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Aviation and Climate Change – the continuing challenge

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Abstract

The latest scientific framing of climate change emphasises the importance of limiting cumulative emissions and the need to urgently cut CO_2. International agreements on avoiding a 2°C global temperature rise make clear the scale of CO_2 reductions required across all sectors. Set against a context of urgent mitigation, the outlook for aviation's emissions is one of continued growth. Limited opportunities to further improve fuel efficiency, slow uptake of new innovations, coupled with anticipated rises in demand across continents collectively present a huge challenge to aviation in cutting emissions. Whilst difficulties in decarbonising aviation are recognised by industry and policymakers alike, the gap between what's necessary to avoid 2°C and aviation's CO_2 projections has profound implications. Biofuel is one of the few innovations that could play a significant role in closing the gap, but with low anticipated penetration before 2020 its contribution would have little impact over the desired timeframe. If the aviation sector does not urgently address rising emissions, there is an increasing risk that investment in new aircraft and infrastructure could lead to stranded assets. This leaves it facing an uncomfortable reality. Either the sector acts urgently on climate change and curtails rising demand, or it will be failing to take responsibility for a considerable and growing portion of climate change impacts.

1. INTRODUCTION TO AVIATION & CLIMATE CHANGE POLICY

International aviation's contribution to global CO_2 emissions has come under scrutiny since the early 2000s. Prior to that, mitigation focused on the CO_2 released within national borders, given the exclusion of international aviation from the Kyoto Protocol's national targets. Although a considerable body of research has since interrogated aviation's CO_2 contribution, discussing cuts in the CO_2 produced by flights remains controversial and unpopular for many reasons voiced by industrial stakeholders and the general public (Budd and Ryley 2013). So while there are arguments for treating aviation on a level playing field with other sectors and implementing stringent mitigation policies aimed at tackling CO_2 (Bows 2010; Budd and Ryley 2013; Peeters Williams and Haan 2009) this is not a universal view.

Aviation's economic importance is regularly cited as a key reason to avoid stringent CO_2 mitigation (Wood, Bows and Anderson 2012). Another argument can be attached to its role in connecting nations at different stages of development. The sector's growth rate, coupled with few options for reducing carbon emissions per passenger-km (gC/RPK), drives up aviation's CO_2 emissions. Increasing mobility and high rates of economic growth in industrialising nations influences demand. These industrialising nations do not in general foresee CO_2 targets for their other sectors before 2020, and therefore few direct drivers towards cutting emissions. Globalisation supports arguments for treating international aviation and shipping differently to sectors that do not operate within international airspace or waters, with policies that can allow for high growth rates in some countries. Whilst this may have some traction, it only holds within a climate change context if globally averaged growth rates do not jeopardise the international commitment to remain within the 2°C global temperature target.

There has been widespread political consensus enshrined in various Accords, Agreements and Declarations that '2°C' represents the threshold between acceptable and dangerous climate change. Controlling emissions of greenhouse gases across sectors is critical if the carbon budgets underpinning this commitment are not to be exceeded. Yet the sizeable and growing emissions from international aviation (and shipping) were exempt from national targets enshrined in the Kyoto Protocol. Domestic aviation emissions were included, but as the USA, with its dominant share of the CO_2 from all internal flights when the Protocol was adopted (63% in 1997, IEA 2014), did not ratify it, the already weak constraints on aviation emissions were watered down still further.

In a bid to include international aviation's CO_2 within global climate commitments, the Kyoto Protocol tasked the UN's specialist agency, the International Civil Aviation Organisation (ICAO), with responsibility for mitigating CO_2 from aviation. However, slow progress during the 1990s led the EU Commission, having voiced its frustration, to independently develop proposals for including aviation within its Emissions Trading Scheme (ETS) and impose a carbon price on the industry (Bows 2010). So by the Kyoto Protocol's final official year, the EU had included aviation within its ETS despite concerns coming from the industry regarding elevated costs, and doubt surrounding the resulting impact on CO_2 emissions.

Yet even before the policy began operating, the EU suspended the inclusion of non-EU nations' flights in response to progress by ICAO towards establishing a global trading scheme, and in light of strong opposition to the scheme from some countries including the US (Bows-Larkin, 2014). This suspension remains in place until 2016, when the ICAO mechanism is scheduled to be agreed. Other policy mechanisms promoted through ICAO include a voluntary global annual 2% fleet fuel efficiency improvement up to 2050, with a 50% reduction in net emissions from 2005 levels and an aim for "carbon neutral growth" from 2020 (ICAO 2013a).

By October 2013, development of ICAO's global trading scheme was underway, with derived revenue hypothecated to alleviate the impact of aircraft engine emissions, and developing low-carbon alternative fuels. However, with no mechanism agreed before 2016, and then further time needed for implementation, emissions are expected to rise unabated at least until then. Meanwhile there have been developments within the USA. In 2014, the US Supreme Court upheld the United States Environmental Protection Agency's (EPA) power to regulate CO_2 under the Clean Air Act. Now the EPA is considering if aviation has an impact on human health, releasing an information sheet with potential plans to impose a CO_2 standard on aircraft.

With cuts of at least 80% from 2010 levels by 2050 necessary across all sectors for a reasonable chance of avoiding 2°C (Bows-Larkin 2014), the current mitigation strategy for international aviation assumes other sectors will proportionally cut CO_2 by more than aviation. Bows (2010) assessed aviation's climate impact, comparing scenarios for future aviation CO_2 with carbon budgets associated with 2°C. The paper presented the mitigation challenges for aviation and highlighted the importance of understanding the broader climate change context when assessing aviation's climate impact. This article updates Bows (2010) by comparing updated aviation scenarios with more recently published 2°C carbon budgets. It discusses insights in the context of emerging developments, to reassess if that paper's conclusion – that "without a large reduction in growth rate or significant penetration of alternative fuel by 2050, aviation's projected CO_2 emissions will be incompatible with the 2°C target", remains sound.

2. TRENDS IN THE AVIATION SECTOR'S CO_2 EMISSIONS

The civil aviation industry's CO_2 emissions have grown almost consistently year-on-year since its emergence. The regional profile of aviation-related CO_2 emissions shifts as economies develop. Nevertheless, growth remains high even in industrialised economies for two principal reasons: its role in connecting nations especially at different stages of industrialisation; the shift from occasional use to frequent flying, facilitated by falling air fares (Randles and Mander, 2009b). Its high growth rate poses great challenges for climate change mitigation. Unlike almost all other sectors, technologies available for deployment in the time window consistent with avoiding 2°C are few and far between. Thus long lifetimes of aircraft coupled with the longevity of design specifications risk leaving the sector locked into conventional technologies for many decades. Even as fuel efficiency improves, Figure 1 illustrates that high demand growth leads to rising CO_2 emissions.

