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Net zero and the role of the aviation industry

How flying less frequently and less far can buy time for decarbonization solutions

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Contents

Summary

- The aviation industry contributes around 1 per cent of UK GDP and provides additional unquantifiable benefits, including aiding the expansion of business investment and enabling people to visit family members who live abroad. However, there is a significant risk that by 2030 the global carbon budget – to retain a 67 per cent chance of averting more than 1.5°C of global warming – will be exhausted. The aviation sector remains extremely difficult to decarbonize, with the deployment of supply-side solutions likely to take decades.
- Near-term policies to manage demand within the aviation sector could play a role in buying time for the development of supply-side decarbonization solutions, such as advanced next generation aircraft and sustainable aviation fuels. While this approach may be politically challenging, the climate risks associated with surpassing 1.5°C – when tipping points may begin to kick in and lead to runaway climate change – make it vital to examine what level of demand management may be required, and what it may entail.
- The focus on demand management in the aviation sector is gaining traction. In December 2022, the European Commission gave France the green light to ban short-haul domestic flights between cities linked by train journeys of less than 2.5 hours. In the UK, the Climate Assembly has shown that the British public supports limits on flying, depending on how technological solutions progress.
- Demand-management policies and technological solutions can work in parallel, as supply-side technologies are commercialized and deployed, demand-management measures could be eased. In October 2022, the UK Committee on Climate Change noted in its progress update that it is considering ways of mitigating the risks of relying on supply-side solutions, ‘The Government’s plans for aviation focus on sustainable aviation fuel and zero/low-emission aircrafts. These technologies have potential, but there are significant risks in their delivery. In the near term, managing demand would have a much greater benefit for the climate.’
- The model developed for this paper explores the role of demand management following analysis of the main emissions abatement mechanisms of the UK government’s Jet Zero Strategy high-ambition scenario. The model covers all UK domestic and outbound international flights.

- According to this analysis, a prudent risk-minimization approach would be to reduce flying in terms of frequency and distances flown, over the remainder of the 2020s. Under this lower-risk scenario, UK demand in terms of passenger-kilometres flown in 2030 would need to be 36 per cent lower than in 2019 to stay within the sector's fair share of global carbon budgets, with demand returning to 2019 levels by 2050, once supply-side decarbonization has caught up.

- In the UK the top fifth of earners fly five times more often than the poorest fifth. It may be possible to achieve a 36 per cent reduction in demand by 2030 if a future demand-management policy shifted behaviour so that most people who currently take more than one return flight per year reduced that number by one return flight and took no more than four. This would leave the 77 per cent of the UK population who currently take no more than one return flight unaffected. This is a moderate level of behaviour change to put the aviation sector on a climate compatible trajectory.

- The impact of non-CO_2 effects – such as water vapour emitted at high altitudes as part of an aircraft's contrails – remains uncertain and poses a further threat to already limited carbon budgets. Even the most optimistic interpretation of this uncertainty indicates that if non-CO_2 effects were to be factored in, there would need to be significantly greater reductions in demand.

- If near-term action to reduce demand is delayed, but the UK aviation sector is still to stay within its fair share of global carbon budgets, demand in 2050 will need to be around one-quarter lower, relative to 2019. This scenario does not factor in non-CO_2 effects and embodies considerable additional risk. Namely, that a significant proportion of the dwindling carbon budget is used up over the next decade, leaving humanity to rely on uncertain future supply-side decarbonization and even greater demand management in the long term.

01 Introduction

Aviation remains one of the most difficult sectors to decarbonize. However, with accelerating risks of climate change, the UK public is supportive of demand-management options such as limits on flying.

The aviation sector has provided significant benefits to society: not only in terms of the expansion of global trade but also in boosting people's happiness as holidays to diverse geographies have become more affordable and accessible. The sector has also enabled people to seek work or visit family in different countries. However, the high-emitting countries of the G20 that have most benefitted from aviation have failed to deploy low-cost, low-carbon technologies with sufficient speed across all sectors of the economy, resulting in accelerating risks of climate change and threats to the quality of life for all.

Climate scientists fear that runaway climate change could occur if global temperatures increase by more than 2°C. Current global warming sits at around 1.2°C above pre-industrial levels,[1] CO_2 and other greenhouse gas (GHG) emissions continue to remain stubbornly high, and the COVID-19 pandemic and associated lockdowns have had little impact on long-term emission reductions.

The historical lack of decarbonization action, combined with the political disdain for constraining demand for high-carbon products and energy services, has led to a growing reliance on the use of technology to remove CO_2 from the atmosphere in the future, commonly termed 'negative emissions'. This approach embodies very significant risk. The shift away from straightforward reduction targets, towards combined reductions and removals targets, has galvanized more countries to pledge and legislate for more ambitious climate action. While this should be applauded, societies also need to step back and scrutinize proposed methods of reaching net zero, across all sectors of the economy, inclusive of aviation.

1 World Meteorological Organization, UN Environment Programme, Global Carbon Project, UK Met Office, Intergovernmental Panel on Climate Change, UN Office for Disaster Risk Reduction (2022), *United in Science 2022: A multi-organization high-level compilation of the most recent science related to climate change, impacts and responses*, https://library.wmo.int/doc_num.php?explnum_id=11309.

As the world wrestles with the reality of failing to decarbonize the global economy with sufficient speed, and a risky, large overshoot of carbon budgets looks increasingly likely, sectors that have historically been deemed 'difficult to decarbonize' are under growing pressure to develop pathways towards net zero emissions. The Intergovernmental Panel on Climate Change (IPCC) has highlighted that the level of decarbonization ambition varies across sectors, with 'emission reduction aspirations in international aviation and shipping lower than in many other sectors (medium confidence)'.[2]

International efforts to reduce CO_2 emissions are dangerously off track, inclusive of the aviation sector. Global aviation emissions account for around 2.5 per cent of CO_2 emissions,[3] but a higher proportion of effective radiative forcing – a more accurate measure of the aviation sector's impact on global warming.

Not only is the aviation sector lacking decarbonization ambition, but along with agriculture it is one of the most difficult sectors to decarbonize based solely on supply-side solutions. Many decarbonization options remain either at the R&D phase; are taking many years to be deployed within a sector with sticky, long-lasting and costly current assets; have yet to be scaled to the levels required; or have significant externalities.

This paper investigates the balance between reliance on future supply-side decarbonization (such as fuel efficiency measures and negative emissions) and demand management (reducing passenger-km flown), and also examines the role of near-term demand management in reducing the risk of reliance on future action. All within the context of a 'fair share' of carbon budgets for the UK's aviation sector. The allocation of a fair share of the UK's carbon budget to the aviation sector is quantified and discussed in section 2.4. The modelling in this paper does not consider the cost of mitigation measures and is not intended to be a lowest-cost optimization study in any way.

The remainder of this chapter highlights the possible impacts of climate change and discusses the potential for demand management in a general sense to swiftly reduce emissions. Chapter 2 presents an overview of the model developed to explore the balance between aviation supply-side decarbonization and demand mechanisms, carbon budgets (and consequently how much time is left to avert the risks of climate change), and the UK government's Jet Zero Strategy high-ambition decarbonization scenario for the aviation sector. Chapter 2 also presents a summary of the generated scenarios from the modelling. This approach of presenting the results upfront has been adopted as a means of guiding the reader through the various scenarios.

Chapter 3 presents the various supply-side decarbonization options, sequentially questioning how much reliance and hence risk is placed on each. For the main supply-side options, an optimistic and potentially high-reliance risk scenario has been generated, alongside a lower risk, more realistic scenario. Furthermore,

2 Intergovernmental Panel on Climate Change (2022), *Technical Summary*, in *Climate Change 2022: Mitigation of Climate Change – Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, https://www.ipcc.ch/report/ar6/wg3.
3 Ritchie, H. (2020), 'Climate change and flying: what share of global CO_2 emissions come from aviation?', Our World in Data, https://ourworldindata.org/co2-emissions-from-aviation.

Chapter 3 quantifies how demand may need to change as reliance on these supply-side technologies alters. Chapter 4 then proposes a risk-minimization approach of increased demand management in the near term and considers the economic benefits of flying against the social cost of carbon as well as potential policy measures. Finally, Chapter 5 presents conclusions and recommendations.

1.1 What are the impacts of climate change that global society is trying to avoid, and how near are we to that point?

The balance between relying on future emissions mitigation and greater near-term action, such as demand-reduction measures, needs to be assessed based on the severity and time frame in which climate risks could manifest, and their likely probability of occurrence.

The emissions gap[4] for a limited-overshoot 1.5/2°C scenario is ever widening. In late 2021 the IPCC defined various carbon budgets for a given chance of avoiding different levels of global warming.[5] For a 67 per cent chance of staying below 1.5°C – the target set out by the Paris Agreement – the world can emit 400 gigatonnes of CO_2 ($GtCO_2$) between the beginning of 2020 until net zero CO_2 emissions are reached.[6] The UN Environment Programme (UNEP) emissions gap report illustrates that to stay on course for a limited-overshoot 1.5°C scenario, global emissions would need to be 12–14 $GtCO_2$/yr lower in 2030 than current nationally determined contributions (NDCs) imply.[7] Interrogation of the emissions gap shows that aggregate emissions over the 2020s would need to decline by an equivalent of more than two years of current global emissions. Net zero targets are a manifestation of this widening gap, and an acknowledgment that there is not enough time to decarbonize if demand grows unchecked.

Clearly the impacts of climate change are already a reality, as has been witnessed in recent years with increased extreme weather, flooding, heatwaves and droughts. Unless decarbonization efforts across the entire energy sector are dramatically increased, many of the worst climate impacts are likely to be locked in by 2040, and could become so severe that they go beyond the limits of what nations can adapt to.[8] Moreover, many of the potential impacts of climate change may turn out to be conservative estimations of the risks, unless efforts are made to radically reduce emissions before 2030, as critical tipping points could be reached at lower levels of temperature increase than previously thought. The IPCC estimates that under

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4 The distance between the emissions reductions promised and the emissions reductions needed to achieve the temperature goal of the Paris Agreement, see UN Environment Programme (2022), *Emissions Gap Report 2022*, https://www.unep.org/resources/emissions-gap-report-2022.
5 Intergovernmental Panel on Climate Change (2021), *Summary for Policymakers,* in *Climate Change 2021: The Physical Science Basis – Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* https://www.ipcc.ch/report/ar6/wg1.
6 The 1.5°C target is more important than ever. See discussion on tipping point thresholds later in this section.
7 UN Environment Programme (2021), *Emissions Gap Report 2021*, https://www.unep.org/resources/emissions-gap-report-2021.
8 Quiggin, D. (2021), *Climate change risk assessment 2021: The risks are compounding, and without immediate action the impacts will be devastating*, Report, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2021/09/climate-change-risk-assessment-2021.

a moderate emissions scenario (SSP2-4.5), the world could pass the 1.5°C objective in 2030.[9] It should be noted that many of the negative emission technologies being considered under net zero targets are only likely to be deployed post 2030. As such, there may well be an overshoot in the 1.5°C temperature limit before negative emissions kick in, but by this time these tipping points may have already been triggered. This indicates the primary risk of relying on supply-side CO_2 removal technologies. It is within this climate risk context that the speed of supply-side decarbonization of the aviation sector should be assessed, and indeed the potential need for demand management.

1.2 Demand-side measures can be enacted swiftly to buy time for supply-side solutions

As citizens are increasingly impacted by climate change, they are likely to call for swifter climate action. Given that demand-side emission reductions can be implemented quickly, with little lead time, demand-side responses are likely to be the only fast-acting policy measure left at our collective disposal to avoid disastrous climate impacts. Developing demand-side policy measures that can be deployed as the climate emergency deepens will be critical to ensure there are viable mechanisms to retain future cooperative international climate action pathways:

> We can't wait for breakthrough technologies to deliver net-zero emissions by 2050. Instead, we can plan to respond to climate change using today's technologies with incremental change. This will reveal many opportunities for growth but requires a public discussion about future lifestyles.[10]

Within the context of Russia's invasion of Ukraine and high energy prices, the need for short-term demand management has had increased political and policy attention. The European Commission set a voluntary 15 per cent gas consumption reduction target, inclusive of encouraging households to turn down their thermostats,[11] and the International Energy Agency (IEA) published an extensive set of least-disruptive options to reduce oil and gas consumption.[12] As part of these demand-side recommendations, the IEA encourages EU citizens to take high-speed trains as a high-quality substitute for flying.[13]

High oil and gas prices are already resulting in inflation-driven energy demand reduction. Consequently, there is a clear win-win scenario whereby a greater focus on the demand side could offer a means to reduce reliance on Russian fossil fuels, lower geopolitical risks and benefit citizens suffering under the cost-of-living crisis, while also reducing climate risks.

9 Carbon Brief (2021), 'Analysis: What the new IPCC report says about when world may pass 1.5C and 2C', https://www.carbonbrief.org/analysis-what-the-new-ipcc-report-says-about-when-world-may-pass-1-5c-and-2c.
10 Allwood, J. et al. (2019), *Absolute Zero*, http://www.eng.cam.ac.uk/news/absolute-zero.
11 European Commission (2022), 'Questions and Answers on the EU "Save Gas for a Safe Winter" Plan', https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_4609.
12 International Energy Agency (2022), *Playing my part: How to save money, reduce reliance on Russian energy, support Ukraine and help the planet*, https://www.iea.org/reports/playing-my-part.
13 Ibid.

In 2022, the IPCC highlighted that the demand side has a significant contribution to make in reducing emissions;[14] and that decent living standards can be maintained while reducing demand for high-emission goods and services:

- 'Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end use sectors by 40–70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. Demand side mitigation response options are consistent with improving basic wellbeing for all (high confidence).'
- 'Decent living standards, which encompasses many SDG dimensions, are achievable at lower energy use than previously thought (high confidence). Mitigation strategies that focus on lowering demand for energy and land-based resources exhibit reduced trade-offs and negative consequences for sustainable development relative to pathways involving either high emissions and climate impacts or pathways with high consumption and emissions that are ultimately compensated by large quantities of BECCS.'

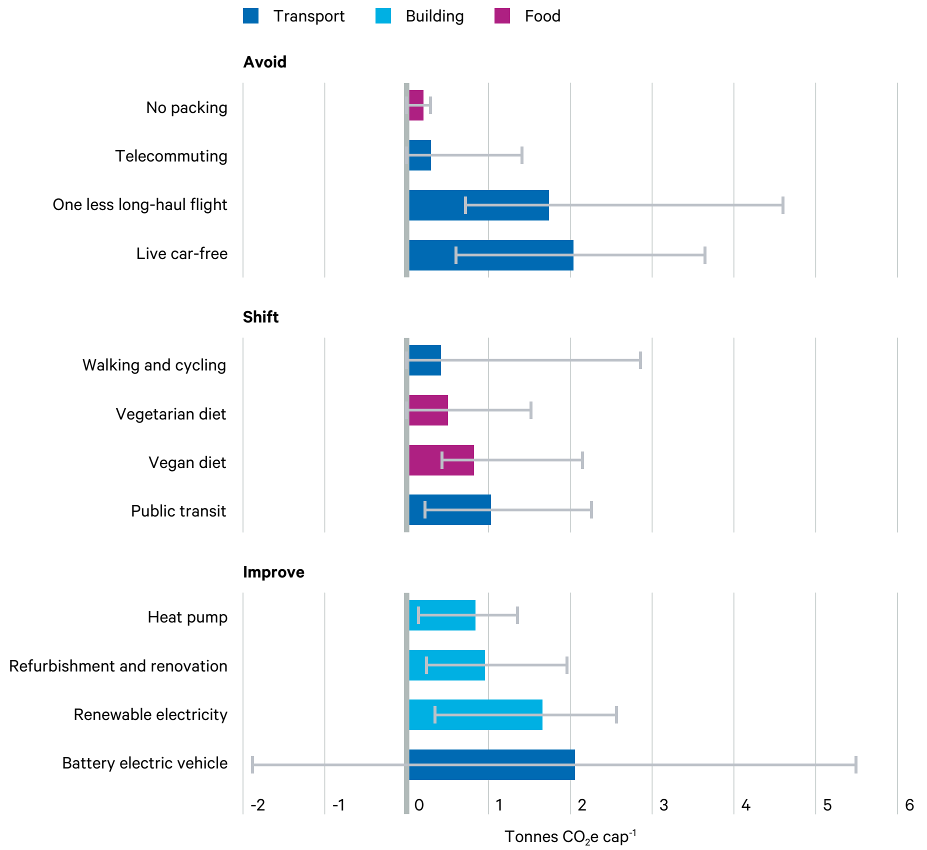
The IPCC also highlighted that COVID-19 policies led to a global decline in CO_2 emissions of around 5.8 per cent in 2020 relative to 2019,[15] and that international aviation emissions declined by a staggering 45 per cent. The IPCC classify future emissions reduction mitigation strategies from the demand side into 'avoid', 'shift' and 'improve' options. As can be seen in Figure 1, one of the greatest avoid potentials for individuals comes from reducing long-haul aviation, which can save slightly more than 1.7 tonnes CO_2 per person.

To balance the severity and time frame of climate risks, and reduce the emissions gap, a near-term focus on the demand side could buy time to develop supply-side solutions, while minimizing the risks of relying on yet to be commercialized and scaled options, such as sustainable aviation fuels (SAFs), zero-emission aircraft and greenhouse gas removals (GGRs). In essence, a new framing is required – focusing on the potential of the demand side in the near term – to enable supply-side solutions to catch up, without baking in over-reliance risks on the supply side, particularly in relation to GGRs.

While undoubtedly politically challenging in any sector, the focus on demand management is gaining traction. In December 2022, the European Commission gave France the green light to ban short-haul domestic flights between cities linked by train journeys of less than 2.5 hours. The French transport minister, Clément Beaune, has said that the measure will come into effect 'as quickly as possible'.[16] Furthermore, within the Committee on Climate Change's sixth carbon budget (CB6), the widespread engagement scenario shows passenger demand declining by 15 per cent in 2050, relative to 2018.[17]

14 Intergovernmental Panel on Climate Change (2022), *Technical Summary,* in *Climate Change 2022: Mitigation of Climate Change – Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
15 Ibid.
16 Limb, L. (2022), 'It's official: France bans short haul domestic flights in favour of train travel', Euronews Green, 2 December 2022, https://www.euronews.com/green/2022/12/02/is-france-banning-private-jets-everything-we-know-from-a-week-of-green-transport-proposals.
17 Committee on Climate Change (2020), *The Sixth Carbon Budget: Aviation,* https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Aviation.pdf.

Figure 1. Low-carbon lifestyles can be classified into avoid, shift and improve options



Source: Figure TS.20(b) in Intergovernmental Panel on Climate Change (2022), Technical Summary, in *Climate Change 2022: Mitigation of Climate Change – Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*

In the UK, the top fifth of earners fly five times more often than the poorest fifth.[18] The Climate Assembly, which was made up of representative members of the UK population, showed that the British public supports limits on demand for flying, and that demand should be controlled depending on how technological solutions progress.[19] The assembly supported supply-side solutions that would allow people to continue flying, but also saw that a balance was needed as to how much air passenger numbers can grow, with 80 per cent of assembly members agreeing or strongly agreeing that taxing those that fly more often and further should be part of how the UK gets to net zero.

18 New Economics Foundation (2021), *A Frequent Flyer Levy: Sharing aviation's carbon budget in a net zero world,* https://neweconomics.org/uploads/files/frequent-flyer-levy.pdf.
19 Climate Assembly UK (2020), *The path to net zero: How we travel by air,* https://www.climateassembly.uk/documents/86/Chapter_4.pdf.

02 Model overview and summary of high-level results

The model used in this paper has developed a realistic outlook for UK aviation decarbonization, sequentially exploring the main decarbonization solutions and the role of demand management.

The model developed for this paper allows the analytical exploration of the role of demand management within the aviation sector, both in terms of the assumptions that underpin the future of supply-side decarbonization options, and a scenario-based assessment of the UK aviation sector's decarbonization pathway. The objectives of the model are to:

- Construct a realistic decarbonization pathway for UK aviation that minimizes the risk of the sector contributing to runaway climate change;
- Determine a realistic annual assessment of supply-side decarbonization of the aviation sector to 2050;
- Estimate the extent to which these mechanisms will reduce emissions commensurate with carbon budgets; and
- Determine the level of demand reduction that will be necessary to close any remaining emissions gap, also within the context of carbon budgets that limit global warming to 1.5°C.

It was important to construct the model with a view to the most influential decarbonization strategies that currently exist, and to reflect how the models that underpin these analyses make assumptions regarding the future development of supply-side decarbonization options. Hence, the model takes into consideration the methodologies and parameter assumptions within the various models and data that feed into the UK Department for Transport's (DfT) Jet Zero Strategy,[20] as well as the aviation industry's own assumptions within the Sustainable Aviation (2020) report.[21]

Figure 2 illustrates the main components of the model, which are summarized as follows:

- Extensive use of Civil Aviation Authority (CAA) primary data, inclusive of millions of air traffic movements (ATMs), thousands of individual routes, and hundreds of operational aircraft.
- The CAA data enabled the remodelling from first principles of the DfT main modelling architecture to forecast the composition of the commercial aircraft in operation to 2050, namely the fleet mix model (FMM).
- The recreation of the FMM is the main element of the model that enables the forecasting of the future fleet composition between the 25 busiest UK airports and 578 of the most visited destinations, across millions of future ATMs.
- The model estimates the emissions of all current and future UK domestic and international routes, enabled by assumptions as to the fuel efficiency improvements of future aircraft and their production roll-out, the retirement of current aircraft, and the integration of the European Environment Agency (EEA) aviation emissions model.[22]
- The modelling of the future fleet composition also enables the model to forecast zero-emission flights (battery and hydrogen power aircraft) across all viable routes, along with assumptions as to their entry into service (EIS) dates and aircraft performance.
- Forecasting of the supply and availability of sustainable aviation fuels (SAF), and their associated supply chain emissions, across a wide variety of feedstocks.
- Forecasting the availability of negative emission offsets to the aviation sector.
- Within the context of defined carbon budgets, around 20 main control variables allow for the construction of scenarios where each of the main supply-side decarbonization solutions can be explored to ascertain how the risks of delays and failure to achieve supply-side decarbonization targets could impact the need to limit demand.

