DECARBONISATION ROAD-MAP: A PATH TO NET ZERO

A plan to decarbonise UK aviation

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Sustainable Aviation is grateful to the following organisations for leading the work in producing this Road-Map:

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CHAIR FOREWORD

Sustainable Aviation declaration

Climate change is a clear and pressing issue for people, businesses and governments across the world. We know aviation emissions will increase if decisive action is not taken, and that's why UK aviation today commits to achieving net zero carbon emissions by 2050, through an international approach, working with governments around the world and through the UN. The UK is well positioned to become one of the leaders in the green technologies of the future, including sustainable aviation fuels and electric flight, creating highly-skilled and well-paid jobs in the process, and we look forward to working in partnership with Ministers to help realise these opportunities.

2020 is a critical year for global climate action. Amidst growing consensus that the global community must act now to avoid the worst consequences of climate change, the UK will host world leaders at COP 26 in Glasgow. Aviation has to play its full part in delivering a zero carbon future, and it is with considerable pride that alongside the publication of our new Decarbonisation Road-Map, UK aviation as represented through Sustainable Aviation, has become the first national aviation sector to commit collectively to achieving net zero carbon emissions by 2050.

Our commitment is a considerable step forward from the existing global industry target to half net emissions by 2050, and recognises the need for aviation to go further, faster in reducing our carbon footprint. We call on the international bodies to build on the achievements that have been made to date by establishing a new long-term target, which is led by climate science and consistent with the Paris Agreement.

Sustainable Aviation's new Road-Map, draws upon the latest science and innovative opportunities to decarbonise aviation. It shows that it is possible for UK aviation to achieve net zero carbon meeting anticipated increasing demand for flying, with all of the benefits that brings to the UK's economy and society. Indeed, the UK can develop its role as a global leader in sustainable aviation technologies – innovating and introducing new, low carbon technologies, from new engine and aircraft designs to ground-breaking sustainable aviation fuels. A successful, sustainable aviation sector offers tremendous opportunities for the UK to create new highly skilled and highly paid jobs.

In the coming years aviation will change, alternative fuels will power more long haul flights, aircraft will become more efficient and increasingly electrified, and precision satellite guidance will drive further efficiencies. Aviation is determined to deliver these changes to meet the critical challenge of climate change, but we cannot do so alone. Alongside this new Road-Map and the industry's commitment is a call to work in close partnership with UK Government. This collaborative approach is essential to achieving the opportunities to decarbonise, and to ensure that the UK leads internationally - delivering a global framework to address aviation emissions in what is, by definition, an international industry.

Neil Robinson
Chair, Sustainable Aviation

FOREWORD BY SUSTAINABLE AVIATION'S ADVISORY BOARD

The climate policy landscape has changed dramatically since the previous CO_2 Road-Map was published in 2016. The United Nation's Paris Agreement called on all countries to engage in climate action to maintain the global average temperature increase below 2°C and aim to limit it to below 1.5°C compared to pre-industrial levels. In 2018, the Intergovernmental Panel on Climate Change (IPCC) Special Report concluded limiting global warming to 1.5°C would require "unprecedented" and "deep emissions reductions in all sectors" and a decrease in global CO_2 emissions by about 45% by 2030 compared to 2010, reaching net zero by 2050. In addition to substantially reducing CO_2 emissions, this will require balancing residual emissions by removing an equal amount from the atmosphere (carbon dioxide removal). At a national level, following this call to action and upon advice from the UK's Committee on Climate Change, in 2019 the UK Government legislated to bring all greenhouse gas emissions to net zero by 2050.

The SA Advisory Board welcomes this Road-Map and the new commitment to net zero carbon emissions for UK aviation by 2050. We acknowledge the efforts that all parts of the industry have made to decarbonise both immediately and going forward. The Road-Map provides a helpful framework for the UK aviation industry on a pathway towards net zero and identifies the policy and support measures the industry requires to get there. It is welcomed that the Road-Map responds to previous SA Advisory Board members' calls for the industry to step up its commitment on decarbonising the sector.

In the future, we encourage SA to build on this Road-Map with further detail that identifies the key policy interventions that would support the UK viation industry both to fulfil its net zero commitment and to grow the level of climate change ambition across the industry. Lastly, CO_2 should not be considered in isolation, as other aviation emissions which also have a warming effect need to be accounted for. We recognise that the associated scientific uncertainty has delayed action in the past, but a clearer understanding is likely to emerge during the lifetime of this new Road-Map and we hope SA will respond appropriately.

We look forward to a continued close working relationship with the UK aviation industry during such a pivotal time for the sector and climate change policy.

The SA Advisory Board

The Sustainable Aviation Advisory Board works with Sustainable Aviation to provide independent

advice and feedback. It provides rigorous challenge to the SA Council in order to enable it to reach its cleaner, quieter, smarter goals effectively and efficiently.

Sustainable Aviation Decarbonisation Road-Map: A Path to Net Zero Emissions

Climate change is a clear and pressing issue for people, businesses and governments across the world. In publishing this report, UK aviation is committing to achieving net zero emissions by 2050, through an international approach, working with governments around the world and through the UN.

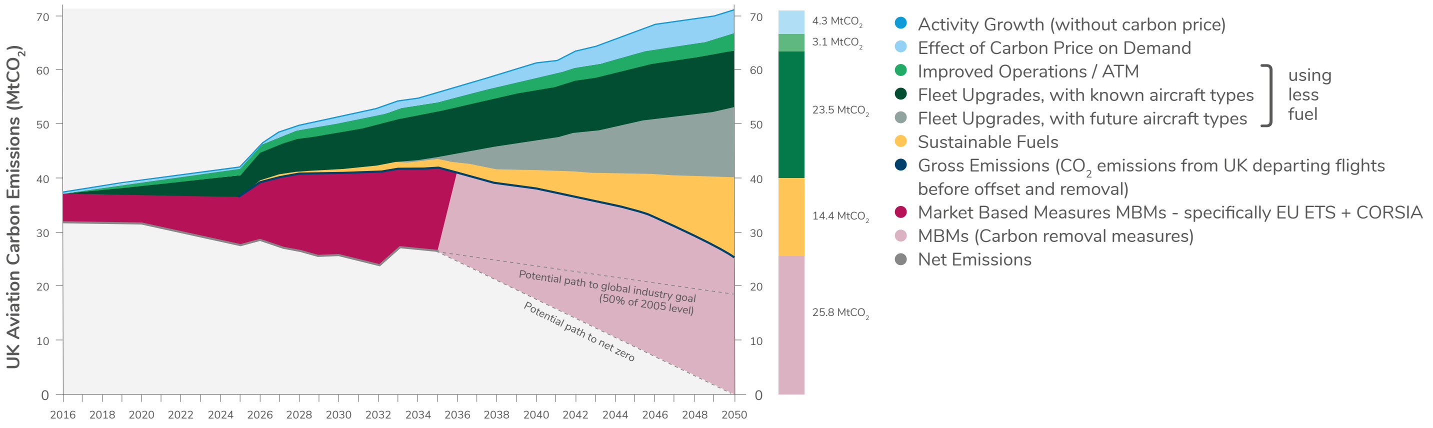
By 2050, the UK aviation industry can achieve net zero carbon emissions through the following initiatives compared with a scenario of growth at today's efficiency:

- 4.3 Million tonnes of carbon dioxide ($MtCO_2$) saving due to carbon pricing impact on demand
- 3.1 $MtCO_2$ saving from better air traffic management and operating procedures
- 23.5$MtCO_2$ saving from introduction of known and new, more efficient aircraft
- 14.4$MtCO_2$ saving from sustainable aviation fuels
- 25.8 $MtCO_2$ saving from effective market-based measures

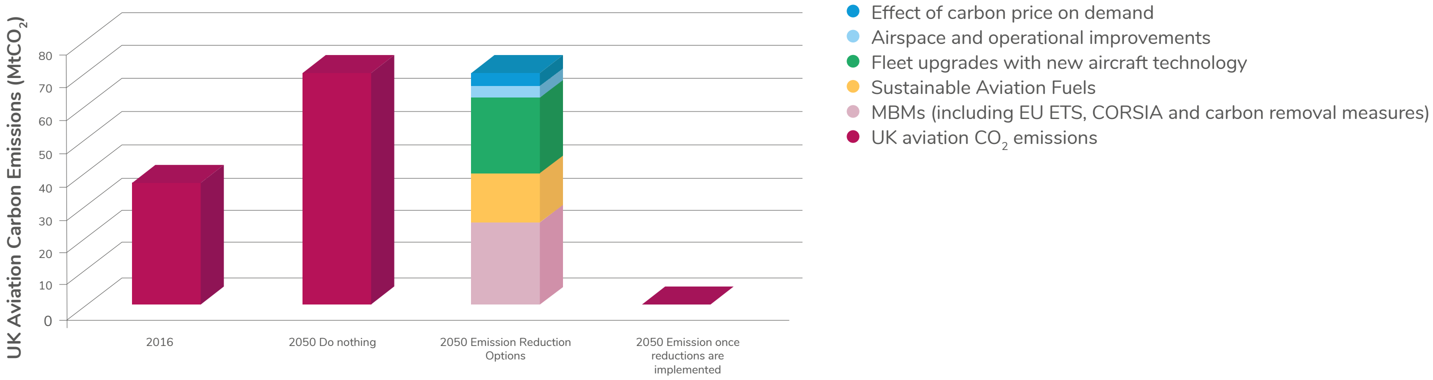
Our Road-Map draws on expertise from all corners of the UK aviation industry, including airlines, airports, aerospace manufacturers and air navigation service providers. It is based on a thorough review of the opportunities to cut aviation carbon emissions through smarter flight operations, new aircraft and engine technology, modernising our airspace, the use of sustainable aviation fuels and significant investment in carbon reductions through effective market-based policy measures.

With these actions, the UK will be able to accommodate 70% growth in passengers through to 2050 whilst reducing net emission levels from just over 30 million tonnes of CO_2 per year down to zero.

Decarbonisation Road-Map for UK Aviation



Opportunities to deliver net zero emissions for UK aviation



Sustainable Aviation Decarbonisation Road-Map: A Path to Net Zero Emissions (continued)

To deliver this will require a partnership approach with Government to ensure the opportunities to cut emissions are realised through smart low carbon policies, collaborative actions from outside the aviation sector and substantial investment from industry and Government in the next generation of sustainable aviation breakthroughs.

As a part of a global industry, with global emissions, the UK Government and industry must also take an international approach to ensure UK actions on emissions do not create unintended carbon emissions elsewhere outside the UK or undermine the UK's international connectivity.

We ask the UK Government to support this commitment in the following ways:

Improvements in Aircraft and Engine Efficiency

With the right support from Government our world-class aviation and aerospace sectors are uniquely placed to capitalise on the opportunities of green aviation technology – such as new propulsion systems, including hybrid and electric technology, and lighter, more efficient aircraft.

- Government should continue to support aerospace research and development through the Aerospace Growth Partnership, and consider accelerating technology development through increased investment in the Aerospace Technology Institute (ATI)

Sustainable Aviation Fuels

It is essential that the UK recognises the immediate and significant role of sustainable aviation fuels (SAF), which have the potential to start reducing UK aviation emissions in the mid-2020s and to reduce aviation emissions by at least 32% in 2050. Actively driving a domestic SAF sector would put the UK at the forefront of world leading aviation climate solutions, create thousands of clean growth jobs and provide a significant UK export opportunity as aviation decarbonises globally. We ask Government to:

- Provide the essential, high-level cross-departmental co-ordination necessary (e.g. through a new Office for Sustainable Aviation Fuels or similar body) to secure the policies needed to support the development and commercial deployment of SAF, and deliver matched public/private funding of £500m over five years (totalling £1bn) to support flagship first-of-a-kind commercial plants, to provide an initial boost to the sector
- Reform the Renewable Transport Fuel Obligation - a requirement on transport fuel suppliers to ensure a percentage of fuel is supplied from sustainable sources by a given period - to incorporate Recycled Carbon Fuels and other advanced fuel technologies, remove barriers to production, and apply at least a 1.2x multiplier for the right kinds of SAF developmental fuels to help suppliers prioritise SAF

Airspace Modernisation

Delivery of airspace modernisation: Government must maintain their vital leadership role providing the necessary policy and regulatory framework to enable the CAA to support the delivery of airspace modernisation. This will ensure that the priorities of all stakeholders in terms of carbon emissions and noise can be appropriately balanced.

Effective Market Based Policy Measures

Effective market-based policy measures are vital to ensure aviation's net emissions will reduce in line with climate goals and to establish carbon pricing. We will fully support UK Government in working to strengthen this framework globally.

- Government should work within the International Civil Aviation Organisation (ICAO), a United Nations body, to support the Carbon Offsetting & Reduction Scheme for International Aviation (CORSIA)
- Through ICAO, set a clear, long term CO_2 target for global aviation at the 2022 general assembly compatible with the Intergovernmental Panel on Climate Change (IPCC) 2018 degree report and 2015 Paris Climate Summit ambition, and develop a framework that will support delivery of the 2050 long-term CO_2 target
- Progress United Nations Framework Convention on Climate Change (UNFCCC) negotiations on Article 6 of the Paris Agreement enabling development of global carbon markets

Carbon Capture and Storage (CCS)

The use of robust carbon offsets and investment in innovative carbon removal solutions will be vital to address residual UK aviation emissions by 2050. We ask the government to:

- Raise ambition on carbon capture, utilisation and storage (CCUS) deployment and commit to supporting at least two clusters to be operational by 2025
- Work with industry to ensure UK carbon removal solutions are eligible for airline investment through CORSIA

INTRODUCTION

Sustainable Aviation is an established UK industry group which sets out the collective approach of UK aviation to tackling the challenge of ensuring a cleaner, quieter, smarter future for our industry. Launched in 2005, it is a world first bringing together of major UK airlines, airports, manufacturers, air navigation service providers and key business partners.

INTRODUCTION

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INTRODUCTION

1.1 Purpose and scope of this Decarbonisation Road-Map

This Road-Map sets out Sustainable Aviation’s view of the expected growth in UK aviation activity and the contribution that can be made by different measures to achieve net zero carbon emissions over the period to 2050. It is based on the latest information available to us at the time of writing.

The Road-Map’s purpose is to inform debate, to highlight the efforts being taken by the aviation industry to reduce its carbon intensity, to assess the likely effectiveness of those efforts in the specific context of UK aviation, and to identify areas where Industry and Government can do more.

As with our previous CO_2 Road-Maps, we interpret “UK aviation” to mean “flights which depart from UK airports”. This is consistent with the accounting convention used by the UK to assess emissions from UK aviation. Due to the intrinsic global nature of aviation, the UK aviation industry knows that approaches to decarbonising aviation must be done as an international endeavour to have the desired impacts; unilateral UK policy measures with respect to aviation emissions will do little to mitigate worldwide climate change impacts. Carbon pricing mechanisms should apply internationally to avoid competitive distortion and carbon leakage (where emissions simply move to other airlines on the same or similar routes) and secure, real and meaningful global net CO_2 reductions.

Besides carbon dioxide, emissions from aviation also include oxides of nitrogen (NOx), water vapour, particulates, carbon monoxide, unburned hydrocarbons, soot and oxides of sulphur (SOx). The climate impact of many of these is discussed in a separate paper [SA, 2014a]. This Road-Map focuses purely on CO_2.

Finally, the impact of changes to the carbon price and level of Government support on UK aviation’s decarbonisation trajectory have been considered to aid further debate.

1.2 Developments in science based climate change targets and UK policy

Since our 2016 CO_2 Road-Map was published new scientific evidence has been provided by the UN Intergovernmental Panel on Climate Change (IPCC)[1] on the need to limit global temperature rise to 1.5ºC. The report found that human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. In future, global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. The report assessed that significant global impacts would occur if temperature rises above 1.5ºC occurred. They assessed temperature rise could be limited at 1.5ºC if global CO_2 emissions decline by about 45% from 2010 levels by 2030, reaching net zero around 2050.

Responding to this report the UK Government sought advice from the UK Committee on Climate Change (CCC). In May 2019 the CCC issued their advice in their ‘Net Zero’ report[2]. The report recommended the UK should set a target for net zero greenhouse gas emissions by 2050. It also assessed that aviation is likely to be the largest carbon emitter in the UK by 2050.

In June 2019 the UK Government responded to this by setting legislation requiring the UK to bring all greenhouse gas emissions to net zero by 2050[3]. Regarding aviation emissions, the Government clarified to Parliament that the target must cover the whole economy, including international aviation and shipping (IAS) emissions, but further advice would be sought from the CCC on how this could be best achieved.