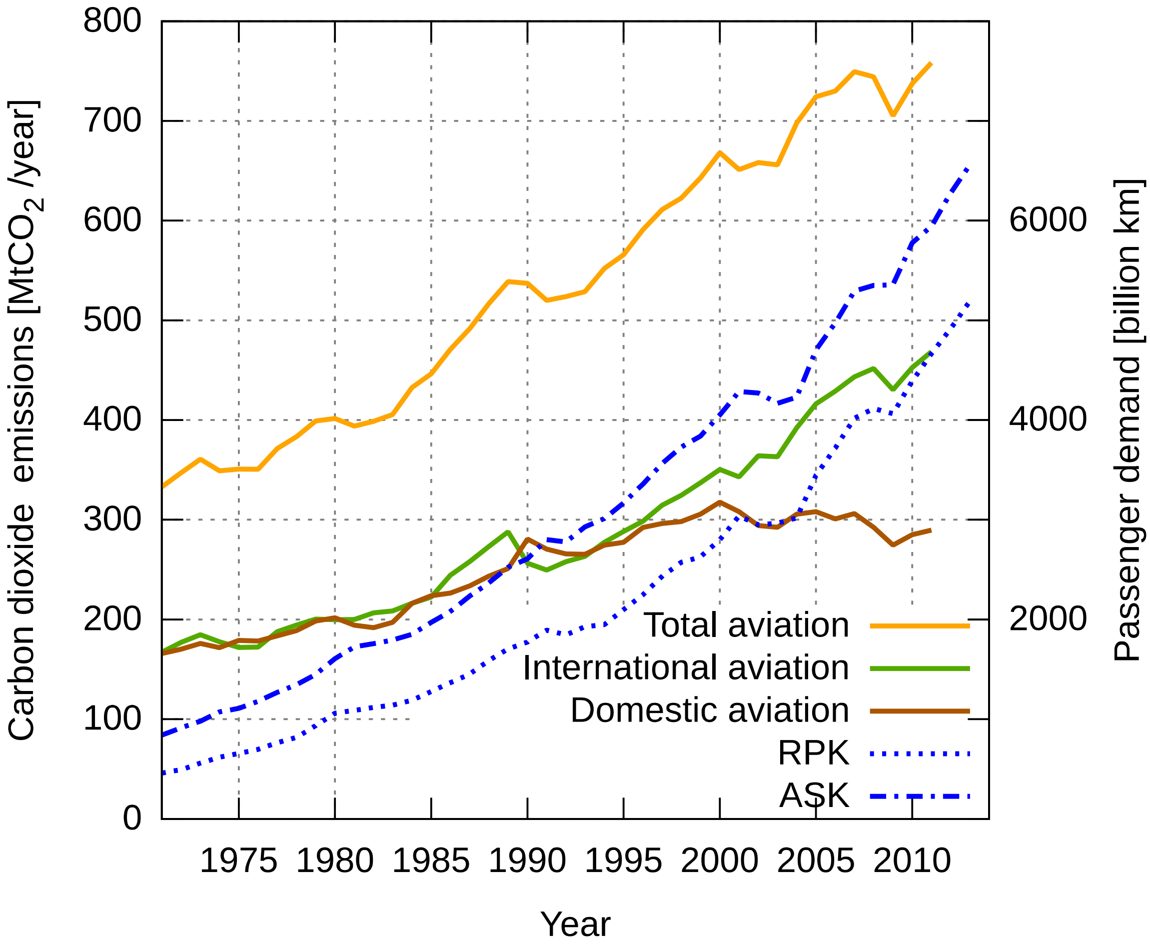

Figure 1: Trends in aviation indicators. Revenue Passenger-km (RPK), Available Seat-km (ASK) and the CO_2 emissions for aviation for international and domestic flights. CO_2 data from the International Energy Agency (IEA, 2014); 1971-2006 RPK and ASK data, Owen (2008); 2007-2013 data calculated from 'Passenger growth rpk' and 'Passenger load factor achieved' (IATA 2014).

Regions currently experiencing rapid growth in aviation CO_2 differ depending on whether domestic or international travel is interrogated. Obviously nations with large land-masses have much greater propensity for domestic air travel than smaller nations, where international flights dominate. Nevertheless, the construct of 'domestic' and 'international' aviation is important in a climate policy context, as international flights are not subject to national mitigation strategies.

2.1 Trends in domestic aviation CO_2 emissions

CO_2 emissions from aviation have historically been dominated by those from domestic flights in the USA – and they remain a major share (50% of the CO_2 from all domestic flights globally in 2011, IEA 2014; Figure 2). However the picture is in flux, with CO_2 from domestic flights in the USA recently declining. China has just one fifth of the domestic aviation CO_2 of the USA, but is growing rapidly at rates close to 10% per year, (IEA 2014). Other parts of Asia are experiencing high growth rates too – 6% per year since 1990, but it is the vast geographical area of some regions that will inevitably lead to high levels of CO_2 from domestic flights.

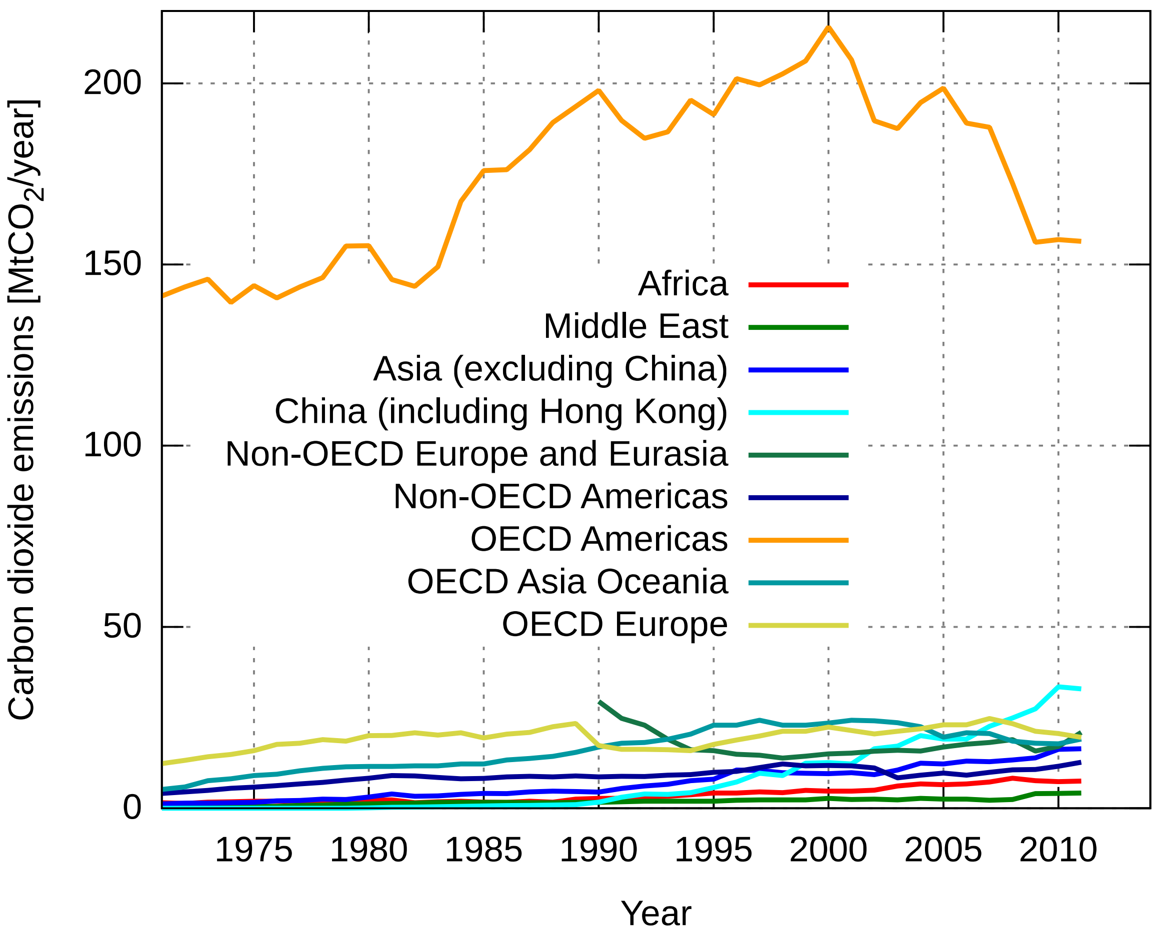

Figure 2: Regional split of CO_2 emissions from domestic flights. Data: IEA Statistics (IEA 2014).

2.2 Trends in international aviation CO_2 emissions

The international aviation CO_2 emissions are captured in Figure 3. OECD Europe dominates in recent years, with OECD Americas and then Asia (excluding China) following. In terms of growth, China has experienced the highest annual rates at 8% on average since 1990 with the rest of Asia at 5%. OECD Europe continues to grow at 3% annually and even in North America where aviation is considered to be a mature industry, average growth has been 2% per year since 1990 – including both the events of September 11th 2001 and the recent global economic downturn.