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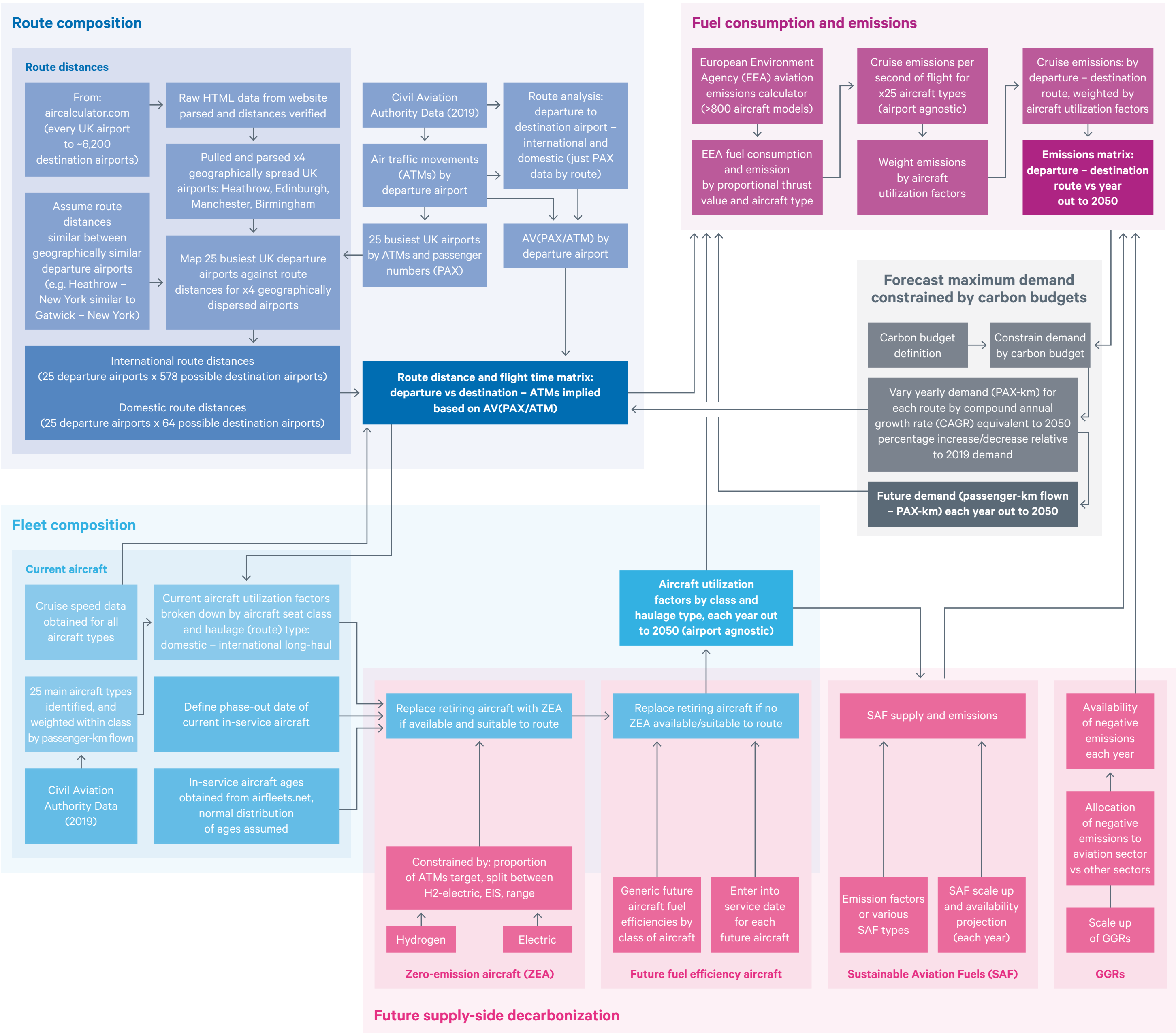
20 Department for Transport (2022), 'Jet Zero: modelling framework', https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1061972/jet-zero-modelling-framework.pdf.
21 Sustainable Aviation (2020), *Decarbonisation Road-Map: A Path to Net Zero – A plan to decarbonise UK aviation,* https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_CarbonReport_20200203.pdf.
22 European Environment Agency (2019), 'Aviation 2 LTO emissions calculator 2019', https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-a-aviation-1-annex5-LTO/view.

There is a critical need to develop robust, realistic and Paris-compliant global decarbonization pathways. However, due to data and time constraints, the scope of the analysis in this paper is limited to UK-departing domestic and international flights. See section 4.5 for a discussion as to what the modelling results here may mean for other countries.

Figure 2. Main modelling components, and how they interconnect

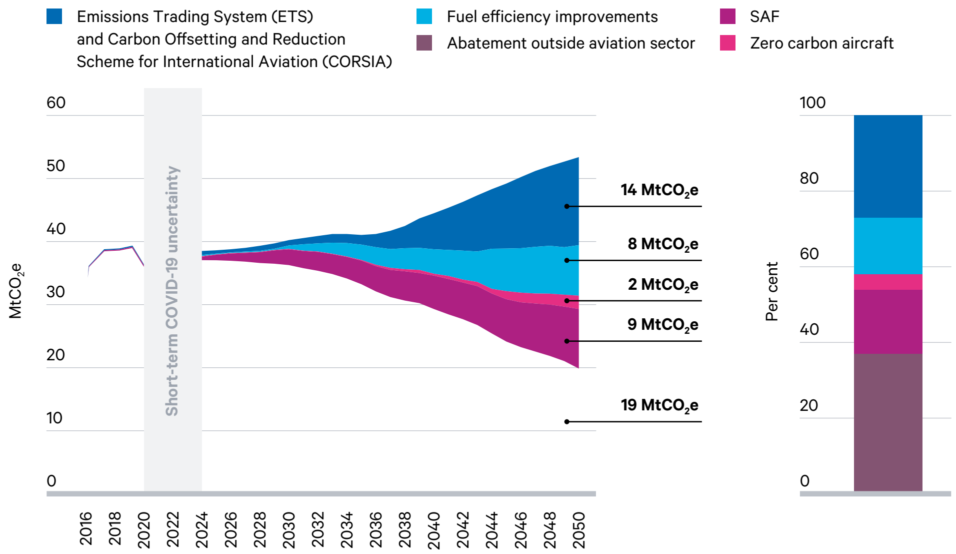


Source: Compiled by the author.

2.1 A starting point: Jet Zero Strategy high-ambition scenario

The DfT Jet Zero Strategy (JZS) contains four scenarios: (1) continuation of current trends, (2) high ambition, (3) high ambition with a breakthrough on SAF, and (4) high ambition with a breakthrough on zero-emission aircraft. The high-ambition scenario represents the core scenario, which is committed to within the policy document as the scenario that 'represents the right level of ambition for aviation and is achievable if technology development continues'.[23] As such, this paper benchmarks against this high-ambition JZS scenario, which DfT forecasts will result in '19.3 $MtCO_2e$ [million tonnes of CO_2 equivalent] of residual emissions in 2050 to be offset or removed', as can be seen in Figure 3. This JZS high-ambition scenario is an optimistic starting point in defining a UK aviation decarbonization pathway, especially considering the risks of relying on offsetting or removing the 19.3 $MtCO_2e$ of residual emissions outside of the aviation sector. Although the DfT characterizes this scenario as 'high ambition' it should be noted that the level of residual emissions it targets in 2050 is around 20 per cent higher than UK aviation emissions in 1990 – the UK's baseline year for its Climate Change Act commitments. Aviation is the only sector that is not expected to make any absolute contribution to UK national emissions reduction targets, while many other sectors of the economy are expected to reduce their emissions by close to 100 per cent on 1990 levels.

Figure 3. JZS high-ambition scenario, abatement of emissions by the main decarbonization mechanisms



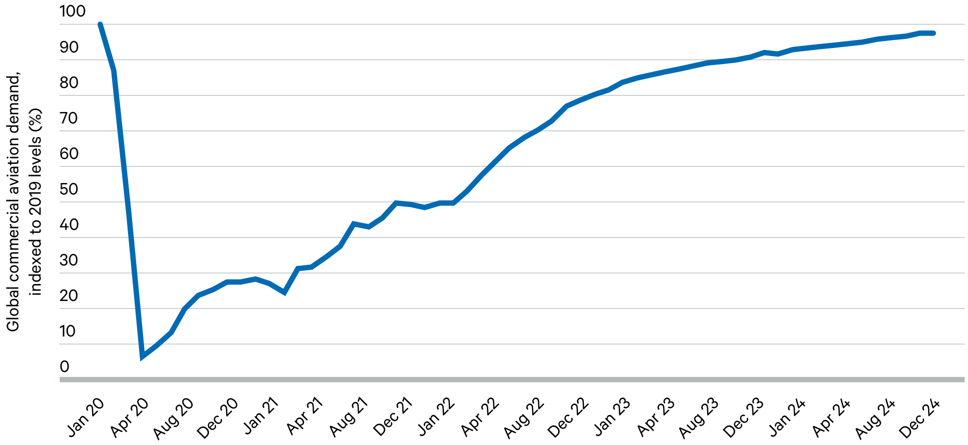
Source: Department for Transport (2022), *Jet Zero illustrative scenarios and sensitivities*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1096929/jet-zero-strategy-analytical-annex.pdf.

23 Department for Transport (2022), *Jet Zero Strategy: Delivering net zero aviation by 2050*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1095952/jet-zero-strategy.pdf.

2.2 Impact of COVID-19 on short-term demand

The impact of COVID-19 on the demand for flights has been significant. Consequently, this paper utilizes 2019 CAA data, as forecasting forward in time from 2019 is more representative of the route-by-route demand for flights over the next few decades. That said, the impact of COVID-19 has been accounted for in the near-term. The baseline scenario of global aviation demand from Bain & Company (2022), conducted in January 2022, was utilized to define both the reduction in passenger numbers (PAX) during the pandemic, and the projected demand out to the end of 2024.[24] The Bain & Company analysis forecasts that by the end of 2024 demand will be 97.6 per cent of the pre-pandemic level, which is illustrated in Figure 4. Appendix A4 provides more information on the modelling of demand. It should be noted that since the modelling conducted here was completed, UK demand for flying has rebounded more strongly than anticipated. However, this faster than anticipated rebound in demand will only have a marginal impact on the headline outputs of the modelling conducted here.

Figure 4. Global commercial aviation demand, indexed to 2019 levels



Source: Baseline scenario, projections as of January 2022, in Bain & Company (2022), 'Air Travel Forecast: When Will Airlines Recover from Covid-19?', https://www.bain.com/insights/air-travel-forecast-when-will-airlines-recover-from-covid-19-interactive (accessed 14 Jan. 2022).

24 Bain & Company (2022), 'Air Travel Forecast: When Will Airlines Recover from Covid-19?', https://www.bain.com/insights/air-travel-forecast-when-will-airlines-recover-from-covid-19-interactive (accessed 14 Jan. 2022).

2.3. Summary of scenarios, abatement potentials and demand under balanced carbon budgets

Four emissions abatement mechanisms are considered under the UK government's JZS high-ambition scenario, along with one additional abatement mechanism: abatement outside of the sector, which, while not explicitly modelled by the JZS, is nonetheless relied upon. The five abatement mechanisms are:

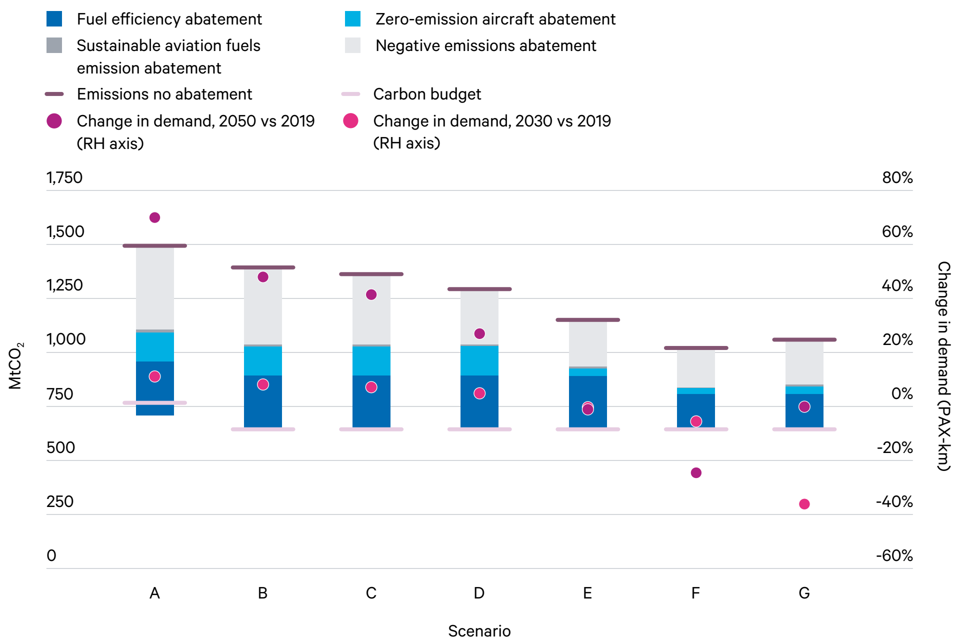
1. Fuel efficiency improvements of the aircraft fleet, and operational and air traffic management measures;
2. Zero-emission aircraft (ZEA);
3. The use of SAFs to substitute for jet fuel;
4. Abatement outside of the aviation sector (negative emissions); and
5. The impact of carbon pricing (Emissions Trading System, and Carbon Offsetting and Reduction Scheme for International Aviation – ETS and CORSIA) on demand.

Table 1. Summary of generated aviation decarbonization scenarios

	Scenario	Description
Supply-side optimistic and high-reliance risk	A	Assumptions held at JZS high-ambition scenario levels. With the global carbon budget proportioned based on current emissions, demand (PAX-km) can increase by 70 per cent (2050 vs 2019), with a small carbon budget surplus.
	B	Relative to (A): with carbon budget reduced by 16 per cent to reflect proportioning global carbon budgets based on per capita emissions, demand can increase by 48 per cent (2050 vs 2019).
	C	Relative to (B): annualized fuel efficiency remains at 1.2 per cent, but with dynamic modelling of fleet composition over time, demand can increase by 41.5 per cent (2050 vs 2019).
	D	Relative to (C): annualized fuel efficiency falls to 0.9 per cent, with dynamic modelling of fleet composition over time, demand can increase by 27 per cent (2050 vs 2019).
	E	Relative to (D): SAF supply reduced from 5.1 to 1.2 Mt in 2050, demand would need to decline by 1 per cent (2050 vs 2019).
Supply-side risks minimized, greater emphasis on demand reduction	F	Relative to (E): with the risk of GGRs under delivering negative emissions factored in (see section 3.4) at a 33 per cent reduction across all years, demand would need to decline by 24.5 per cent (2050 vs 2019).
	G	Relative to (F): emphasis of demand reduction is placed on the near term to minimize the risk of relying on future decarbonization that may underdeliver, resulting in 2030 demand declining by 36.1 per cent relative to 2019. Demand in 2050 is equivalent to 2019 levels.

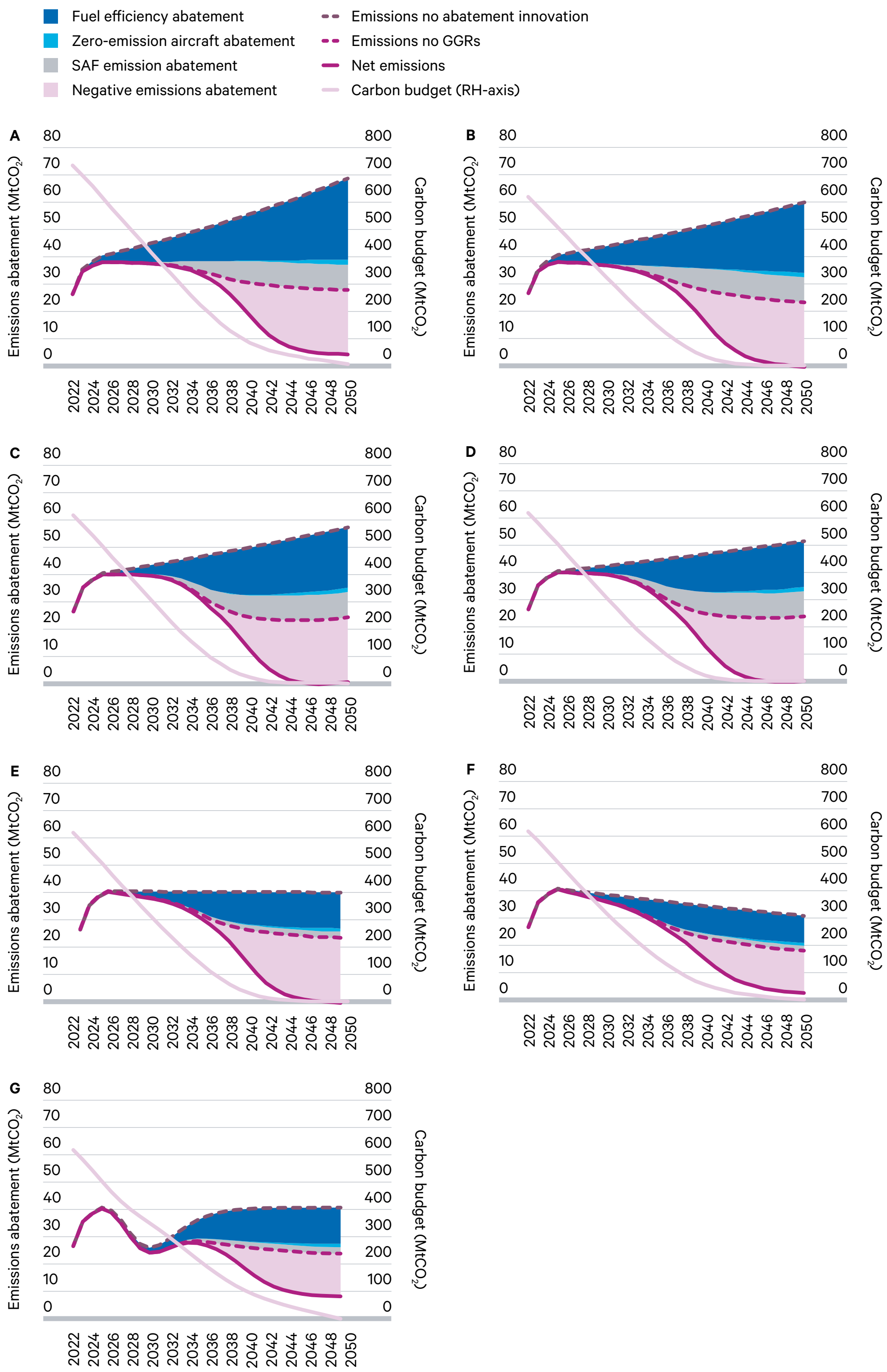
The modelling conducted here has sequentially considered the first four of the five emissions abatement mechanisms of the JZS high-ambition scenario, assessing the viability of the underlying assumptions of each decarbonization mechanism – such as the future fuel efficiency of the aircraft fleet (see Chapter 3 for more details). Where an adjustment to those assumptions has been made, the model has asked the question – what is the maximum allowable demand (passenger-kilometre flown – PAX-km), while ensuring the UK aviation sector remains within its fair share of the global carbon budget? Each adjustment to the underlying assumptions generated a corresponding scenario. This process generated seven scenarios (A–G), which are summarized in Table 1. Figure 5 illustrates all seven scenarios, showing the aggregate (2022–50) emissions abatement of each decarbonization mechanism, and the maximum demand (PAX-km) in 2030 and 2050, relative to 2019, that would keep the aviation sector within its fair share of global carbon budgets (see section 2.4). Or in other words, the minimum demand reduction required. Figures 6A–G illustrate the emission abatement profiles of the seven scenarios.

Figure 5. Summary of UK aviation sector aggregate emissions abatement (2022–50), and maximum demand (PAX-km) to stay within a fair share of global carbon budgets, under all modelled scenarios



Source: Compiled by the author.
Note: See Table 1 for descriptions of the scenarios. Scenario (A) is the most optimistic, through to (G) being the most realistic, with least risk of over reliance on future decarbonization options.

Figure 6. Emissions abatement across all modelled scenarios



Source: Compiled by the author.

2.4. Aviation specific carbon budgets

The modelling here was constructed to investigate the scale of demand reduction that may be needed to enable the UK aviation sector to stay within a fair share of global carbon budgets, taking into consideration realistic supply-side decarbonization options.

Defining carbon budgets for individual sectors is fraught with trade-offs and misleading simplifications. Global carbon budgets from the beginning of 2020 until global net zero CO_2 emissions are reached, as defined by the IPCC (2021),[25] are reasonably robust for a given probability of staying below 1.5°C or 2°C of global warming. However, defining a carbon budget for a country, and indeed a sector within a country, is more complex and requires assumptions and simplifications. These simplifications stem from the relative speed and scale of decarbonization that may, or may not, take place within each sector and country. Questions arise as to which countries should reduce their emissions the most, and which sectors are the most difficult technically and economically to decarbonize. For instance, while proven low-cost electricity sector decarbonization options exist (solar, wind etc.), given the high historical emissions of the US and low access to electricity in India, should India be allowed a greater per capita carbon budget? And, as electricity decarbonization is cheaper and more viable based on today's technology than the agricultural sector, should the electricity sector be assigned a smaller carbon budget than agriculture?