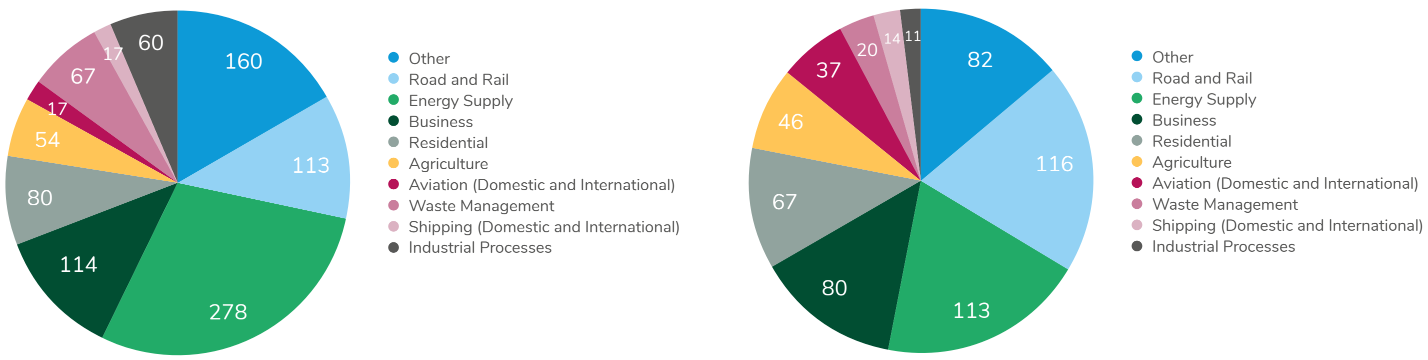
In September 2019 the CCC sent a letter to the Government, setting out their advice on how to include aviation emissions[4]. Specifically, they stated that the UK planning assumption for International Aviation should be to achieve net-zero emissions by 2050 (domestic UK aviation emissions are already included in UK carbon targets). They recommended this is reflected in the UK Aviation Strategy (currently under development). In addition to ‘in sector’ emission reductions the CCC also stated that this is likely to require some use of greenhouse gas removals (GGRs) to offset remaining emissions.

At the time of writing the UK Government have yet to respond to this CCC letter. A consultation on the ‘decarbonisation of transport’ is planned[5] with the expectation that this will inform the final Aviation Strategy white paper[6].

1.3 UK aviation CO_2 emissions performance

Currently UK aviation gross emissions account for 7% of total UK carbon emissions[2]. In 2017 the gross emissions from flights departing the UK was 37 $MtCO_2$, up by 20 $MtCO_2$ since 1990. As a result of effective market based measures (MBMs), there has been a reduction in net emissions from UK aviation of 5.2$MtCO_2$ in 2017.

1.3.1 Comparison of UK emissions by sector (2017 versus 1990)



UK 1990 CO_2 emissions by sector ($MtCO_2$)

UK 2017 CO_2 emissions by sector ($MtCO_2$)

Figure 1.1

Source: UK Government greenhouse gas statistics

1.3.2 Aviation emissions in context

Globally, carbon emissions from all sectors, including aviation, have risen by 60% since 1990. Across Europe and the UK however emissions have fallen, primarily due to the move to cleaner energy generation. Aviation emissions, whilst only representing a small proportion (around 2%) of the total, have grown faster than the average across all sectors. To effectively address this, it is important to understand the figures in more detail for the UK and the opportunities to reduce them.

Table 1.1

Year	Global emissions (All sectors)	Global Aviation Emissions	EU Emissions (All sectors)	EU Aviation Emissions*	UK Emissions (All sectors)	UK Aviation Emissions**
1990	20,520	410	4,023	88	818	17
2017	32,840	859	3,209	171	503	37
% Chg 2017 vs 1990	60%	110%	-20%	94%	-39%	114%
Source	IEA	IATA	IEA	EASA	UK Government	UK Government

All carbon figures are reported in $MtCO_2$
NOTES:
* Latest published data is 2016
** includes international and domestic emissions

1.3.3 Annual changes in UK aviation emissions

Since 1990 emissions from flights departing the UK have more than doubled. However, since 2005 UK aviation has decoupled growth in activity from carbon emissions[3] due to significant fleet upgrades. This mirrors the changes in UK aviation fuel use reported by the Government[4].

Changes in UK aviation carbon emissions and passengers since 1990

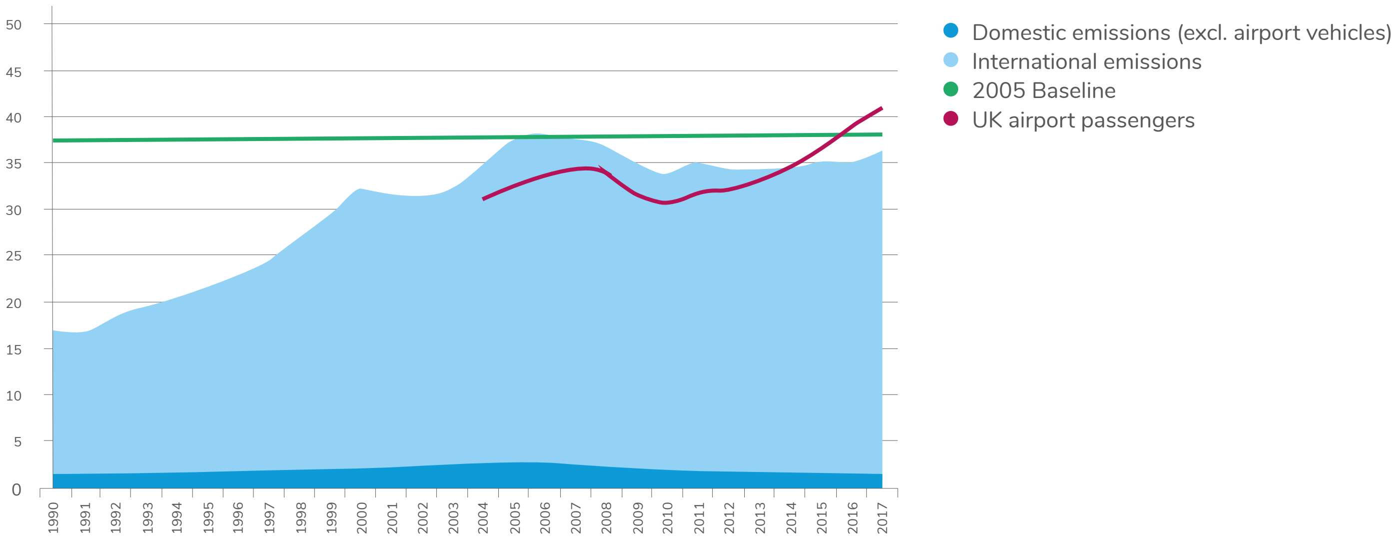
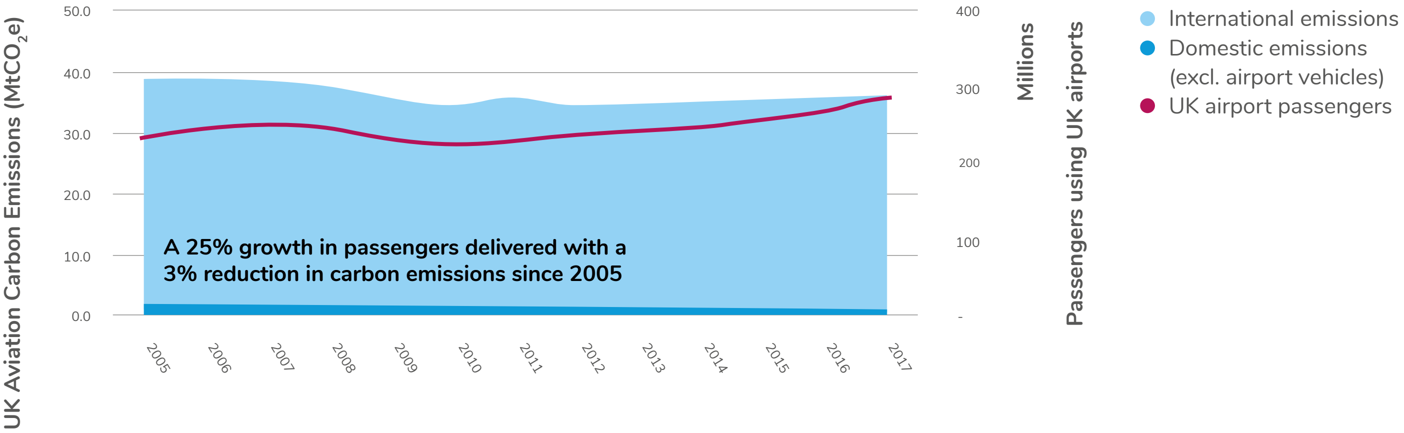


Figure 1.2

Source: Data from UK Government Greenhouse Gas statistics (2005 used as peak emissions)

Changes in UK aviation carbon emissions and passengers since 2005



A 25% growth in passengers delivered with a 3% reduction in carbon emissions since 2005

Figure 1.3

Source: Data from UK Government Greenhouse Gas statistics

1.3.4 Summary of significant recent industry innovations

Between 2005 and 2016 Sustainable Aviation's member airlines carried 26% more passengers and freight but only grew absolute CO_2 emissions by 9%[5]. Disconnecting growth in aviation activity from CO_2 emissions is due to a combined range of initiatives from across the aviation industry.

Investment in new aircraft and engine technology

- Since 2005, UK airlines have introduced more than 470 new aircraft into service, representing an investment of over £37.6 billion
- Continuing to invest in new aircraft and engine technology is critical
  - The UK Aerospace Technology Institute (ATI) has funded 260 projects with a grant value of £1.3 billion up to October 2019
  - The UK Aerospace industry itself has invested billions of pounds on new technology development over the same period

Aircraft operations & Airspace management

- Development of new UK policy and guidance agreed to modernise UK airspace 2019
- Introduction of over 425 airspace initiatives within the UK offering aircraft more direct routes and vertically efficient flight profiles. These arise from changes to the structure of airspace, improvements to the tactical delivery of flight profiles, new controller support tools and concepts of operation
- Improvements to aircraft operations from higher passenger load-factors, better optimisation of aircraft fuel-loading and miscellaneous measures such as maintenance of door seals and repairing of dents, regular cleaning of engines and airframes, and reducing aircraft on-board weight
- Improvements to reduce emissions on the ground by replacing the use of aircraft Auxiliary Power Units with more efficient airport infrastructure

Aircraft technology

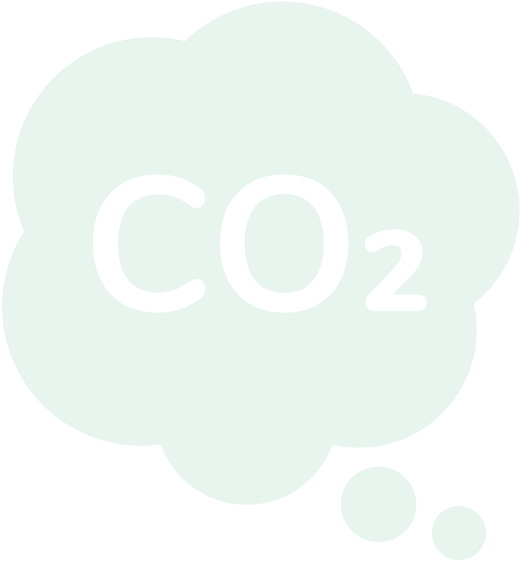
- Introduction of the Airbus A350, A330neo and A320neo, Boeing 787, 737 MAX and other latest generation aircraft into airline operations
- Development of new engine technology such as the Rolls-Royce Trent XWB

Sustainable aviation fuels

- Publishing a UK specific Road-Map in 2014, highlighting the potential for SAF
- By 2018, building a SAF special interest group network of over 400 in the UK
- Almost 200,000 flights worldwide have now taken place using SAF
- There are now six qualified routes to making SAF
- SAF is now included in the UK Renewable Transport Fuel Obligation, helping to reduce the gaps in terms of compared to fossil jet fuel and incentives favouring ground transport biofuels

Effective market-based measures (MBMs)

- Delivered a 5.2 Mt CO_2 reduction in net emissions as a result of compliance with the EU Emissions Trading System in 2017
- Development and implementation by ICAO of the global aviation Carbon Offset and Reduction Scheme for International Aviation (CORSIA) with robust sustainability eligibility criteria for carbon emissions reduction units. Key requirements being:
  - The greenhouse gas reduction or removal used as an offset need to be 'additional' to business-as-usual activity
  - Offsets must also represent a permanent reduction of emissions that cannot be reversed
  - An activity that generates offsets should not result in unintended increases in emissions elsewhere



2050 EMISSIONS: HYPOTHETICAL ‘NO-IMPROVEMENTS’ SCENARIO

Summary

Our hypothetical no improvement scenario sets out the ‘do nothing’ case. It is derived from the UK Government 2018 aviation forecast, assuming no carbon price, and shows a 70% growth in passengers to 2050 and assumes this extra activity is delivered with no improvement in the aircraft technology, fuel or the way we operated the aircraft in 2016.

Based on this approach carbon emissions from UK aviation would grow with extra flights and rise from around 37 Mt of CO_2 in 2016 to around 71 Mt in 2050.

Progressively applying a carbon price that rises to around £220 a tonne of CO_2 by 2050, to UK aviation emissions is estimated to reduce demand for flying, reducing CO_2 emissions in 2050 to around 67 million tonnes. This has been built into our UK aviation demand baseline.

2050 EMISSIONS: HYPOTHETICAL “NO-IMPROVEMENTS” SCENARIO

2.1 Introduction

This chapter sets out the hypothetical path that UK aviation’s CO_2 emissions would follow without any action to improve the carbon efficiency of flights relative to a year 2016 baseline, and in the absence of a carbon price. Specifically, this assumes a locked level of aircraft and engine technology, airspace system and operational flight efficiency plus sustainable aviation fuel penetration as achieved in 2016. Extra flights are then added to this constant performance level assuming the same load factors, on the same types of aircraft, airspace system operational techniques and fuel used. The results provide a hypothetical “no-improvements” trajectory for UK aviation CO_2 and serves as a reference against which the potential impact of anticipated improvements, and the impact upon demand of carbon pricing, can be assessed.

Clearly, this hypothetical scenario does not correspond to a “business as usual” scenario, since “business as usual” involves the rigorous pursuit of cost-reduction opportunities and improved fuel efficiency as set out in the introduction to this Road-Map.

2.2 Defining ‘Growth in Aviation Activity’

Understanding how demand for air travel from the UK will change between now and 2050 is crucial before then assessing how carbon emissions will change and how they can be managed. Since 2008 Sustainable Aviation has used forecasts for aviation growth produced by the UK Government. At the time of writing the most recent forecast was published in 2018 within the ‘Beyond the Horizon – The future of UK Aviation - Making Best Use of Existing Runways’ document[7].

This includes the opening of a third runway at Heathrow by around 2030 as set out in the Airports National Policy Statement (NPS)[8], plus it allows for all UK airports to make best use of their existing runway capacity.

We also show how applying a carbon price to aviation emissions could change demand for flying. This is calculated using three different scenarios.

1. The base case scenario

This is the published UK Government 2018 ‘Making best use of existing runways’ forecast, also referred to in this work as ‘LHR NWR + MBU’ (Department for Transport (DfT) scenario for London Heathrow North West Runway and make best use). It includes built in assumptions about how carbon price affects demand[6] and uses a carbon price trajectory which rises to £221 per tonne of CO_2 by 2050. It assumes this cost is applied to every tonne of CO_2 emitted by flights departing the UK.

2. The ‘no carbon price’ scenario

This modifies the base case by assuming there is no carbon price. This would effectively make flying cheaper which is expected to increase the demand to fly. Our work has applied the same change in demand assumed by the DfT 2017 Aviation Forecast ‘no carbon price’ sensitivity results[9] which predicts an 11% increase in passenger demand to travel in 2050 compared to the base case scenario.

3. The ‘realistic carbon price’ scenario

This modifies the base case scenario by applying a carbon price only to UK aviation CO_2 emissions for which permits must be paid for according to the current criteria of the European Union Emissions Trading System (EU ETS) and the UN Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to 2035. In the initial years to 2035 the cost of compliance with EU ETS and CORSIA does not equate to all UK aviation carbon emissions having the full carbon unit cost applied. By 2035 it is assumed that UK aviation emissions face around a third of the full carbon unit cost when averaged out. Between 2035 and 2050 it assumes an increasing proportion of the full carbon unit cost is applied to UK aviation emissions reaching 100% by 2050. This assumption causes demand suppression to be less compared to the base case scenario over this period

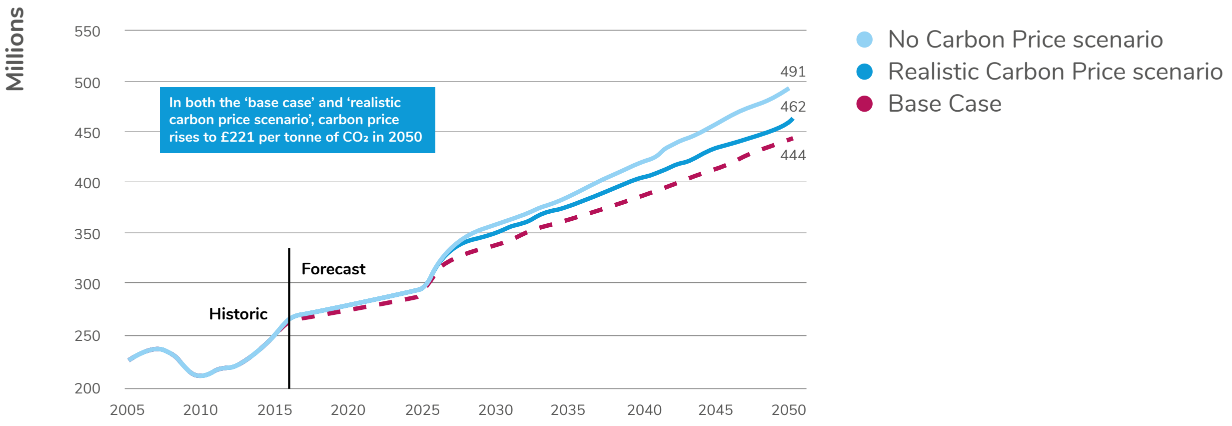
2050 EMISSIONS: HYPOTHETICAL “NO-IMPROVEMENTS” SCENARIO

2.2 Defining ‘Growth in Aviation Activity’ (continued)

The output of these scenarios is anticipated to produce different passenger demand forecasts to 2050[7] as shown.