2.3 Future aviation CO_2 emissions

In recent years, aviation's CO_2 profile shifted emphasis from domestic to international, driven primarily by a rise in international travel by EU citizens, as well as fall in demand for US domestic flying, particularly following the events of 11 September 2001 and recent recession. However, the emergence of China as a rapidly growing source of domestic aviation CO_2 suggests the balance could shift back again. Another driver of CO_2 will stem from rapid growth in international flying across all nations, influenced by connections with nations experiencing high levels of economic development. This new landscape raises questions. What might be the impact on innovation and climate policy of rapidly growing domestic aviation in China? Will the growing source of international flight CO_2 continue to fall outside of policy regimes aimed at other fossil-fuel consuming sectors? And finally, what drives passenger demand for flying in the first place?

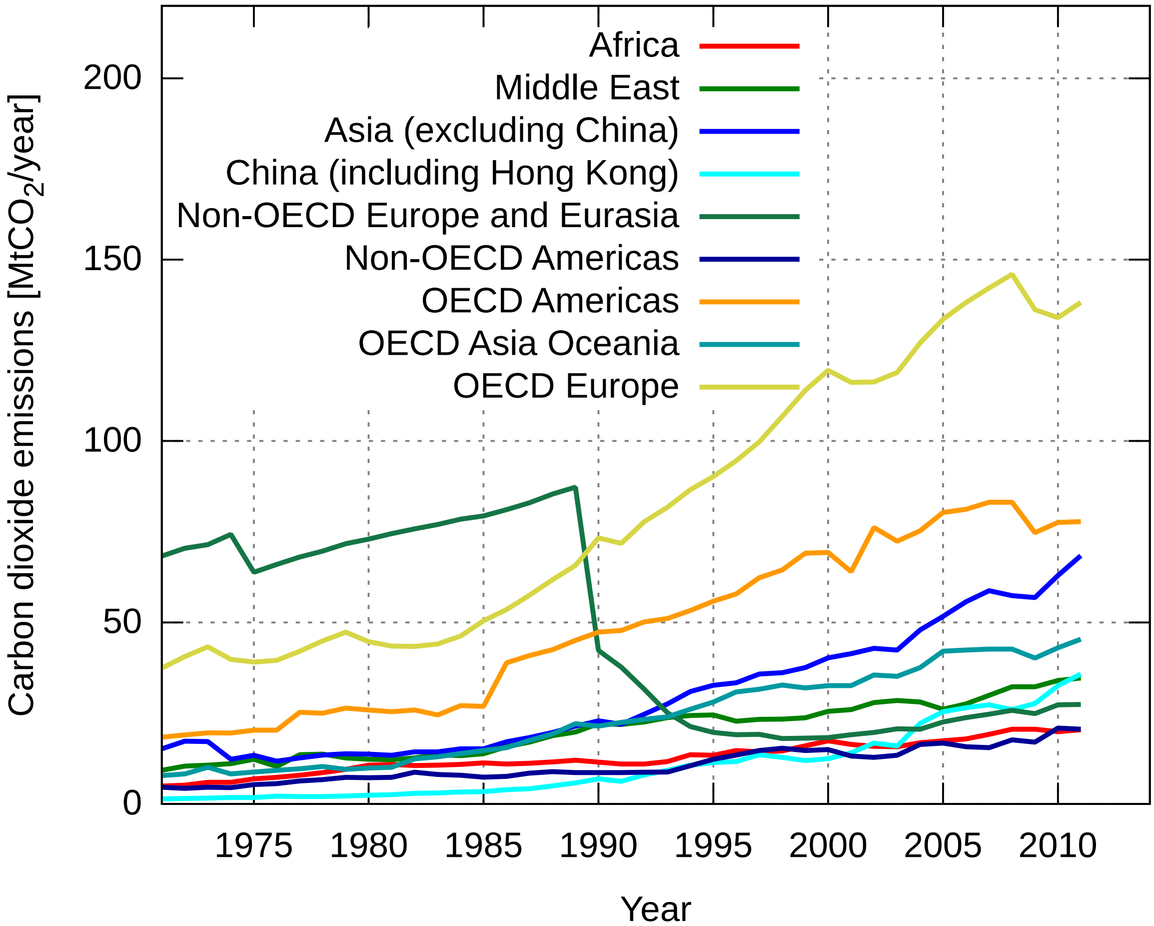

Figure 3: Regional split of CO_2 emissions from international flights. Data: IEA Statistics (IEA 2014).

3. DRIVERS OF DEMAND FOR AIR TRAVEL

To explore some of the drivers of demand for flying, it is worth considering what air travel is primarily used for. In summary, aviation accounts for approximately 10% of all transport (vehicle) km travelled and moves 35% by value of goods traded internationally (ATAG 2014). 53% of international travellers arrive at their non-domicile destination by air compared with 47% by other modes, 40% by road, 2% by rail and 5% by water (UNWTO 2014). 52% of flyers do so for leisure, 27% to visit friends and family, religious or health reasons while 14% fly for business (UNWTO 2014). Understanding the drivers of demand for air travel is a key piece of the jigsaw.

3.1 Growing demand around the world

Recently, passenger numbers have been on an upward trend following a decline around 2008/2009 (Figure 1), with monthly passenger kilometres for September 2014 in the region of 510 billion (IATA 2014). Emphasising the link between the state of economies and demand for aviation, as of September 2014, the International Air Transport Association (IATA) judged the outlook for aviation to be positive though inconsistent across the globe; faltering economic improvement in the EU contrasted with recovery in the US and on Asia Pacific routes (IATA 2014). Whilst year-on-year growth in passenger kilometres for September 2014 compared with September 2013 averaged 5.3% globally, there is significant regional variation. The Middle East is the only region where the *rate* of growth continues to increase due to its strong regional economy, with a fall in other regions related to economic slowdown and factors such as strikes and market volatility. Overall growth in demand is highest in emerging economies (IATA 2014). 40% of the international market is centred on Europe, followed by Asia Pacific with 25%. 41% of the domestic market is the US with China in second place at 23% (IATA 2014) and industry forecasts suggest China will become the largest domestic market within 10 years. In terms of flights per capita, in 2014 North Americans and Europeans are the most likely to fly, averaging, 1.6 and 1 flight per person per year respectively. In 2033, Airbus predicts flights per capita in China will reach 0.95 up from 0.25 in 2014, with India reaching 0.26 up from 0.06.

3.2 The role of socio-economic factors in shaping demand

Demand for aviation is shaped by factors that affect people's ability and desire to fly, and by supply side factors within the aviation industry such as capacity or infrastructure. To unpack demand for aviation, a variety of modelling approaches can be used including econometric modelling (for instance Department for Transport 2013). Aviation demand is often related to economic activity and air fares (see for example Department for Transport 2013), whilst other studies (see additional reading) include variables such as exchange rates, purchasing power overseas and perceived level of household wealth (O'Connell *et al.* 2013).

Studies show that most people do not fly because they want to fly per se, but because flying enables them to do things they wish to do. Thus to gain a more nuanced understanding of drivers for demand for aviation, much can be gained from complementing economic modelling studies with sociological and psychological research. Migration and changing household demographics are an important driver for aviation given that increasing globalisation means friends and family can be dispersed; this is reflected in figures that suggest around a quarter of flights are to visit friends and family, (Hibbert *et al.* 2013). Urry (2012) argues that society views high mobility lifestyles positively, whereby someone's standing is reflected by the places they have visited and mobility patterns; frequent flyer programmes and the marketing strategies of airlines also link status with mobile lifestyles.

Supply-side changes, namely the emergence of low-cost airlines specialising in domestic and short-haul routes has helped create new markets. For those who can afford it, the low cost of flights in the UK has contributed to raising the 'standard' of occasions such as a hen party or trip with friends (Randles and Mander 2009). Changing practices of celebrating, holidaying and visiting friends and family abroad represents an upward ratchet on the number of flights taken per year. Growth is facilitated further by interacting aspects such as easy internet booking and online check-in, speeding up the purchasing and delivery of service (Randles and Mander 2010).