The answers to these questions are complex and are traditionally dealt with by cost-optimization, whole-economy models, which investigate the allocation of carbon budgets either within a singular nation state's economy, or on a global basis. These models make assumptions and forecasts as to the relative rate of decarbonization between sectors, based on minimizing costs. Here, and within the JZS, the aviation sector is modelled in isolation, meaning to define a carbon budget requires an assumed input that is defined outside of the model.

This paper considers two different carbon budget scenarios for the UK aviation sector. In the first scenario, a proportion of the global carbon budget, defined by the IPCC (2021) as 400 $GtCO_2$ between 2020 and when global net zero CO_2 emissions are reached, is allocated to the UK's aviation sector. This carbon budget gives the world a 67 per cent chance of limiting temperature increases to 1.5°C, the goal of the Paris Agreement. One adjustment and two assumptions are made to translate this 400 $GtCO_2$ global carbon budget down to the UK aviation sector. Firstly, adjusting for global emissions since 2020, and then assuming that the UK is allocated 1 per cent of this budget, on the basis of current emissions,[26] and that the aviation sector is allocated 24.5 per cent of the UK's carbon budget. The latter is based on the time-averaged yearly emissions from the aviation sector as a proportion

25 Intergovernmental Panel on Climate Change (2021), *Summary for Policymakers,* in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*
26 Department for Business Energy and Industrial Strategy (2022), *2020 UK Greenhouse Gas Emissions, Final Figures,* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1051408/2020-final-greenhouse-gas-emissions-statistical-release.pdf.

of economy-wide emissions to 2050 within the all-sector modelling of the Committee on Climate Change (CCC) CB6.[27] This proportional allocation results in the UK aviation sector being allocated 767 $MtCO_2$ between 2022 and 2050.

The second carbon budget scenario is based on a per capita allocation of the 400 $GtCO_2$ IPCC carbon budget, and allocation to the aviation sector based on the 24.5 per cent time-averaged yearly emissions from the aviation sector as a proportion of economy-wide emissions within the all-sector modelling of CB6. This results in a carbon budget of 644 $MtCO_2$ for the UK aviation sector. It should be noted that even this lower carbon budget is arguably an overallocation of the carbon budget to the UK aviation sector, as Article 4.1 of the Paris Agreement specifies that developed countries will need to have a proportionally higher reduction in emissions. This is due to developing countries' emissions peaking later in time than developed countries, and on 'the basis of equity, and in the context of sustainable development and efforts to eradicate poverty'.[28]

By defining a carbon budget for the UK's aviation sector, the paper is not proposing to put in place sector emission caps, rather the model utilizes a sectoral carbon budget as an analytical tool to investigate the challenges of decarbonizing the aviation sector within the time frame of the UK net zero target: 2050.

2.4.1 The implications of carbon budgets for demand reduction

Under the larger UK aviation sector carbon budget of 767 $MtCO_2$ (scenario A, Figure 6A), demand (PAX-km) by 2050 could increase by 70 per cent, with a small carbon budget surplus of 58 $MtCO_2$ remaining, equivalent to 1.5 years of 2019 emissions. Under the more equitable 644 $MtCO_2$ carbon budget, allocated on a per capita basis (scenario B, Figure 6B), demand (PAX-km) could increase by 48 per cent. Hence, under the more equitable carbon budget based on a per capita basis, demand would need to be constrained by an additional 22 percentage points. These emission abatement pathways can be seen in Figure 6A and Figure 6B. It should be noted that both these scenarios broadly follow the input assumptions of the JZS high-ambition scenario,[29] where the displacement of jet fuel by low-carbon alternatives and availability of negative emissions is optimistically high, and hence these scenarios embody a high degree of reliance risk (see Chapter 3).

The results of re-modelling the JZS high-ambition scenario do not mean that demand (PAX-km) can increase by 48–70 per cent, between 2019 and 2050. The abatement assumptions prescribed by DfT in relation to fuel efficiency improvements, SAFs and negative emissions are all optimistic, and as such embody risks associated with under delivery. Chapter 3 unpacks these supply decarbonization assumptions, lowering the associated reliance risks, and exploring the required demand management to stay within the aviation sector specific carbon budget of 644 $MtCO_2$.

27 Committee on Climate Change (2020), 'Sixth Carbon Budget – Dataset (Version 2 – December 2021)', https://www.theccc.org.uk/publication/sixth-carbon-budget.
28 United Nations (2015), *Paris Agreement,* https://unfccc.int/sites/default/files/english_paris_agreement.pdf.
29 Department for Transport (2022), *Jet Zero illustrative scenarios and sensitivities,* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1096929/jet-zero-strategy-analytical-annex.pdf.

03 Supply-side emissions abatement

Supply-side decarbonization efforts are crucial, but time is running out to implement them and current assessments of their effectiveness are unrealistic.

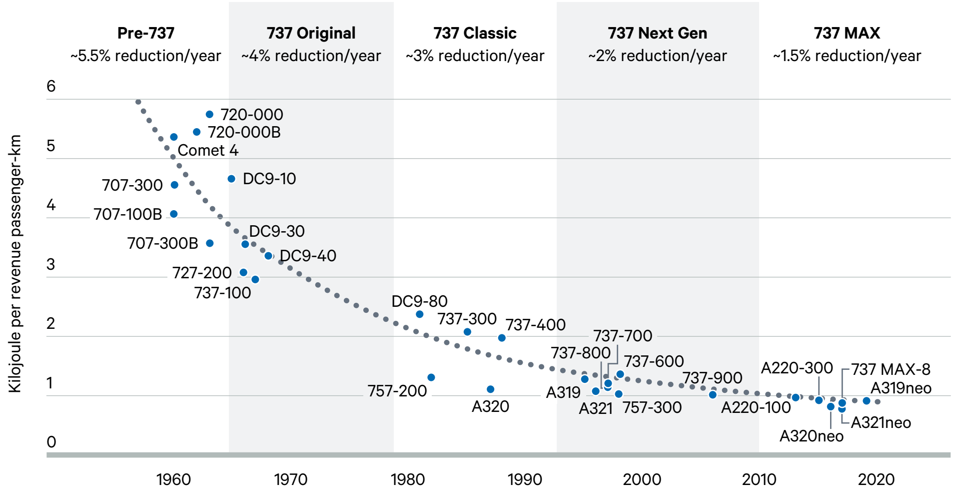
3.1 Fuel efficiency emissions abatement

Significant advances in aircraft fuel efficiency are becoming progressively more challenging to achieve. Figure 7 shows that fuel efficiency improvements for single-aisle commercial aircraft have slowed over time as they approach the limit of current designs.[30]

Possible fuel efficiency innovations are numerous but can be grouped into three manageable categories: efficiency measures applied to the aerodynamics and aircraft structural weight, aircraft fuselage, wings and associated materials; the efficiency of jet engines; and operational and air traffic management measures. Research by Air Transportation Analytics (ATA),[31] commissioned by the UK government jointly with the CCC in 2018, provides a resource that explores the 'prospective and potential changes to aircraft technology, air traffic management and airline operations', enabling the future fuel efficiency of the next generations of aircraft to be estimated across various future potential innovations.

30 Mallory, G. et al. (2022), 'A Need for Speed in Aerospace and Defense', Boston Consulting Group, 21 July 2022, https://www.bcg.com/publications/2022/a-and-d-industry-need-for-speed.
31 Air Transportation Analytics (2018), *Understanding the potential and costs for reducing UK aviation emissions: Report to the Committee on Climate Change and the Department for Transport*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/785685/ata-potential-and-costs-reducting-emissions.pdf.

Figure 7. Fuel efficiency of commercial aircraft over time



Source: Mallory, G. et al. (2022), 'A Need for Speed in Aerospace and Defense', Boston Consulting Group, 21 July 2022, https://www.bcg.com/publications/2022/a-and-d-industry-need-for-speed.

The JZS high-ambition scenario assumes that the introduction of new aircraft over time leads to significant improvements in fuel efficiency. On an annualized basis this averages 2 per cent less fuel used year-on-year, inclusive of operational and air traffic management measures. As such, if demand remained static, in 2050 the entire fleet would burn 43 per cent less fuel, relative to 2022. The research for this paper re-modelled the processes of the DfT fleet mix model (FMM). The fleet composition and fuel efficiency improvement forecast modelling is described in Appendices A1 – A4.

The main components in modelling fleet fuel efficiency out to 2050 are:

- The fuel efficiency of the aircraft in operation currently, and their associated retirement dates;
- Which aircraft fly which routes between 25 departure and 578 destination airports;
- Which seat classes of aircraft types fly given haulage distances;
- How future aircraft enter the fleet based on EIS dates and the anticipated fuel efficiency;
- Production rates of future aircraft; and
- The impact of phase-out dates of current aircraft.

When calculating the emissions, and associated demand reduction to stay within a given carbon budget, there are three options pertaining to fleet fuel efficiency improvements. First, to simply apply the 2 per cent per annum improvement assumed in the JZS. However, given that the raw data from the JZS describing the changing fleet composition is not publicly available, this first option must be applied based on a static annualized 2 per cent, rather than varying over time based on aircraft retiring and new more fuel-efficient aircraft entering into service. The JZS 'optimistic'

2 per cent annualized efficiency improvement is based on research by ATA.[32] The JZS estimates that around 60 per cent of the efficiency improvements in the 'optimistic' scenario derive from future aircraft fuel efficiency improvements, or 1.2 per cent annualized.[33] The remaining 40 per cent is from operational and air traffic management measures, or 0.8 per cent annualized. The fuel efficiency improvement under this option can be seen in Figure 8, and is labelled 'option 1', resulting in a fuel efficiency improvement of 29 per cent in 2050, relative to 2022. The operational and air traffic management improvement of 0.8 per cent is applied separately under option 1.

The second option bases a variable yearly fuel efficiency improvement on the underlying fleet composition and fuel efficiency forecast modelling components. Under this second option, in 2050 the entire fleet saves the same proportion of jet fuel as option 1, namely a 29 per cent fuel efficiency improvement, relative to 2022. Hence, the annualized fuel efficiency improvement is also 1.2 per cent, equivalent to option 1. However, an operational and air traffic management improvement of 0.6 per cent annualized is applied, which is the average between the 'optimistic' and 'likely' JZS scenarios. This operational and air traffic management improvement follows an inverse S-curve, and by 2050 it is predicted to achieve a 15.5 per cent reduction in fuel burn. As can be seen in Figure 8, in the mid-2030s the dynamic fuel efficiency improvement of option 2 accelerates, due to a next generation of more fuel efficient aircraft entering into service, and older aircraft being phased out or retired at a greater rate than in previous years. Conversely, in the late-2040s the fuel efficiency improvements level off approaching 2050, as very few aircraft are retiring or being phased out in this period and as such the entire fleet reaches its maximum fuel efficiency improvement.

The third option available within the model is to reduce the fuel efficiency improvement of all future aircraft, to align with the 'likely' JZS scenario. As can be seen in Figure 8, this third option results in a 22 per cent improvement in fuel efficiency across the fleet by 2050, relative to 2022. This 2050 value corresponds to an annualized improvement of 0.9 per cent, equivalent to that in the 'likely' JZS scenario. This third option continues to apply the 0.6 per cent annualized improvement from operational and air traffic management measures.

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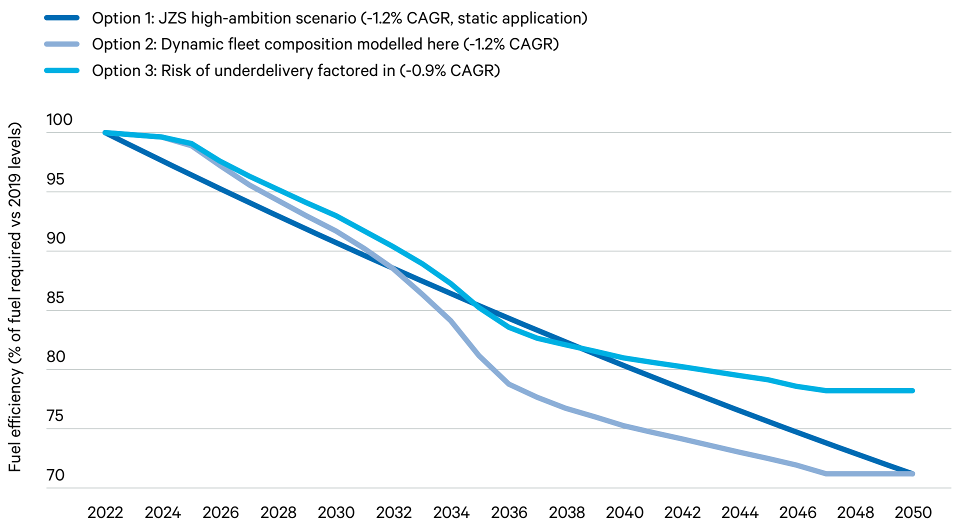
32 Ibid.
33 Department for Transport (2022), *Jet Zero: further technical consultation,* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1062042/jet-zero-further-technical-consultation.pdf.

Figure 8. Fleet fuel efficiency over time, based on the JZS high-ambition scenario



Source: Compiled by the author.
Note: CAGR = compound annual growth rate.

3.1.1 The impact of fuel efficiency assumptions on demand reduction requirements

As discussed in section 2.4.1., with the static 1.2 per cent annualized fuel efficiency improvement applied (option 1), demand (PAX-km) could be allowed to increase by 48 per cent (2050 vs 2019) (scenario B, Figure 6B). Under the dynamic modelling of fuel efficiency improvements of option 2 (1.2 per cent annualized), demand growth in 2050 would need to be constrained to 41.5 per cent above 2019 levels (scenario C, Figure 6C). Under option 3, factoring in the risk of future aircraft not meeting the 'optimistic' assumptions of the JZS, demand growth would need to be further constrained to 27 per cent above 2019 levels (scenario D, Figure 6D). These scenario results (i.e. scenarios C and D) do not mean that demand can increase by 27–41.5 per cent, as these scenarios are inclusive of optimistic assumptions regarding SAFs and negative emissions that will be unpacked in the following sections.

3.2 Zero-emission aircraft

Electrification of aircraft is a potential innovation that could, in the long term, be a game changer. However, the energy density of current affordable battery technology prohibits long-haul flight electrification. This is a critical consideration considering that international flights account for the majority of total aviation emissions. Current lithium-ion batteries have an upper energy density of around 250 watt hours per kilogramme (Wh per kg). The energy density of jet fuel is around 12,000 Wh per kg. With improved efficiency in electric propulsion systems and lightweight aircraft, the gap closes, but still means jet fuel is around 14 times more energy-dense than battery-powered alternatives.[34] For these reasons, the aviation industry's assessment that battery-powered aircraft will only be suitable for routes up to 400 km, from 2040 onwards, appears realistic.[35] It should be noted that while the route distance between Heathrow and Cardiff airports is around 200 km, the route distances from Heathrow to Aberdeen, Belfast, Edinburgh, Inverness and even Newcastle all exceed 400 km, to name a few.

Hydrogen production and distribution to airports faces its own challenges. While electrolysers to produce green hydrogen are falling in cost, one recent paper notes that 'global capacity needs to grow 6,000–8,000-fold from 2021 to 2050 to meet climate neutrality scenarios compatible with the Paris Agreement'.[36] This level of capacity growth is similar to the scale up of military equipment production, achieved by the US in the Second World War.[37] Blue hydrogen, produced utilizing carbon capture and storage (CCS), also faces cost challenges.[38] Both green and blue hydrogen will be challenging to produce and deploy at scale, store, transport and distribute.[39]

Climate Assembly members, representative of UK public opinion, are strongly in favour (87 per cent) of investing in new technologies for air travel, inclusive of electric aircraft.[40] As such, it is reasonable to assume that as 2030 approaches and the impacts of climate change increase in frequency and severity, the UK public is likely to want to see greater advancements in technologies that most significantly cut emissions. It should be noted that while the point source emissions of electric flight would be zero, the life cycle of batteries is not. However, the modelling in this paper, and that of the JZS, have assumed these aircraft are indeed zero emission.

The assumptions regarding zero-emission aircraft (ZEA) made under the JZS high-ambition scenario are realistic. Hence, these assumptions have been broadly applied within the fleet composition and fuel efficiency improvement forecast modelling here. These assumptions are as follows:

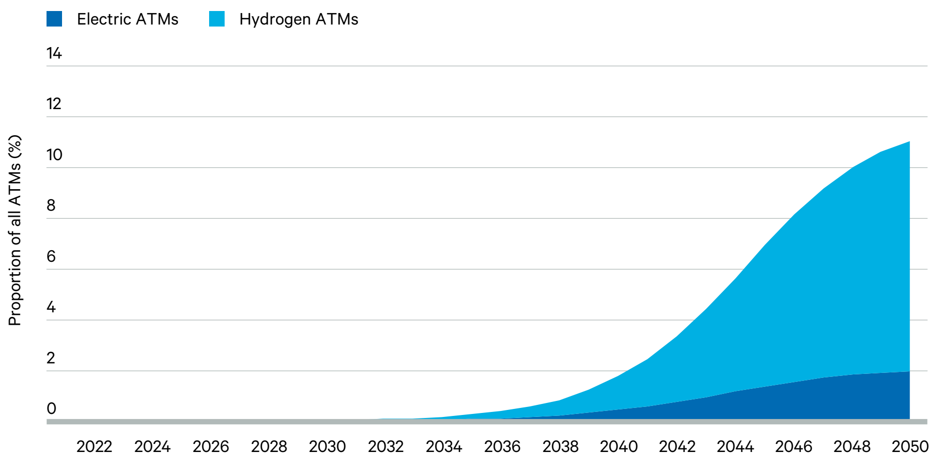
- 27 per cent of eligible ATMs to be zero emission by 2050, with a 50:50 split between hydrogen and electric aircraft;
- EIS of both hydrogen and electric aircraft in seat class 1 and 2 in 2035 (for seat class definition see Appendix A1);
- EIS of both hydrogen and electric aircraft in seat class 3 in 2040; and
- Maximum range of electric aircraft constrained to 400 km.

34 Adams, E. (2017), 'The Age of Electric Aviation Is Just 30 Years Away', *Wired*, 31 May 2017, https://www.wired.com/2017/05/electric-airplanes-2.
35 Sustainable Aviation (2020), *Decarbonisation Road-Map: A Path to Net Zero – A plan to decarbonise UK aviation.*
36 Odenweller, A. et al. (2022), 'Probabilistic feasibility space of scaling up green hydrogen supply', *Nature Energy* 7, 854–865, https://doi.org/10.1038/s41560-022-01097-4.
37 Odenweller, A. and Ueckerdt, F. (2023), 'Guest post: Can 'green hydrogen' grow fast enough for 1.5C?', *Carbon Brief*, 23 January 2023, https://www.carbonbrief.org/guest-post-can-green-hydrogen-grow-fast-enough-for-1-5c.
38 Department for Business, Energy and Industrial Strategy (2021), *Hydrogen Production Costs 2021*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011506/Hydrogen_Production_Costs_2021.pdf.
39 Ishaq, H., Dincer, I. and Crawford, C. (2022), 'A review on hydrogen production and utilization: Challenges and opportunities', *International Journal of Hydrogen Energy*, 47(62), https://doi.org/10.1016/j.ijhydene.2021.11.149.
40 Climate Assembly UK (2020), *The path to net zero: How we travel by air.*

The main difference between these assumptions and the JZS high-ambition scenario is that in the latter the EIS of ZEA is constrained to 50 per cent of retiring class 3 aircraft, here no such constraint exists. Furthermore, the JZS does not prescribe a 50:50 split between eligible hydrogen and electric ATMs. It is also not clear within the JZS if a production ramp-up constraint is applied subsequent to the EIS. Here the model applies s-curves to model the production ramp-up of all ZEA entering service for eligible ATMs. Considering all the above constraints, the fleet composition modelling forecast applied here finds that ZEA account for 11 per cent of all UK ATMs in 2050 (Figure 9).

Unlike with carbon budgets, fuel efficiency, SAFs and negative emissions, the model does not have multiple options or scenarios in relation to ZEA. As such, all the aforementioned and subsequent modelling results are produced with the set of assumptions described here. It should be noted that the final emissions abatement achieved by ZEA in the modelling here is similar to that within the JZS high-ambition scenario.

Figure 9. ZEA proportion of all ATMs, once all constraints are applied (range, EIS, production s-curve ramp up)



Source: Compiled by the author.

3.3 Sustainable aviation fuels

The aviation sector is increasingly reliant on the future scale up of sustainable aviation fuels (SAFs) to provide a major contribution to the supply-side decarbonization of the sector. The IPCC states that, 'decarbonisation options for shipping and aviation still require R&D, though advanced biofuels, ammonia, and synthetic fuels are emerging as viable options (medium confidence)'.[41]

41 Intergovernmental Panel on Climate Change (2022), *Technical Summary,* in: *Climate Change 2022: Mitigation of Climate Change – Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

SAFs have similar combustion properties to jet fuel and can, therefore, be blended and used in existing aircraft without requiring modifications. SAFs tend to be derived from bioenergy feedstocks, but synthetic fuels based on capturing carbon from the atmosphere and turning this carbon into fuel are increasingly being advocated and researched. Carbon Engineering is a company developing an 'air-to-fuel' process based on direct air capture (DAC), where the captured carbon is combined with hydrogen.[42] There are two main steps in this process in which significant energy inefficiencies can creep in. First, DAC itself requires large inputs of both heat and electricity, both of which would result in a diversion of low-carbon energy sources away from energy sectors (residential heating and the electricity sector, along with electrified surface transport) that are struggling to decarbonize at sufficient speed. Secondly, the production of either green or blue hydrogen results in further inefficiencies.