Forecast of UK Airport Terminal Passengers (millions) depending on carbon price

Figure 2.1



In both the ‘base case’ and ‘realistic carbon price scenario’, carbon price rises to £221 per tonne of CO_2 in 2050

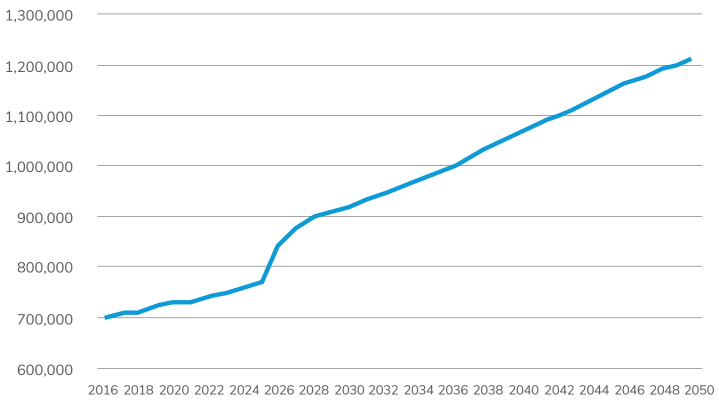
The average annual growth rates for passengers in this work are in line with those assumed by the UK Government’s aviation forecasts. For the three scenarios presented, the growth rates vary from 1.5% per annum for the base case to 1.8% per annum for the no carbon price. These are significantly lower than growth rates anticipated in other parts of the world. Globally, growth rates of over 4% per annum are predicted[9].

To calculate the contribution from freight-only flights a range of assumptions have been made. These are detailed in Appendix 2.5.

To best determine emissions from growth in aviation activity it is important to understand the distance flown. We have based our emission calculation on distance information provided by the UK Government set out below (this includes the new runway at Heathrow).

Passenger distance flown (million km)

Figure 2.2



The rest of this chapter sets out how this forecast has been used to define the hypothetical no improvement baseline for the decarbonisation Road-Map.

2.3 The Hypothetical “No-Improvements” Scenario

The carbon emissions from UK aviation activity, for each carbon-cost scenario, have been calculated assuming no improvement in the 2016 aircraft and operations efficiency level, referred to as ‘Hypothetical no improvement’.

For the ‘base case’ scenario the ‘no improvement’ carbon emissions are calculated in three steps.

- First by determining the combined passenger and freight distances flown. The passenger distance flown in kilometres has been supplied by the UK Government for the 2018 making best use forecast (base case scenario). It is assumed that passenger flights (many of which also carry some freight in the belly-hold) account for 97% of UK aviation CO_2 emissions. The final 3% of UK aviation’s CO_2 emissions is assumed to be accounted for by dedicated freight-only flights
- Secondly, how these figures change compared to the base year of 2016 is then calculated
- Finally, the 2016 base year carbon emissions are multiplied by the index change in total distance flown for each year from 2017 to 2050

2050 EMISSIONS: HYPOTHETICAL “NO-IMPROVEMENTS” SCENARIO

2.3 The Hypothetical “No-Improvements” Scenario (continued)

Carbon emissions for the ‘no carbon price’ and ‘realistic carbon price’ are then calculated by modifying the results of the ‘base case’ scenario. Specifically, these have been calculated as follows[10]:

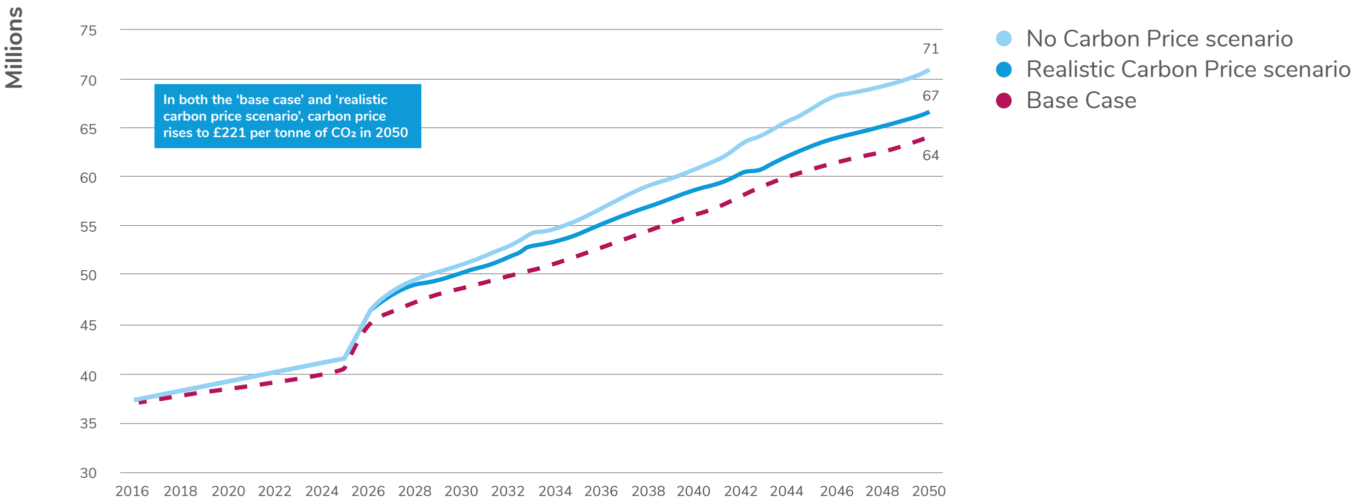
- ‘No carbon price’ annual emissions = Base case emissions multiplied by percentage change in passenger demand forecast in Table 41 of the DfT 2017 Aviation forecast[11]
- ‘Realistic carbon price’ annual emissions = no-carbon-price emissions minus [proportion of CO_2 emissions incurring a price multiplied by (no-carbon-price emissions minus base-case emissions)]

An iterative procedure was employed to take account of the feedbacks between changes in aviation activity and changes in emissions, hence changes in the number of tonnes of CO_2 regulated and the associated cost of compliance, which in turn affects demand.

2.3.1 Resultant carbon emissions for scenarios

Hypothetical no improvement UK aviation CO_2 emission scenarios (million tonnes)

Figure 2.3



Using the methodology set out, this chart shows how UK aviation carbon emissions to 2050 vary for the three scenarios.

The Sustainable Aviation ‘realistic carbon price’ scenario represents a growth in aviation activity to 462 million passengers and 3.2 million air transport movements per year by 2050. Assuming (hypothetically) no improvement in the carbon efficiency of flights, this would be expected to produce 67 $MtCO_2$ from UK aviation in 2050.

The UK government 2018 ‘base case’ scenario corresponds to 444 million passengers and 3 million air transport movements per year by 2050. Assuming no improvement in the carbon efficiency of flights, this would be expected to produce 64 $MtCO_2$ from UK aviation in 2050.

Finally, in the ‘no carbon price’ scenario, passenger numbers could grow to 492 million with 3.4 million air transport movements and, with no improvement, would produce 71 $MtCO_2$ by 2050. The passenger numbers in this scenario exceed the DfT modelled UK airport passenger capacity, based on the ‘DfT 2017 Aviation Forecast’. Therefore, such a scenario could only be achieved if additional UK airport passenger capacity were approved, beyond that assumed by the DfT in their 2017 Aviation Forecast.

Based on these results it can be concluded that applying a carbon price to UK aviation CO_2 emissions, which rises to £221 a tonne by 2050, will reduce demand by around 30 million passengers per year. This reduction in demand is then expected to reduce CO_2 emissions from UK aviation buy around 4 $MtCO_2$ in 2050, compared to the no carbon price scenario.

Due to the high level of demand for air travel however, even with a carbon price applied, passenger numbers are expected to grow by 73% by 2050 relative to 2016.

These results are used to introduce a new, first wedge to the SA CO_2 Road-Map. It is called ‘Effect of carbon price on demand’ and appears prior to the industry ‘in sector’ and ‘out of sector’ CO_2 mitigation wedges, used in previous versions of the SA CO_2 Road-Map.

THE SUSTAINABLE AVIATION DECARBONISATION ROAD-MAP

3.1 Introduction

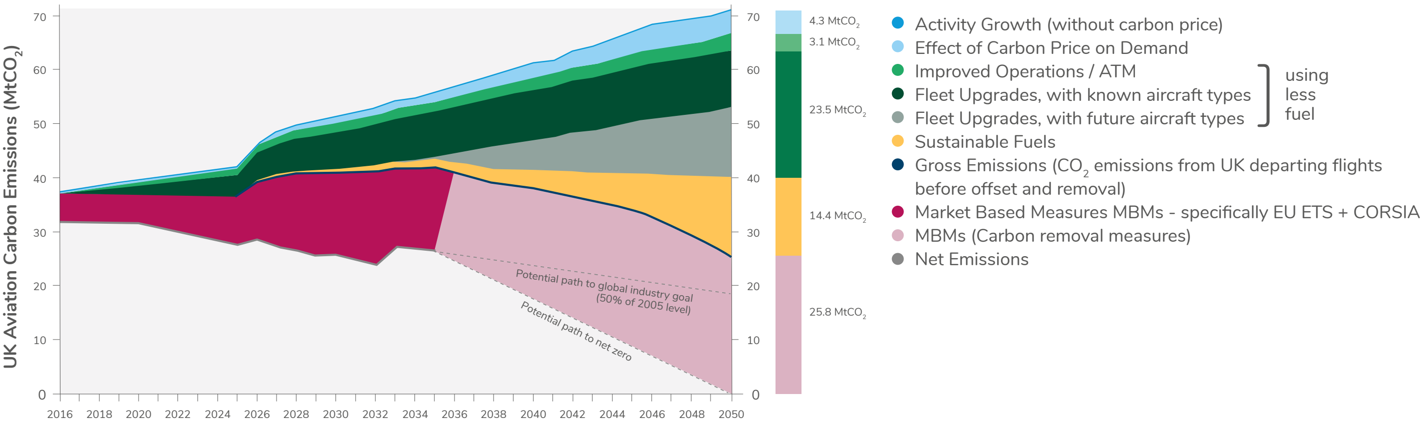
This CO_2 Road-Map has drawn on expertise from all actors across the UK aviation industry, including and beyond governments, science and NGO's, airlines, airports, aerospace manufacturers and air navigation service providers. Starting from UK-specific aviation demand-growth forecasts which also takes account of additional runway capacity in the South East of England. The rest of this document sets out in a transparent manner the assumptions underpinning our Road-Map, the method of working used to transform our assumptions into the results of our analysis, and the distinction between those areas in which quantitative data-driven analysis has been possible and those areas where informed judgement has been necessary.

3.2 The 2020 Decarbonisation Road-Map

Our Road-Map is developed using the latest knowledge, data and experience from across SA members and beyond. The resulting opportunities to reduce emissions are considered out to 2050. To demonstrate their decarbonisation potential they have been compared against latest UK Government demand growth forecasts and a hypothetical scenario where no improvements in aviation emissions are achieved. The results are split into ‘in sector’ and ‘out of sector’ decarbonisation opportunities. The ‘in sector’ opportunities show Sustainable Aviation’s view of the most likely carbon reduction developments from airspace modernisation, new aircraft technology and how these are incorporated into airline fleets and the development and use of sustainable aviation fuels. The ‘out of sector’ opportunities explore the potential of carbon capture and storage innovations, plus carbon trading and offsetting measures. In making this distinction we are explicitly including airlines, airports, and airframe and engine manufacturers OEMs and oil companies as ‘in sector’.

Our Road-Map uses the ‘no carbon price’ and ‘realistic carbon price’ scenarios as defined in Chapter 2. These bound the first wedge on the chart to define the expected growth in UK aviation emissions in a ‘no carbon price’ situation from 37 $MtCO_2$ in 2016 to 71 $MtCO_2$ in 2050. Carbon pricing through effective market-based measures affects demand by 6% and reduces emissions by 4 MtCO in 2050.

Decarbonisation Road-Map for UK Aviation



Using the assumptions provided on aircraft operational and air traffic management improvements around a 4% reduction in CO_2 emissions is added.

Introduction of new and future aircraft technology offer the greatest in sector opportunity to reduce CO_2 emissions. Known aircraft technology are forecast to deliver a 17% fuel efficiency improvement by 2050 and for future aircraft technology, the figure is 24% compared to 2016. This results in a combined potential reduction in UK aviation CO_2 emission of 37% by 2050 from aircraft technology.

Developing and growing the use of sustainable aviation fuels contributes up to 32% reduction in emissions by 2050.

Combined, the in-sector CO_2 reduction measures provide the opportunity to remove 41 of 71 million tonnes of CO_2 per year from UK aviation activity in 2050 compared to a no improvement situation from 2016.

To achieve the goal of net zero emissions by 2050 effective market-based measures (MBMs) developed internationally, building on the CORSIA mechanism, will be necessary to obligate airlines to also invest in carbon reductions from outside of the aviation sector. In 2050 this will require around 26 million tonnes of CO_2 to be offset or removed outside of aviation.

3.2 The 2020 Decarbonisation Road-Map (continued)

The exact level of MBMs required in 2050 will depend on the rate of take up of other technology solutions e.g. new aircraft, engines or SAFs that can be achieved reasonably cost effectively over this period. While in-sector emission reductions are initially expected to be more expensive that offsets in the early technology development phase, over time we expect costs to drop significantly. Higher carbon prices will also drive investment for in-sector emission reductions. Therefore the exact dependence of the sector on MBMs is highly dependent on both technology development and associated costs of carbon mitigation. However, SA believes it is imperative for the aviation sector to aim for as much carbon reduction within the sector as possible. To avoid competitive distortion and carbon leakage (where emissions move between airlines on the same routes because of unilateral policies), and ensure effective and efficient emissions reductions, international solutions established via UN and country-agreed policies such as CORSIA are essential. Any unilateral action could simply move the carbon emissions away from the UK to another country (Carbon leakage). The aviation industry is supporting UN and other bodies to encourage the most robust and effective policies possible.

Summary of aviation decarbonisation opportunities

Proposal/Timescale	Sustainability benefit	Short term (2019-2025)	Medium Term 2025-2040)	Long Term (2040-2050 plus)
New aircraft technology (Purchase)	Cleaner & quieter flights	360 latest generation aircraft joining UK airlines	Regional short range hybrid electric flights from 2035	Increasing use of hybrid electric for regional and European flights
Sustainable Aviation Fuel (SAF)	SAF gives at least 70% life cycle carbon saving compared to using fossil fuel	Roll out of commercial plants. Ongoing fuel testing and qualification	By 2035: • 14 UK operational plants creating up to 5,200 jobs • C. 1.0 million tonnes of SAF produced per annum	By 2050, c.4.5 million tonnes of UK SAF produced per annum delivering a reduction in emissions of around 32%
New aircraft technology (development and deployment)	Cleaner & quieter flights	360 latest generation aircraft joining UK airlines. Research for hybrid electric aircraft and the next long-haul aircraft	Manufacturing of hybrid electric aircraft and next generation long-haul aircraft	Increasing use of hybrid electric for regional and European flights
Effective Market Based Measures (MBM's)	Achieve net carbon targets by reducing emissions outside of the sector	• EU ETS for domestic and European flights • CORSIA for International Flights from 2021 • Improve natural carbon sink solutions • Develop carbon removal solutions	Further development of effective carbon MBMs and carbon reduction options such as Carbon sinks and removal solutions	Further development of Effective carbon MBMs and carbon reduction options such as Carbon sinks and removal solutions
Airspace improvements	More efficient flights (CO_2, noise and air quality improvements)	Delivering modernisation programme		Airspace modernisation delivering reduction in emissions and fuel burn[12]

3.3 Recommendations to Government

To realise the potential set out in this Road-Map it is critical that UK Government support industry commitments. Sustainable Aviation recommends this is developed across four key areas:

3.3.1 Technology

With the right support from Government our world-class aviation and aerospace sectors are uniquely placed to capitalise on the opportunities of green aviation technology – be it more efficient gas-turbine engines, hybrid electric or fully electric aircraft. These exciting technologies promise a substantial reduction in CO_2 emissions from UK aviation.

- **Government and industry must continue to support aerospace research and development through the Aerospace Growth Partnership. This is vitally important for the long-term sustainability of the industry**

- **Other measures such as effective market-based measures and new breakthroughs in advanced, affordable sustainable aviation fuels (SAF) will meet the carbon reduction targets until future fleet technology secures further long-term solutions**

3.3.2 Sustainable Aviation Fuels

It is essential that the UK recognises the immediate and significant role of sustainable aviation fuels (SAF). SAF is the next big breakthrough for aviation carbon reductions which desperately needs appropriate government support to become the mainstay of long-haul flights – necessary if UK aviation is to get to net zero. SAFs have the potential to reduce UK emissions in 2050 by at least 30%, and offer at least 70% lifecycle reduction in carbon emissions compared to current fossil fuels. Full details are outlined in the SA partner publication, the Sustainable Aviation Fuels Road-Map 2020. SAFs have the potential to bring multiple benefits to the UK, world-leading breakthrough carbon solutions, clean growth, jobs, IP and improved fuel security. They are a fully tested and qualified technology compatible with today's aircraft. UK airlines are already investing heavily in SAF, including Virgin Atlantic and British Airways. But urgent government support is needed to scale and commercialise sustainably robust and affordable SAF, particularly given that other countries – like the Netherlands and United States – are pulling ahead. A domestic SAF sector would create thousands of jobs and provide a world leading export opportunity as aviation decarbonises globally.