Finally, aviation is an area of consumption where there is a gap between attitudes towards the environment, and behaviour. Climate awareness does not lead to people not flying. Instead, a lack of alternatives and the habitual nature of flying lead people away from sustainable choices, in contrast to some other areas of decision making (Hares Dickinson and Wilkes 2010). Frew and Winter (2009) highlight how concerns about the time, family commitments and a desire to see the world can outweigh consideration of the environmental cost of travel (Frew and Winter 2009). The extent to which flying practices in many wealthy parts of the world transfers to emerging markets, particularly those now served by their own 'low cost' airlines such as AirAsia, remains to be seen.

3.3 Future demand for air travel

Future demand for aviation is likely to be driven by an increasing middle class population, primarily in emerging economies, whose desire to travel is enabled by supply-side developments such as expanding infrastructure and deregulation of markets. Although national models of deregulation and liberalisation differ, a competitive aviation industry is seen as crucial to reduce costs and improve service, both domestically and as carriers look to compete internationally (O'Connell *et al*. 2013). Airport expansion has supported the enlargement of domestic aviation in emerging economies as shown by the development of airports in smaller cities to support regional commuter travel in China for example. In emerging markets, the development of regional airports can drive growth in international air travel as 'Hub and spoke' configurations can be used to attract international travellers (O'Connell *et al*. 2013). With the support that national governments are giving to the aviation industry within emerging economies, the building blocks that enable industry growth predictions to come to fruition are being put in place (O'Connell *et al*. 2013).

4. TECHNICAL OPTIONS FOR CUTTING CO_2 IN AVIATION

Redrawing attention to climate change, how can rising demand be met if absolute CO_2 emissions from the sector are to be reduced? The obvious place to seek solutions resides in innovative technologies and operational practices available to deliver change. However, previous work highlights the very incremental nature of much of what is available (Bows-Larkin 2014).

4.1 Improving aircraft efficiency

Most technological improvements to reduce fuel burn address structural weight, aerodynamics or engine efficiency. Decreasing the structural weight of the aircraft and reducing drag to increase the lift-to-drag ratio, both cut propulsive power and thereby reduce fuel consumption. Increasing aircraft engine fuel efficiency also lowers the CO_2 intensity of flight. Incremental change across all three leads to efficiency improvements between different aircraft generations. With fuel making up a significant share of the running costs for airlines, unsurprisingly, fuel efficiency has been a major research and development goal for many decades. Advances in engine design, optimised wing and body shapes, and material science contributed to new generations of aircraft that consume less fuel per Available Seat Kilometre (ASK) than their predecessors. Coupled with increased utilisation factors, this has led to significant fuel efficiency improvements (Figure 4). While there is still potential for future generations of aircraft to be more fuel efficient that today's, the best fit regression line in Figure 4 illustrates how aviation faces diminishing returns as technology matures. Aircraft are highly optimised and must meet rigorous safety standards as well as respond to other constraints on noise and local pollution, meaning that fundamental design changes are difficult and costly to achieve. So, whilst there is certainly promise over the longer-term for more advanced, more fuel efficient and lower-carbon intensity aircraft, the current challenge is that such changes are highly unlikely within a timeframe compatible with climate change targets. Alternative fuels have therefore become attractive, but they come with un-resolved issues, such as their full life-cycle CO_2 impacts and wider sustainability concerns.

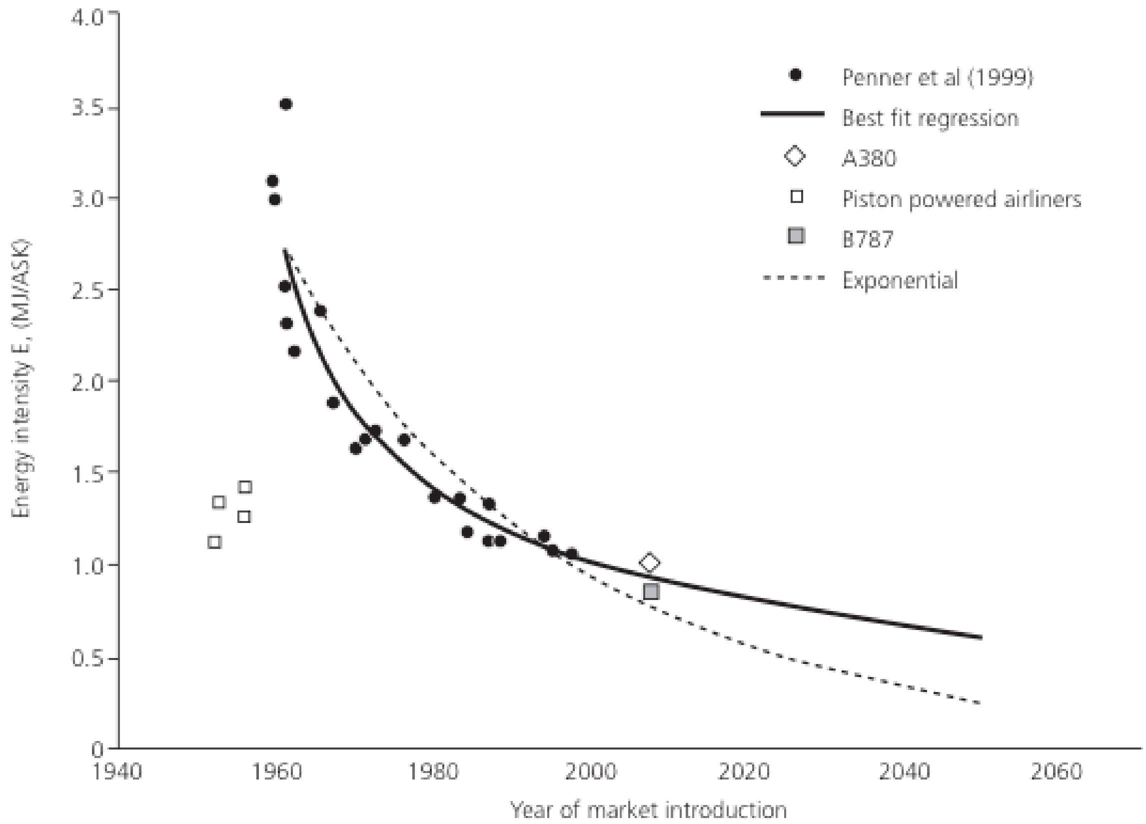

Figure 4: Trends in energy intensity in the aviation sector since the emergence of the civil aviation industry projected out to 2050. Sourced from p.294 Peeters Williams and Haan (2009) with thanks to the authors.

4.2 Beyond efficiency

To reduce CO_2 emissions beyond annual incremental change, alternative fuels will have to come into play. The only ones considered realistic in the near term are biofuels or other synthetic fuels. The fuel itself would not be fundamentally different from kerosene, but rather than of fossil origin, produced from biomass or from another low-CO_2 feedstock. There is a burgeoning range of initiatives in this direction but emission savings delivered depend on feedstocks and production methods. Some of the CO_2 from biofuels may be negated by the CO_2 taken up by the plants grown to produce them. However the CO_2 benefits of producing jet fuel from, for example, jatropha, depend on the current vegetation or land use it displaces and for many areas this may be negative. Furthermore, large-scale production raises wider sustainability issues as feedstock production displaces food production.

In general, life-cycle assessments yield a wide range of potential emission savings or otherwise, depending on the specific production process (Hileman and Stratton 2014). On-going research seeks to resolve issues around biofuels with different properties from standard jet fuel and create production routes for second and third generations biofuels, such as jet fuel from algae. Replacing plants with alternative mechanisms of using solar (or another source of) energy to combine water and CO_2 into hydrocarbons could open a production route for a wholly synthetic jet fuel. Going beyond hydrocarbons, hydrogen and battery-electric powered propulsion have been considered, but are far from offering a realistic alternative within an appropriate timescale (Hileman and Stratton 2014).