There is growing concern that aviation is just one of many sectors increasingly reliant on bioenergy-based decarbonization, and that as the scale of reliance grows the risks of future poor supply chain choices increases.

SAFs are likely to develop based on bioenergy feedstocks. Depending on the bioenergy feedstock choice and supply chain properties, SAFs can have reduced life cycle GHG emissions. Most of the controversy and debate around the long-term viability and sustainability of SAFs centres around these supply chain choices. If the feedstocks used to produce SAFs derive from food crop production wastes or municipal waste, many of the potential downsides and controversies of SAFs are minimized or eliminated. However, there is growing concern that aviation is just one of many sectors increasingly reliant on bioenergy-based decarbonization, and that as the scale of reliance grows the risks of future poor supply chain choices increases. The two principal concerns are that land tensions with food production could lead to increased staple crop prices, especially impacting vulnerable populations, and that supply chain emissions – inclusive of land-use change emissions – undermine the abatement potential of SAFs.

Regarding food prices and land tensions, land is a limited resource, with much of the highly productive land already used for food production. It should be noted that many of the integrated assessment models (IAMs) that the IPCC and researchers rely upon to model whole-economy decarbonization pathways do not contain detailed and robust land-use modelling, and as such future land tensions with food production remain uncertain.

Supply chain emissions of SAFs are impacted by direct and indirect land-use change when bio-crops are initially planted, the use of fertilizers and pesticides, the change in soil carbon due to the health of the ecosystem being impacted by a monoculture

42 Carbon Engineering (2023), 'Air to Fuels', https://carbonengineering.com/air-to-fuels.

of bio-crops, and the use of fossil fuels in the cultivation, harvesting, processing and transport of the bio-crop. While it is theoretically possible to significantly minimize supply chain emissions, at the scale of individual farms the supply chain decisions are primarily driven by cost considerations, meaning the theoretical potential often hugely differs to the realities on the ground.

The emissions abatement potential of SAFs assumed in the JZS is in the range of 67–75 per cent emissions savings relative to kerosene.[43] And the high-ambition scenario projects around 5 million tonnes of SAF being required by 2050.[44] This volume of SAFs is equivalent to around 40 per cent of the UKs pre-pandemic jet fuel consumption.

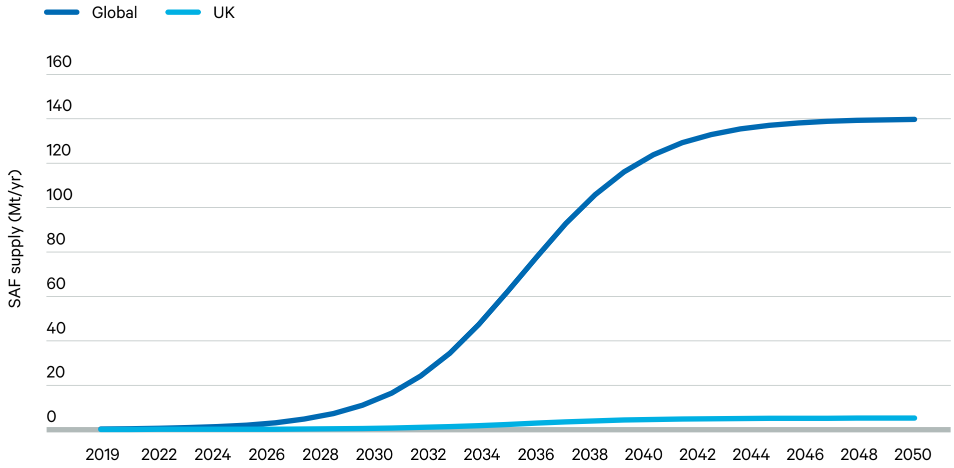
Determining the land area that this target may require is complex and depends on the type of land the bio-crops are grown on, the associated yield of that land, the process to convert the biomass into SAFs, the composition of the portfolio of feedstocks, and the proportion of wastes and residues utilized. However, an illustrative example is to assume all the biomass comes from miscanthus, which would require between 13–22 per cent of all UK agricultural land, based on the methodology of the Royal Society (2023).[45]

There are two model options to forecast the scale-up trajectory of SAFs. The first is based on the industry led *Sustainable Fuels UK Road-Map* report,[46] which is likely to be on the optimistic end of scale-up trajectories. This roadmap indicates that if the global aviation sector were to rely on SAFs to the same scale as the UK, 140–180 Mt of SAFs per year would be required by 2050. Given supply chains are likely to be global in nature and the UK will likely source various SAFs from global markets, it is assumed that the available supply of SAFs to the UK market is proportional to the UK's share of global jet fuel consumption, namely 3.6 per cent, where the lower bound is achieved by 2050. Hence, in the first SAF supply option in the model around 5.1 Mt is available to the UK aviation sector by 2050, a similar value to that assumed within the JZS high-ambition scenario.

While land availability could be a significant limitation to this global scale of SAFs, it is perhaps the rate of production ramp-up required that is more likely to limit supply in the near term. In 2020, global production of SAFs was around 0.1 Mt/yr,[47] meaning that out to 2050 supply would need to increase 1,400-fold to meet the global target of 140 Mt/yr, or at a compound annual growth rate (CAGR) of just less than 30 per cent per year. This rate of scale-up clearly embodies significant reliance risk. The modelling here assumes an s-curve scale-up trajectory (rather than a linear scale up), shown in Figure 10. The s-curve reaches its asymptotic value in 2050, the time horizon of net zero.

43 Department for Transport (2022), *Jet Zero illustrative scenarios and sensitivities*.
44 Department for Transport (2022), *Jet Zero Strategy: Delivering net zero aviation by 2050.*
45 The Royal Society (2023), *Net zero aviation fuels: resource requirements and environmental impacts,* https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/net-zero-aviation-fuels.
46 Sustainable Aviation (2018), *Sustainable Fuels UK Road-Map*, https://www.sustainableaviation.co.uk/wp-content/uploads/2018/06/SA-SAF-Roadmap-FINAL-24-Nov-2.pdf.
47 SkyNRG (2021), 'A Market Outlook on Sustainable Aviation Fuel', https://skynrg.com/a-market-outlook-on-sustainable-aviation-fuel.

Figure 10. S-curve scale up of global and UK SAF supply, from known current base



Source: Compiled by the author.

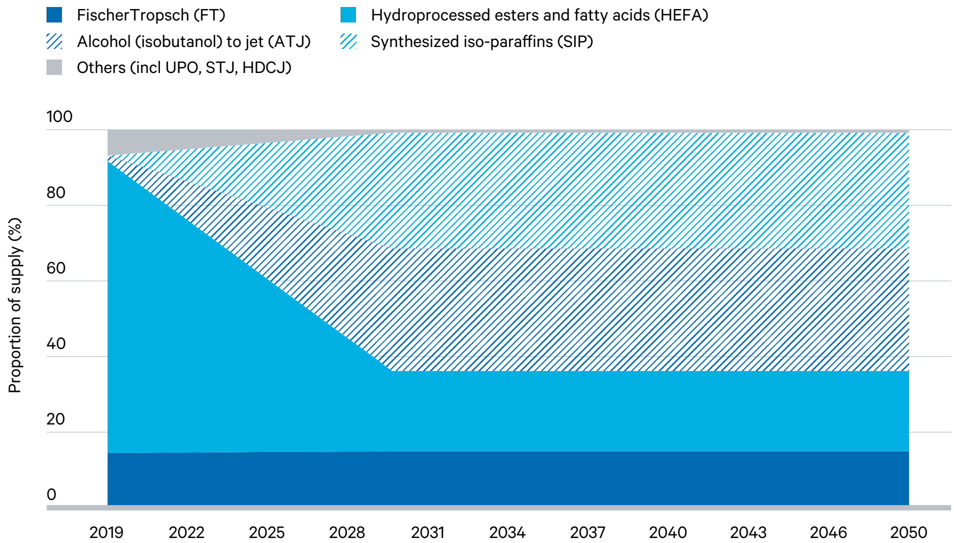
It should be noted that many other sectors, beyond aviation, are currently looking to bioenergy, including bio-crop feedstocks, within their decarbonization pathways, such as biofuels for road transport, biomass-based domestic heating and biomass feedstocks for BECCS. And as the IPCC working group 3 (WGIII) report recently stated, 'the potential to scale up bio-based SAF volumes is severely restricted by the lack of low cost and sustainable feedstock options'.[48] In an open letter to the secretary of state for transport in 2019, the CCC states, 'Our scenario has a 10% uptake of sustainable fuels in 2050. It is not appropriate to plan for higher levels of uptake at this stage, given the range of competing potential uses for biomass across the economy and uncertainty over which use will be most cost-effective.'[49]

The second option the model considers is that SAFs account for 10 per cent of jet fuel supply as assumed under the continuation of the current trends scenario of the JZS.[50] This second option can be thought of as a scenario in which reliance on bioenergy is reduced as supply may be limited due to competition between sectors for bioenergy production, as a means of limiting land tensions with food production, and more broadly as a means of minimizing reliance risks. It should be noted that the nature of this assumption means the 2050 supply varies depending on future demand (PAX-km). For instance, if demand increases by 70 per cent SAF supply in 2050 is around 2.2 Mt per year. However, if demand falls by 30 per cent, SAF supply in 2050 is around 0.9 Mt per year.

48 Intergovernmental Panel on Climate Change (2022), *Technical Summary, in Climate Change 2022: Mitigation of Climate Change – Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
49 Committee on Climate Change (2019), 'Letter: International aviation and shipping and net zero', page 9, https://www.theccc.org.uk/publication/letter-international-aviation-and-shipping.
50 Department for Transport (2022), *Jet Zero illustrative scenarios and sensitivities*.

The modelling of SAF emissions here differs from that of the JZS. As previously mentioned, the JZS assumed SAFs reduce emissions by 67–75 per cent, relative to kerosene.[51] The model for this paper takes an approach that forecasts the composition of the supply portfolio of SAFs, and their respective supply chain emissions, weighting these emissions by the proportion of the supply portfolio a given SAF represents. This results in a 58 per cent reduction in emissions relative to jet fuel, which is 13 percentage points lower than the average value used within the JZS. The modelled proportional split in SAF types over time is shown in Figure 11, and Figure 12 illustrates the assumed emissions for each SAF type compared to jet fuel.

Figure 11. Proportional split in SAF types over time



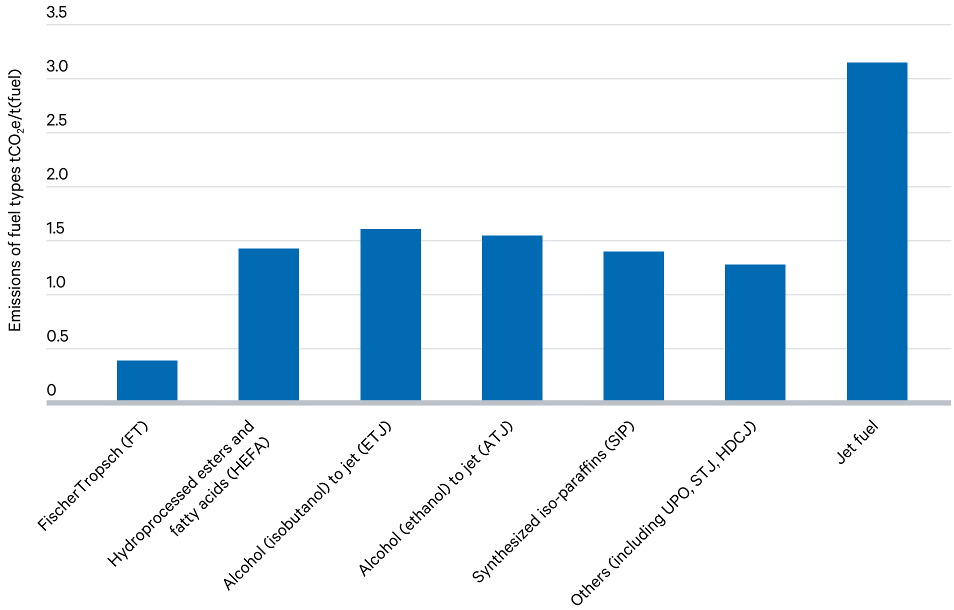
Source: Based on tables 5.1 and A5.7 in Sustainable Aviation (2018), *Sustainable Fuels UK Road-Map*, https://www.sustainableaviation.co.uk/wp-content/uploads/2018/06/SA-SAF-Roadmap-FINAL-24-Nov-2.pdf.

The life cycle emissions of each SAF type shown in Figure 12 are based on those defined by the International Civil Aviation Organization (ICAO) in 2021 for CORSIA eligible fuel, and an average for each SAF type across each production region.[52] The proportional split between SAF types over time (Figure 11) is based on current and assumed future production capacities within the *Sustainable Fuels UK Road-Map* report (2018) by the Sustainable Aviation industry consortium,[53] which assumes that 'the main constraint to the supply of sustainable fuels to 2030 is limited production capacity, due to the low levels of existing capacity and the early stage of development of the majority of technologies'. As such, from 2030 onwards global production capacity is based on the average between the reported

51 Ibid.
52 International Civil Aviation Organization (2021), *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels*, Table 1, https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202021.pdf.
53 Sustainable Aviation (2018), *Sustainable Fuels UK Road-Map*.

lower and upper build rates of SAF production facilities, average plant size and aviation fuel fraction.[54] The current SAF production proportional split is based on the reported operational and near-term planned facilities annual capacities.[55]

Figure 12. Life cycle emissions of SAF types, compared to jet fuel



Source: Based on Table 1, in International Civil Aviation Organization (2021), *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels*, https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202021.pdf.

3.3.1 The impact of SAF assumptions on demand reduction

This section summarizes the results of including a constrained SAF supply assumption within the modelling (scenario E). Previously, under the dynamic modelling of fuel efficiency improvements (scenario D), which factored in the risk of future aircraft not meeting the 'optimistic' assumptions of the JZS (see Figure 8 – option 3) and applied the per capita carbon budget (644 $MtCO_2$), demand (PAX-km) growth in 2050 would need to be constrained to 27 per cent above 2019 levels (scenario D, Figure 6D). However, this assumed SAF scale-up followed option 1 for supply, namely 5.1 Mt/yr supply in 2050. With option 2 (supplying 10 per cent of jet fuel supply), where reliance risks are reduced due to supply limitations as a consequence of feedstock competition between sectors, and there are land tension risks with food production, demand (PAX-km) would need to decrease by 1 per cent to achieve a balanced carbon budget (scenario E, Figure 6E). Under this scenario, SAFs supply is 1.2 Mt/yr in 2050.

54 Ibid., Table 5.1.
55 Ibid., Table A5.7.

3.4 Negative emissions

Along with agriculture, aviation is one of the most difficult sectors to decarbonize. Such sectors are likely to represent the largest residual emissions as 2050 approaches. Under net zero, it is generally accepted that these sectors will require the greatest share of negative emissions to balance their residual emissions. As was highlighted in section 1.1, there may well be an overshoot of the 1.5°C temperature limit before negative emissions technologies (NETs) are deployed. However, by this time tipping points may have already been triggered, vastly accelerating climate change and generating catastrophic impacts. This indicates the primary risk of relying on supply-side CO_2 removal technologies – i.e. that by the time they are ready, it may be too late to have a sufficient impact.

An increasing tension exists between public support for negative emissions arising from GGRs in a general sense, and the level of reliance on these technologies within prominent, policy-informing, decarbonization models and associated pathways. To explore this, it is first important to differentiate between GGR options. Nature-based solutions (NBS) include storing more carbon by increasing the amount of wood in construction, restoring peatlands and wetlands, and afforestation. Meanwhile, engineered NETs mainly centre around BECCS and DAC. While the public are generally in favour of NBS, they are less supportive of the engineered approach, and policy-informing models (such as the IAMs and CB6 of the CCC) tend to foresee greater technical potential from these engineered approaches.

A common concern among assembly members regarding BECCS and DAC was that they are 'treated as [a] magic solution' that 'takes the focus off the amount that we are emitting in the first place'.

For instance, 75 per cent of Climate Assembly members 'strongly agreed' or 'agreed' that they would like to see the aviation industry invest in GGRs, as a means of achieving net zero.[56] And while 'forests and better forest management' was supported by 99 per cent of assembly members, BECCS and DAC did not feature in the top four favoured GGR methods. Indeed, only 42 per cent of assembly members 'strongly agreed' or 'agreed' that BECCS and DAC should be part of how the UK gets to net zero, respectively. Furthermore, 36 per cent of assembly members 'strongly disagreed' or 'disagreed' with the inclusion of BECCS, with 39 per cent for DAC. This is concerning, given that the balanced net zero pathway forecasts slightly more than 53 per cent of negative emissions coming from BECCS, and 5 per cent from DAC. Although BECCS has the least public support, prominent decarbonization pathways rely on this technology.

A common concern among assembly members regarding BECCS and DAC was that they are 'treated as [a] magic solution' that 'takes the focus off the amount that we are emitting in the first place'.[57] This concern has been echoed by a prominent

56 Climate Assembly UK (2020), *The path to net zero: How we travel by air*.
57 Ibid.

analysis that highlights that 'promises of GGR might instead deter or delay emissions reduction' and that the possible extent of 'mitigation deterrence' could result in an additional temperature rise of up to 1.4°C, in pathways expected to limit increases to 1.5°C.[58] In 2018, a report from the European Academies' Science Advisory Council, which advises the EU and is comprised of the national science academies of the 27 member states, highlighted that relying on NETs, including BECCS, rather than pursuing greater emissions reductions, could catastrophically fail, resulting in 'serious implications for future generations'.[59]

In 2022, the sustainability of BECCS was questioned by the UK government. In a meeting with MPs, Kwasi Kwarteng, the then secretary of state for business, energy and industrial strategy, admitted that biomass was not developing at the pace of other renewables, and said, 'I can well see a point where we just draw the line and say [biomass] isn't working, this doesn't help carbon emission reduction and so we should end it', adding, 'All I'm saying is that we haven't quite reached that point yet', and that imported biomass was 'not something that the UK should be relying on at large scale'.[60]

As with SAFs, a big risk of BECCS is potential land tensions with food production. In the near term, BECCS in the UK is likely to be deployed with the use of wood pellet feedstocks.[61] The leading BECCS developer (Drax) uses 97 per cent woody biomass (3 per cent agricultural residues[62]), and the global supply of pellets comprised of other feedstocks remains marginal. However, many decarbonization pathways envisage the use of a wide range of feedstocks, inclusive of bio-crops, with land tensions minimized as sustainable agricultural practices are assumed to increase the yield of crops per hectare of land use. However, future climate risks indicate crop yields could be under threat. Regardless, land tensions are likely to be significant. In 2022, the IPCC AR6 WGIII report indicated the cropland area to supply biomass for bioenergy and BECCS would equate to 199 (from a range of 56–482) million hectares (Mha) in 2100, equivalent to 13 per cent of global cropland.[63]

To scale BECCS in the UK, based solely on the combustion of wood pellets to meet the CCC CB6 2050 target of 51 $MtCO_2$/yr would require the combustion of more than four times that currently burnt at Drax. It is also interesting to note that the BECCS removal target of 51 $MtCO_2$/yr would require 119 per cent of the 26 Mt of wood pellets consumed across the EU27 and the UK, which in turn represents 50 per cent of global consumption.[64]

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58 McLaren, D. (2020), 'Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques', *Climatic Change* 162, pp. 2411–2428, https://doi.org/10.1007/s10584-020-02732-3.
59 European Academies' Science Advisory Council (2018), *Negative emission technologies: What role in meeting Paris Agreement targets?*, https://easac.eu/publications/details/easac_net.
60 Hodgson, C. and Parker, G. (2022), 'UK minister questions sustainability of Drax biomass fuel', *Financial Times*, 10 August 2022, https://www.ft.com/content/3b18291e-9449-45fd-9517-8edb8433fbfe.
61 Quiggin, D. (2021), *BECCS deployment: The risks of policies forging ahead of the evidence*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/sites/default/files/2021-09/2021-10-01-beccs-deployment-quiggin.pdf.
62 Drax (2021), 'Sourcing Sustainable Biomass', https://www.drax.com/sustainability/sustainable-bioenergy/sourcing-sustainable-biomass.
63 Intergovernmental Panel on Climate Change (2022), *Technical Summary*, in *Climate Change 2022: Mitigation of Climate Change – Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
64 Bioenergy Europe (2019), *Statistical Report 2019*, https://epc.bioenergyeurope.org/wp-content/uploads/2020/02/SR19_Pellet_final-web-1.pdf.

Given that the principal objective of BECCS is to remove CO_2 from the atmosphere and permanently store it in geological formations, feedstock choice should ensure the greatest carbon efficiency and hence net negativity. Carbon efficiency can be thought of as the proportion of carbon input to the whole BECCS system that is geologically stored. To produce any feedstock for BECCS the supply chain will involve processes that result in the emission of CO_2. For instance, from land-use change, farming practices, the drying of the biomass, palletization of the dried biomass, transport and any uncaptured emissions in the final process. The greater the carbon efficiency (proportion of CO_2 geologically stored) the less feedstock required to achieve a given removal target. If less feedstock is required, less land is needed, which in turn minimizes the risk of land tensions with food production. In the UK, wheat straw may be the feedstock with the optimal carbon efficiency: 74–72 per cent of CO_2 is geologically stored, and 26–28 per cent emitted to the atmosphere. As such, for a finite land area, wheat straw-based BECCS would remove more CO_2 from the atmosphere, compared to other feedstocks, when the risks of carbon debt of woody biomass are factored in.[65]

Box 1. What is BECCS?

