their treatment in terms of global climate governance differs from others, and it is also the case that both sectors
have emissions growing above the global average rate, with little sign of a reduction. However, when the scale of the climate challenge presents itself, and options for decarbonisation considered in more depth, clear differences between these two sectors become apparent. In short, the shipping sector has a range of technological and operational options that, in many cases, can be retrofitted to cut emissions in the short- to medium-term. Aviation does not. The irony is that if it were the case that options existed for the aviation sector, it has a much less complicated institutional set-up, with a smaller number of markets and actors that would potentially help to facilitate change. Moreover, the significant portion of aviation emissions attributable to domestic flying (particularly for places with large land-masses), could lead to knock-on learning for mitigating emissions from international flights. Yet, given the technologies are not forthcoming for aviation, demand-management must be seriously considered, or alternatively, the case made for why the aviation sector takes priority over others for the use of biofuels. Whilst the shipping sector does many options on the horizon, its complex nature presents a significant barrier to rapid change. Nevertheless, external drivers such as the decarbonisation of the energy sector in EU nations, may well serve to drive change from the demand side.

International shipping and aviation are similar in CO₂ growth rates and decarbonisation efforts to date, but differ significantly in terms of future decarbonisation options. If urgent and rapid decarbonisation is required, a pragmatic approach would be to influence, incentivise or set standards around technology options for shipping and constrain demand for aviation. Combining slow-steaming with a range of renewable technologies such as Flettner Rotors, and encouraging a widespread programme of retrofit through port-state influence, could start to see a significant shift in the emissions associated with shipping, at least at an EU scale. The issue of paramount importance for decarbonising the shipping sector is how to influence this complex confluence of varied markets and ship types. For aviation, the message is simple, nations where per-capita flying is high, and growth rates maintained, have no option but to consider constraining growth in the short-term, until fuel efficiency improvements can off-set rises in passenger-km. Even with 2% per year improvements in fuel efficiency, international aviation growth rates must be constrained to zero by 2020 to 2025.

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