5. FUTURE OF AVIATION & CLIMATE CHANGE

With rising demand and a limit to the technical options available for cutting CO_2 emissions it is essential to place aviation in the context of broader climate change policy objectives.

5.1 Global climate policies and scenarios

In 2014 the Intergovernmental Panel on Climate Change (IPCC) released its latest synthesis of the global climate change challenge. One of the new areas brought to the fore is the importance of cumulative greenhouse gas emissions in dictating the future global mean temperature increase. Global cumulative carbon budgets constrain emission pathways for all sectors, varying depending on the desired climate outcome. In short, from 2015 onwards there remains around 1100-1400GtCO_2 for a 50:50 ('reasonable') chance of avoiding the 2°C target threshold between 'acceptable' or 'dangerous' climate change (IPCC 2014). Naturally there are various paths that can be followed to remain within this constrained budget, in addition to a range of contributions by sectors that release CO_2. However when the numbers are scrutinized it becomes clear how very challenging this global budget is for any sector. For a reasonable chance of avoiding 2°C, all sectors will need significant and absolute cuts in CO_2 in the coming decades. More realistically, energy systems in wealthier countries, including the transportation sector, need to eliminate CO_2 emissions by very soon after 2050 (Anderson and Bows 2011).

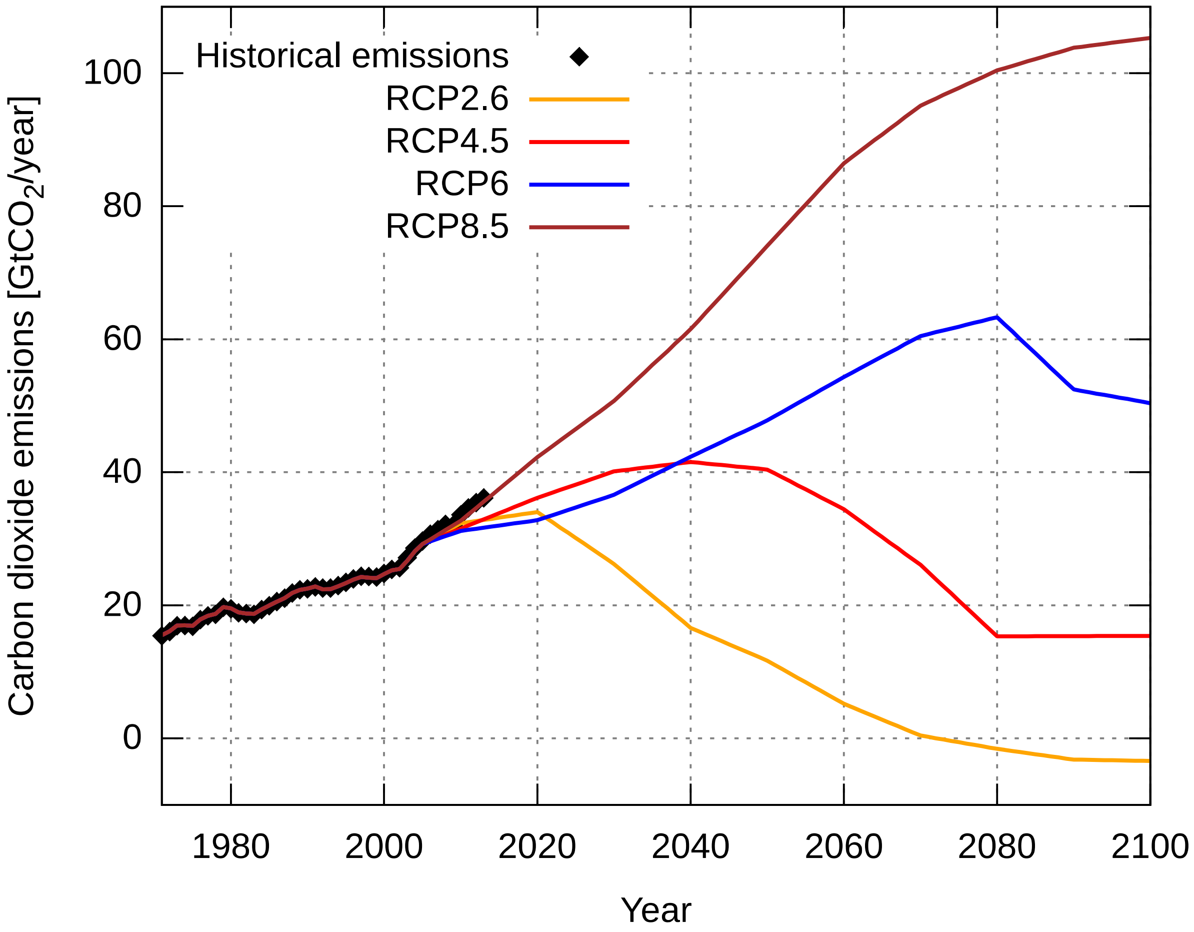

Figure 5: Representative Concentration Pathways (RCPs) and historical emissions of fossil fuel and industrial CO_2. Historical data taken from the Global Carbon Project (Le Quéré *et al*. 2014) and RCPs taken from (Meinshausen *et al.* 2010; Moss *et al.* 2010). The number after each 'RCP' stands for the amount of future radiative forcing.

A more conservative take is presented by the Representative Concentration Pathways (RCP) (Figure 5). The most constrained scenario (RCP2.6) has the best chance within this suite of avoiding 2°C. Considering this pathway in detail however, it becomes clear that global CO_2 emissions have in reality risen faster than this '2°C' scenario. Furthermore, in the vast majority of energy scenarios assumed to 'fit' with this emissions pathway, 'negative emissions' play a significant part in maintaining low temperature rises. In other words, much confidence is placed in the large-scale and rapid deployment of biomass energy sources coupled with carbon capture and storage and/or carbon sinks through land-use change. Without this, the budgets become much more challenging, with all sectors needing to radically adjust expected levels of future emissions to avoid 2°C.

5.2 New scenarios and forecasts of CO_2 from aviation

To formulate a response to the challenge posed by climate change, it is necessary to look out into the future. There are many outlooks, forecasts and scenarios in the literature, some of which are making predictions, while others are formulated to explore potential future change.

'What-if' type scenarios have gained prominence in climate and energy policy, given the nature of end-point climate objectives, such as the 2°C temperature target. They are also used in various forms within sectors, and aviation is no exception. It is therefore instructive to revisit existing scenarios and consider them in the context of recent trends in CO_2 emissions from aviation. Figure 1 presents data on emissions from domestic and international aviation, which followed a very similar growth trajectory until the mid-90s. Since then, growth in domestic and international CO_2 combined has for the most part been due to increases in emissions from international aviation, but as discussed, there is a large potential for domestic aviation within China, and other emerging economies with large land-masses, to change this.

Taking a future perspective, Figure 6 presents examples from two generations of aviation emission scenarios alongside the historical CO_2 trajectory from Figure 1. Ten scenarios from the literature (Newton and Falk 1997; Penner *et al.* 1999; Vedantham and Oppenheimer 1994) including a new suite from ICAO (ICAO 2013b) are scaled to 1992. Out of the older ten scenarios, the three highest and one lowest-growth scenarios were considered at the time to be implausible. Indeed over the time period since 1992, many of the older scenarios projected emissions significantly higher than has materialised. This is in part due to the events of September 11th 2001 and recent global economic downturn. It is unsurprising that scenarios influenced by industry perspectives tend to be optimistic about expected demand or lack incentives to develop low-growth scenarios.