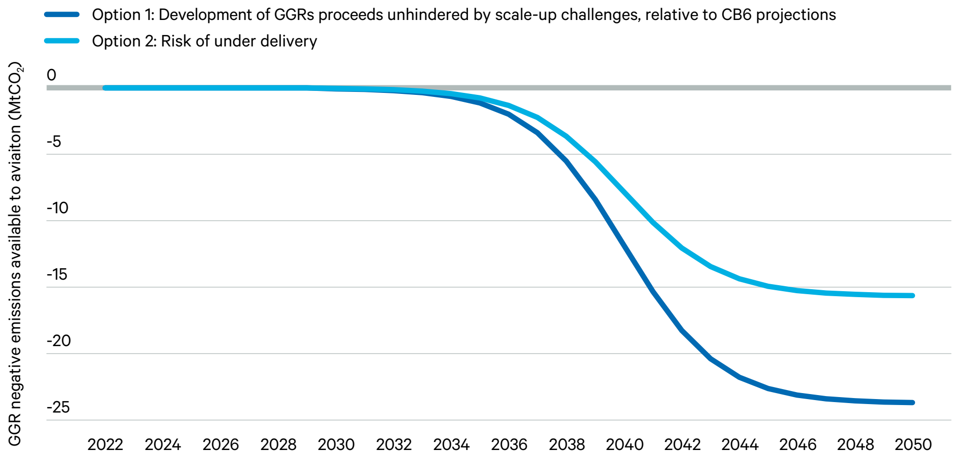
BECCS refers to any technology that utilizes bioenergy to produce energy, while also capturing and storing the majority of the resulting CO_2 emissions. Bioenergy could take the form of woody biomass (whole trees and forest wastes, such as thinnings) or dedicated bio-crops such as switchgrass, and agricultural wastes and residues. The produced energy can take the form of electricity, hydrogen or biofuels.

All crops and trees absorb atmospheric CO_2 as they photosynthesize. If CO_2 emissions from the combusted biomass (in the case of BECCS-to-power) can be captured and stored, and the combusted biomass replaced by new growth, then in aggregate CO_2 could be removed from the atmosphere. This is contingent on emissions along the supply chain being lower than the CO_2 stored.

Carbon capture and storage (CCS) is therefore key to transforming a bioenergy power plant into a BECCS facility. The 'capture rate' is the proportion of CO_2 that the CCS equipment captures, relative to that released to the atmosphere, and is generally cited as being 90 per cent or more. Post-combustion capture generally utilizes a solvent that the stack emissions are passed over. The molecules of the solvent attach themselves to CO_2 molecules, which are then released from the solvent by applying heat. This heat can be supplied from the combustion of the initial biomass. However, this is the same heat that is being utilized within the turbine to generate electricity. As such, there is an 'energy penalty' attached to the CCS process that lowers the efficiency of the BECCS power plant relative to an equivalent bioenergy power plant. Or in other words, BECCS-to-power facilities will experience greater declines in power production efficiency to achieve higher capture rates. The permanence of stored CO_2 is critical, as is the ability of the system to safely and efficiently transport the captured CO_2 to underground geological formations.

65 Quiggin, D. (2021), *BECCS deployment: The risks of policies forging ahead of the evidence*, Research Paper, London: Royal Institute of International Affairs https://www.chathamhouse.org/sites/default/files/2021-09/2021-10-01-beccs-deployment-quiggin.pdf.

Figure 13. Assumed availability of negative emissions



Source: Compiled by author.

To assess the availability of negative emissions to offset aviation sector emissions, it is integral not just to evaluate the likely supply of the various GGR options, but also to consider the decarbonization trajectory of all sectors of the economy, and hence the competing demands for such offsets. The CB6 modelling of the CCC provides UK ministers with advice on the volume of greenhouse gases the UK can emit between 2033 and 2037. Under the balanced net zero pathway of CB6, aviation represents 24.5 per cent of the time-averaged proportion of emissions across all sectors of the UK economy. As such, the model used in this paper allocates this proportion of all negative emissions to the aviation sector in any given year. Furthermore, the balanced net zero pathway forecasts that there will be 97 $MtCO_2$/yr of negative emissions available by 2050, across engineered removal options, and land use, land-use change and forestry (LULUCF) sinks.[66] From this starting point, the model allows for two options. The first presumes the development of GGRs proceeds unhindered by scale-up challenges, relative to CB6 projections. The second option builds in the risk of under delivery, reducing the availability of negative emissions in all years by 33 per cent. Both options follow s-curve scale-ups, with the resulting availability of negative emissions to the aviation sector shown in Figure 13. This 33 per cent reduction in the availability of negative emissions is representative of four main factors:

1. Public acceptance of engineered negative emissions in the UK does not match the level of reliance indicated by prominent decarbonization pathways that are influencing policy decisions.

2. Land-use tensions with food production could prohibit the large-scale deployment of BECCS, particularly if global food price inflation continues and climate impacts reduce future yields.

3. Political support for BECCS in the UK appears to be waning.

4. The supply chain emissions of BECCS may partially undermine the net-negativity of BECCS.

66 Climate Change Committee (2021), 'Sixth Carbon Budget – Dataset (Version 2 – December 2021)', https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-Dataset_v2.xlsx.

Box 2. The UK aviation sector must consider the risks of relying on negative emissions offsetting

The IAMs used by the IPCC to assess decarbonization pathways are critical to understanding why future negative emissions and associated offset credits have become so important to net zero, across many sectors, both globally and nationally. The cost-optimizing nature of the IAM scenarios is critical to understanding the reasons for such heavy reliance on BECCS.[67] The models attempt to find the least-cost means of achieving a given temperature limit. As BECCS is anticipated to produce energy and remove atmospheric CO_2 simultaneously, and both these societal goods have associated costs and benefits to them, it is arguable that there is an inbuilt bias in IAMs towards selecting BECCS. This is a concern as certain cost assumptions in some IAM decarbonization options are 'out of date', such as those for solar PV and other renewables,[68] which have rapidly fallen in cost over the last decade. For instance, in 2019, researchers noted that a paper published in 2015 reporting on the results from one IAM included solar PV and storage capital costs based on a 2008 analysis.[69]

With estimates of net zero targets now covering around 90 per cent of the world's economic activity,[70] the robustness of the UK's development of negative emissions to offset residual emissions is crucial to ensure that reliance on negative emissions does not undermine efforts to decarbonize. Recent reports have highlighted this risk, for instance, the Energy and Climate Intelligence Unit's March 2021 report states, 'Studies show that offsets [including removal offsets] do not always provide fully additional effort, and reliance on them may present risks to effective mitigation… Put simply, offsetting cannot be a substitute for significant emissions cuts'.[71] As is discussed in section 4.4, there are severe concerns that most carbon offsets eligible under the aviation sector's offset scheme (CORSIA) only 'have minor climate integrity'.[72]

As was recently highlighted by Rogelj et al. (2021) – 'sometimes the targets [net zero] do not aim to reduce emissions, but compensate for them with offsets… cheap offsets can mean that a company makes limited effort to address its own emissions… targets must specify… whether the intent is to reduce, remove or offset the emissions'.[73] Microsoft is considering using BECCS and DAC, British Airways' parent company International Airlines Group (IAG) is exploring DAC, and of the 42 companies that had announced net zero targets in 2019–20, nearly two-thirds plan on using NETs.[74] Many of these companies simply plan on compensating for emissions with offsets, rather than committing to actual reductions.[75]

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67 Gambhir, A. et al. (2019), 'A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS', *Energies*, 12(9), doi:10.3390/en12091747.
68 Ibid.
69 Ibid.
70 UNEP (2022), 'Climate + nature = one agenda to reach net zero', https://www.unepfi.org/themes/climate-change/climate-nature-one-agenda-to-reach-net-zero.
71 Energy & Climate Intelligence Unit (2021), *Taking stock: A global assessment of net zero targets*, London: ECIU, https://eciu.net/analysis/reports/2021/taking-stock-assessment-net-zero-targets.
72 Wozny, F., Grimme, W., Maertens, S. and Scheelhaase, J. (2022), 'CORSIA–A Feasible Second Best Solution?', *Applied Sciences*, 12(14), 7054, https://doi.org/10.3390/app12147054.
73 Rogelj, J., Geden, O., Cowie, A. and Reisinger, A. (2021), 'Net-zero emissions targets are vague: three ways to fix', https://www.nature.com/articles/d41586-021-00662-3.
74 Vivid Economics (2020), *An investor guide to negative emission technologies and the importance of land use*, https://www.vivideconomics.com/casestudy/an-investor-guide-to-negative-emission-technologies-and-the-importance-of-land-use.
75 Rogelj, Geden, Cowie and Reisinger (2021), 'Net-zero emissions targets are vague: three ways to fix'.

Furthermore, the CCC recently stated, 'High-integrity carbon credits purchased by businesses can play a small but important role in supporting the transition to Net Zero. But before growing voluntary carbon markets, Government must put in place stronger guidance, regulation and standards to ensure purchase of carbon credits is not used as a substitute for direct business emissions reduction, and to improve the integrity and transparency of carbon credits. In the absence of these measures, there is a real risk that voluntary carbon markets slow progress towards Net Zero.'[76]

3.4.1 The impact of negative emission assumptions on demand reduction

If the risks of under delivery assumed in option 2 in Figure 13 were to become a reality, aviation demand (PAX-km) would need to reduce further. Previously, with dynamic modelling of fuel efficiency improvements – factoring in the risk of future aircraft not meeting the 'optimistic' assumptions of the JZS (Figure 8 – option 3), applying the per capita carbon budget (644 $MtCO_2$), and taking into account the more realistic assumption of 10 per cent of jet fuel supply from SAFs – demand (PAX-km) would need to decrease by 1 per cent to achieve a balanced carbon budget (scenario E, Figure 6E). Keeping all of these assumptions constant, but in addition assuming the negative emissions availability of option 2 shown in Figure 13, demand (PAX-km) would need to reduce by 24.5 per cent (scenario F, Figure 6F).

76 Committee on Climate Change (2022), *Voluntary Carbon Markets and Offsetting*, https://www.theccc.org.uk/publication/voluntary-carbon-markets-and-offsetting.

04 Balancing demand management and reliance on future supply-side solutions

Near-term demand reduction policies could preserve an outside chance of remaining within carbon budgets and minimize the impacts of climate change.

4.1 Demand management in the near term can buy time for supply-side solutions in the long term

Stepwise through Chapter 3 this paper investigated the supply-side options for decarbonizing the UK aviation sector, with the aim of reducing the risks of overly relying on yet unscaled supply-side solutions, and simultaneously keeping within the UK aviation sector's fair share of carbon budgets. The net result of reducing these risks is that aviation demand in 2050 would need to be 24.5 per cent lower than in 2019.

Given the severe risks of climate change, the continuing inflationary period that is impacting the global economy, and the dampened demand for aviation particularly due to the COVID-19 pandemic, there is an opportunity to consider a greater near-term reduction in the number of flights and the average journey distance. This approach could add significant value to net zero strategies as many of the supply-side decarbonization solutions available to the aviation sector are still in their infancy, and hence need time to develop. Furthermore, given how tight carbon budgets are to avoid catastrophic climate change, a precautionary approach is not just prudent, but necessary. As such, the analysis in this paper includes one last scenario that puts the emphasis of demand reduction on the near-term, rather than relying on incremental demand reduction each year out to 2050. To model the demand reduction required in the near term, demand follows a Wald or inverse gaussian distribution, which can also be thought of as an inverse bell curve. As with all other scenarios, the model is constrained to ensure that the level of demand balances against the defined carbon budget with all the supply-side decarbonization options applied.

Given how tight carbon budgets are to avoid catastrophic climate change, a precautionary approach is not just prudent, but necessary.

The net result of this final scenario is that demand (PAX-km) in 2030 would need to be 36.1 per cent lower than in 2019, with demand returning to 2019 levels by 2050 (scenario G, Figure 6G). For context, demand in 2022 is modelled as being 34.7 per cent lower than 2019, due to the COVID-19 pandemic. It should be noted that the future deployment of supply-side decarbonization options results in the emission intensity of flights in the near-term being greater than that in the future. As such, for an equivalent carbon budget, demand management in the near term would need to be greater than future demand management. Hence, in this final scenario (scenario G, Figure 6G), the necessary demand reduction of 36.1 per cent in 2030 is 11.6 percentage points greater than the 24.5 per cent reduction in 2050 of scenario F. This approach of near-term demand management to enable supply-side decarbonization is aligned with the CCC progress update of October 2022,[77] which states, 'The Government's plans for aviation focus on sustainable aviation fuel and zero/low-emission aircrafts. These technologies have potential, but there are significant risks in their delivery. In the near term, managing demand would have a much greater benefit for the climate.'

Within all scenarios, inclusive of near-term demand management scenario G, it is assumed that demand (PAX-km) continues to rebound from the impact of COVID-19 lockdowns in 2020 and 2021, recovering to pre-pandemic levels by the end of 2024. And that any UK government policy to enact near-term demand management will take time to implement, be that by means of a frequent flyer levy or equivalent policy that encourages passengers to fly less frequently and shorter distances. The net result of this can be seen in Figure 6G, where demand initially recovers from a low of 34.7 per cent below 2019 levels in 2022, back to 2019 levels

77 Committee on Climate Change (2022), 'Progress Snapshot: October 2022', https://www.theccc.org.uk/uk-action-on-climate-change/progress-snapshot (accessed 23 Jan. 2023).

at the end of 2024, and then starts to decline again in 2026 as a frequent flyer levy or equivalent policy mechanism begins to reduce the number and distances of flights taken, towards the 2030 low of 36.1 per cent below 2019 levels. Through the 2030s demand then starts to return and by 2040 is almost 99 per cent that of 2019 levels as supply-side decarbonization measures ramp up.

Clearly a demand suppression policy mechanism, such as the frequent flyer levy, could be pursued before 2026. However, it is unlikely that the UK government will act before that time. This is particularly true given the prime minister's recent net zero announcements that included a pledge not to introduce 'new taxes to discourage flying'.[78] This is based on two main factors. Firstly, that the political motivation to limit flying immediately post the pandemic, just as the public is enjoying a return to 'normality', is low. Secondly, accelerating climate impacts will likely result in additional public pressure on the government to act swiftly to reduce additional future impacts, and that this dynamic will take a few years to fully manifest. That said, the faster the UK government acts, the lower the risk of severe climate impacts and the smaller the UK contribution will be to both exceeding carbon budgets and runaway climate change.

As previously highlighted, many of the supply-side solutions to decarbonizing the aviation sector are yet to be commercially scaled, and significant uncertainty and risk surrounds many of the technologies, particularly regarding engineered negative emissions. Near-term demand management offers policymakers a risk minimization scenario that enables supply-side solutions time to develop and catch up, commensurate with the risks embodied by dwindling carbon budgets.

This final scenario also has the opportunity of stimulating greater investment in sustainable supply-side solutions. Clearly lower demand will result in lower profits, which could undermine investment from the aviation sector itself. However, given that this scenario forecasts demand to return to 2019 levels, following the near-term demand management measures, this scenario actually represents a greater long-term growth outlook than the supply-led decarbonization pathways modelled here that factor in under delivery. Furthermore, if demand management is prioritized out to 2030, the aviation sector and wider investment community is likely to increase funding for supply-side decarbonization solutions in order to unleash future demand.

It should be noted that, the CCC progress report of June 2023 recommended the development of an aviation demand-management policy framework,[79] to be deployed in the late-2020s in the event of underperformance of decarbonization measures against the JZS projections (recommendation 116). In addition, the CCC also explicitly recommended fiscal policies should be used to raise the price of flying to act as 'an effective signal to consumers that aviation has high emissions costs', and suggested the use of either taxation, quotas or a frequent flyer levy (recommendation 58).

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78 Coffey, H. (2023), 'No Rishi, there aren't any 'new taxes to discourage flying' – if only there were', *Independent*, 21 September 2023, https://www.independent.co.uk/travel/news-and-advice/rishi-sunak-taxes-flights-flying-b2415807.html.
79 The Committee on Climate Change (2023), *2023 Progress Report to Parliament*, https://www.theccc.org.uk/publication/2023-progress-report-to-parliament.

4.2 Inclusion of non-CO_2 warming would increase the need for demand reduction

Google has recently been at the centre of controversy around the non-CO_2 effects of flying.[80] Having previously reported emissions in kilogrammes of carbon dioxide equivalent (CO_2e), inclusive of water vapour emitted at high altitudes as part of an aircraft's contrails, Google has now halved the emission figures it reports to users, stating that 'we strongly believe that non-CO_2 effects should be included in the model, but not at the expense of accuracy for individual flight estimates'.

Within the JZS, the UK government omits non-CO_2 effects from its decarbonization pathways for the aviation sector, citing scientific uncertainties in the global warming effect.[81] However, while there is a wide range of associated uncertainty, there is still a high probability that non-CO_2 aviation emissions (particularly cirrus contrails) cause significant additional global warming.

The inclusion of non-CO_2 effects in the model used in this paper results in a significant contraction of carbon budgets, and an increase in the need for demand management measures.

A recent scientific study found that non-CO_2 impacts comprise about two-thirds of the net radiative forcing from aviation.[82] The minimum likely effective radiative forcing (ERF) value is 55 mWm^{-2} (milliwatts per square meter), which is 60 per cent higher than the warming from CO_2 alone (34.3 mWm^{-2}). The maximum likely ERF value is 420 per cent higher than the warming from CO_2 alone. The most probable ERF value of 100.9 mWm^{-2} is 294 per cent higher than the warming from CO_2 alone.

There are mitigations, besides flying less, that could reduce non-CO_2 effects. Contrail cirrus contributes the bulk of non-CO_2 aviation warming and can be reduced through alternative flightpaths to avoid areas susceptible to contrail formation, and alternative 'low aromatic' fuels to reduce combustion soot, which in turn reduces contrail formation. Both solutions could be deployed rapidly, within a few years, to eliminate a significant portion of non-CO_2 warming.

A recent study,[83] looking at aviation contrail climate effects in the North Atlantic from 2016 to 2021 showed that, 'around 12% of all flights in this region cause 80% of the annual contrail energy forcing'. Furthermore, Teoh et al. (2020) state that, 'a small-scale strategy of selectively diverting 1.7% of the fleet could reduce the contrail energy forcing by up to 59.3%'. And that this would only increase both

80 Hern, A. (2022), 'Google accused of airbrushing carbon emissions in flight search results', *Guardian,* 25 August 2022, https://www.theguardian.com/technology/2022/aug/25/google-accused-airbrushing-carbon-emissions-flight-search-results.
81 Department for Transport (2022), *Jet Zero: further technical consultation,* p. 14, section 3.4.
82 Lee, D. S. et al. (2021), 'The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018', *Atmospheric Environment*, Volume 244, 117834, https://doi.org/10.1016/j.atmosenv.2020.117834.
83 Teoh, R. et al. (2022), 'Aviation contrail climate effects in the North Atlantic from 2016 to 2021', *Atmospheric Chemistry and Physics*, 22(16), pp. 10919–10935, https://doi.org/10.5194/acp-22-10919-2022.

total fuel consumption and CO_2 emissions by 0.014 per cent each.[84] Alternative flightpaths could therefore be implemented on a relatively small proportion of flights to achieve significant reductions in contrails. For journeys where altering a flightpath may result in an unacceptable increase in fuel consumption, alternative 'low aromatic' fuels could be deployed.[85]

NGOs have raised concerns about the exclusion of non-CO_2 effects within the DfT modelling:

> DfT pathways are substantially underestimating the warming impact of aviation emissions. The DfT currently excludes non-CO_2 emissions as they feel scientific understanding is lacking but this is unlikely to be the case by 2035 when it could be included in the modelling. This presents a major risk that the aviation emission budget could suddenly become much more challenging to reduce with limited time to respond with new technology solutions.[86]

The inclusion of non-CO_2 effects in the model used in this paper results in a significant contraction of carbon budgets, and an increase in the need for demand management measures. Assuming that non-CO_2 effects result in a CO_2e value that is 2.94 times greater (see above) than CO_2 emissions for the years 2022 to the end of 2024, it is estimated that demand reduction in 2030 would change from 36.1 per cent to more than 60 per cent in scenario G. It is also assumed that by 2025 non-CO_2 warming has been eliminated based on the mitigation measures mentioned earlier. However, in the author's view, this assumption is highly optimistic. Furthermore, it should be noted that for every year that passes where non-CO_2 effects continue to go unaccounted for, and unaddressed through policy, the non-CO_2 warming effect is eating into the remaining effective carbon budget.

4.3 The economic benefits of flying, and the social cost of carbon emissions

If the UK government were to pursue policy mechanisms to manage flight demand, it would be crucial to consider the benefits accrued from avoiding the worst impacts of climate change, relative to the reduction in gross domestic product (GDP) that demand management may bring about. It is out of the scope of this research paper to determine what the economic impact may be for a given level of demand reduction. However, in designing demand-management policies it is vital to consider the indirect contributions towards GDP as well as the counterfactual benefits.

Calculating the economic benefits of aviation in terms of the sector's contribution towards GDP and gross value added (GVA) is complex, with different reports and studies providing varying estimates. As a 2021 study states, 'no theoretical

84 Teoh, R., Schumann, U., Majumdar, A. and Stettler, M. E. J. (2020), 'Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption', *Environmental Science and Technology*, 54(5), pp. 2941–2950, https://doi.org/10.1021/acs.est.9b05608.
85 CE Delft (2022), *Potential for reducing aviation non-CO_2 emissions through cleaner jet fuel,* https://ce.nl/wp-content/uploads/2022/04/CE_Delft_210410_Potential_reducing_aviation_non-CO2_emissions_cleaner_jet_fuel_FINAL.pdf.
86 Element Energy (2022), *The Role of Aviation Demand Reduction in UK Decarbonisation: Report for Aviation Environment Federation,* http://aef.org.uk/uploads/2022/05/The-Role-of-Aviation-Demand-in-Decarbonisation-Full-Report.pdf.

framework has yet been presented that comprehensively captures the full set of mechanisms by which aviation can contribute to economic development. Such a framework would cover both positive and negative regional impacts, as well as the mechanisms and spatial distribution behind them'.[87] An Oxford Economics (2014)[88] report breaks down the positive economic contributions into four categories:

— **Direct:** the output and employment of the firms in the aviation sector.