To support the development of SAF:

- **Through a new Office for Sustainable Aviation Fuels (or something similar):** Government must recognise the importance of SAF through the creation of a cross-departmental Office for Sustainable Aviation Fuels – based on the Office for Low Emission Vehicles (OLEV) - and by a commitment of at least £500m[13] public private funding over five years (totaling £1bn) to deliver flagship plants and support nascent commercial UK production capability. These measures will help provide the essential cross-government co-ordination necessary to progress the development and commercial deployment of sustainable aviation fuels

- **Reform the Renewable Transport Fuel Obligation:** It is essential that Recycled Carbon Fuels are incorporated into The Renewable Transport Fuel Obligation (RTFO) to remove barriers to production, and that investment is supported through applying of at least 1.2x multiplier for SAF advanced developmental fuels. This will increase the attractiveness to investors giving a clear signal from HMG as to their intentions and to the long term viability of this sector together with incentivising producers to manufacture SAF

3.3.3 Effective market-based measures (MBMs)

Sustainable Aviation recommends the Government work with industry to address the following issues:

Global leadership in ICAO and UNFCCC: By 2022, work through ICAO to set a clear, long term CO_2 target for aviation compatible with the IPCC 1.5 degree report and 2015 Paris Climate Summit ambition. Concerted, global action on aviation emissions is absolutely essential. COP26 in 2020 in Glasgow presents an ideal opportunity for the UK to show climate change leadership on the global stage by progressing the international framework for aviation emissions to support delivery of the 2050 long-term CO_2 target. To support development of the wider carbon markets, UK government should continue to focus on a successful outcome of UNFCCC negotiations on Article 6 of the Paris agreement.

Align intra-European policy with CORSIA. UK government should transition from the current ETS model into a policy that is aligned with the CORSIA framework.

Set a clear UK strategy to develop and implement carbon removal projects and technologies across the UK. This should include both natural carbon removal and technology-based carbon removal solutions.

3.3.4 Airspace Modernisation

Delivery of airspace modernisation: Government must maintain their vital leadership role providing the necessary policy and regulatory framework to enable the CAA to support the delivery of airspace modernisation. This will ensure that the priorities of all stakeholders in terms of carbon emissions and noise can be appropriately balanced.

IMPROVEMENTS IN AIRCRAFT AND ENGINE EFFICIENCY

Summary

1. Introduction of "known" aircraft types will improve fleet-average fuel efficiency of UK aviation by some 17% by 2050 relative to the year 2016 baseline fleet, with the bulk of this improvement delivered by around 2040
2. Introduction of "future" aircraft types from 2035 onwards (including conventional and hybrid-electric aircraft) and from 2040 onwards (pure-electric aircraft on shorter range flights) has the potential to further reduce fleet CO_2 emissions within UK aviation by some 24% by 2050, taking account of likely fleet penetration by that date
3. This yields a combined potential reduction in CO_2 from UK aviation by 2050 of some 37%[14] relative to the fuel-efficiency of a year 2016 baseline fleet
4. Post 2050, improvements in fleet-average fuel efficiency will continue due to the ongoing penetration into the fleet of "future" aircraft types. Potentially, all-electric aircraft of progressively greater range-capability could offer additional substantial carbon reductions. However, those improvements lie beyond the time-horizon of our Road-Map

We acknowledge the significant levels of government support to the UK aerospace industry provided through initiatives such as the Aerospace Growth Partnership (AGP) and Aerospace Technology Institute (ATI). In the coming years Government must ensure that access by UK aerospace industry to ongoing funding for high-value collaborative R&D, essential for delivering highly-efficient future aircraft and propulsion systems, remains in place.

IMPROVEMENTS IN AIRCRAFT AND ENGINE EFFICIENCY

Key features of the fleet refresh model used in this 2019 road-map

This Road-Map uses 2016 as its baseline year, while our previous Road-Map used 2010 as its baseline year. Fleet upgrades performed in the 2010-2016 period clearly do not fall within scope of our current Road-Map. As a result, the remaining fuel-efficiency improvement opportunity due to upgrading the year-2016 fleet with "known" aircraft types is correspondingly smaller than if we had considered a year-2010 baseline fleet.

Furthermore, unlike our previous Road-Maps, any remaining baseline aircraft which have not been upgraded to "known" aircraft types by the time a corresponding "future" aircraft type becomes available are assumed in this Road-Map to be replaced by the "future" aircraft type rather than the "known" aircraft type. This reduces slightly further the percentage improvement attributable to "known" aircraft in this Road-Map and causes a corresponding increase in the improvement attributable to "future" aircraft.

From 2040, a large proportion of aviation activity on short routes (up to 400km in length) is assumed to migrate over a ten-year period to all-electric "future" aircraft types running on low-carbon electricity. This is a new feature which has not appeared in any of our previous CO_2 Road-Maps.

From 2035, any aviation activity not suitable for migration to all-electric aircraft is assumed to migrate over a 20-year period to conventional or hybrid-electric "future" aircraft types offering a 25% improvement in fuel efficiency relative to their respective predecessors.

4.1 Introduction and Framework

This chapter sets out our view of the potential for improvements in aircraft and engine fuel efficiency to reduce UK aviation's carbon intensity by 2050. We detail our assumptions concerning the CO_2-reduction potential of "known" and "future" aircraft types relative to their respective predecessors, their likely entry into service dates, and their resulting impact on fleet CO_2 emissions. For the first time in one of our CO_2 Road-Maps, we include an initial assessment of the impact of all-electric aircraft. We also provide an update concerning technology options being explored by aerospace manufacturers, which collectively underpin our assumptions for "future" aircraft. Throughout, we define "the fleet" as aircraft used to conduct flights falling within the scope of "UK aviation".

4.2 Contributing Factors

This section reviews some of the factors which can influence the fuel-efficiency and CO_2 emissions from the in-service fleet.

4.2.1 Fuel Price

Historically, the cost of fuel has accounted for a substantial proportion of the total cost of ownership of commercial aircraft. Even in the brief period since our previous Road-Map in 2016, fuel prices have risen significantly. The International Air Transport Association (IATA) estimates that in 2019 the global aviation sector would spend some $206 billion on fuel, representing 25% of operating costs[15].

Aircraft and engine manufacturers experience strong demand from customers for more fuel-efficient aircraft and have responded to this with successive generations of aircraft offering improved fuel-efficiency over their predecessors. Competition between manufacturers drives very significant investment in research and development activities, often over very long timescales.

4.2.2 Carbon Price

Since there is a direct link between fossil-fuel use and CO_2 emissions[16], a carbon price applied to aviation CO_2 emissions can be viewed as a surcharge on the price of fossil-fuel, further incentivising improvements in fuel efficiency.

The EU Emissions Trading System (ETS) has for many years included aviation CO2 emissions within its scope, while the CORSIA scheme[17,18,19] agreed by the International Civil Aviation Organization (ICAO) will commence its pilot phase in 2021.

Although the "price" of a tonne of CO_2 is currently relatively small in comparison to the cost of the fuel required to produce a tonne of CO_2, it is anticipated that the price of carbon will rise substantially over time, driven in part by demand created by schemes such as CORSIA.

In particular, this Road-Map assumes a carbon price trajectory which reaches £221 per tonne of CO_2 by 2050[20], consistent with UK government's "central" carbon price assumptions used for policy assessments.

4.2.3 New Entrants

The extent to which aircraft from emerging competitors such as Mitsubishi, UAC[21] and COMAC[22] will influence UK aviation fuel-efficiency in the future is unclear at present. As a result, in this Road-Map we do not explicitly model the impact on fleet fuel efficiency of aircraft from those manufacturers. This approach introduces no material error to the Road-Map, since for new entrants to take a material share of the market will require products of similar fuel-efficiency to those offered by established market participants. Furthermore, all manufacturers' aircraft will be subject to the same ICAO CO_2 emissions standard (**see section 1.1.4**). Greater clarity on this issue will no doubt emerge over time.

IMPROVEMENTS IN AIRCRAFT AND ENGINE EFFICIENCY

4.2.4 ICAO CO_2 Emissions Standard

In March 2017, the International Civil Aviation Organization (ICAO) adopted a CO_2 emissions standard[23] for aircraft. The standard will apply to the certification and production of new aircraft types from 2020, modified existing types from 2023, and unmodified existing aircraft types from 2028.

The aim of this certification standard is to reduce CO_2 emissions from aviation by encouraging the integration of fuel-efficient technologies into aircraft designs and developments and the replacement of older aircraft by newer, more efficient designs.

The CO_2 Standard is a certification standard, not an operational standard, and as such does not impact current aircraft in use or (until 2028) in production. However, it will impact the next generation of aircraft designs represented by the "future" aircraft wedge of this Road-Map.

While ICAO's CORSIA (see above) places an obligation upon aircraft operators, ICAO's CO_2 emissions standard represents an obligation upon aerospace manufacturers and their products.

4.2.5 Freighters

Freight-only flights account for only a small single-digit percentage of UK aviation CO_2 emissions and we expect their materiality to remain constant or perhaps even decline relative to that of passenger flights. In the absence of available UK-specific data concerning the likely usage balance within UK aviation between passenger-conversions and new-build freighters, we make the simplifying assumption that the efficiency of the freighter fleet will improve at a similar rate to that of the passenger fleet. The error this may introduce to the overall analysis is small, due to the low materiality of freight-only flights within UK aviation.

4.2.6 Technology Goals

In Europe, the goals of Flight Path 2050 include "In 2050 technologies and procedures available allow a 75% reduction in CO_2 emissions per passenger kilometre.... relative to the capabilities of typical new aircraft in 2000"[24]. The ACARE[25] organisation has established a strategic research and innovation agenda as a route towards those goals, and significant R&D programmes such as CleanSky as a means to deliver them.

4.2.7 Nationally Funded Initiatives and R&D Programmes

Significant technology research programmes are required in order to deliver future aircraft with substantially improved fuel efficiency. Aerospace-specific initiatives, strategic alliances and programmes such as the Aerospace Growth Partnership[26] (AGP), the Aerospace Technology Institute[27] (ATI) and the Future Flight Challenge[28], in combination with other multi-sector initiatives such as the Faraday Battery Challenge[29], the Industrial Strategy Challenge Fund[30], and the High Value Manufacturing Catapult[31], help to secure the long-term competitiveness of UK aerospace and support the acquisition and development of transformational technologies which can help to reduce CO_2 emissions from future aircraft. It is essential that programmes such as these continue into the future.

4.3 Baseline Fleet Characteristics

Figure 4.1 shows, for flights departing from UK airports in year 2016, the distribution of CO_2 emissions between aircraft families. Using data for passenger flights from OAG[32] in conjunction with the fuel-burn lookup-table from ICAO's carbon-calculator[33], account is taken of the distance covered by each flight (including a surcharge to represent non-great-circle routes) and the efficiency of each aircraft type for the specific distance travelled. Using this methodology, total CO_2 emissions from UK passenger-flights in year 2016 are modelled as 36.7 $MtCO_2$, a figure which is slightly higher than the value of 35.2$MtCO_2$ (also including freight-only flights) reported for the same year in the UK's National Atmospheric Emissions Inventory[34], but slightly smaller than the value for the same year of 37.3 $MtCO_2$ (also including freight-only flights) used by DfT in their 2018 forecasts.[35]

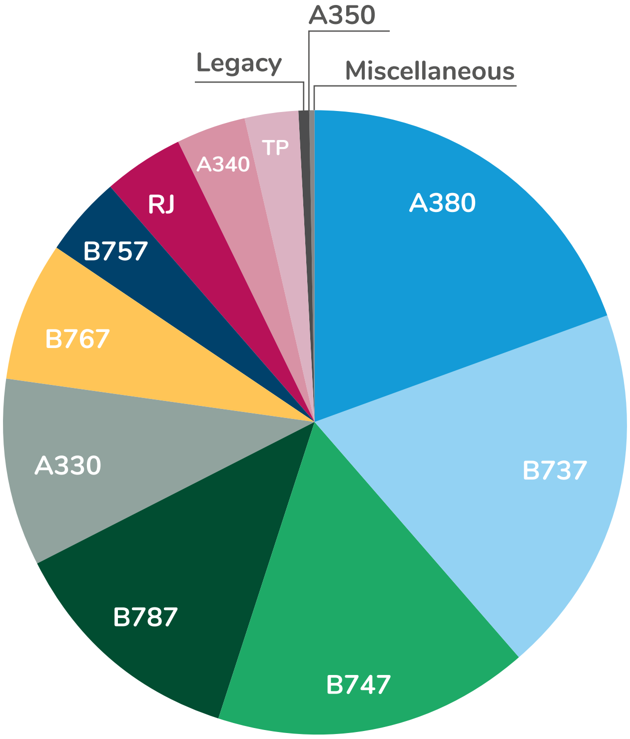


Figure 4.1 – distribution of CO_2 emissions between aircraft types or categories. Year: 2016: Scope: UK aviation.
Source: SA analysis of data from OAG and ICAO as described in the main text. RJ = regional jets; TP = turboprops.

4.4 Fleet Refresh Model – General Characteristics

In this Road-Map, UK aviation activity is sub-divided into 11 sub-fleets or categories whose names correspond to aircraft types or size-classes present in the year 2016 baseline fleet. In our fleet model, some of those 11 aircraft categories initially comprise aircraft from specific aircraft families: “737-NG”, “A320”, “757”, “A330”, “767”, “747-400”, “A380”; while other categories comprise a range of aircraft types in a broader size-class: “TP” (turboprop), “RJ” (regional jet), “LTA” (large twin aisle), “other”. The “other” category represents UK aviation activity which, by 2016, had already been upgraded to the latest aircraft currently available (787 and A350). For convenience the “other” category also includes “miscellaneous” and “legacy” aircraft whose materiality is very small as shown in **Figure 1**.

We assume that the proportion of UK aviation activity delivered by each of the 11 aircraft categories is largely unchanged over time from the 2016 position. Consequently, in the absence of any fleet upgrades, CO_2 emissions from each aircraft category would grow in line with CO_2 emissions from UK aviation as a whole. However, as will be seen below, our model does accommodate migration of activity from one aircraft size-class to another size class where there is a compelling reason to do so.

During the period 2016 to 2050, each sub-fleet undergoes fleet upgrades from “baseline” aircraft types to “known” aircraft types, and from “known” aircraft types to “future” aircraft types. In some categories, the transition from “baseline” to “known” aircraft types is not complete by the time “future” aircraft types become available, and so any remaining “baseline” aircraft from that point onwards are assumed to be replaced directly by “future” aircraft types concurrently with replacement of “known” types with “future” types.

During a defined fleet upgrade period of say 20 years, the amount of aviation activity delivered in an aircraft category by the “old” aircraft type is assumed to decay linearly to zero. Replacement-activity and also growth-activity is delivered by the corresponding “new” type. The percentage fuel-efficiency improvement offered by the “new” type relative to the old type thus applies to a greater proportion of the fleet as time progresses.

4.5 “Known” Aircraft: CO_2-Reduction Opportunity

In this section we consider how upgrading the baseline (year 2016) fleet can reduce CO_2 emissions through improving fuel efficiency. A key aspect of this first wave of fleet renewal is that the aircraft entering the fleet are already defined and available for order, which means that the fuel-efficiency improvement they offer - relative to the baseline aircraft they will replace - is already known and forms part of the value proposition considered carefully by prospective operators of those aircraft.

With reference to **Figure 1**, we can look at each aircraft category in turn and consider what fuel-efficiency improvement may be achieved by upgrading to the latest corresponding “known” aircraft types offering similar payload-range capability. In some cases there is not an obvious one-to-one replacement route, so we consider multiple options within an aircraft size category. Readers are reminded that the discussion concerns flights which depart from UK airports and comments should be interpreted in that context.