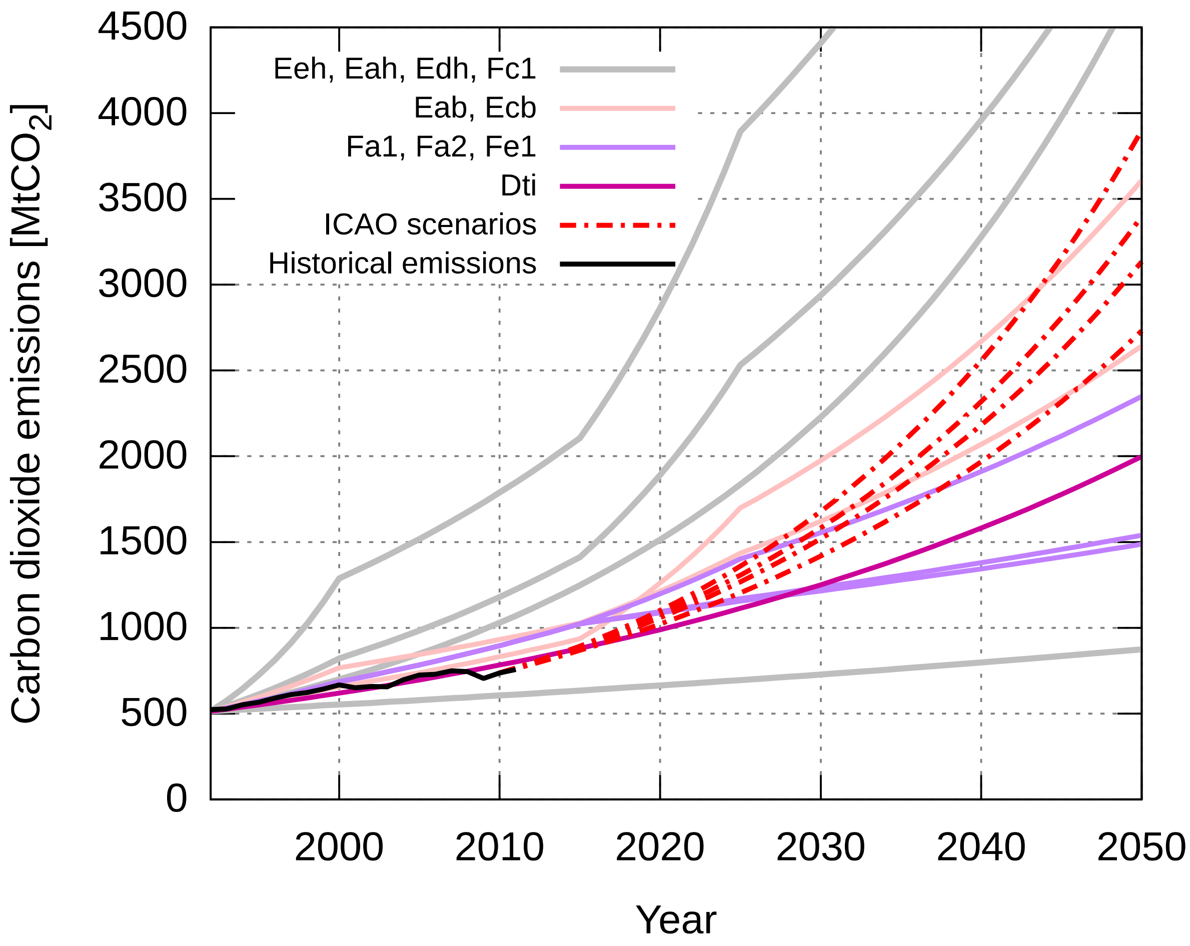

Figure 6: Future aviation emission scenarios. The ICAO scenarios (ICAO 2013b) are underpinned by one rising demand scenario. Data for the other scenarios is from (Newton and Falk 1997; Penner *et al*. 1999; Vedantham and Oppenheimer 1994). The Environmental Defence Fund (EDF) scenarios (designated E**) have 'high' growth assumptions (designated E*h) and base growth assumptions (designated E*b). The Forecasting and Economic Analysis Sub-group (FESG) scenarios are designated F**, with variations in growth differentiated by 'a', 'c' or 'e'.

The set of scenarios considered in ICAO's 2013 Environmental Report (ICAO 2013b) in Figure 6 all use the same mid-range demand scenario with different assumptions about efficiency gains from technology and operations, resulting in a range of future CO_2 levels. There has not been sufficient analysis yet to include the potential CO_2 savings from alternative fuels out to 2050, although some assessment is made up to 2020 in ICAO's 2013 report, where it is estimated that approximately 3% of fuel consumed could be from 'sustainable alternative' sources. ICAO scenarios' average annual passenger demand growth of 4.9% is similar to the rate expected over the time period 2014 to 2033 by Boeing in its Market Outlook 2014. Of course this and other assumptions can be called into question. Nevertheless, comparing the outlook with results from climate science allows for conclusions to be drawn.

The 'ICAO' scenarios in Figure 6 all show a growing trajectory for aviation's CO_2 emissions. This is in stark contrast to ICAO's target of "carbon-neutral" growth from 2020 onwards

(ICAO 2013b) and subsequent cutting of emissions in half by 2050. This demonstrates that either a step change in technological or operational advancements is required, or the CO_2 reductions will need to be met by other sectors through emission trading. Whilst reasonable to assume some sectors will cut emissions more rapidly than others and at different times over the coming decades, the aviation sector will too need to cut its CO_2 significantly during that timeframe, given the constraining 2°C CO_2 budget. Furthermore, as emissions trading has so far failed to deliver emission reductions in line with 2°C, and such a scheme is unlikely to be operational for aviation before 2020, pinning hope on trading to deliver on mitigation objectives is arguably misplaced (Bows-Larkin 2014).

5.3 Contrasting the outlook for aviation with avoiding 2°C

The most recent future aviation scenarios taken from ICAO are contrasted with the global CO_2 scenarios compatible with avoiding 2°C (Figure 7). In addition to the RCP2.6 scenario, which is already out of kilter with the current global CO_2 trajectory, (global CO_2 emissions are closer to a much higher climate impact scenario since 2000, RCP8.5 and Figure 5) three global scenarios from (Anderson and Bows 2011) are overlaid to emphasise the scale of CO_2 reduction necessary across all sectors. These additional global pathways from Anderson and Bows (2011) are commensurate with a reasonable chance of avoiding 2°C, but take into account a more explicit recognition of momentum within energy systems (for more information on their derivation see Anderson and Bows 2011). All trajectories are indexed to 1992=1 to highlight how projected aviation emissions, under all scenarios, are at odds with the cross-sector 2°C pathway. Comparing Figures 5 and 6, it is also notable that the absolute level of aviation emissions in 2050 is ~30-40% of total global CO_2 under the RCP2.6. However, these ICAO scenarios do not have a storyline consistent with RCP2.6 where strong mitigation is assumed across all sectors.