— **Indirect:** the output and employment supported through the aviation sector's purchases of input goods and services from its UK supply chain.

— **Induced:** employment and output supported by the aviation sector and the firms in its supply chain paying wages to their staff, who spend part of their income in the UK.

— **Catalytic:** the economic activity enabled by the aviation sector. Some of these include the activity supported by the spending of foreign visitors travelling to the UK via air, and the level of trade directly enabled by the transportation of merchandise.

Based on the first three of these categories, Oxford Economics' headline estimate of the aviation sector contribution towards GVA in 2014 was £52 billion per annum. Adding in the catalytic benefits, this total increases to around £71.5 billion.[89]

More recently, the Aerospace Growth Partnership in 2022 estimated the 'UK aerospace industry had an annual turnover of £22.4 billion in 2021' and reported the sector's GVA contribution as £8 billion in 2021.[90] Cumulatively out to 2035, the Aerospace Growth Partnership anticipates the sector will contribute £191 billion towards GVA, or an average of £14 billion per annum over the next decade.[91] The UK government's JZS[92] and the Sustainable Aviation industry report[93] both estimate that the aviation sector directly contributed at least £22 billion per year to the UK economy prior to the COVID-19 pandemic. However, the House of Commons Transport Committee suggests the 'entire aviation industry' contributed *almost* £22 billion in 2019.[94]

Not only are indirect, induced and catalytic economic benefits of the aviation sector complex to calculate, but the official UK authority on GDP statistics, the Office for National Statistics (ONS), does not calculate or record GDP values specifically for the aviation sector.[95] When turning to GVA values, the ONS lists 'Air transport'

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87 Lenaerts, N., Allroggen, F. and Malina, R. (2021), 'The economic impact of aviation: A review on the role of market access', *Journal of Air Transport Management*, https://www.sciencedirect.com/science/article/pii/S0969699720305822.
88 Oxford Economics (2014), *Economic Benefits from Air Transport in the UK*, https://www.aoa.org.uk/wp-content/uploads/2014/11/Economic-Benefits-from-Air-Transport-in-the-UK.pdf.pdf.
89 Ibid.
90 Aerospace Growth Partnership (2022), *Destination Net Zero*, https://aerospacegrowthpartnership.files.wordpress.com/2022/07/destination-net-zero-agp-strategy-for-net-zero-aerospace.pdf.
91 Noting the report is not clear as to its baseline year.
92 Department for Transport (2022), *Jet Zero Strategy: Delivering net zero aviation by 2050*.
93 Sustainable Aviation (2023), *Roadmap for the development of the UK SAF industry*, https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/Sustainable-Aviation-SAF-Roadmap-Final.pdf.
94 House of Commons Transport Committee (2022), *UK aviation: reform for take-off – Fifth Report of Session 2021–22*, https://committees.parliament.uk/publications/21967/documents/163200/default.
95 Office for National Statistics (2023), 'Standard Industrial Classification', https://www.ons.gov.uk/filters/f097989b-1467-4478-b3ca-a34ed5763776/dimensions/unofficialstandardindustrialclassification.

(sector code KK7P) as contributing around £5.5 billion in 2019.[96] To derive the value of almost £22 billion,[97] the House of Commons Transport Committee report draws on this ONS data series, and includes the additional sector of 'Air and spacecraft and related machinery' (sector code KK65), as well as the results of the ONS Annual Business Survey on the non-financial business economy.[98]

Not only do GDP and GVA estimations vary significantly for the aviation sector, so, too, do the number of jobs that the industry supports. The Aerospace Growth Partnership estimates 111,000 direct jobs,[99] the House of Commons Transport Committee suggests 500,000 jobs of an unspecified type,[100] and Oxford Economics produced a figure of up to 1.4 million (across all the categories listed above).[101]

Taking the average yearly GVA projection of the Aerospace Growth Partnership (£14 billion/yr) as a lower bound, and the 2014 estimate by Oxford Economics (£71.5 billion) as an upper bound, this translates to a range of £354–£1,805 per tCO_2 emitted, based on 2019 emissions from the sector. However, if non-CO_2 warming is factored in (see section 4.2) this economic benefit falls to around £120–£614 per tCO_2 emitted. For the more commonly quoted value of around £22 billion, the economic benefit would be around £189 per tCO_2 emitted (inclusive of non-CO_2 warming).

It is instructive to compare the economic benefit of the aviation sector to the social cost of carbon (SCC), which measures the marginal cost (commonly in dollars or pounds per tCO_2) of climate impacts brought about by each extra tonne of carbon emissions. A recent Nature paper[102] – which uses 'improved probabilistic socioeconomic projections, climate models, damage functions, and discounting methods' – estimates the mean SCC at \$185 per tCO_2 (\$44–\$413 per tCO_2: 2020 US dollars), or £144 per tCO_2 (£34–£322 per tCO_2, based on the average 2020 exchange rate[103]).

As with most calculations of the SCC, this mean value of £144 per tCO_2 is calculated within an IAM. It is important to note that the damage functions – which define the damage to society due to climate change – within IAMs regularly fail to fully capture the potential impacts of climate change, especially in the context of the tipping points highlighted in section 1.1. This was highlighted in a 2021 paper by the world-renowned economists Nicholas Stern and Joseph Stiglitz,[104] who stated, 'the estimates of damages from climate change in these IAMs is much smaller than is likely to occur. Not surprisingly, results on optimal

96 Office for National Statistics (2023), 'GDP output approach – low-level aggregates', https://www.ons.gov.uk/economy/grossdomesticproductgdp/datasets/ukgdpolowlevelaggregates/current.
97 UK Parliament (2022), *UK aviation: reform for take-off: Government Response to the Committee's Fifth Report of Session 2021-22*, footnote 71, https://publications.parliament.uk/pa/cm5803/cmselect/cmtrans/542/report.html.
98 Office for National Statistics (2021), *Non-financial business economy, UK and regional (Annual Business Survey): 2021 results*, https://www.ons.gov.uk/businessindustryandtrade/business/businessservices/bulletins/nonfinancialbusinesseconomyukandregionalannualbusinesssurvey/2021results.
99 Aerospace Growth Partnership (2022), *Destination Net Zero*.
100 UK Parliament (2022), *UK aviation: reform for take-off: Government Response to the Committee's Fifth Report of Session 2021-22*.
101 Oxford Economics (2014), *Economic Benefits from Air Transport in the UK*.
102 Rennert, K. et al. (2022), 'Comprehensive evidence implies a higher social cost of CO_2', *Nature*, 610, pp. 687–692. https://doi.org/10.1038/s41586-022-05224-9.
103 Average exchange rate in 2020: 0.7798 GBP.
104 Stern, N. and Stiglitz, J. (2021), *The social cost of carbon, risk, distribution, market failures: an alternative approach*, NBER working papers, National Bureau of Economic Research, https://files.static-nzz.ch/2021/4/26/7e32b21f-81b9-4033-907c-7aaeba85e7a5.pdf.

policy change dramatically if the assumed damages from climate change are much larger'. Stern and Stiglitz go further, stating that there is 'a systematic bias towards reducing the strength of action on climate change, that results from underestimating the benefits and overestimating the costs of such action', and that the 'intuitions of the scientific community may well be right: the simplistic models of the economists have simply not captured essential aspects of the societal decision problem'.

According to world-renowned economists Nicholas Stern and Joseph Stiglitz, 'the estimates of damages from climate change in these IAMs is much smaller than is likely to occur. Not surprisingly, results on optimal policy change dramatically if the assumed damages from climate change are much larger'.

To avoid distortions in the economic costs and benefits of demand management within the aviation sector, assessments should consider the positive economic impacts of demand management alongside the resulting lowered emissions and the reduced likelihood of climate change impacts. Positive economic impacts include, but are not limited to, a shift to other modes of transportation that may increase investment and job opportunities in these alternative forms of transport, as well as the potential for the expansion of domestic tourism. Furthermore, another benefit of flying that is difficult to quantify is the increased likelihood of securing foreign investment in UK businesses and improved trade. The counterfactual to this is how online meetings have expanded since the pandemic, meaning senior executives potentially have more time for multiple online investment meetings in the time of the average business flight. It should be noted that since 2002 business travel has fallen as a proportion of all flights, from 24 per cent in 2002, to 17 per cent in 2019.[105] At the same time, the proportion of homeworking has grown, with one recent report indicating that flexible working could contribute £37 billion to the UK economy.[106]

In July 2023, the New Economics Foundation found that increased air capacity can result in improved economic growth in less developed and less connected nations, as well as nations with a 'strong inbound tourism bias'. But in nations such as the UK, with a 'strong outbound tourism bias', economic growth from the aviation sector 'appears to rely almost entirely on the presence of business air passengers'.

105 Statistica (2020), 'Distribution of travel purpose from selected airports in the United Kingdom (UK) between 2002 and 2019', https://www.statista.com/statistics/303774/travel-purpose-trends-at-uk-airports/#:~:text=This%20general%20UK%20trend%20shows,to%2017%20percent%20in%202019.
106 Consultancy.UK (2021), 'Flexible working contributes £37 billion to the UK economy', https://www.consultancy.uk/news/29874/flexible-working-contributes-37-billion-to-the-uk-economy.

Furthermore, the report highlights that with net business travel growth having 'effectively ceased, the macroeconomic benefits of British air capacity growth appear to have diminished'.[107]

As previously mentioned, it is out of the scope of this research to quantify the economic costs and benefits of flight demand management. However, it is clear that a 36 per cent reduction in demand by 2030, as determined within the modelling here, would not necessarily result in a proportional reduction in the aviation sector's contribution towards GDP.

While the post-pandemic financial recovery of the aviation industry is a crucial issue for the UK government and other policymakers, there are clear signs that this recovery is well underway. A 2023 KPMG report highlighted that, while global airline losses in 2020 amounted to around $140 billion, net profitability is expected to return in 2023.[108] Pre-pandemic profit across the sector was around $35.5 billion in 2019.[109]

Throughout the pandemic, the aviation sector (airports, airlines and related services) benefited from around £8 billion of government support.[110] Given the climate benefits of near-term demand management indicated by the analysis here, with demand returning to pre-pandemic levels by 2050, it is conceivable that the UK government could incentivize airlines to accelerate climate action by providing financial support linked to decarbonization progress during the demand-management period. Airlines performing well could also see demand-management policies relaxed sooner, if they make sufficient decarbonization progress.

4.4 Demand-management policy options

This research paper has focused on the balance between supply-side decarbonization and demand management options. It is out of the scope of this research to fully examine the policy mechanisms to achieve the level of demand management required. However, it is instructive to investigate the type of policies that may be needed, including reform to existing policies such as air passenger duty (APD), fuel duty, value added tax (VAT), carbon pricing and offsetting schemes. In addition, new policy options include the introduction of a frequent flyer levy and reducing the availability of flights via management of airport capacity.

In various scenarios the CCC considers demand reduction to be an important element of decarbonization and explores all policy options in delivering demand management,[111] which in the widespread engagement scenario of the CCC sixth carbon budget shows passenger demand declining by 15 per cent in 2050, relative

107 New Economics Foundation (2023), *Losing altitude: The economics of air transport in Great Britain*, https://www.aef.org.uk/uploads/2023/07/Losing-altitude-The-economics-of-air-transport-in-Great-Britain-.pdf.
108 KPMG (2023), *Aviation Leaders Report 2023: New horizons for the aviation industry,* https://kpmg.com/ie/en/home/insights/2023/01/aviation-leaders-report-2023.html.
109 International Air Transport Association (2018), 'IATA forecasts $35.5bn net profit for airlines in 2019', https://airlines.iata.org/news/iata-forecasts-355bn-net-profit-for-airlines-in-2019.
110 UK Parliament (2022), *UK aviation: reform for take-off: Government Response to the Committee's Fifth Report of Session 2021-22*.
111 Committee on Climate Change (2020), *The Sixth Carbon Budget: Aviation*.

to 2018.[112] In June 2022, the CCC published its progress report to parliament, in which it called for the UK government to 'Implement a policy to manage aviation demand as soon as possible so the mechanisms are in place in the likely event that low emission technology are not commercially available to meet the Government's aviation pathway'.[113]

4.4.1 Air passenger duty

Since 1994, all passenger flights from UK airports are subject to APD, with some exemptions (e.g. for connectivity flights to remote islands within the UK).[114] The rates vary depending on the class of the ticket and distance. Rates from April 2023 for economy class are £13, £87 and £91 for short-, medium- and long-haul flights, respectively.[115]

Studies investigating the effects of taxation on demand for flights are limited. In 2018, a survey-based contingent valuation method study investigated people's willingness to pay (WTP) APD.[116] The mean WTP for short-haul flights was found to be £16.54 in economy class and £24.11 in business class. For medium- and long-haul flights, the mean WTP ranged from £22.89 to £36.80. At the time of the study, the economy class ADP rates were comparable to those of 2023. Based on the 2018 APD rates, the study concluded that ADP rates for medium- and long-haul flights may largely decrease demand from the 'average tourist' who is 'prepared to accept the current APD rate for short-haul trips'. Furthermore, this study investigated demand elasticities for six trip scenarios, finding that: short-haul tourist demand is inelastic for APD below £37.51, for long-haul flights tourist demand becomes highly elastic above £52.51, and that WTP is higher for business class than for economy class. It should be noted that this study mainly targeted holiday travellers and suggested that future research could include business travellers.

4.4.2 Fuel duty and VAT

Unlike petrol and diesel for road transport, which incurs excise duty and constitutes a significant portion of the pump price paid by motorists, aviation kerosene for both domestic and international flights is untaxed in the UK.[117]

Countries such as the Netherlands and Norway have implemented kerosene taxes on domestic flights within their jurisdictions.[118] The introduction of fuel duty

112 Ibid.
113 Committee on Climate Change (2022), *Progress in reducing emissions: 2022 Report to Parliament*, https://www.theccc.org.uk/wp-content/uploads/2022/06/Progress-in-reducing-emissions-2022-Report-to-Parliament.pdf.
114 HM Revenue & Customs (2018), 'Guidance: Exemptions from Air Passenger Duty', https://www.gov.uk/guidance/exemptions-from-air-passenger-duty.
115 Office for Budget Responsibility (2023), 'Air passenger duty', https://obr.uk/forecasts-in-depth/tax-by-tax-spend-by-spend/air-passenger-duty.
116 Seetaram, N., Song, H. and Page, S. (2014), 'Air passenger duty and outbound tourism demand from the United Kingdom', *Journal of Travel Research*, 53(4), pp. 476–487, https://doi.org/10.1177/0047287513500389.
117 Seely, A. (2019), *Taxing aviation fuel*, Briefing Paper Number 523, House of Commons Library, https://commonslibrary.parliament.uk/research-briefings/sn00523.
118 Transport and Environment (2019), 'State of the aviation ETS', https://www.transportenvironment.org/state-aviation-ets; Transport and Environment (2019), 'Legal obstacles no barrier to introducing aviation fuel tax in Europe, say experts', https://www.transportenvironment.org/press/legal-obstacles-no-barrier-introducing-aviation-fuel-tax-europe-say-experts.

on all UK flights may inadvertently incentivize carriers to engage in 'tankering'[119] to avoid paying taxes.[120] By filling their aircraft to capacity whenever they touch down at international destinations, airlines could bypass the fuel duty tax. In turn this could increase the level of aviation emissions, counteracting the intended environmental benefits of taxation.

The VAT applied to flight tickets from UK airports is zero rated. This tax treatment places flight tickets in a category alongside various essential goods and services such as water, most food, children's clothes and wheelchairs. By placing flight tickets in this category, air transportation is in essence being treated as a necessity rather than a luxury. The UK, Ireland and Denmark are the only European countries that do not apply VAT to domestic flights.

4.4.3 UK Emissions Trading Scheme

The UK launched its own emissions trading scheme (UK ETS) in January 2021 to replace the country's participation in the EU Emissions Trading Scheme (EU ETS). To ensure stability for participating companies, the initial phase of the UK ETS has been designed to align with the EU ETS until 1 January 2024. The UK ETS encompasses energy-intensive industries, such as aviation, including UK domestic flights as well as UK flights to European Economic Area states, Gibraltar and Switzerland. The cap-and-trade scheme enables emitters to buy and sell a decreasing number of carbon emission allowances. In 2021, the UK government provided UK airlines with a surplus of free allowances, resulting in a direct subsidy from the British taxpayer to the industry. The total number of free allowances distributed amounted to 4.4 million, valued at £242 million based on the average 2021 UK ETS price of £55.59.[121] However, only 3.4 million allowances were required to cover airline emissions. This created an excess of allowances that airlines could sell on the secondary market.[122] In 2022, the UK government continued to give away free allowances to airlines, estimated to be worth more than £300 million.[123] In July 2023, the UK government released many more permits than had been expected, contributing to a crash in the traded UK carbon price, which at the time of writing (August 2023) was running at a 45 per cent discount relative to prices under the EU ETS.

The rationale behind allocating free allowances is to prevent carbon leakage, which refers to the risk of emissions-intensive industries relocating their operations to regions with more lenient emission regulations. However, the aviation industry poses minimal risk of carbon leakage, making the distribution of free allowances unnecessary in practice; unlike manufacturers, airports and airlines cannot simply relocate operations to another jurisdiction. Thus, under the UK ETS, the provision of free allowances has effectively functioned as a transfer of funds from the British

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119 Eurocontrol (2019), 'Fuel Tankering: economic benefits and environmental impact', Aviation Intelligence Unit, Think Paper #1, https://www.eurocontrol.int/sites/default/files/2020-01/eurocontrol-think-paper-1-fuel-tankering.pdf.
120 Seely (2019), 'Taxing aviation fuel'.
121 Transport and Environment (2022), *UK ETS: Broken, but fixable,* https://www.transportenvironment.org/wp-content/uploads/2022/06/UK-ETS-Briefing.pdf.
122 Ibid.
123 Amin, L. and Webster, B. (2023), 'UK government lets airlines off the hook for £300m air pollution bill', https://www.opendemocracy.net/en/emissions-trading-scheme-uk-airlines-300m-pollution-permits-free.

taxpayer to the airline industry. The Transport and Environment group, which campaigns for clean transportation, has called for free allowances to be completely withdrawn from 2024, and for the scheme to be applied to all departing flights, regardless of destination.[124] The Aviation Environment Federation has also called for an end to free allowances, and for the current practice of assuming a 100 per cent emissions reduction under the ETS for CO_2 from SAFs to end.[125]

4.4.4 CORSIA: the multilateral approach to aviation decarbonization

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a global initiative aimed at mitigating the growth of CO_2 emissions from international aviation. The pilot phase started in 2021 and will run until the end of 2023; it will be followed by a first phase (2024–26) and a second phase (2027–35). Participation is voluntary during the first two phases, but from 2027 onwards participation will be determined based on 2018 revenue tonne kilometre (RTK) data – one RTK is created when a metric tonne of revenue-generating load is carried one kilometre. CORSIA requires airlines to purchase carbon offset credits for the international flights they provide. Offset projects aim to reduce or store GHG emissions, for example renewable energy projects, or prevent deforestation, to compensate for emissions elsewhere.

In 2016, the EU determined that only 2 per cent of CDM projects had a 'high likelihood' of delivering CO_2 reductions.

The UN's clean development mechanism (CDM) is the world's largest and oldest offsetting scheme. In 2016, the EU determined that only 2 per cent of CDM projects had a 'high likelihood' of delivering CO_2 reductions.[126] In 2019, an assessment of the first 14 applications of offsetting programmes under CORSIA 'hardly meet any of the requirements and may not even be considered carbon-offsetting', and 'most programs do not yet have procedures in place or planned for avoiding double counting'.[127]

In voluntary carbon markets, companies utilize carbon offsets to fulfil self-defined emissions reduction targets. These offsets are typically issued in accordance with independent crediting standards, although some entities may also procure them through international or domestic crediting mechanisms. However, there is increasing scepticism over the effectiveness of these voluntary carbon offsets and doubts over whether they offset emissions at all.

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124 Transport and Environment (2022), *UK ETS: Broken, but fixable.*
125 Aviation Environment Federation (2022), '"Strengthen UK ETS to Help Ensure Aviation Pays its Climate Costs,' Says AEF', https://www.aef.org.uk/2022/06/22/strengthen-uk-ets-to-help-ensure-aviation-pays-its-climate-cost-says-aef.
126 Cames, M. et al. (2016), *How additional is the Clean Development Mechanism? Analysis of the application of current tools and proposed alternatives,* Freiburg: Öko-Institut eV, https://www.oeko.de/publikationen/p-details/how-additional-is-the-clean-development-mechanism.
127 Schneider, L. et al. (2019), *Lessons learned from the first round of applications by carbon-offsetting programs for eligibility under CORSIA, Berlin, Zurich*, Seattle: Öko-Institut eV, https://www.oeko.de/publikationen/p-details/lessons-learned-from-the-first-round-of-applications-by-carbon-offsetting-programs-for-eligibility-u.