- **Airbus A320 family** - members of the Airbus A320neo family offer a “20% fuel burn per seat improvement”[36], relative to corresponding members of the A320ceo family

- **Boeing 737 family** - the Boeing 737 MAX offers a “14% reduction in carbon emissions and fuel use compared to Next-Generation 737” aircraft[37]

- **Airbus A350 and Boeing 787** - examples of these aircraft types in the year 2016 baseline fleet represent upgrades that have already taken place from previous-generation aircraft

- **Boeing 747-400** - analysis of OAG data shows that in year 2016 virtually all 747-400 operations in the UK were operated by British Airways (BA) and Virgin Atlantic Airways (VAA). According to Cirium fleets data, BA received their last Airbus A380 in early 2016, and so we assume that any remaining 747s will be replaced by other wide-body aircraft types currently on BA’s order books (Boeing 787, Airbus A350 and Boeing 777-X). Both BA and VAA state that their remaining 747-400 fleets will be replaced by aircraft offering a fuel-efficiency improvement of 30%,[38,39]. VAA will complete the transition by the end of 2021, BA by 2024

4.5 "Known" Aircraft: CO_2-Reduction Opportunity (continued)

- **Airbus A380** - like the A350 and 787, the A380 represents replacements of older types (such as the 747-400) that have already taken place. However, unlike the A350 and 787, whose production runs are likely to continue for some time, the last A380 delivery is scheduled for 2021[40]. This means that any growth in aviation activity in the segment serviced in 2016 by the A380 is likely to be fulfilled by other aircraft types such as the A350 and 777-X. Furthermore, some phase-out of A380s can be expected over the next decade or two as early models reach the end of their in-service lives. Analysis of data from OAG shows that available seat kilometres delivered on UK-departing flights by A380 aircraft peaked in 2017 and fell by approximately 4% in each of the following 2 years. For this Road-Map we make the assumption that 50% of year 2017 A380 activity will transfer to "known" large twin-engined aircraft, offering a 15% reduction[41] in fuel-consumption per available seat-kilometre, over the 18 years to 2035, after which any remaining A380s will be replaced by "future" large twin-engine aircraft as part of a subsequent phase of fleet refresh as described later in this chapter

- **Boeing 757** - the Airbus A321LR and A321XLR "offers 30% lower fuel burn per seat compared with previous generation competitor aircraft"[42]. For the purposes of this Road-Map, we assume that if Boeing launches its proposed NMA aircraft, it will offer a fuel efficiency improvement that is no less than that of the A321LR/A321XLR

- **Boeing 767** - the Boeing 787 Dreamliner "enables airlines to reduce fuel use and emissions by 20 to 25 percent compared to previous airplanes"[43]

- **Airbus A330** - the Airbus A330neo offers 14% lower fuel consumption per seat than the previous A330ceo[44]. We note that orders so far received for A330neo aircraft are almost entirely for the larger A330-900 version[45], while year 2016 A330ceo activity within UK aviation was split much more evenly between the smaller -200 and larger -300 models[46]. Observing that typically the larger members of an aircraft family are capable of higher fuel efficiency per seat kilometre, the 14% improvement opportunity we have noted here may prove to be an under-estimate as smaller A330ceo family members may be replaced with larger A330-900 models rather than the smaller -800 model

- **Turboprops** - this category's CO_2 footprint in 2016 was dominated by the Bombardier Q400 with the balance comprising a large number of other aircraft types. It is not clear at present what newer generation aircraft may be available in this category to provide an upgrade route. As a result, in our Road-Map we envisage no improvement to the efficiency of the turboprop fleet until such time as "future" aircraft types relevant to this category become available. Since turboprops are responsible for only a small fraction[47] of UK aviation's CO_2, the impact of this assumption on the outcome will be small

- **Regional Jets** - the Airbus A220 has "20% lower fuel burn per seat compared to previous generation aircraft[48], while the Embraer E195-E2 delivers "25.4% better fuel efficiency per seat compared to the first-generation E195"[49]. For our Road-Map we assume a 20% fuel-efficiency improvement in this category

- **Large Twin-Aisles** - the baseline fleet in this category comprises the Airbus A340 and Boeing 777 families. Opportunities for upgrade include the Airbus A350 XWB and the Boeing 777-X. We are not able to predict, nor would Sustainable Aviation adopt a position regarding, the likely market share between these two aircraft families, and so for this Road-Map we have grouped them into a single category. The Airbus A350 XWB "delivers 25% lower fuel burn, operating cost and CO_2 emissions, than previous generation aircraft"[50]. The Boeing 777X "reduces fuel use and CO_2 emissions by 20% compared to previous generation aircraft"[51] and more specifically is 20% more fuel efficient than the Boeing 777-300ER[52]. Furthermore, the 777-300ER is 10% more fuel-efficient on a per-seat basis than the 777-200ER[53]. Analysis of data from OAG, British Airways and Cirium[54] shows that in year 2016, a little over half of UK 777 activity was delivered by 777-300ER aircraft with the remainder delivered by less fuel-efficient models of that same family. For our Road-Map we therefore assume that a 25% fuel-efficiency improvement in this category is achievable when upgrading from the 2016 baseline fleet to a mixture of A350 and Boeing 777-X aircraft

4.5 “Known” Aircraft: CO_2-Reduction Opportunity (continued)

Using the above we can construct a table summarising the fleet upgrade opportunity for “known” aircraft relative to the baseline fleet. In each row of the table, fleet refresh commences at the entry-into-service date of the earliest available upgrade aircraft type, subject to an earliest start year of 2016. Recognising that the proportion of an aircraft’s total operating cost which is attributable to fuel is typically greater for wide-body aircraft performing long range flights than for single-aisle aircraft performing shorter flights, the value of a percentage-point improvement in fuel efficiency is correspondingly greater for a wide-body aircraft, motivating earlier adoption of more efficient aircraft where available. As a result, the default duration of the fleet refresh process in our model is chosen as 25 years for single-aisle aircraft and 20 years for wide-body aircraft, but in some categories that value has been shortened to take account of the age-distribution of the baseline-fleet, the extent to which the fleet upgrade process may already have been partly completed, and the likelihood that retirement of those (remaining) aircraft will take place over a shorter timescale. In the case of the 747-400 the 8-year fleet refresh period is driven by the date of 2024 declared by British Airways (see above). In our model the A380 is artificially assigned a much longer fleet-refresh period of 36 years to reflect our assumption that 50% of A380s are phased out by 2035. The remaining 50% of A380s are assumed to be replaced as part of a subsequent phase of fleet refresh as described below. In the ‘large twin-aisle’ category, we assume that the fleet refresh period will continue for some 20 years from the initial availability of the 777X, having started in 2016 due to availability at that time of the A350.

Category (Baseline Fleet)	Year 2016 Materiality	Upgrade route	Start-year	Number of years for full phase-out	Improvement Opportunity
Regional Jets	2.39%	A220, E195-E2	2016	20	20%
A320	20.72%	A320neo	2016	25	20%
737 NG	11.17%	737 MAX	2017	25	14%
757	2.38%	A321LR, A321XLR, NMA	2016	15	30%
A330	5.53%	A330neo	2019	15	14%
767	4.35%	787	2016	10	20%
Large Twin Aisle	23.27%	A350, 777-X	2016	24	25%
747-400	9.53%	787, 777-X, A350	2016	8	30%
A380	11.34%	A350, 777-X	2017	36	15%
Turboprops	1.63%	N/A	N/A	N/A	0%
Other (787, A350, miscellaneous, legacy)	7.69%	N/A	N/A	N/A	0%

Table 4.1 – fuel-efficiency improvements offered by “known” aircraft types relative to corresponding types in the baseline year 2016 fleet

4.5 “Known” Aircraft: CO_2-Reduction Opportunity (continued)

From each row of **Table 4.1** the improvement opportunity (e.g. 30%) is multiplied by the corresponding materiality factor (e.g. 9.5%) and the results summed over the aircraft categories to give an overall fleet-wide fuel-efficiency improvement opportunity of 18.8% associated with upgrading the year 2016 fleet entirely with “known” aircraft types.

However, in some of the aircraft categories[55], a “future” aircraft type (see below) may become available before replacement of the baseline aircraft with “known” aircraft according to the above table has been completed. In such cases, any baseline aircraft remaining in the fleet at the entry-into-service date of the “future” aircraft type will be replaced by a corresponding “future” aircraft type. As a result, the fleet-wide improvement associated with “known” aircraft is reduced slightly to 16.9%. The extent of this reduction depends, of course, upon the entry-into-service dates of the “future” aircraft types.

4.6 “Future” Aircraft: CO_2-Reduction Opportunity

In this section we consider a further fleet-upgrade to “future” aircraft types, which are either all-electric, and are assumed to become available from 2040, or are fuel burning (a category which encompasses hybrid-electric propulsion as well as conventional propulsion) and are assumed to become available from 2035.

In most size categories the first phase of fleet refresh from baseline aircraft to “known” aircraft will be complete by 2035 or 2040, and so the subsequent fleet refresh is entirely from “known” aircraft to “future” aircraft.

However, in some size categories we expect some baseline aircraft to remain in the fleet beyond 2035 (or 2040), replacement after that date being directly by examples of the corresponding “future” aircraft types rather than by the corresponding “known” aircraft types. In such cases the fuel-efficiency improvement or CO_2 reduction step is correspondingly larger than the step from “known” to “future” types. We also assume that any remaining fleet-refresh time is halved (subject to rounding up to the next whole number of years). For example in the A380 size category, in which a further 18 years of fleet refresh would remain beyond 2035 if replacement with “known” aircraft types were to continue according to **Table 4.1**, we assume that replacement of those remaining A380 aircraft with corresponding “future” aircraft will complete in only 9 years i.e. by 2044, due to the additional fuel-cost savings offered by the “future” aircraft type.

4.6.1 Battery-Electric Aircraft

For the first time in our CO_2 Road-Map, here we consider the potential impact of battery-electric aircraft upon UK aviation’s CO_2 emissions.

Analysis of trends in battery technology, particularly with regards to improvements over time in specific energy and specific power, suggests that by 2040, battery-powered aircraft suitable for sub-regional missions of up to 400km would be feasible.

Analysis of flight data from OAG[56] in conjunction with the fuel-burn lookup-table from ICAO’s carbon-calculator[57] allows us to determine that flights up to 400km in length accounted for 2.6% of UK aviation CO_2 in year 2016. Our fleet refresh model takes account of changes over time in this relative materiality as aviation activity delivered in various aircraft categories is migrated to “known” aircraft types offering differing levels of fuel-efficiency improvement ranging from zero (turboprops) up to 30% (747-400, 757). Nonetheless it is clear that replacing fuel-burning aircraft on only these very short-range flights can deliver only a small improvement to UK aviation’s overall CO_2 footprint. It is too early to say with any certainty whether, in subsequent years, all-electric aircraft will be able to offer a greater range capability and therefore address a greater proportion of UK aviation activity.

We make the following assumptions:

- Activity on flights up to 400km can be migrated to all-electric aircraft. The all-electric aircraft may be smaller than the aircraft they replace, thus requiring increased numbers of flights to deliver the equivalent passenger numbers
- Not all flights within the assumed aircraft-size and flight-length limitations will migrate to all-electric aircraft, due for example to reasons of maintaining fleet commonality across fleet operations which may also include longer routes. We assume that 80% of the within-scope activity will migrate to all-electric aircraft
- Electricity used to charge such battery-powered aircraft will be zero-carbon
- Fleet refresh will be fairly rapid following initial availability of battery-electric aircraft, due to the substantial savings in energy costs enabled by battery-electric aircraft relative to their fuel-powered predecessors, and the relatively small size of the fleet of aircraft performing very short-range missions. We assume a 10-year fleet-refresh period, starting in 2040

In cases where replacement of baseline aircraft by the corresponding “known” aircraft type is not complete by 2040, the fuel-efficiency improvement enabled by replacement instead by “future” aircraft, available from that date onwards, is correspondingly larger as shown in **Table 4.2**.

4.6.1 Battery-Electric Aircraft (continued)

Generation	Category to replace	CO_2 Reduction due to "Future" Aircraft (on routes where deployed) (replacing only 80% of in-category activity on routes of up to 400km)	Entry Into Service	Fleet Refresh Period (years)
"Known"	TP, RJ, 737 MAX, A320neo	80%	2040	10
Baseline (those not yet replaced by "known" aircraft)	737 NG[58]	82.8%	2040	1
	A320ceo	84%	2040	1

Table 4.2 – characteristics of "future" all-electric aircraft relative to aircraft they will replace on flights up to 400km range
NOTE – the CO_2 reduction figures presented in this table apply only to the small proportion of UK aviation activity that takes place on such short routes. CO_2 reductions on longer routes are discussed below

4.6.2 Conventional and Hybrid-Electric Aircraft

Any aviation activity which does not migrate to all-electric aircraft from 2040 as described in the previous section is assumed in our model to migrate to fuel-burning "future" aircraft types offering a 25% fuel-efficiency improvement relative to corresponding "known" aircraft types, during a 20-year period starting from 2035. These fuel-burning aircraft types may or may not include hybrid-electric propulsion systems.

The 20-year default fleet-refresh period assumed here for all aircraft categories matches that used for twin-aisle aircraft types in the fleet transition from "baseline" aircraft to "known" aircraft, but is shorter than that used in that earlier transition for single-aisle aircraft types. This difference is motivated by the recognition that by 2035, according to the carbon-price trajectory used as the basis for this Road-Map, the additional costs of purchasing carbon credits, over and above the cost of buying fuel itself, will increase the cost savings associated with each percentage point of fuel-efficiency improvement. As a result, the penetration into the fleet of "future" aircraft types is likely to be driven more strongly than in previous generations of fleet refresh. Nonetheless, constraints related to production capacity may prevent the fleet refresh from shrinking much beneath 20 years.

In cases where replacement of baseline aircraft by the corresponding "known" aircraft type is not complete by 2035, the fuel-efficiency improvement enabled by replacement instead by "future" aircraft is correspondingly larger, as shown in **Table 4.3**.

Generation	Category to replace	CO_2 Reduction due to "Future" Aircraft	Entry Into Service	Fleet Refresh Period (years)
"Known"	All	25%	2035	20
Baseline (those not yet replaced by "known" aircraft)	A380[59]	36.25%	2035	9
	A320ceo	40%	2035	3
	737 NG	35.5%	2035	4
	LTA	43.75%	2035	3

Table 4.3 – characteristics of "future" fuel-burning aircraft relative to aircraft they will replace

4.6.3 UK Aviation CO_2 Reduction from "Future Aircraft"

Combining the CO_2 reduction both from all-electric "future" aircraft and from fuel-burning "future" aircraft, relative to the efficiency of the fleet in service at the point of their initial availability, gives an overall CO2 reduction by 2050 of 24.1%. Combined with the 16.9% from "known" aircraft, the overall improvement in 2050 relative to an unimproved 2016 fleet delivering the required level of aviation activity in 2050 is 36.9%.

4.7 "Future Aircraft" – Comparison with External References

In this section we compare our assumptions concerning the fuel-efficiency improvement opportunity in various aircraft categories against external goals or studies previously published independently of Sustainable Aviation. Our sources of reference are as follows.

- The Flightpath 2050 goal for aircraft CO_2 emissions: "In 2050 technologies and procedures available allow a 75% reduction in CO_2 emissions per passenger kilometre…. relative to the capabilities of typical new aircraft in 2000"[60]. If we assume that improved air traffic management and aircraft operations will contribute 15% towards this improvement, this means that the fuel-efficiency improvement required from aircraft themselves is 70.6%[61]. Alternative assumptions of a lower contribution from ATM/ops would result in a requirement for higher levels of aircraft fuel-efficiency improvement in order to attain the 75% target
- A study [ATA et al, 2018] completed by Air Transportation Analytics Ltd and Ellondee Ltd for the UK's Committee on Climate Change and Department for Transport considered the range of fuel-efficiency improvement opportunities reported in the literature for a large variety of technologies. Potential improvements from individual technologies were then combined using a root-mean-square (RMS)[62] approach to estimate the combined fuel-efficiency improvement that might be achieved by new aircraft embodying a bundle of technologies. Further consideration was then given to which technologies might be ready for deployment and be sufficiently cost effective for inclusion on an aircraft in the 2030-35 timeframe and also in the 2045-2050 timeframe. This process was conducted relative to the following baseline aircraft: A319, A320, B777-200ER, and B747-400
    - Three technology-effectiveness scenarios ("worst", "nominal", "best") were considered, spanning the range of improvement opportunity reported in the literature for individual technologies and the corresponding range (derived using the RMS approach) spanned by bundles of technologies. In our comparisons, we use the **"nominal"** scenario for technology effectiveness
    - Three technology development and deployment scenarios ("pessimistic", "likely", "optimistic") were considered, reflecting the potential for different rates of technology development and/or differing economic conditions in which a particular technology or bundle of technologies might or might not be incorporated into an aircraft platform by a certain date. In our comparisons we use the **"optimistic"** scenario for technology deployment, motivated by the intensifying focus on fuel-efficiency and climate change and the reasonable expectation that the price of fuel-plus-carbon could increase substantially in the future
    - It is worth noting that the improvement opportunities quoted in [ATA et al, 2018] assume a like-for-like replacement. In particular, the improvement opportunities relative to a Boeing 747-400 assume that the corresponding future aircraft would be a large four-engined aircraft of similar capacity and range. Our Road-Map does not make that assumption, instead reflecting the current migration towards arge twin-engined aircraft
- A study published by the International Council on Clean Transportation [ICCT, 2016] considered three scenarios ("evolutionary", "moderate", "aggressive") for the deployment of cost-effective technologies to improve the fuel-efficiency of single aisle aircraft (relative to an Airbus A320-200) and twin aisle aircraft (relative to a Boeing 777-200ER) in 2024 and in 2034. The study excluded "non-conventional airframes like blended wing body or strut-based wings." In our comparisons, we use the ICCT's **"moderate"** scenario

The charts below show a comparison between our assumptions in various aircraft size categories and the corresponding figures from the above three external references (where applicable). We also compare the annual fuel-efficiency improvement rates between various generations of aircraft according to our assumptions. Observations concerning these charts can be found on the following page.