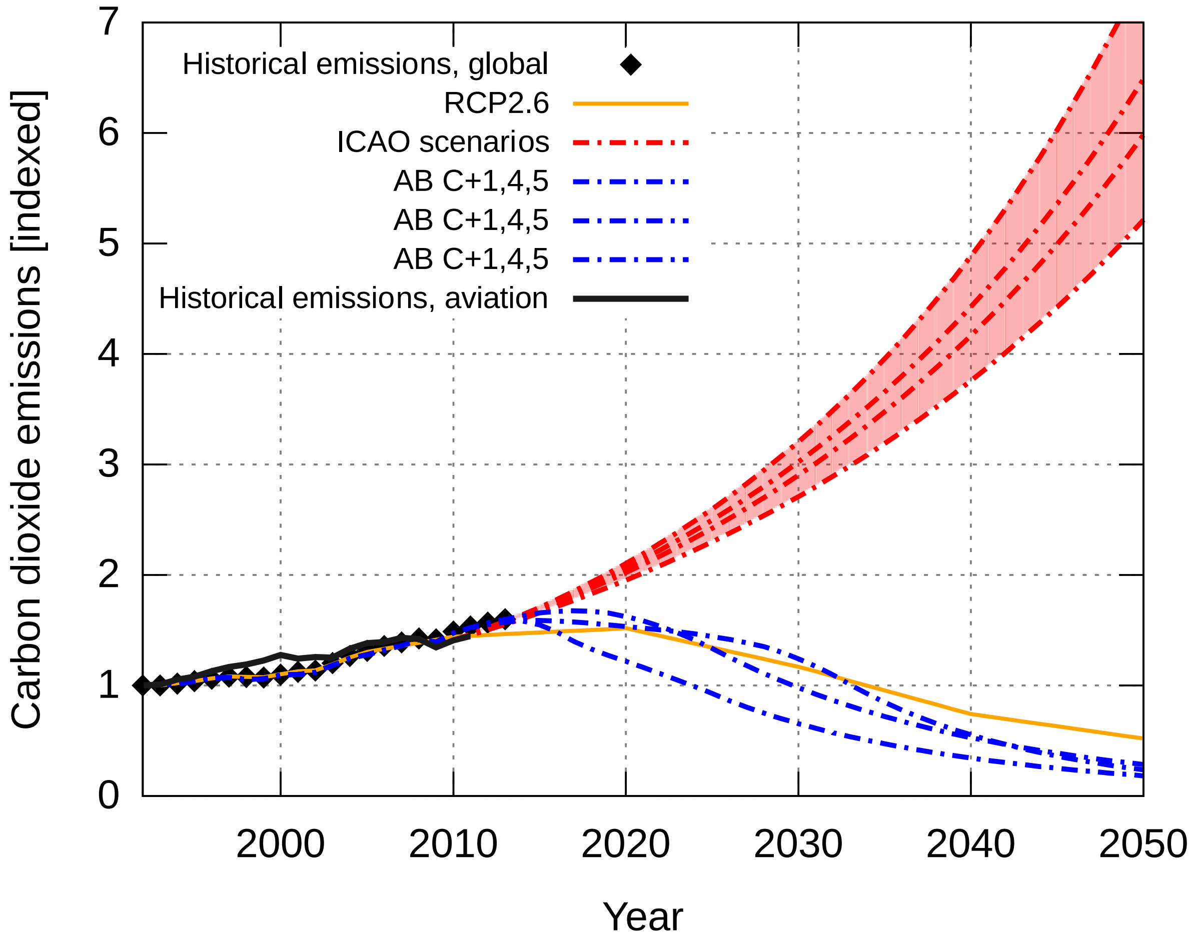

Figure 7: Four global CO_2 scenarios for all sectors (RCP2.6, AB C+1 C+4 and C+5) and a suite of ICAO aviation CO_2 scenarios from ICAO 2013b (red). All scenarios are indexed to 1992=1.

Looking back to Bows (2010), where this gap was previously illustrated, it is clear that its conclusion "…without a large reduction in growth rate or significant penetration of alternative fuel by 2050, aviation projected CO_2 emissions will be incompatible with the 2°C target" remains, albeit within a now more constrained 2°C budget. There are few indications that any new technical or operational advances will start to make CO_2 cuts in real terms and across the world's aircraft fleet that would negate the rise in CO_2 due to growth in activity. Many parts of the world continue to see very high rates of growth which, without a significant acceleration towards overcoming technical and sustainability barriers around the use of biofuels for aircraft propulsion, will only serve to maintain the high and growing levels of CO_2 from air transport. While other sectors will too struggle to decarbonise in line with 2°C, it will be necessary for all sectors to play their part. Unpopular as it is, and as long as emissions trading remains inconsistent with the 2°C goal, there is a clear role in aviation for demand management.

CONCLUSION

The headline conclusion is clear and unequivocal; the aviation industry's current projections of the sector's growth are incompatible with the international community's commitment to avoiding the 2°C characterisation of dangerous climate change. Even a highly optimistic uptake of the most promising technologies for reducing the CO_2 intensity of flying cannot deliver the rapid and deep rates of mitigation illustrated in Figure 7 to comply with the IPCC's carbon budgets for a reasonable to likely chance of staying below 2°C. This stark conclusion holds even with the heroic assumption that other sectors may be able to shoulder some additional mitigation effort to compensate for the aviation sector mitigating less than its counterparts. Ultimately, however construed, the maths forthcoming from the IPCC's 2°C carbon budget, mandates that the demand for aviation will need to be constrained if the global community is not to renege on its 2°C commitments.

In contrast to such demand management, market analysis highlights how many nations have rapidly growing aviation sectors, and that if China's domestic aviation broadly follows that of the US, it will emerge as a strong driver of future CO_2 emissions. As it stands, there is a clear and significant risk that current expansion plans will extend the flying practices of today's frequent fliers both *within* wealthier nations, and *to* and *within* emerging economies. Such a prospect plays against the international community's commitments to mitigate emissions in line with 2°C.

Juxtaposing existing scenarios and forecasts of aviation-related CO_2 emissions with global CO_2 scenarios for 2°C illustrates a huge and widening gap between the two. At present there are few signs that the sector, like most sectors, takes the 2°C target and carbon budget framing of climate change seriously. While the industry has set out proposals for carbon neutral growth from 2020 and to reduce the sector's emissions by 50% by 2050, there is little evidence to demonstrate that this is at all feasible, even with emissions trading. Furthermore, the 50% reduction falls short of cuts commensurate with a reasonable chance of avoiding 2°C, leaving the industry relying on other sectors curbing their emissions even more. It will be an enormous challenge for *all* sectors to reduce their own emissions in line with a reasonable to likely chance of avoiding 2°C, so any assumption that sufficient sectors will be in a position to make much greater cuts than aviation misunderstands the scale of the mitigation challenge. Consequently, if the aviation sector is to reduce emissions in line with the 2°C commitment, it must acknowledge the veracity of the climate challenge, and put in place the internal mechanisms to manage its own demand in accord with the necessary levels of mitigation.

With the publication of the IPCC's fifth report and explicit inclusion of carbon budgets associated with the 2°C threshold, a clear framework within which to consider emissions from aviation now exists. Against this backdrop, the United Nations Environment Programme's Gap report (UNEP 2014) draws attention to the high-level and widespread failure of the global community to constrain emissions in line with 2°C. This failure is exemplified by ICAO predicting a significant and on-going rise in emissions, whilst at the same time continuing to emphasise the industry's commitment to a sustainable future.

Aviation, as is the case for virtually all sectors, has thus far failed to develop a scientifically credible emission pathway towards a 2°C future. If such a pathway is not forthcoming in the next few years, it will be evident that the sector either rejects the international community's 2°C commitment, or has judged itself too important to make its full contribution, relying instead on the untenable assumption that other sectors will compensate. The aviation industry cannot be isolated from the dialogue on climate change, and as a mature industry it is incumbent on it to be clear as to its position on 2°C, carbon budgets and the mitigation challenge.

References

Anderson K and Bows A. Beyond 'dangerous' climate change: emission scenarios for a new world. *Philosophical Transactions A.* 2011; **369**(1934): 20-44.

ATAG. Aviation Benefits Beyond Borders, Air Transport Action Group, Report by Oxford Economics, http://aviationbenefits.org/media/26786/ATAG__AviationBenefits2014_FULL_LowRes.pdf2014.

Bows A. Aviation and climate change: confronting the challenge. *The Aeronautical Journal.* 2010; **114**(1158): 459-468.

Bows-Larkin A. All adrift: aviation shipping and climate change policy. *Climate Policy.* 2014: 1-22. doi: 10.1080/14693062.2014.965125

Budd L and Ryley T. An international dimension: aviation. In *Transport and sustainability,* Ison S and Shaw J (eds). Emerald, 2013; 39-64.

Department for Transport. UK Aviation Forecasts. London. 2013.

Frew E and Winter C. Tourist Response to Climate Change: Regional and Metropolitan Diversity. *Tourism Review International.* 2009; **13**(4): 237-246.