While new rules under Article 6 of the Paris Agreement are designed to achieve credible approaches to both offsetting and the establishment of international compliance carbon markets,[128] these examples indicate the challenges offsetting faces, and concerns remain over double counting – when carbon credits are claimed by more than one entity.[129] Furthermore, a 2022 study investigated CORSIA's emissions reduction potential,[130] utilizing registry data from the largest carbon offset verifiers eligible under CORSIA. This study drew similar conclusions to that of the 2019 assessment. Namely, that 'the majority of carbon offsets have minor climate integrity', and that to 'increase environmental effectiveness, a narrower scope of eligibility rules is necessary'. The study also questioned if future, tighter eligibility rules could improve the prospects of CORSIA – 'it is highly questionable whether there is enough potential supply of offsets to ensure such high integrity, indicating that carbon offsetting should be considered as a transitory measure only'.

This research paper is not attempting to put forward options that oppose existing multilateral frameworks. Rather, given the concern that CORSIA may be inadequate, the severity of climate risks and how soon these are likely to manifest, the demand management policy options discussed are an attempt to indicate what more could be done.

4.4.5 New policy options: management of airport capacity and a frequent flyer levy

The complexity of the tax policy landscape surrounding aviation in the UK, encompassing APD, UK ETS and CORSIA, presents challenges. Critics contend that the current treatment of aviation fails to achieve the necessary demand transformation to address the climate crisis effectively. Furthermore, given the prime minister's recent pledge not to introduce 'new taxes to discourage flying',[131] under the current UK government any change in the tax passengers pay appears unlikely in the near term. Additionally, potential subsidies provided to the sector continue to raise concerns, particularly considering the free allocation of credits under the UK ETS and the support received during the COVID-19 pandemic.[132]

The CCC allows for 25 per cent growth in aviation passenger numbers on 2018 levels under its balanced net zero pathway, and a decline of 15 per cent under the widespread engagement scenario.[133] Furthermore, the CCC states that, 'There should be no net expansion of UK airport capacity unless the sector is on track to sufficiently outperform its net emissions trajectory and can accommodate the

128 World Bank (2022), 'What You Need to Know About Article 6 of the Paris Agreement', https://www.worldbank.org/en/news/feature/2022/05/17/what-you-need-to-know-about-article-6-of-the-paris-agreement.
129 Carbon Market Watch (2022), 'COP27 FAQ: Article 6 of the Paris Agreement explained', https://carbonmarketwatch.org/2022/11/02/cop27-faq-article-6-of-the-paris-agreement-explained.
130 Wozny, Grimme, Maertens and Scheelhaase (2022), 'CORSIA–A Feasible Second Best Solution?'.
131 Coffey (2023), 'No Rishi, there aren't any 'new taxes to discourage flying' – if only there were'.
132 New Economics Foundation (2021), *A Frequent Flyer Levy: Sharing aviation's carbon budget in a net zero world*.
133 Committee on Climate Change (2020), *The Sixth Carbon Budget: Aviation*.

additional demand'.[134] However, current planned and recently approved airport expansions will result in nearly three times the passenger numbers under the balanced net zero pathway.[135]

The idea of a frequent flyer levy has been around since at least 2015,[136] with the tax paid by a passenger increasing with the number of flights, or the distance travelled. In its simplest terms, a passenger taking their third flight of the year would pay a higher tax on that flight than someone taking their first.[137] When Climate Assembly members were asked, what considerations should government and parliament bear in mind when making decisions about air travel and the path to net zero? The fourth most voted for consideration for the UK government was that frequent flyers and those that fly furthest should pay more, with 44 per cent of assembly members choosing this measure as a priority.[138]

A frequent flyer levy could also make access to air travel fairer, as the increased tax for those who fly most frequently could incentivize them to make the biggest reductions. As a 2022 paper concludes, both a frequent flyer levy and a carbon tax could reduce emissions, but a frequent flyer levy is more progressive and effective at reducing emissions.[139] Another recent paper concluded that while a 'frequent air miles' tax is the most progressive option, recent migrant families could be impacted more than other low-income groups.[140]

While not directly translatable in terms of being proxies for success, both the soft drinks industry levy and plastic bag tax in the UK are widely accepted as being successful. The Institute for Government highlights that between 2015 and 2019, the sales-weighted average sugar content of soft drinks declined by 43.7 per cent, with 17 per cent of reductions being driven by consumers switching towards lower-sugar drinks.[141] And the relatively modest penalty of 5 pence on plastic bag use has reduced plastic bag usage by 97 per cent since 2015.[142]

In terms of the effectiveness of changing behaviours, clearly the level of any tax or levy would need to be appropriately set. Under the most recent frequent flyer levy proposal, produced by the New Economics Foundation (NEF) and climate charity Possible in 2021,[143] a passenger would be charged no tax on the first return leisure flight they take in a year, increasing to £25 on the second, £60 on the third, all the way to £585 on their tenth flight of the year. For business passengers, the first flight would start at £25. NEF modelled these levy rates based on limiting air passenger demand to 25 per cent above 2018 levels. Under NEF's proposals the

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134 Ibid.
135 Aviation Environmental Federation (2023), 'UK Airport Expansions', https://www.aef.org.uk/uk-airport-expansions.
136 New Economics Foundation (2015), *Managing aviation passenger demand with a Frequent Flyer Levy*, https://www.hacan.org.uk/wp-content/uploads/2015/06/FFL-FINAL-DRAFT-in-template_updated.pdf.
137 New Economics Foundation (2021), *A Frequent Flyer Levy: Sharing aviation's carbon budget in a net zero world.*
138 Climate Assembly UK (2020), *The path to net zero: How we travel by air.*
139 Fouquet, R. and O'Garra, T. (2022), 'In pursuit of progressive and effective climate policies: Comparing an air travel carbon tax and a frequent flyer levy', *Energy Policy*, Volume 171, https://doi.org/10.1016/j.enpol.2022.113278.
140 Buchs, M. and Mattioli, G. (2022), 'How socially just are taxes on air travel and 'frequent flyer levies'?', *Journal of Sustainable Tourism*, https://www.tandfonline.com/doi/full/10.1080/09669582.2022.2115050.
141 Sasse, T. and Metclafe, S (2022), 'Sugar tax', Institute for Government, https://www.instituteforgovernment.org.uk/article/explainer/sugar-tax#:~:text=Despite%20these%20criticisms%20the%20SDIL,135%2C500%20tonnes%20to%2087%2C600%20tonnes.
142 Department for Environment, Food & Rural Affairs (2022), '10p bag charge turns the tide on plastic waste', https://www.gov.uk/government/news/10p-bag-charge-turns-the-tide-on-plastic-waste.
143 New Economics Foundation (2021), *A Frequent Flyer Levy: Sharing aviation's carbon budget in a net zero world.*

frequent flyer levy would replace the APD, but retain the exemptions (e.g. to remote islands). As such, passengers who only fly once a year would see a small decrease in the cost of their tickets, enabling greater access to air travel to the UK's poorest households. NEF also projects that this frequent flyer levy would result in the top fifth of earners flying around 30 per cent less, with the lowest fifth of earners flying very slightly more. A peer reviewed study published in August 2022 indicates that a frequent flyer levy would be the most distributionally progressive option for managing demand through taxation.[144]

UK government polling published in June 2021 showed significant support for a frequent flyer levy, with 27 per cent of participants answering 'strongly support', and 27 per cent answering 'somewhat support', compared with 11 per cent and 8 per cent 'somewhat opposed' and 'strongly opposed', respectively.[145] Research in 2021 by Ipsos and the Centre for Climate Change and Social Transformations has also found that over two-thirds of the UK public support a frequent flyer levy, the highest level of support for any of the eight key net zero policies they tested.[146] However, a frequent flyer levy introduced in isolation would be insufficient to achieve the future demand management goals. If implemented, a levy would need to be accompanied by other measures, such as a kerosene tax, to avoid distortions.

An aviation sector-backed report estimates that between now and 2050 an annual average investment of $175 billion will be required to enable the aviation sector to meet the net zero target.[147] The implementation of a frequent flyer levy could go a significant way to raising this level of investment. The International Council on Clean Transport (2022) has shown that $121 billion could have been raised in 2019 alone with a flat $25 tax on one-way flights, or by implementing a frequent flyer levy of $9 for each person's second flight, increasing to $177 for their twentieth within the same year.[148]

If the UK government were to pursue demand management via a frequent flyer levy, the additional tax generated could be utilized to support airline workers in obtaining new employment. Furthermore, as the New Economics Foundation highlights, a frequent flyer levy is likely to ensure the best protection of airline jobs outside of London and the Southeast.[149] Clearly, given Rishi Sunak's recent announcements promising not to introduce new aviation taxes,[150] the introduction of a frequent flyer levy will not occur unless there is a change in government or government policy.

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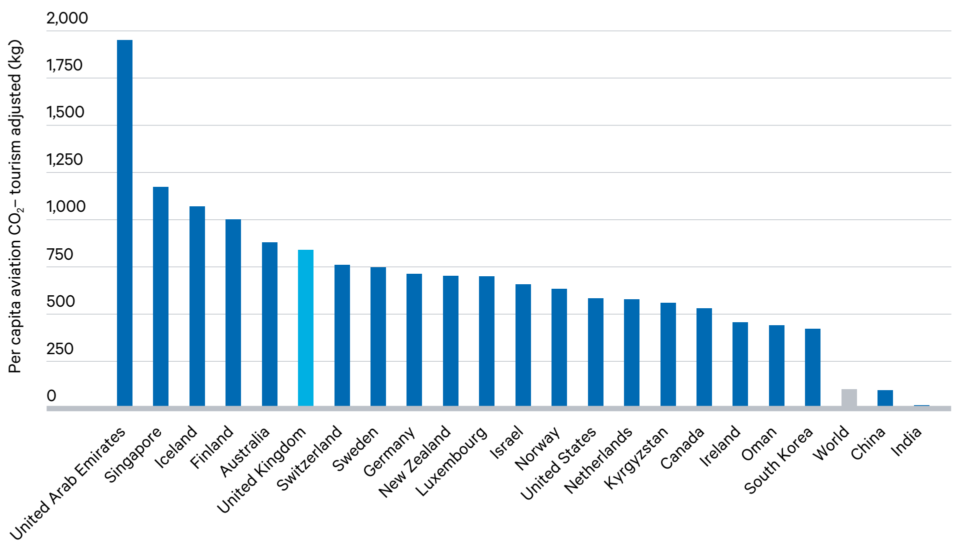
144 Buchs and Mattioli (2022), 'How socially just are taxes on air travel and 'frequent flyer levies?'.
145 Department for Business, Energy & Industrial Strategy (2021), 'Climate change and net zero: public awareness and perceptions. Annex 1: data tables', https://www.gov.uk/government/publications/climate-change-and-net-zero-public-awareness-and-perceptions.
146 Ipsos (2021), 'Public support majority of net zero policies … unless there is a personal cost', https://www.ipsos.com/en-uk/public-support-majority-net-zero-policies-unless-there-is-a-personal-cost.
147 Mission Possible (2022), *Making Net Zero Aviation possible*, https://missionpossiblepartnership.org/wp-content/uploads/2022/07/Making-Net-Zero-Aviation-possible.pdf.
148 Zheng, X. S. and Rutherford, D. (2022), *Aviation climate finance using a global frequent flying levy*, The International Council on Clean Transportation, https://theicct.org/publication/global-aviation-frequent-flying-levy-sep22.
149 New Economics Foundation (2021), *A Frequent Flyer Levy: Sharing aviation's carbon budget in a net zero world.*
150 Coffey (2023), 'No Rishi, there aren't any 'new taxes to discourage flying' – if only there were'.

4.5. What about the aviation sector in other high emitting countries?

As the IEA's net zero scenario has highlighted,[151] even if the global aviation sector deploys all supply-side decarbonization measures, some demand management will be required to keep within 1.5°C. Indeed, the majority of the sector emissions reductions assumed by the IEA out to 2050 are derived from reductions in demand, primarily for long-haul business flights. And as the IPCC have highlighted, the 'avoid' potential for individuals choosing to reduce long-haul aviation is slightly more than 1.7 tCO_2 per person, globally.

Figure 14. Per capita CO_2 emissions from aviation, tourism-adjusted, 2018



Source: Our World in Data (2020), 'Where in the world do people have the highest CO_2 emissions from flying?', https://ourworldindata.org/carbon-footprint-flying.

This paper has limited the scope of the model to UK aviation. However, the results are an indication of the level of demand management that may be required in other highly emitting countries, especially those that have contributed the largest share of historical emissions. It should be noted that demand (PAX-km) differs between nations, as does the average flight length, in part depending on the geographical size and location of the country, the wealth of its inhabitants and the prevalence of domestic short-haul flights. Globally, aviation accounts for around 2.5 per cent of CO_2 emissions, increasing to 3.5 per cent when non-CO_2 impacts are taken into account.[152] The level of demand reduction calculated here for the UK aviation sector was based on a per capita allocation that aligns with 1.5°C compliant carbon budgets. As such the level of demand reduction that may be required in other

151 International Energy Agency (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector,* https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.
152 Our World in Data (2020), 'Climate change and flying: what share of global CO_2 emissions come from aviation?', https://ourworldindata.org/co2-emissions-from-aviation; Lee et al. (2021), 'The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018'.

countries is linked to the per capita aviation sector emissions, which for 2018 are shown in Figure 14. In terms of G20 countries, this means the demand reduction implications of the modelling conducted here for the UK are most applicable to Australia, Germany, the US, Canada and South Korea.

4.6 Demand in the JZS high-ambition scenario

Under the modelling conducted by DfT, aviation demand in the JZS high-ambition scenario is forecast to increase by 70 per cent by 2050, relative to 2018.[153] However, this demand increase measures the rise in UK terminal passenger numbers rather than PAX-km. The DfT uses a modelling component called the national air passenger demand model (NAPDM) to determine demand. NAPDM consists of econometric models that estimate demand elasticities for different passenger markets, journey purposes and regions of the world. The result of this approach is that while terminal passengers are expected to increase by 70 per cent, passenger-kilometres travelled will not increase by an equivalent proportion, as NAPDM forecasts changes in the routes flown by passengers. Analysing the data underpinning Figure 3, before any abatement measures are applied (e.g. fuel efficiency improvements), emissions increase by around 38 per cent (2019 to 2050). This lower increase in emissions (prior to abatement mechanisms being applied) relative to the increase in terminal passengers indicates that the econometric models applied within NAPDM are resulting in the average passenger journey length significantly decreasing, hence proportionately there will be fewer long-haul flights.

Another key consideration is the impact on demand of carbon pricing under emissions trading schemes (ETS) and CORSIA, which Figure 3 shows may reduce emissions in 2050 by a little less than 14 MtCO_2e. As the technical consultation of the JZS states, 'carbon costs lead to higher fares and therefore lower demand and emissions'.[154] Within the high-ambition scenario the mid-point ETS carbon price is assumed to be £150/t in 2030, and £378/t in 2050, and the mid-point price of CORSIA is £6/t in 2030, £378/t in 2050, applied to all international flights between participating states.[155] It should be noted that the EU ETS price varied between £70–£85/t during the first quarter of 2023, and in August 2023 the UK carbon price was around £40/t, around 45 per cent lower than the EU ETS price. This indicates that the JZS is anticipating extremely significant increases in carbon prices by 2050.

Considering that the impact of carbon prices within Figure 3 indicates that passenger-kilometres flown are flat between 2018 and 2050. The near-zero growth in passenger-kilometres flown is a significantly different way of framing forecasted demand relative to the headline message of the JZS where demand is framed in terms of terminal passengers increasing by 70 per cent.

153 Department for Transport (2022), 'Jet Zero: modelling framework'; Department for Transport (2022), *Jet Zero illustrative scenarios and sensitivities*.
154 Department for Transport (2022), *Jet Zero: further technical consultation.*
155 Department for Transport (2022), *Jet Zero illustrative scenarios and sensitivities.*

05 Conclusions and recommendations

Demand management could be achieved via a frequent flyer levy with regular flyers reducing usage by at least one return flight per year, and those currently only taking one return flight unaffected.

In the context of combating climate change, demand management is often associated with government interference, or with a decline in standards of living, but this does not need to be the case. In fact, the Climate Assembly has shown that the UK public supports limits on demand for flying, provided the measures used to achieve this are fair. Indeed, the climate impacts now evident around the world will only get worse over time, lowering global standards of living. In addition, demand management and technological solutions can work together, with the policy emphasis applied to each changing over time. This is particularly important in the aviation sector where it will take many years to deploy supply-side decarbonization solutions, and carbon budgets to prevent runaway climate change are rapidly diminishing. Finally, if indeed demand management is an inevitability due to the slow pace of decarbonization in the aviation sector, but continues to be overlooked in the short term, it is increasingly likely that a sudden and abrupt demand management policy may be imposed on the sector as climate impacts accelerate over the coming decades. This could cause an unexpected major crash in the sector and an even greater reduction in air traffic than would otherwise be necessary.

The current cost of living and energy crises highlight how important demand management can be in reducing harmful impacts. Inflationary cost pressures, the supply–demand tightness of oil markets and the Russian invasion of Ukraine are all being felt in the aviation sector too. Meaning people may begin flying less in the near term simply due to increased airfares as a result of high jet fuel prices. As early as January 2022, the International Air Transport Association (IATA) began warning of rising airfares, due to fuel costs.[156] Perhaps this is unsurprising given that fuel represents around 25 per cent of an airline's costs.[157] In July 2022, the director of IATA, Willie Walsh said, 'Flights are getting more expensive because of the high price of oil and it's becoming clear to everybody that that will be reflected in higher ticket prices'.[158] However, with more airlines hedging fuel prices,[159] and airlines desperate not to pass on prices to consumers as demand returns in the post-pandemic world,[160] only time will tell if the tightness of the oil market continues and how consumers respond if airfares do substantially rise, in a world of households having to deal with inflationary pressures across the economy. But it is clear from the Climate Assembly, that the UK public supports limits on demand for flying – provided that the approach taken is perceived as fair – and that demand should be controlled depending on how technological solutions progress.

A prudent risk-minimization approach would be to fly less far, less frequently, over the remainder of the 2020s. Under this lower-risk scenario, the analysis in this paper shows that demand in terms of passenger-kilometres flown in 2030 would need to be 36.1 per cent lower than in 2019, with demand returning to 2019 levels by 2050. This precautionary principled approach of minimizing the risks is fast becoming more akin to a necessary approach, particularly when non-CO_2 effects of flying are considered. Taking action to supress near-term demand to enable supply-side decarbonization to catch up is aligned with the CCC progress update of October 2022,[161] which states, 'The Government's plans for aviation focus on sustainable aviation fuel and zero/low-emission aircrafts. These technologies have potential, but there are significant risks in their delivery. In the near term, managing demand would have a much greater benefit for the climate.'

If near-term demand action is delayed, but the UK aviation sector is still to stay within its fair share of global carbon budgets, demand in 2050 will need to be around one-quarter lower, relative to 2019. This scenario embodies significant risk. Namely, that a large proportion of the dwindling carbon budget is expended over the next decade, reliance on uncertain future supply-side decarbonization, and the requirement for even greater demand reduction over the long term.

While non-CO_2 effects – such as water vapour emitted at high altitudes as part of an aircraft's contrails – remain uncertain, even the most optimistic interpretation of this uncertainty indicates carbon budgets for the aviation sector may need to be

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156 Harper, L. (2022), 'IATA warns of airfare impact as high jet fuel prices push up airline operating costs', *Flight Global*, 25 January 2022, https://www.flightglobal.com/strategy/iata-warns-of-airfare-impact-as-high-jet-fuel-prices-push-up-airline-operating-costs/147246.article.
157 Bouwer, J. et al. (2022), 'Why rising fuel prices might not be as bad for the airline sector as it seems', *McKinsey & Company,* 15 July 2022, https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/why-rising-fuel-prices-might-not-be-as-bad-for-the-airline-sector-as-it-seems.
158 Caird, J. (2022), 'Cost of flights to 'inevitably' rise as fuel prices soar, says aviation boss', *Independent*, 11 July 2022, https://www.independent.co.uk/travel/news-and-advice/flights-cost-air-fare-ticket-price-b2120292.html.
159 Longley, A. and Kumar, D. K. (2022), 'Airlines Set to Save Billions With Fuel Hedges Amid $100 Oil', *Bloomberg*, 3 August 2022, https://www.bloomberg.com/news/articles/2022-08-03/airline-fuel-hedges-set-to-save-billions-for-some-with-100-oil; Okorodus, A. (2022), 'Airlines reluctant to pass on costs, but for how long?', *Delano*, 10 August 2022, https://delano.lu/article/airlines-reluctant-to-pass-on-.
160 Okorodus, A. (2022), 'Airlines reluctant to pass on costs, but for how long?'.
161 Committee on Climate Change (2022), 'Progress Snapshot. October 2022', https://www.theccc.org.uk/uk-action-on-climate-change/progress-snapshot (accessed 23 Jan. 2023).

significantly revised down. As a result, demand would need to be constrained by more than 60 per cent out to 2030, relative to 2019, to minimize devastating climate risks.

The analysis in this paper strongly suggests that DfT's modelling of the aviation sector's supply-led decarbonization pathway is highly optimistic. If DfT and the industry are confident this pathway can be achieved, they will need to implement – and enforce – emissions limits that decline to 2050. This would mean putting in place the right policy environment to encourage and incentivize the rapid development and deployment of technological solutions, otherwise this will not happen. This must include financial mechanisms to discourage emissions and encourage cleaner flights, such as rising kerosene tax and carbon price, along with policies to ensure social and political consent by prioritizing fairness via a fiscal mechanism such as a tax on frequent flying.

Because of the unequal distribution of who takes flights, relatively large reductions in aviation emissions can be achieved without changing travel behaviours for the majority of people – or preventing or even changing people's annual family holiday patterns. If a demand-management policy, such as a frequent flyer levy, were to be introduced, it is instructive to estimate how passenger behaviour would need to change to achieve the required demand reduction indicated by the modelling here. Analysing National Travel Survey statistics,[162] and assuming average flight distances flown remain roughly constant, it may be possible to achieve a 36 per cent reduction in demand if a future demand-management policy shifted behaviour such that most people who currently take more than one return flight per year reduced that number by one return flight and took no more than four. This would leave the 77 per cent of the UK population who currently take no more than one return flight unaffected. This is a moderate level of behaviour change to put the aviation sector on a climate compatible trajectory, affecting only a small proportion of people with a high consumption of flights.