4.7 “Future Aircraft” – Comparison with External References (continued)

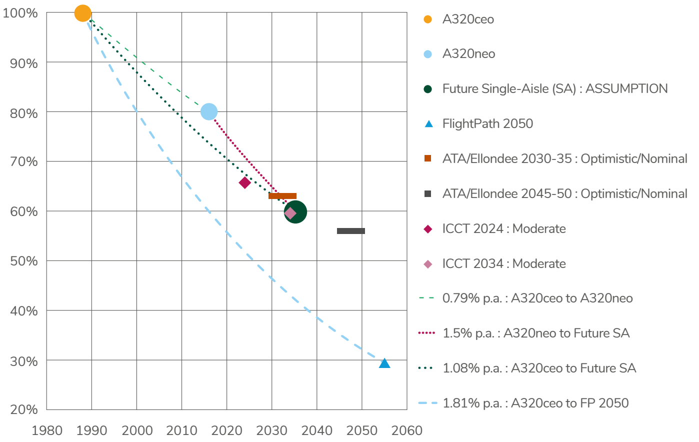


Figure 4.2 – fuel-efficiency comparison relative to A320ceo. **Source:** SA analysis; [ATA et al, 2018] figures 45 & 46 ; [ICCT, 2016] Table 8

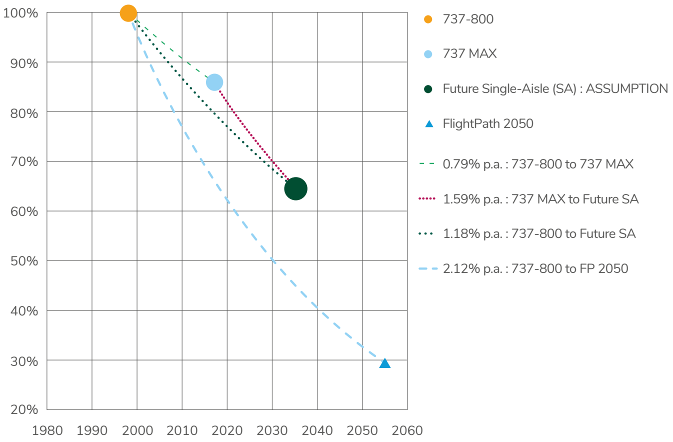


Figure 4.3 – fuel-efficiency comparison relative to 737-800. **Source:** SA analysis

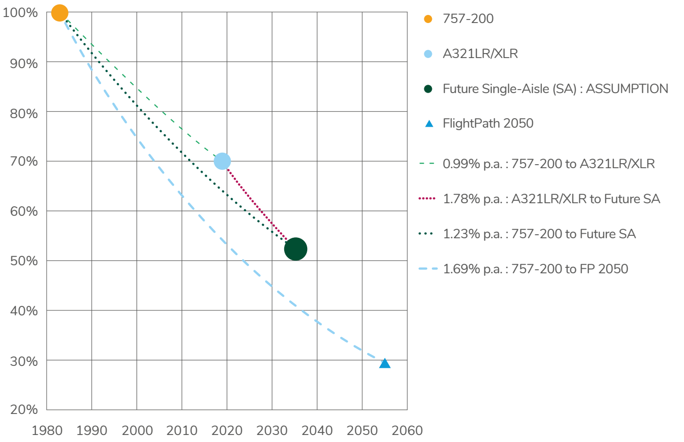


Figure 4.4 – fuel-efficiency comparison relative to 757-200. **Source:** SA analysis

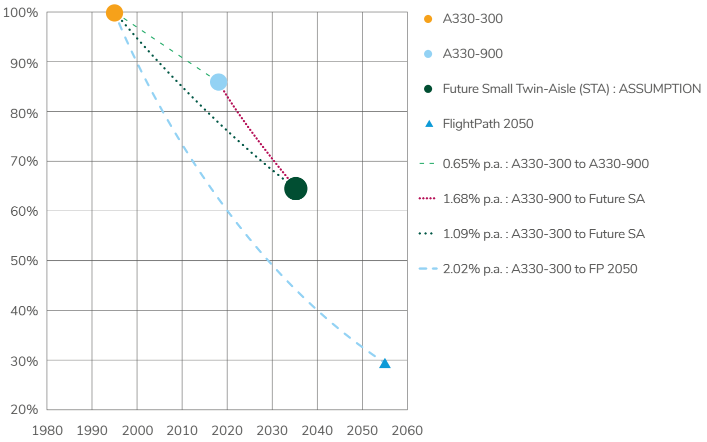


Figure 4.5 – fuel-efficiency comparison relative to A330-300. STA = small twin aisle. **Source:** SA analysis

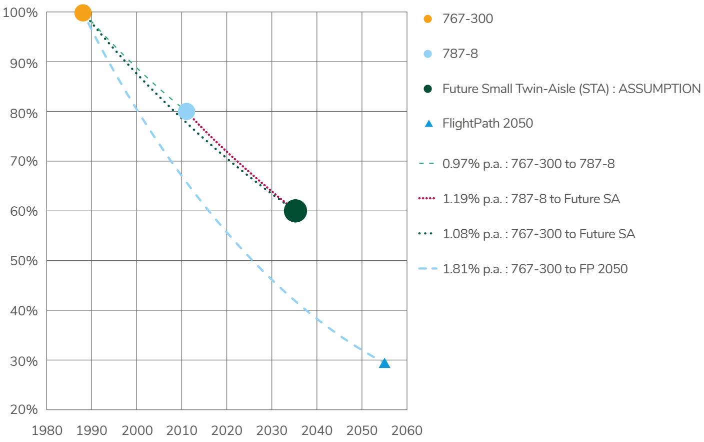


Figure 4.6 – fuel-efficiency comparison relative to 767-300. STA = small twin aisle. **Source:** SA analysis

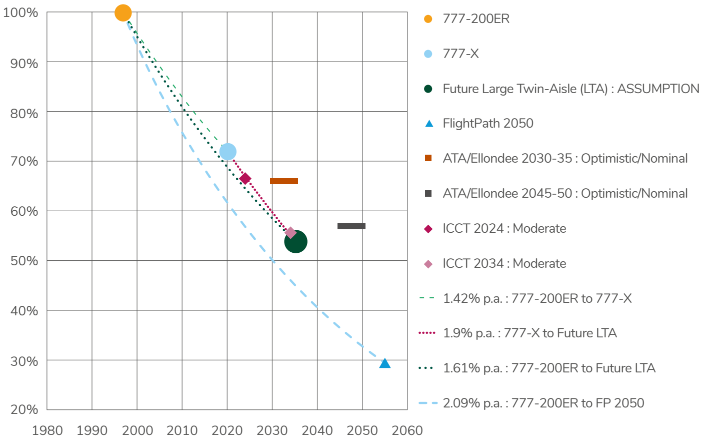


Figure 4.7 – fuel-efficiency comparison relative to 777-200ER. **Source:** SA analysis; [ATA et al, 2018] figures 45 & 46 ; [ICCT, 2016] Table 8

IMPROVEMENTS IN AIRCRAFT AND ENGINE EFFICIENCY

4.7 “Future Aircraft” – Comparison with External References (continued)

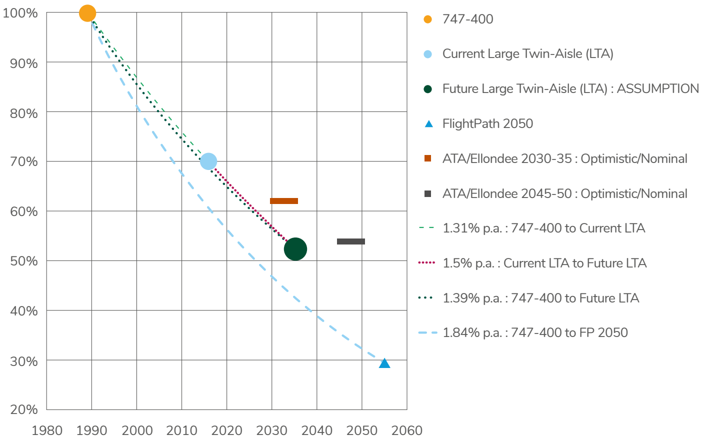


Figure 4.8 – fuel-efficiency comparison relative to 747-400.
Source: SA analysis; [ATA et al, 2018] figures 45 & 46.

Several conclusions can be drawn from these charts:

- In order to achieve our assumed fuel-efficiency improvement (25%) for an entry-into-service in year 2035, the rate of annual average improvement, relative to current re-engined aircraft (A320neo family, 737 MAX, A330neo, 777-X), will need to be rather higher than the annual average fuel-efficiency improvement rate observed between the corresponding baseline aircraft and the re-engined aircraft. On the other hand, when considering the 767-300 to 787 to Future small twin-aisle (STA), and also the 747-400 to Current large twin aisle (LTA) to Future LTA, the required rate of future improvement is very similar to that observed in the past
- In the case of A320ceo and 777-200ER, our assumptions for the corresponding “future” aircraft are very close to those given in the “moderate” scenario of [ICCT, 2016]. In the former case, our assumptions are also well in alignment with the chosen scenario (“optimistic” / “nominal”) of [ATA et al, 2018]
- In the case of 777-200ER, our assumptions for the corresponding “future” aircraft are a little more ambitious than that given in the chosen scenario (“optimistic” / “nominal”) of [ATA et al, 2018]
- In the case of 747-400, our assumptions for the corresponding “future” aircraft are a little more ambitious than that given in the chosen scenario (“optimistic” / “nominal”) of [ATA et al, 2018]. However, this is not surprising since the [ATA et al, 2018] figures refer to a “like-for-like” replacement while our numbers include an improvement opportunity associated with migration from the four-engine aircraft configuration to two engines
- In all aircraft categories our assumptions for the fuel-efficiency of “future” aircraft entering service from 2035 are substantially less ambitious than the Flightpath 2050 technology goal adopted by the industry

It is worth considering what factors may allow the rate of efficiency improvement to be maintained or even accelerated relative to that observed in recent decades. First, customer demand for more efficient products continues to strengthen, driven by the cost of fuel and potentially by additional carbon costs together with growing awareness of environmental impacts. Second, analysis, simulation, design and manufacturing capabilities continue to improve, giving the industry greater capability with which to address that customer demand. Third, the overall size of the market for aircraft continues to expand rapidly, allowing amortisation of increasing R&D expenditure over a greater number of aircraft. Fourth, technologies representing opportunities for a step-change improvement in fuel efficiency have been demonstrated and are progressing well through their development phases. Finally, aircraft concepts have been proposed which are claimed to have the potential to achieve fuel-efficiency levels at or close to the Flightpath 2050 goal (and the corresponding the NASA N+3 goal), which are substantially more ambitious than our assumed levels of efficiency for “future” aircraft. Of course, there are many practical factors that must be considered to enable such rates of improvement to occur, for example changes in infrastructure necessary to allow deployment of certain technologies.

The following section explores some upcoming technologies which may contribute towards enabling our assumed levels of fuel-efficiency to become reality.

4.8 "Future" Aircraft Efficiency – Enabling Technologies

In this section we explore some recent developments along the route to improved aircraft efficiency and reduced CO_2 emissions. This section does not purport to be exhaustive, and in particular is intended to supplement, rather than replace, the corresponding section of our 2016 Road-Map.

Illustrating the scale of the technology development effort within the aerospace industry, [ATAG, 2016] reports that "aircraft and engine manufacturers spend an estimated $15 billion each year on research and development".

In June 2019, the Chief Technology Officers (CTOs) of seven of the world's leading aerospace manufacturers[63] released a joint statement "to demonstrate how they are collaborating and sharing approaches to drive the sustainability of aviation and reach the industry-wide ATAG targets[64]. The statement includes a strategy comprising the following three items[65].

1. "Continuing to develop aircraft and engine design and technology in a relentless pursuit of improvements in fuel efficiency and reduced CO_2 emissions."
2. "Supporting the commercialization of sustainable, alternate aviation fuels. Around 185,000 commercial flights have already proven that today's aircraft are ready to use them."
3. "Developing radically new aircraft and propulsion technology and accelerating technologies that will enable the 'third generation' of aviation."

Conscious of the challenge to deliver the right product to the marketplace, aircraft and engine manufacturers continue to accelerate the exploration of technologies and innovation. Through demonstrator programmes, manufacturers strive to demonstrate that new technologies can work.

4.8.1 Aircraft Technologies, Configurations and Operations

During 2020, Airbus will commence flight tests as part of its fello'fly project which "aims to demonstrate the technical, operational and commercial viability of two aircraft flying together for long-haul flights"[66]. By flying in formation, the follower aircraft can reduce fuel consumption by 5-10%. "The technical solution that Airbus is working on involves pilot assistance functions necessary to ensure the aircraft they are flying remains safely positioned in the updraft of air of the aircraft they are following, maintaining the same distance, at a steady altitude."[67]

Building upon previous demonstrations of zero-emissions aircraft such as E-Fan 1.0, which crossed the English Channel in 2015 and the Vahana single-seat demonstrator, which has now accumulated more than 90 flights, the first flight of Airbus' 4-seat demonstrator "City Airbus" took place in May 2019, marking the start of a rigorous flight-test campaign. To take electric technologies towards commercial aviation of 100-seats and more, Airbus, in collaboration with Rolls-Royce, has also launched the E-FAN X demonstrator which will have its first flight in 2021 (see below).

Boeing's ecoDemonstrator program "first took to the skies in 2012. Five airplanes — a 737-800, 787-8 Dreamliner, 757, Embraer E170 and 777 Freighter — have tested 112 technologies through 2018. More than a third of the technologies have transitioned to implementation at Boeing or by program partners. Nearly half remain in further development."[68]

- In 2016, tests with an Embraer E170 included "ice-phobic paint that... reduces drag"[69] as well as "wireless measurement of airflow over the surface of the wing (boundary layer)"[70]
- In 2018, a "777 Freighter tested nearly 40 new innovations, including flight deck updates that enable pilots to more effectively manage their routes to save fuel.... Other technologies included a compact thrust reverser that improves fuel efficiency"[71]
- Another ecoDemonstrator, using a 777 as the test vehicle, was planned for late 2019

In January 2019, Boeing revealed its latest Transonic Truss-Braced Wing (TTBW), "designed to offer unprecedented aerodynamic efficiency while flying at Mach 0.80, which is consistent with the speed of many of today's jetliners[72]. Wind-tunnel testing by Boeing and NASA of previous designs, as reported in our 2016 CO2 Road-Map, has shown a supported wing arrangement can reduce fuel use "by 5 to 10 percent over advanced conventional wings"[73].

Looking further into the future, wind-tunnel testing as part of NASA's Mission Adaptive Digital Composite Aerostructure Technologies (MADCAT)[74,75] project has demonstrated the characteristics of aircraft wing structures composed of small injection-moulded building blocks bolted together to form a lattice structure. This project also explored opportunities to tune the wing's characteristics by substituting building blocks with different mechanical properties in some parts of the structure. In the long term, this could open up new design opportunities for aircraft wings, leading to weight savings.

NASA's Spanwise Adaptive Wing project [76,77] is exploring the use of shape-memory alloys as actuators for changing the shape of aircraft wings in flight, with the aim of reducing drag and fuel consumption.

IMPROVEMENTS IN AIRCRAFT AND ENGINE EFFICIENCY

4.8.2 Integration of Propulsion System and Airframe

Consideration of how the engine and airframe are integrated will become increasingly important in the coming years as the industry drives for reduced drag and noise and increased efficiency. In the US, [NAP, 2016] identifies “advances in aircraft–propulsion integration” as being one of four highest-priority research areas for reducing global civil aviation CO_2.

Integration of engine and airframe is essential to enable key efficiency improvements such as boundary layer ingestion (BLI), in which a propulsor is sited close to the aircraft structure and is able to ingest air that the aircraft has already slowed down (through for example skin friction), thus reducing the disadvantageous inlet momentum of air entering the propulsor. Successful implementation of BLI may offer fuel-efficiency improvements of several per cent.

The use of distributed electrical propulsion, whether hybrid or pure-electric, acts as an enabler for boundary layer ingestion, by making possible the positioning and sizing of propulsive fans to maximise the possibilities for ingestion of slower-moving boundary layer air rather than free-stream air.

Previous issues of our CO_2 Road-Map have highlighted design concepts such as Bauhaus Luftfahrt’s “Propulsive Fuselage”, NASA’s Starc-ABL, and MIT’s D8 “Double Bubble” as examples of boundary-layer ingesting designs.

In the UK the Aerospace Integration Research Centre (AIRC) at Cranfield University, co-funded by Airbus, Rolls-Royce and HEFCE[78], focuses on all aspects of integration in aerospace, including integrating power plant with platform”[79].

4.8.3 Propulsion Technology

Our 2012 and 2016 CO_2 Road-Maps collectively provide an overview of the technology options and research programmes which could contribute towards improved engine fuel efficiency. In this section we cover some additional items not reported in that earlier document, and report on recent developments.