Hares A, Dickinson J and Wilkes K. Climate change and the air travel decisions of UK tourists. *Journal of Transport Geography.* 2010; **18**(3): 466-473.

Hibbert JF, Dickinson JE, Gössling S and Curtin S. Identity and tourism mobility: an exploration of the attitude–behaviour gap. *Journal of Sustainable Tourism.* 2013; **21**(7): 999-1016.

Hileman JI and Stratton RW. Alternative jet fuel feasibility. *Transport Policy.* 2014; **34**(0): 52-62.

IATA. Air passenger markets: September 2014. http://www.iata.org/whatwedo/Documents/economics/passenger-analysis-sep-2014.pdf (2014).

ICAO. 2013a. Reducing Emissions from Aviation Through Carbon Neutral Growth From 2020, Position paper presented by the Global Aviation Industry, 38th ICAO Assembly, October 2013.

ICAO. 2013b. Environmental Report. Destination green: aviation and climate change, 2013. 23-25.

IEA. *CO_2 emissions from fuel combustion: detailed estimates*. International Energy Agency, 2014.

IPCC. Intergovernmental Panel on Climate Change Fifth Assessment, Synthesis Report, IPCC. 2014.

Le Quéré C, Moriarty R, Andrew RM, Peters GP, *et al*. Global carbon budget 2014. *Earth Syst. Sci. Data Discuss.* 2014; **7**(2): 521-610.

Meinshausen M, Smith S, Riahi K and van Vuuren D. Figure compilation: RCP final release, 2010.

Moss RH, Edmonds JA, Hibbard KA, Manning MR. *et al*. The next generation of scenarios for climate change research and assessment. *Nature.* 2010; **463**(7282): 747-756.

Newton PJ and Falk RS. *DTI Forecast of Fuel Consumption and Emissions from Civil Aircraft in 2050 Based on ANCAT/EC2 1992 Data*. London: The Stationery Office; 1997.

O'Connell JE, Krishnamurthy P, Warnock-Smith D, Lei Z. *et al*. An investigation into the core underlying problems of India's airlines. *Transport Policy.* 2013; **29**: 160-169.

Owen B. Fuel efficiency development and prediction main thematic area: climate change. *Omega MMU.* 2008.

Peeters PM, Williams V and Haan Ad. Technical and management reduction potentials. In *Climate change and aviation: issues challenges and solutions,* Upham PJ and Gossling S (eds). Earthscan, London, 2009; 293.

Penner JE, Lister DG, Griggs DJ, Dokken DJ. *et al*. Aviation and the global atmosphere; a special report of IPCC working groups I and III. Cambridge, Cambridge University Press, 1999.

Randles S and Mander S. Practice(s) and Ratchet(s): A Sociological Examination of Frequent Flying. In *Climate change and aviation: issues challenges and solutions.* Gossling S and Upham P (eds). London, Earthscan, 2009.

Randles S and Mander S. Mobility Markets and 'Hidden' Intermediation: Aviation and Frequent Flying. In *Shaping urban infrastructures intermediaries and the governance of socio-technical networks,* Guy SM, Medd W and Moss T (eds). Earthscan, 2010.

UNEP. *The Emissions Gap Report 2014: A UNEP Synthesis Report*. Washington D.C . USA, 2014.

UNWTO. UNWTO Tourism Highlights 2014 Edition. http://dtxtq4w60xqpw.cloudfront.net/sites/all/files/pdf/unwto_highlights14_en.pdf, 2014.

Urry J. Social networks mobile lives and social inequalities. *Journal of Transport Geography.* 2012; **21**(0): 24-30.

Vedantham A and Oppenheimer M. Aircraft Emissions and the Global Atmosphere. New York. 1994 Vol. 77.

Wood FR, Bows A and Anderson K. Policy Update: A one-way ticket to high carbon lock-in: the UK debate on aviation policy. *Carbon Management.* 2012; **3**(6): 537-540.

ADDITIONAL READING

Achten WMJ, Trabucco A, Maes WH, Verchot LV. *et al*. Global greenhouse gas implications of land conversion to biofuel crop cultivation in arid and semi-arid lands – Lessons learned from Jatropha. *Journal of Arid Environments.* 2013; **98**(0): 135-145.

Adams P, Bows-Larkin A, Gilbert P, Hammond J. *et al*. Understanding greenhouse gas balances of bioenergy systems. Supergen Bioenergy Hub. 2013.

Airbus. Flying on demand: global market forecast 2014-2033. http://www.airbus.com/company/market/forecast/?eID=dam_frontend_push&docID=40815 (2014).

Anger A and Köhler J. Including aviation emissions in the EU ETS: Much ado about nothing? A review. *Transport Policy.* 2010; **17**(1): 38-46.

Boeing. Current Market Outlook: 2014-2033. http://www.boeing.com/assets/pdf/commercial/cmo/pdf/Boeing_Current_Market_Outlook_2014.pdf (2014).

Bows A, Anderson K and Upham P. *Aviation and Climate Change: Lessons for European Policy*. London: Routlege Taylor & Francis 2008.

Dargay J and Hanley M. The determinants of demand for international air travel to and from the UK. WCTR Conference, Seoul, South Korea. 2001.

EPA. *U.S. Aircraft Greenhouse Gas Rulemaking Process*. http://www.epa.gov/otaq/documents/aviation/us-ghg-endangerment-ip-9-3-14.pdf; 2014.

European Commission. *Decision of the European Parliament and of the Council*. Strasbourg: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2012:0697:FIN:EN:PDF; 2012.

Furler P, Scheffe JR and Steinfeld A. Syngas production by simultaneous splitting of H_2O and CO_2 via ceria redox reactions in a high-temperature solar reactor. *Energy & Environmental Science.* 2012; **5**(3): 6098-6103.

Gossling S and Nilsson JH. Frequent flyer programmes and the reproduction of aeromobility. *Environment and Planning A.* 2010; **42**(1): 241-252.

Graham WR, Hall CA and Vera Morales M. The potential of future aircraft technology for noise and pollutant emissions reduction. *Transport Policy.* 2014; **34**(0): 36-51.

Graham, A. Demand for leisure air travel and limits to growth. *Journal of Air Transport Management*. 2000; **6**: 109-118.

Grosche T, Rothlauf F and Heinzl A. Gravity models for airline passenger volume estimation. Journal of Air Transport Management. 2007; **13**: 175-183.

Hamelinck C, Cuijpers M, Spoettle M and van den Bos A. Biofuels for aviation, Vol. BIENL13187. Ecofys. 2013.

IATA. IATA 2013 Report on Alternative Fuels, Montreal Geneva. 2013.

Lee DS, Fahey DW, Forster PM, Newton PJ, *et al*. Aviation and global climate change in the 21st century. *Atmospheric Environment.* 2009; **43**(22–23): 3520-3537.

Peters GP, Andrew RM, Boden T, Canadell JG. *et al.* The challenge to keep global warming below 2°C, *Nature Climate Change*. 2012; **3**: 4-6.

Randles S and Mander S. Aviation consumption and the climate change debate: "Are you going to tell me off for flying?".*Technology Analysis & Strategic Management.* 2009a; **21**(1): 93-113.

Renouard-Vallet G, Saballus M, Schmithals G, Schirmer J. *et al*. Improving the environmental impact of civil aircraft by fuel cell technology: concepts and technological progress. *Energy & Environmental Science.* 2010; **3**(10): 1458-1468.

Steiner H-J, Vratny P, Gologan C, Wieczorek K. *et al*. Optimum number of engines for transport aircraft employing electrically powered distributed propulsion. *CEAS Aeronautical Journal.* 2014; **5**(2): 157-170.

Subbaraman N. Airlines ahead on algae. *Nat Biotech.* 2010; **28**(12): 1230-1230.

UNFCCC. *Article 2*. United Nations Framework Convention on Climate Change: http://unfccc.int/resource/docs/convkp/conveng.pdf; 1992.