Under the frequent flyer levy proposal, produced by the New Economics Foundation and climate charity Possible in 2021, leisure passengers would be charged no frequent flyer levy on their first return flight, increasing to £585 on their tenth flight of the year. These indicative levy rates were modelled based on limiting air passenger demand to 25 per cent above 2018 levels. As such, to achieve the demand reduction indicated by the modelling here a higher levy would be required, although it remains to be seen whether a frequent flyer levy implemented as the sole tax or policy measure can achieve this. Research in 2021 by Ipsos and the Centre for Climate Change and Social Transformations found that over two-thirds of the UK public support a frequent flyer levy.

While this paper has highlighted demand management within the aviation sector in the context of a frequent flyer levy, many potential policies exist to reduce demand. These include carbon pricing, fuel duty, reforms to air passenger duty or VAT, and reductions in the availability of flights via management of airport capacity.

162 Department for Transport (2022), 'Statistical data set: Mode of travel', https://www.gov.uk/government/statistical-data-sets/nts03-modal-comparisons. Note: previous version of Table NTS0316 utilized for this analysis has subsequently been replaced by a summary table with less detailed data. Statistics are for England only (not the whole of the UK) aggregated across the years 2006–19.

A coherent policy approach will be required to ensure fairness, public consent and effectiveness, including multiple measures along with changes to the wider transport sector, particularly around affordability of international train travel.

Demand management measures in the aviation sector and beyond will have geopolitical implications. The geopolitical consequences of reduced energy demand will most acutely play out between oil and gas producer and consumer nations, with oil and gas trade forming an integral part of international relations over the last century.

While greater focus on the demand-side offers a pathway to significant emissions reductions, it is also clear that demand-side emission reductions can be implemented swiftly – as was demonstrated during the COVID-19 pandemic. For instance, during 2020 Europe lowered primary energy consumption by 8.6 per cent, compared to 2019,[163] equivalent to over one-third of Russian supplied fossil fuels. Furthermore, the pandemic highlighted the role of individuals in collective action, and many people felt morally compelled and responsible to act for others.[164]

163 European Environment Agency (2022), 'Primary and final energy consumption in Europe', https://www.eea.europa.eu/ims/primary-and-final-energy-consumption (accessed 1 Oct. 2022).
164 Budd, L. and Ison, S. (2020), 'Responsible Transport: A post-COVID agenda for transport policy and practice', *Transportation Research Interdisciplinary Perspectives*, Volume 6, 100151, https://doi.org/10.1016/j.trip.2020.100151.

Appendix A1. Current fleet composition

Many aircraft in operation today will likely be in existence for the next decade or more. Based on historically observed trends, typical aircraft lifetimes are around 22.5 years.[165] Given that one of the main supply-side decarbonization mechanisms is to improve the fuel efficiency of aircraft, the current fleet composition is integral to ensure that the relatively high emissions of the current fleet are adequately modelled over time.

CAA aircraft type and utilization data indicate that in 2019 around 1,000 individual aircraft were in operation, across 68 models.[166] By including any aircraft model that represents at least 1 per cent of all the operational aircraft, the 25 models shown in Table 2 represent 86 per cent of all aircraft in service. More importantly, these 25 aircraft models represent 95 per cent of all passenger-km flown. The seat class classification criteria applied to the 25 operational aircraft (Table 2) utilized within the model are shown in Table 3, where the range of seats mirrors that used by DfT and the CCC.[167] For validation purposes the aircraft models in operation were checked against those identified by DfT.[168]

Table 2. Aircraft models selected for inclusion in model, based on CAA aircraft type and utilization data from 2019

Aircraft model	Cruise speed (km/h)	Max no. seats	Seat class	Range (max nmi)	Weight within class*
Airbus A320 200	829	186	3	3,750	26%
Boeing 737 800	838	215	3	3,825	22%
Boeing 787 9	903	290	4	7,355	44%
Airbus A319 100	829	156	3	3,700	20%
Boeing 777 200	892	317	4	5,240	39%
Boeing 747 400	933	660	6	7,285	78%
Airbus A321 200	829	236	3	4,000	11%
Airbus A320 200N	829	180	3	3,300	9%
Boeing 787 8	903	250	4	6,899	17%
Boeing 777 300ER	892	212	3	3,119	5%
Boeing 757 200	854	239	3	3,850	5%
De Havilland DHC8 400	612	90	2	1,100	44%
Airbus A380 800	903	853	6	7,285	22%

165 Destination 2050 (2021), *A route to Net Zero European Aviation*, https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf.
166 UK Civil Aviation Authority (2022), 'UK aviation market: Airports and Airlines datasets', https://www.caa.co.uk/Documents/Download/4007/41d1c005-464b-4ae2-967c-40ab4e723a0c/549.
167 Air Transportation Analytics (2018), *Understanding the potential and costs for reducing UK aviation emissions: Report to the Committee on Climate Change and the Department for Transport*.
168 Department for Transport (2022), 'Jet Zero: modelling framework', Figure 9, p. 30.

Aircraft model	Cruise speed (km/h)	Max no. seats	Seat class	Range (max nmi)	Weight within class*
Airbus A330 300	871	440	5	6,100	100%
Airbus A321 200N	833	180	3	3,119	2%
Embraer ERJ190 100	829	94	2	2,438	23%
Embraer ERJ170 200	797	70	2	2,150	13%
Boeing 737 300	836	149	2	2,375	13%
Embraer EMB145	854	48	1	2,000	51%
ATR ATR72 200	526	78	2	2,438	7%
Saab 340	524	37	1	470	36%
BAE Jetstream 4100 4100	546	30	1	1,397	9%
Cessna 560	796	8	1	1,397	2%
Beech 200	574	11	1	1,720	1%
Boeing 737 400	836	168	3	3,119	0%

Source: UK Civil Aviation Authority (2022), 'UK aviation market: Airports and Airlines datasets', https://www.caa.co.uk/Documents/Download/4007/41d1c005-464b-4ae2-967c-40ab4e723a0c/549.
Note: Weight within class based on the proportion of passenger-km flown within the given seat class.
NMI = nautical miles.

Table 3. Seat classification ranges

Seat class	Min no. seats	Max no. seats
1	–	70
2	71	150
3	151	250
4	251	350
5	351	500
6	501	–

Source: Air Transportation Analytics (2018), *Understanding the potential and costs for reducing UK aviation emissions: Report to the Committee on Climate Change and the Department for Transport*, p. 14, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/785685/ata-potential-and-costs-reducting-emissions.pdf.

Appendix A2. Which aircraft fly each route?

CAA data detail the air traffic movements (ATMs) between departure and destination airports, as well as aircraft type and utilization. However, as the CAA data do not explicitly link aircraft types to ATMs, assumptions as to which aircraft comprise these ATMs are needed to estimate the fuel consumption and emissions. This linking of ATMs to aircraft type has been performed with a view to the seat-class-based modelling of future aircraft fuel efficiencies, as is applied in the DfT FMM model.[169] As such, ATMs are categorized into domestic as well as international short-, medium- and long-haul routes based on Eurocontrol definitions of these distances. Medium-haul routes are between 1,500 km and 4,000 km, with short-haul routes anything less than this, and long-haul routes anything more. Combined with the seat class of the 25 representative aircraft types, their associated maximum range (see Table 2), and the proportion of all passenger-km flown by each of the six seat classes, this enables a weighting to be applied to each seat class within the four route length types (see Table 4).

Table 4. Weighting of each seat class within four route length types

Route length	Range (km)		Seat class weightings					
	Min	Max	1	2	3	4	5	6
Domestic	–	1,000	1%	9%	89%	–	–	–
International short haul	–	1,500	1%	9%	89%	–	–	–
International medium haul	1,501	4,000	–	–	67%	33%	–	–
International long haul	4,001	–	–	–	58%	28%	2%	12%

Source: Compiled by the author.

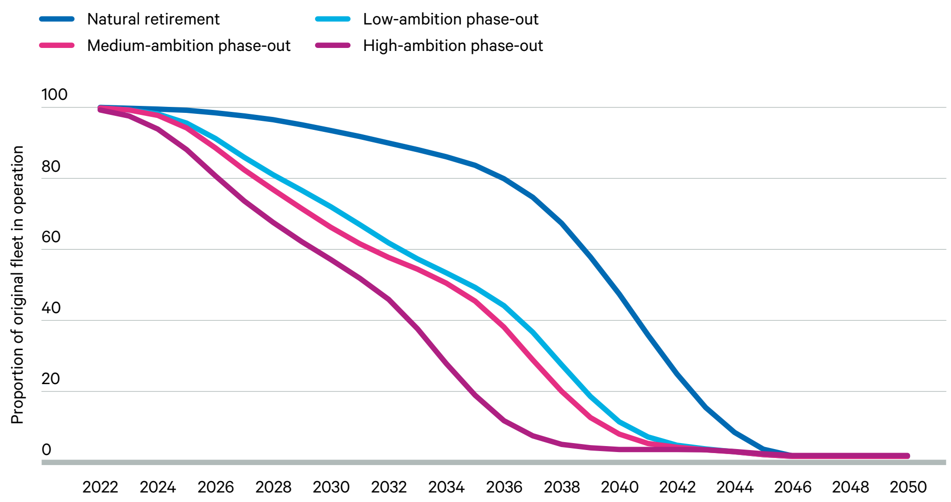
Retirement of aircraft, and phase-out ambition

To ascertain when aircraft will be retired from service, and hence when they will be replaced by new, more fuel efficient aircraft, requires both the assumed 22.5 years of average operation as well as the current ages of operational aircraft. The most reliable, comprehensive and recently updated data (2022) was obtained from airfleets.net.[170] A normal distribution has been assumed as to the spread of ages. Four retirement scenarios have been constructed to explore how ambition to phase out current aircraft impacts total fleet emissions. The first scenario is one of natural retirement, when aircraft models reach the assumed 22.5 years

169 Ricardo Energy & Environment (2017), *A review of the DfT aviation fleet mix model: Report for Department for Transport*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/653876/a-review-of-the-dft-aviation-fleet-mix-model.pdf.
170 Airfleets.net (2022), 'Airlines by country: United Kingdom', https://www.airfleets.net/recherche/list-country-United%20Kingdom.htm.

of average operation. The subsequent three phase-out scenarios are based on those utilized by DfT within their FMM.[171] Figure 15 illustrates the retirement profiles of the entire fleet of current aircraft, based on the assumed natural retirement age of 22.5 years, as well as the three phase-out scenarios. Throughout the scenarios presented in the body of this research paper the high-ambition phase-out scenario has been assumed.

Figure 15. Retirement profiles of fleet of current aircraft, under four retirement scenarios



Source: Complied by the author.

Appendix A3. Future aircraft: fuel efficiencies and fleet composition over time

As new aircraft enter into service, they replace current aircraft that are being retired. The DfT FMM and CO_2 model utilizes generic future aircraft types, with defined EIS dates and fuel efficiency improvements relative to current aircraft types.[172] The model in this paper assumes the same EIS and fuel efficiency improvements of the future generic types, and are shown in Table 5. It should be noted that not all the future aircraft types enter the fleet at the given EIS date in Table 5. Rather, aircraft production follows a normal distribution to mimic the manner in which aircraft are manufactured. Given that the retiring aircraft are also assumed to have been produced in the same manner – following a normal distribution of production – the retirement distributions dictate the production distributions.

171 Ricardo Energy & Environment (2017), *Carbon Abatement in UK Aviation,* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/653776/carbon-abatement-in-uk-aviation.pdf.
172 Ibid.

The aircraft-level fuel burn and CO_2 modelling utilizes the emissions calculator accompanying the EEA air pollutant emission inventory guidebook.[173] This approach allows fuel efficiencies and emissions to be determined for the 25 current aircraft types modelled as well as the generic future types. It should be noted that not all of the 25 current aircraft types could be precisely mapped to those in the EEA fuel efficiency database. As such, the closest similar aircraft type was selected.

Table 5. Assumed fuel efficiencies of future generic aircraft types

Seat class	Aircraft ID	Assumed EIS	Relative fuel efficiency improvement	Current aircraft type to which fuel efficiency improvement relative to
6	G16	2026	-18%	A380
1	G21	2030	-25%	ATR42
2	G22	2034	-25%	B734
3	G23	2035	-25%	B734
4	G24	2031	-28%	B772
5	G25	2031	-28%	Av of A343 and B772
6	G26	2036	-28%	A380
1	G31	2040	-32%	ATR42
2	G32	2045	-32%	B734
3	G33	2045	-32%	B734
4	G34	2041	-30%	B772
5	G35	2041	-30%	Av of A343 and B772
6	G36	2046	-30%	A380

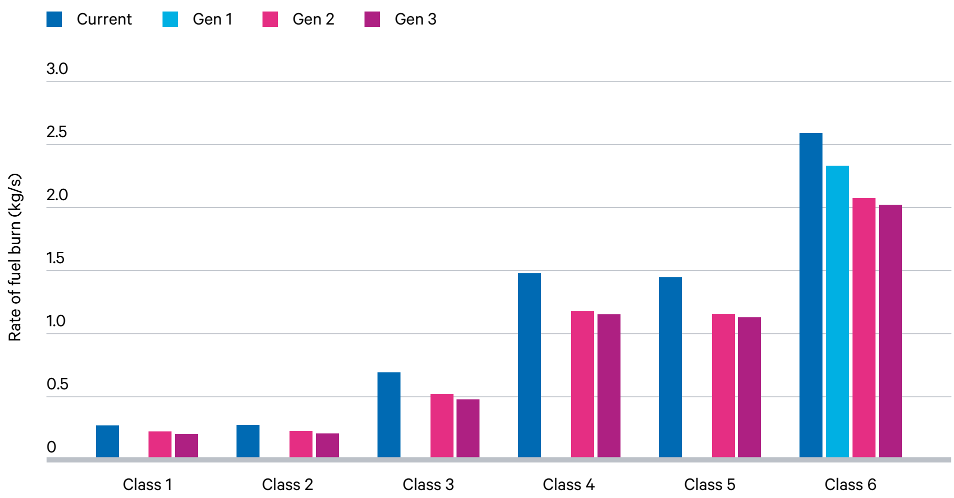
Source: Ricardo Energy & Environment (2017), *Carbon Abatement in UK Aviation*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/653776/carbon-abatement-in-uk-aviation.pdf.

The relative fuel efficiency of future generic classes of aircraft are listed in the right-hand columns of Table 5. Where the fuel efficiency of the relative aircraft type is greater than the weighted average of all current aircraft within that class, the latter has been selected. The weighted average is applied based on the proportion of passenger-km flown within the class of aircraft, as listed in Table 2. This is an optimistic approach given this weighted average is often lower than the relative fuel efficiencies of aircraft types listed in the right-hand column of Table 5. For example, Table 5 shows the fuel efficiency of the G16 is anticipated to perform with an 18 per cent fuel efficiency improvement relative to the A380, which based on the EEA database has a fuel efficiency of 2.84 kg/s. However, the weighted average

173 European Environment Agency (2019), 'Aviation 2 LTO emissions calculator 2019'.

across all class 6 aircraft is 2.59 kg/s. Hence, the 18 per cent improvement in fuel efficiency has been applied to this lower value, representing an optimistic forecast of future fuel efficiencies of all future class 6 aircraft modelled.

Figure 16. Fuel efficiencies of all six classes of aircraft, current aircraft and future generic types



Source: Complied by the author.

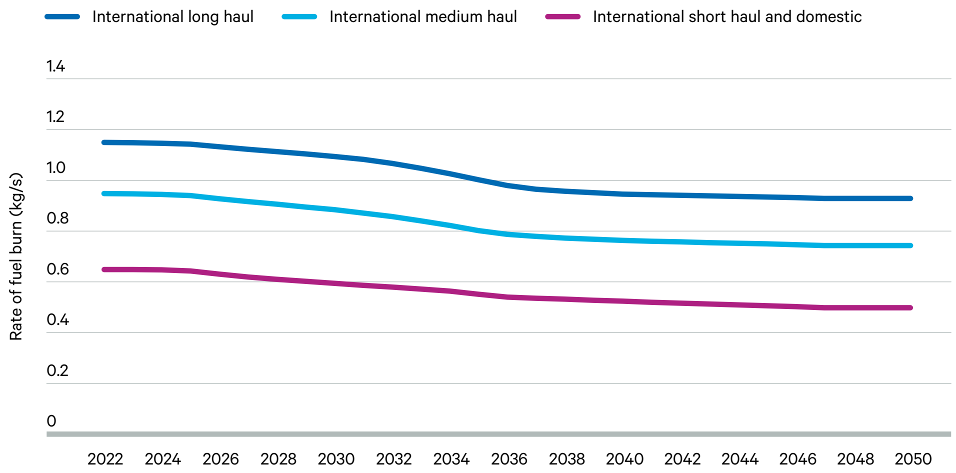
Fleet composition over time

The fleet composition changes over time as the model considers the retirement of aircraft, as well as the EIS of the various future aircraft types (G16 to G36 of Table 5). It should be noted that many of the EIS dates of the future aircraft types (Table 5) exceed either the phase-out dates of current aircraft, or their natural retirement date. As a result, the model assumes that the replacement aircraft has a fuel efficiency improvement equal to the average of both the class efficiency of current aircraft types and the next generation aircraft of that class, as per those current class efficiencies shown in Figure 16. For instance, the EIS of generation 2 class 3 (G23) aircraft is 2035. Hence, any class 3 aircraft retiring or phased out before 2035 is replaced by an aircraft with a fuel efficiency of 0.57 kg fuel burnt per second, down from the weighted average of current class 3 aircraft of 0.69 kg/s, rather than the 0.52 kg/s that the G23 may exhibit in 2035. These intermediary aircraft are then replaced by the relevant future generic type.

Fuel efficiency of fleet by haulage type

Following the model determining the changing fleet composition in each year out to 2050, it is then possible to forecast the rate of fuel burn for each seat class. Each aircraft within each class is weighted by the passenger-km flown. Following the model forecasting the rate of fuel burn for each seat class, the weighting of classes within the four route length types of Table 4 is applied to forecast the rate of fuel burn across; domestic, international short-haul, medium-haul and long-haul flights. The rate of fuel burn profiles for each route length type shown in Figure 17 are applied to the projected ATMs between the 25 modelled UK airports and their respective destinations to forecast the route-by-route breakdown of fuel consumption and associated emissions.

Figure 17. Rate of fuel burn (kg/s) of the four route length types



Source: Complied by the author.

Appendix A4. Forecasting demand: route-by-route air traffic movements

Alongside processing CAA data to determine the current utilization of aircraft types, CAA data also underpin route-by-route air traffic movements (ATMs), for both international and domestic flights.[174] The top 25 busiest UK airports were identified based on ATMs recorded within the CAA data. These 25 airports represent more than 98 per cent of international ATMs and PAX, 86 per cent of domestic ATMs, and 98 per cent of domestic PAX.

Route distances were obtained and mapped against the CAA departure and destination airport route data.[175] A total of 578 unique destinations were identified within the CAA data. The wider model selects four representative UK airports when mapping route distances from each of the 25 modelled airports ATMs by route, these are as follows:

- Heathrow → X: Gatwick, Luton, Stansted, London City, Bristol, Southampton, Guernsey, Jersey, Norwich, Southend, Cardiff, Exeter
- Manchester → X: Liverpool, Newcastle, Leeds, Isle of Man
- Edinburgh → X: Glasgow, Aberdeen, Belfast
- Birmingham → X: East Midlands

174 UK Civil Aviation Authority (2022), 'UK aviation market: Airports and Airlines datasets', https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/uk-airport-data-2019/annual-2019.
175 Aircalculator.com (2022), 'Route Distances', www.aircalculator.com.

For both international and domestic flights, the CAA data contain departure-destination route PAX values, as well as separate datasets on ATM and PAX values for each departure airport,[176] unconnected to the destination airport. As such, to obtain ATMs for all combinations of departure-destination routes, the average PAX per ATM for each departure airport was assumed to be consistent for all destination routes for each of the 25 departure airports. For instance, the average flight (ATM) from Heathrow carries 173 passengers (PAX), whereas the average PAX per ATM from Norwich is 27.

To forecast demand beyond 2024 – the point in time at which demand is anticipated to reach pre-pandemic levels – the model calculates the compound annual growth rate (CAGR) required to meet a given level of demand in 2050, scaling ATMs for each departure-destination route by the annualized increase, with the starting indexed value of 97.6 per cent at the end of 2024. The DfT demand model (NAPDM) forecast changes in demand differently to that performed here. NAPDM consists of econometric models that estimate demand elasticities for different passenger markets, journey purposes and regions of the world.

176 UK Civil Aviation Authority (2022), 'UK aviation market: Airports and Airlines datasets'.

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Dr Daniel Quiggin is a senior research fellow with the Environment and Society Centre at Chatham House. He specializes in the analysis of how national and global energy systems will evolve out to 2050. His current research and policy engagement focuses on negative emissions under net zero policies, climate risks and impacts, the role of demand reduction within the energy transition, and the trade of lithium-ion battery raw materials.

Previously he worked as a senior policy adviser at the Department for Business, Energy & Industrial Strategy, on the post-Brexit policy implications for the energy sector's trade of goods and services. At Investec Asset Management, he helped develop a global renewable energy investment strategy, and modelled the investment potential of various renewable sectors across all major economies.

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Cover image: Grounded aircraft at London Gatwick airport while UK airspace was closed due to a volcanic ash-plume over northern Europe, April 2010.
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