- Rolls-Royce’s UltraFan® engine design will deliver “significant weight, noise and fuel burn reductions, and will be 25% more efficient than a first-generation Trent engine”[80]. Development progress since our 2016 CO_2 Road-Map includes the following:
    - In 2017, Rolls-Royce announced that it had “set a new record for the world’s most powerful aerospace gearbox[81]”. The Power Gearbox, which will play a central role in the UltraFan® engine “successfully reached 70,000 horsepower while on test at Rolls-Royce’s dedicated facility in Dahlewitz, Germany.”[82]
    - In 2018, the Advance 3 demonstrator ran at full power. “The Advance3 demonstrator…is a key element in Rolls-Royce’s future technology strategy to develop the Advance core for the UltraFan® engine design”[83]. This demonstrator includes work funded by the Aerospace Technology Institute (ATI)[84,85]
    - IIn 2019, “for the first time, all composite elements of the Advanced Low Pressure system (ALPS), including fan blades, a fan case and annulus fillers, were tested together”[86]

The prospect of hybrid-electric propulsion for aircraft has moved forward considerably since our 2016 Road-Map was published:

- The E-Fan X hybrid-electric aircraft demonstrator, due to fly in 2021, is a collaboration between Airbus and Rolls-Royce. It “will explore the challenges of high-power propulsion systems, such as thermal effects, electric thrust management, altitude and dynamic effects on electric systems and electromagnetic compatibility issues”[87]. “In the test aircraft, one of the four jet engines will be replaced by a 2MW electric motor”[88], “the most powerful in the world to ever fly”[89]. This programme includes work funded through the ATI’s strategic programme[90,91]
- Rolls-Royce has also announced that it will work with APUS and the Brandenburg University of Technology (BTU), Cottbus to develop “a hybrid electric flight demonstrator based on its hybrid M250 propulsion system”[92]
- Project Fresson, led by Cranfield Aerospace Solutions and supported by ATI strategic program funding, will “design, manufacture and integrate a hybrid-electric propulsion system into a 9-seat Britten-Norman (B-N) Islander aircraft, which is typically used on short flights such as island-hopping routes”[93,94]

4.8.3 Propulsion Technology (continued)

Significant progress towards pure battery-electric propulsion for aircraft is also being made:

- Accelerating the Electrification of Flight (ACCEL[95]) is a collaborative project by Rolls-Royce and partners YASA and ElectroFlight, receiving funding through the ATI's strategic programme. ACCEL "plans to set new records for an electrically powered aircraft including highest power density achieved for a propulsion battery system"[96]. Other features of the design include 90% energy efficiency and zero-emissions flight[97]. First flight is planned for 2020. "This zero-emissions plane is expected to make a run for the record books with a target speed of 300+ MPH"[98].

- In 2019, NASA took delivery of its first all-electric experimental aircraft, the X-57 Maxwell[99]. "A goal of the X-57 project is to help develop certification standards for emerging electric aircraft markets, including urban air mobility vehicles, which also rely on complex distributed electric propulsion systems. NASA will share the aircraft's electric-propulsion-focused design and airworthiness process with regulators and industry, which will advance certification approaches for aircraft utilizing distributed electric propulsion"[100]

Electric propulsion using non-battery sources is also being explored.

- In the HyFlyer project, ZeroAvia & partners will "demonstrate principal technology readiness for a hydrogen fuel cell powertrain", including a "UK-based 250-300 nautical mile (NM) flight"[101], supported by funding through the ATI's strategic programme.

4.8.4 Manufacturing Capability and Materials

Advanced manufacturing technologies not only open up new design opportunities leading potentially to improved product performance, but they also form a critical element of lowering unit cost, making aerospace products more affordable and enhancing the viability of aircraft or engine concepts which, without suitable manufacturing technologies, might not see the light of day as commercial products.

A key manufacturing technology receiving much research attention at present is additive manufacturing (AM), sometimes referred to as 3D printing[102,103,104]. AM offers the prospect of manufacturing components of entirely new shapes which were previously not possible to make, opening up the design space and presenting opportunities for weight reduction which is one of the key enablers for improved aircraft fuel-efficiency. Components in which material properties vary from one area of the component to another can also be envisaged using AM.

4.8.5 Discussion

This section has set out some examples of the technologies and design configurations being explored for potential use in future aircraft types. The scope for improving aircraft fuel-efficiency through deploying various combinations of these technologies and design configurations is substantial.

The UK has a strong aerospace manufacturing sector, underpinned by high levels of technological capability built on decades of research. The UK Government must ensure that access to funding for high-value collaborative R&D programs is maintained in the coming years, to ensure continued competitiveness in the global market, and must consider potential infrastructure changes as enablers for those technologies to materialise on the market.

SUSTAINABLE AVIATION FUELS

Summary

Sustainable Aviation Fuel (SAF) is the next big breakthrough opportunity for aviation carbon reductions. Today SAF is at a global tipping point, with projects on the verge of commercial-scale production. This is thanks to the technological, political and commercial developments since the first SAF Road-Map was published in 2014. Globally, fourteen airports now supply sustainable aviation fuels, although overall fuel prices remain high and therefore volumes remain low. Some airlines, technology developers and some fossil fuel companies are now making investments in sustainable aviation fuels through a number of joint ventures and in the USA first-of-a-kind plants are now under construction. IAG and Virgin Atlantic are pursuing advanced solutions made from over-abundant wastes, with have the potential to bring SAF solutions close to the fossil jet price. This is crucial as this is when fuels will be produced and flown routinely, resulting in life cycle carbon savings of upwards of 70% compared to fossil jet.

In the UK we have seen encouraging progress since the UK government provided more support to aviation fuels through the introduction of a new developmental fuels sub-target which became into effect through the Renewable Transport Fuels Obligation (RTFO) in 2019. These factors, combined with other low carbon policies, have led us to revise our projection for CO_2 reduction provided by SAF in this CO_2 Road-Map. We now estimate a 32% reduction in emissions from UK aviation is possible from the use of SAF in 2050. This assumption is based on a 32% penetration of SAF into the global aviation fuel market, coupled with an average 100% life-cycle CO_2 saving per litre of fossil-based aviation fuel displaced. This is based on the greater take up of carbon capture technologies from the 2030s which will be associated with the production of SAF therefore also yields greater greenhouse gas reductions.

We believe that as the whole economy moves towards net zero emissions and other sectors decarbonise, there will be further increased potential for sustainable fuels in aviation. Work carried out by E4Tech highlights that with support, by 2035 the development of a domestic industry to produce sustainable fuels could generate a Gross Value Added (GVA) of up to £742m annually. This would support up to 5,200 jobs in the UK and an additional 13,600 jobs could be generated from the growing market for sustainable aviation fuels through global exports. This export market is worth up to an additional £1.952bn to 2035 and bringing the full value to the UK of £2.7bn from UK production and global exports. In addition to this, UK manufactured fuels could add £550m per annum benefit to the UK's balance of payments.

However, aviation fuels are presently not prioritised within the RTFO and this means without greater government support, larger volumes of SAF are unlikely to be realised post 2035. Realising the full potential for UK production and deployment of sustainable aviation fuels requires Government to develop a high level, cross departmental co-ordinated UK vision and strategy for their deployment, enabling the creation of UK expertise and IP technologies; implementing financial support mechanisms for demonstration and commercial-scale facilities and ensuring that aviation fuels are prioritised in future policy and in research and development.

5.1 Introduction

The development and commercialisation of Sustainable Aviation Fuels (SAF) is vital over the next decade, representing an essential near-term ‘bridge’ to technologies like hybrid-electric and all-electric aircraft. The introduction of Sustainable Aviation Fuels could reduce UK emissions in 2050 by 32% - and maybe more - and make the UK a world-leader in the technology. Since 2008, six new sustainable aviation fuels (SAF) technical pathways have been qualified for use in commercial aviation, utilising a variety of feedstocks including non-crop sources such as waste oils, waste gases and municipal wastes. These fuels are “drop-in” and fully compatible with existing aircraft and infrastructure. These high-quality fuels comprise the same hydrocarbons (compounds containing only carbon and hydrogen) as fossil jet fuel and therefore they can be used without any modification to present aircraft. They are qualified for use in up to a 50% blend with fossil fuel, with the potential for higher blends in future. A more complete description of the ASTM technical qualification process for new fuels can be found in the new partner publication, the Sustainable Aviation SAF Road-Map 2020.

SA greatly appreciates the support UK Government have given the domestic SAF market since publishing our first Sustainable Aviation Fuels Road-Map in 2014. Projects to produce SAF providing at least a 70% life cycle carbon savings compared to fossil fuel are presently under development in the UK.

However, investment and commercial scale up barriers still exist. To ensure these opportunities are fully realised the industry wishes to continue our work with Government in four key areas:

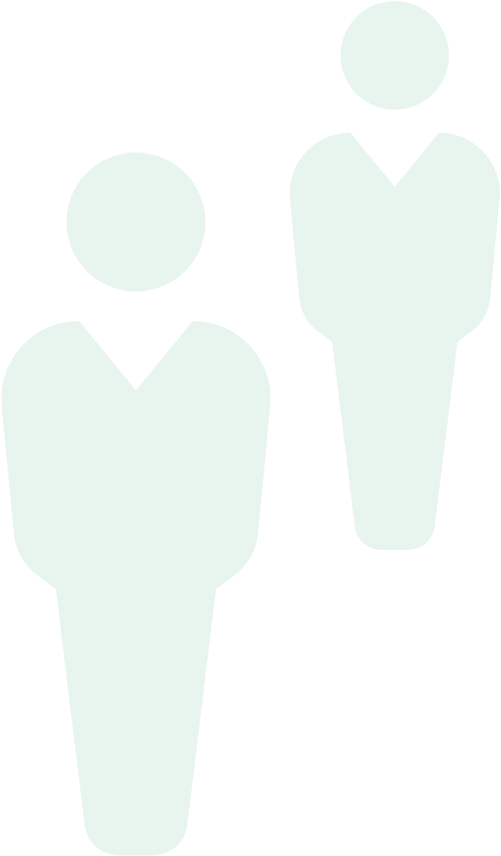
- **Office for Sustainable Aviation Fuels (OSAF) (Or similar)** - Given the significant near-term opportunities offered by sustainable aviation fuels as both a measure to cut aviation carbon emissions and deliver economic benefits to UK industry, a dedicated **Office for Sustainable Aviation Fuels (OSAF)** is needed to provide the cross-government strategic co-ordination necessary to progress the development and commercial deployment of SAF

- **Fund flagship SAF plants - £500m** would support flagship commercial plants across the UK utilising wastes and residues to manufacture SAF, as well as a UK centre of excellence for SAF development a new UK network of fuels development. This would signal to investors the long-term opportunities of this sector and is more than matched by the current and planned investments (up to £1.2 billion) by industry. This funding should also support additional fuels development and testing to utilise the UK’s considerable fuels testing expertise to expedite the approvals process for new aviation fuel technologies, attracting investment and helping to anchor new fuels technology providers in the UK

- **Incorporate Recycled Carbon Fuels into the RTFO** - Applying the Renewable Transport Fuels Obligation (RTFO) to include all sustainable, waste-based feedstocks gave a major boost to SAF development, and recycled carbon fuels should now be included to remove barriers to these ground-breaking technologies. The RTFO should also be flexible enough to rapidly respond to and include further appropriate SAF technology breakthroughs

- **Support investment in SAF** through applying at least a 1.2x multiplier within the RTFO incentive for SAF developmental fuels to provide a signal to fuel producers to invest in aviation fuel production Further we ask the Government to undertake analysis of what would be required to encourage suppliers towards production of advanced, sustainably robust SAF and away from volumes of older generation ground transport biofuels, while the road transport sector simultaneously focuses on deploying carbon free alternatives like electric vehicles (EVs)

SA members wish to play a full role in a partnership with the government to deliver on SAF potential and are currently committed to developing a number of sustainable fuel initiatives. SA members are collectively planning to invest £3.5 billion in supporting new plant construction, fuels testing and R&D, as well providing bankable fuel offtake agreements, over the next 20 years.



Progress since the last Road-Map

More than 200,000 regular commercial flights and revenue flights have been undertaken around the world with “drop-in” SAFs from an array of sustainable feedstocks, including municipal waste, waste carbon rich gases from heavy industry, algae and sustainable crops – those grown on non-agricultural land having no Indirect Land Use Change (ILUC) impacts – and crop wastes and residues. Five different fuel production and conversion processes have been qualified by the ASTM International Fuels Standards Committee under its D7566 standard[105]. In addition, a new Fast Track process has been introduced to enable a more streamlined path for new technologies to attain qualification as a drop-in fuel. As well as a considerable amount of technical progress, policies have also been developing to recognise the aviation sector’s dependence on hydrocarbon fuels, the difficult task of decarbonising aviation and the need to rapidly deploy sustainable fuel technologies.

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a key long-term driver for SAF demand in international aviation (domestic aviation is not included in CORSIA). Given that airlines can comply with CORSIA through supplying sustainable aviation fuel more states have started to consider policies to support the use and supply of SAF.

In the UK the prospects for new SAF production plants have been enhanced by the inclusion of aviation within the Renewable Transport Fuels Obligation in 2018 as well as the UK’s Future of Freight and Flight competition. The recent UK SAF Special Interest Group (SAF SIG)[106] also highlights the significant interest from SMEs in the potential for SAF. In March 2019 the group celebrated the results of the initial two years’ work[107]:

- **107** companies supported
- **406** people in the SAF SIG network
- **82** introductions made
- **9** collaborations brokered
- **4** companies signed NDAs with a UK airline

Therefore, SA is revising the Road-Map to reflect this progress, with the assistance of E4Tech who have remodelled both the global potential and the UK’s share of this growth.

Case Study: British Airways investment in Altalto Immingham project

Altalto is a collaboration between three co-investors: Velocys, British Airways and Shell that will utilise Velocys’ proprietary gas to liquids technology. Velocys has a specialist catalyst technology that was developed by Oxford University and this technology has been deployed at commercial scale in the USA.

The Altalto project is developing the first commercial scale waste-to-transport-fuels plant in the UK in Immingham, North East Lincolnshire, subject to planning, permitting and final investment decisions. The project was a recipient of a DfT grant awarded under the Future Fuels for Flight and Freight (F4C) competition in 2017.

The new plant will combine proven technologies in an integrated process which turns household and office waste into a cost effective and sustainable supply of transport fuels – especially aviation fuel. This will also prevent this waste from going into unsustainable landfills. Technologies able to take low quality waste materials and transform them into fuels and chemicals will have a global export market once the fully integrated plants have been built at commercial scale. Velocys is also developing a waste wood to fuels project in the USA that will be coupled with Carbon Capture and Storage technology, able to deliver negative emission reductions and the project in the UK is also CCS ready.

Subject to planning permission and funding and once fully operational, this plant will take hundreds of thousands of tonnes per year of post recycling waste, otherwise destined for landfill or incineration, and convert it into over 60 million litres of clean burning sustainable jet and road fuel each year[108]. As the UK seeks to find more efficient and low carbon technologies for the treatment of residual wastes (i.e. those that cannot feasibly be recycled) there should be great potential to develop more projects to convert low value wastes into high value fuels and chemicals. The DfT plans changes to the RTFO in 2020 and this provides the UK with an opportunity to include Recycled Carbon Fuels and to strengthen the structure of existing policy frameworks to support investment. These will be essential in supporting innovative technologies utilising residual wastes. This will ensure the UK becomes a leader in waste to fuels technologies, unlocking much bigger global market.

Case Study: Virgin Atlantic and LanzaTech Sustainable Aviation Fuel Partnership

Lanzatech uses a novel carbon capture and utilisation (CCU) approach to recycle waste carbon-rich gases (carbon monoxide – CO) from heavy industries (e.g. steel mills, oil refineries) into ethanol (first stage) and subsequently a range of other low carbon products, including jet fuel. The waste CO is otherwise usually flared direct to the atmosphere as greenhouse gas CO_2 – or used much less efficiently for ground heat or power, where much better, carbon-free, renewable options are being encouraged.

LanzaTech' s jet fuel has no land, food or water competition issues and greater than 70% lower Life Cycle Analysis (LCA) carbon emissions compared with regular fossil jet fuel. The LanzaTech process can also efficiently utilise other plentiful, unavoidable waste streams.

Since partnering with Virgin Atlantic in 2011, LanzaTech has gone from pilot to demonstration to commercial scale ethanol production and secured full or part-funding for five commercial ethanol plants, in China, Belgium, US, India and South Africa. Commercial ethanol production from steel mill waste CO started in China in May 2018.

Waste ethanol-derived alcohol to-jet (ATJ) is now being scaled too: the first significant batch was produced in 2016 (1,500 USG); US DOE funding was awarded in 2016 to design US demonstration jet plant; and in 2018, UK DfT Future Fuels for Flight and Freight (F4C) funding was secured to scope out sites for the world's first full size, commercial jet fuel plant in the UK.

In April 2018, ASTM International added ethanol as a qualified feedstock for alcohol-to-jet synthetic paraffinic kerosene (SPK), which means ethanol-derived jet fuel can now be used on commercial flights. As a result, in October 2018 Virgin Atlantic flew the world's first CCU to ethanol commercial flight from Orlando to London Gatwick[109] demonstrating this pioneering advanced, waste-based fuel is now ready to commercialise. However, this technology, which could bring multiple benefits to the UK, still needs inclusion in the Renewable Transport Fuels Obligation. With this critical inclusion the economics are transformed and LanzaTech will be able to produce affordable SAF at a price on a par with the fossil kerosene price. Further, with it, LanzaTech has committed to at least three 30 mill USG UK SAF plants in the 2020s, enough to provide all Virgin Atlantic's fuel out of the UK as a 50:50 mix (as per ASTM qualification limits, at 2018 volumes), bringing 70+% life cycle carbon savings compared to fossil jet and a stepped reduction in carbon emissions. We urge the DfT to act quickly include CCU or 'Recycled Carbon Fuel' technologies like this in the RTFO and enable Virgin Atlantic and LanzaTech to turn this carbon breakthrough into a commercial reality in the UK.

5.2 The Opportunities – a New Sustainable Fuels Sector in the UK

Sustainable, low carbon aviation fuels offer a growing opportunity to cut CO_2 emissions. Promising opportunities for the UK exist following Sustainable Aviation's latest review of the sustainable fuels market and its potential in the UK.

The analysis carried out by E4Tech for SA highlighted where the UK prioritises aviation for sustainable fuels. The main opportunity is for waste feedstocks (Municipal Solid Waste, Gaseous wastes etc.) giving rise to the potential by 2035 for:

- Between 5-14 SAF plants in the UK by 2035 producing a range of transport fuels and other chemicals (currently there are no plants producing SAF in the UK)
- Gross Added Value to the UK economy of £742 million
- 5,200 UK jobs created (an increase of 800 since the 2014 Road-Map)
- £1,952 million export value (over 8 times the 2014 prediction) by 2035
- Overall a GVA of £2.7bn from UK production and the value of UK IP and new export markets
- A £550m value to the UK's balance of payments from indigenous UK production by 2035

The result of this would be that by 2050, 32% of the UK demand for kerosene could be met by SAF and (4.5 million tonnes per year of SAF production would be required.) This corresponds to an annual growth rate from 2035 of around 11% (under the high SAF production scenario) to 18% (under the low SAF production scenario). The growth rate for first generation fuels averaged 20% over the 10 years from 2001 to 2011 so we believe that the growth rates are achievable, especially as additional liquid fuels capacity will become available as road transport increasingly electrifies.

As well as the economic opportunities presented by SAF, these fuels are also considerably cleaner burning than conventional kerosene. The absence of aromatic (cyclic hydrocarbons) and sulphur means that levels of soot/particulate matter are much lower and reductions of up to 90% have typically been observed from the combustion of these fuels. There is also interest in more fully understanding the benefits of these fuels from an engine maintenance perspective as initial results indicate that in addition to air quality benefits, these fuels can offer engine performance benefits and improved fuel efficiency.

5.2 The Opportunities – a New Sustainable Fuels Sector in the UK (continued)

SA believes that the opportunity for the UK is great and the UK can establish a global leadership position in the development and production of SAF, which will play a key role in decarbonising aviation, as well as delivering benefits for employment, exports and waste reduction. Sustainable Fuels projects are under development in the North of England and South Wales and there are many opportunities for regional development from supporting sustainable fuels.

To do this, the UK must draw on its wealth of talent across academia, research and industry bodies and to establish a comprehensive cross departmental strategy in support of this new sector.

5.3 Overcoming Barriers

Many of the technologies supported under the RTFO's developmental fuels sub-target have not been built at commercial scale so realising these opportunities will require government support. To realise this SA is committed to working with Government in four key areas:

- **Office for Sustainable Aviation Fuels (OSAF) (Or similar)** - Given the significant near-term opportunities offered by sustainable aviation fuels (SAF) as both a measure to cut aviation carbon emissions and deliver significant economic and fuel security benefits to the UK, we need a dedicated focus on SAF to provide the essential cross-government co-ordination necessary to progress the development and commercial deployment of SAF. As the UK leaves the EU and builds a consistent, long-term and ambitious industrial strategy, there is an opportunity to make the UK a global leader in the decarbonisation of aviation, both through our expertise in electric aircraft and in the development of sustainable aviation fuels.

- **Fund flagship SAF plants** - Matched public/private funding of £500m over 5 years (totaling £1bn) would support flagship first-of-a-kind commercial plants across the UK utilising wastes and residues to manufacture SAF, as well as a UK centre of excellence for SAF development. This funding should also support additional fuels development and testing to utilise the UK's considerable fuels testing expertise to expedite the approvals process for new aviation fuel technologies, helping to attract investment and anchor new fuels technology providers in the UK.

  SAF falls outside the remit of the Aerospace Growth Partnership (AGP) and ATI, and other dedicated funding that exists for electrification and hybrid aircraft. We need UK Government to take a similar strategic approach for SAF as investor confidence is critical to what remains a nascent industry. Government support would help to 'de-risk' public and private investments in SAF and help the sector in the UK to reach a critical mass. Support is further needed to help move some of these technologies from R&D and fuels testing, through development to full commercial-scale plants (of which none presently exist in the UK).

  Additional funding would allow the UK to create a comprehensive aviation fuels strategy, allowing the UK to capitalise on its leadership in global aerospace and aviation and seize the opportunities presented by the emerging sustainable fuel market to reduce emissions, create jobs and bolster investments in science and technology.

  Presently the UK imports almost 80% of its jet fuel and this volume continues to increase annually. New sustainable fuel production would also increase the UK's fuel supply chain resilience and open up a whole new market for UK companies. £500m would support flagship commercial plants across the UK utilising wastes and residues to manufacture SAF, as well as a UK centre of excellence for SAF development a new UK network of fuels development. This funding should also support additional fuels development and testing to utilise the UK's considerable fuels testing expertise to expedite the approvals process for new aviation fuel technologies, attracting investment and helping to anchor new fuels technology providers in the UK.

- **Incorporate Recycled Carbon Fuels into the RTFO and ensure the RTFO is flexible enough to incorporating further exciting new sustainably robust SAF developments** - Applying the Renewable Transport Fuels Obligation (RTFO) to sustainable, waste-based feedstocks gave a major boost to SAF development, and recycled carbon fuels should now be included to remove barriers to these ground-breaking technologies. These policy changes are essential to the success of many of the projects that are hoping to bring new technologies to the UK – some are based on mixed residual waste streams, others on waste carbon rich gases, with the potential to produce fuels from atmospheric CO2 in the not too distant future.

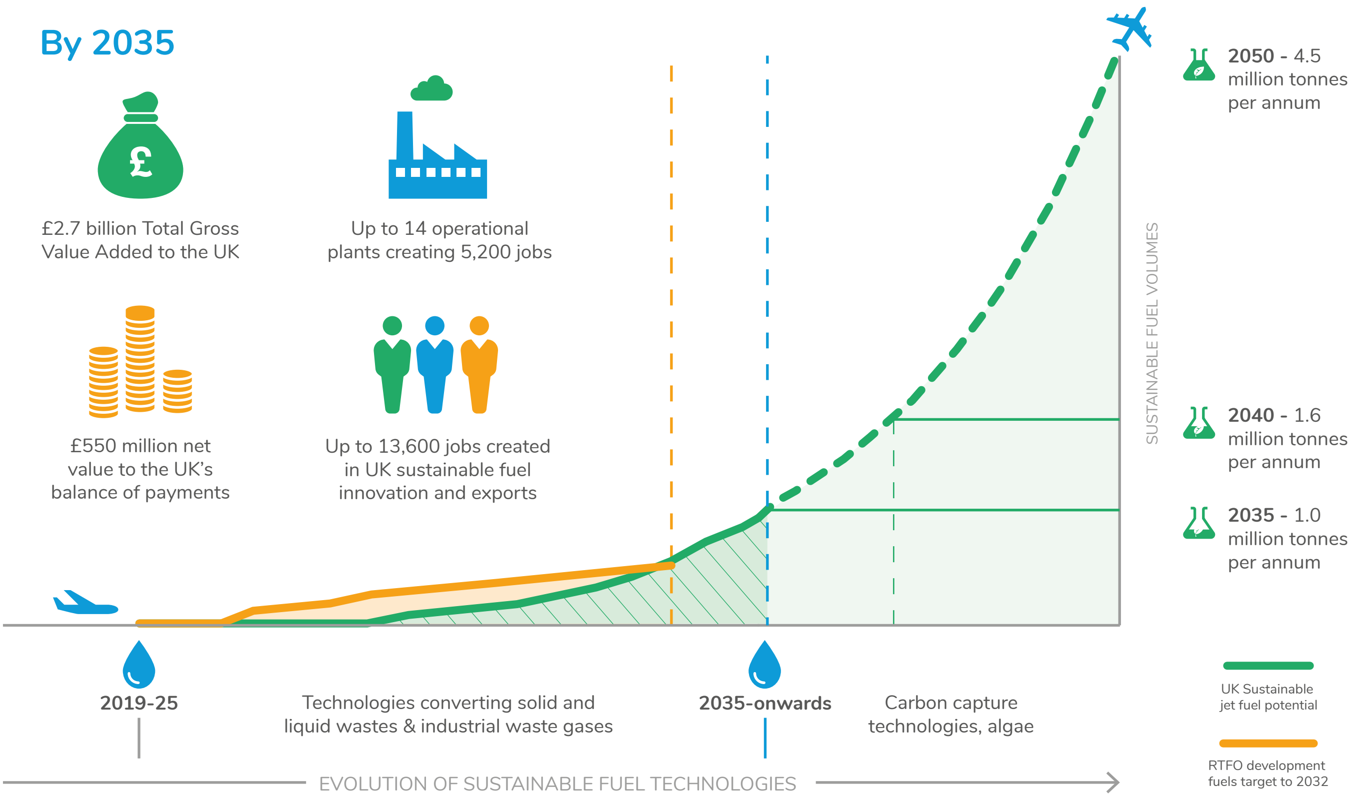
- **Support investment in SAF** through applying a multiplier of at least 1.2x for SAF developmental fuels to provide a signal to fuel producers to invest in aviation fuel production. This is needed because there is a large overlap between the diesel and kerosene fuel specifications. In most cases, commercial factors influence the choice for fuel producers as to whether to produce diesel or kerosene. The more stringent quality and technical requirements for aviation fuels mean that producers presently prioritise road transport fuels over aviation and the 1.2x multiplier was introduced via the EU Renewable Energy Directive II in recognition that aviation fuels need a higher level of incentive support to be competitive. We further encourage the UK to review appropriate incentives support to accelerate wholesale SAF developments around the joint industry and government ambition to decarbonise our hard to decarbonise sector.

5.4 Potential CO_2 Savings from SAF

Through the modelling conducted by E4Tech, the ramp-up of sustainable aviation fuel production in the UK could give greenhouse gas (GHG) emissions savings of up to 2.8 million tonnes CO_2e in 2035 (aviation-optimised, fast-growth scenario) in 2035 compared to a business-as-usual scenario where no sustainable aviation fuel is produced. We estimate that beyond 2035, there is an increasing role for carbon capture and storage (CCS) technologies – in fact for the UK to meet its net zero ambitions, investment in CCS needs to begin in the next decade. In the USA where financial incentives for CCS exist, some projects have already begun to integrate this technology with fuels production, e.g. Velocys has already announced an integrated CCS agreement is in place for their project in Mississippi.[110]

In 2050, for 32% of the UK's carbon savings to be met through the use of sustainable aviation fuel, 4.5 Mt/year of sustainable aviation fuel production would be required. This corresponds to an annual growth rate from 2035 of 11% (under the low sustainable aviation fuel production scenario) to 18% (under the high sustainable aviation fuel production scenario). These annual growth rates are not dissimilar to historic growth rates in global biofuels production. For example, between 2001 and 2011 biofuel production grew from 16 billion litres to 100 billion litres, corresponding to an average annual growth rate of 20%.[111] If the RTFO does not continue beyond 2032 (or if an equivalent method to promote the take up of sustainable fuels is not developed) the continued take up of SAF beyond 2032 is uncertain. Fuel and carbon pricing, coupled with improvements in process efficiency and reducing cost of production may be sufficient to ensure future production continues, but at present it is not possible to determine this.

UK Potential: Sustainable Fuels Road-Map



The Renewable Transport Fuel Obligation (RTFO) is the Government's policy to reduce greenhouse gas emissions from fuel by providing incentives for sustainable fuels. To encourage investment in fuels manufactured from wastes and residues in line with the UK's long-term strategic needs, a 'development fuels' target was set as part of the RTFO from 2019. This includes sustainable aviation fuels. The RTFO only extends to 2032 at present.

Based on the high-growth, aviation-optimised model

CARBON PRICING THROUGH EFFECTIVE MARKET-BASED MEASURES

Summary

- Net emissions from UK aviation have reduced substantially since 2012 and they will continue to decline
- Effective market-based policy measures are vital to ensure aviation's net emissions will reduce in line with climate goals and to establish carbon pricing. In this model, carbon is given a value and airlines pay for emissions via carbon savings from projects on the ground, for example, efficiency, renewable and nature based solutions
- Carbon reductions are made in other sectors where they cannot be made within aviation. Carbon pricing means airlines pay for some or all of the CO_2 they emit, and this provides an increasing incentive to accelerate in-sector carbon savings as well as moderating aviation demand
- CORSIA will make a significant contribution to net emissions in the UK context, and should be the central policy framework to which any other policy initiative should align
- International aviation, where airlines from different countries fly and compete on the same routes, need measures that treat airlines equally and prevent carbon from simply moving between airlines on the same routes. With 'blunt' policy measures like unilateral taxes heightens the risk of carbon leakage and potential net increases in carbon emissions, and funds tend to go into national government accounts, rather than directly into carbon reduction projects
- At the same time, we recognise the European political desire to continue with more stringent policy for intra-European flights, and we believe the current ETS model should transition into a policy that is aligned with the CORSIA framework

CARBON PRICING THROUGH EFFECTIVE MARKET-BASED MEASURES

6.1 Context for effective market-based measures

The aviation industry is investing in ever more fuel-efficient aircraft, fuel saving operational measures and sustainable aviation fuels as well as breakthrough technologies for the future such as hybrid electric aircraft. The evidence and our determination to deliver continued improvements from these ‘in-sector’ areas is strong and demonstrated in this Road-Map. However, to achieve ambitious carbon targets effective market-based policy measures and associated carbon pricing are essential. When designed appropriately these policy measures not only guarantee achievement of carbon targets, but they also strengthen the incentive to deliver in-sector improvements as well.

Effective market-based policy measures are fundamental to government, business and society to enable cost and environmentally effective emission reductions across the global economy. These policy measures are especially important to aviation because additional in-sector reductions at the margin are more costly than in many other sectors. To the extent in-sector aviation savings are insufficient to meet carbon targets, such measures require airlines to pay for emissions reductions in other parts of the economy to make up the difference.

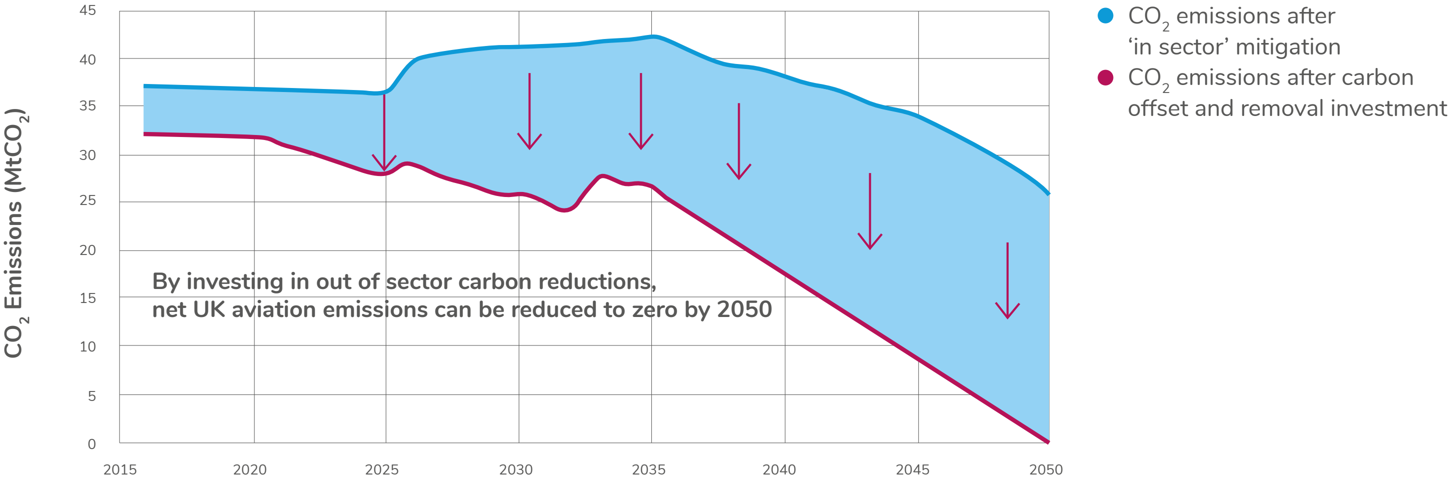
With the start of the ground-breaking global Carbon Offset and Reduction Scheme for International Aviation (CORSIA) agreement in 2021, the aviation sector is taking significant steps to harness the power of market forces to tackle climate change. A low or zero carbon economy will need carbon pricing across all sectors, with appropriate policy frameworks. This will require governments to continue developing the structures and policies for effective carbon markets worldwide. A key area for governments to address in the near term is conclusion of the Article 6 element of the UNFCCC Paris Agreement. In this context, the approach to aviation emissions will need to evolve, strengthen and support global carbon market developments.

6.2 Determining the UK Aviation Residual Emissions to 2050

The UK aviation industry is prioritising the removal of carbon emission though ‘in sector’ actions, and we forecast maintaining a decoupling in growth in aviation activity from emissions growth, but by 2050 the industry is still forecast to generate around 25 million tonnes of CO_2. Given the need to achieve net zero emissions by 2050, market-based policy measures agreed internationally will be necessary to define the trajectory of net emissions reductions, strengthen carbon pricing and provide the framework to obligate the aviation industry to invest in carbon offset and removal solutions for these residual emissions.

The chart sets out the assumed trajectory to achieve net zero by 2050.

UK aviation forecast requirement for carbon offset and removal (including effect on demand of MBM costs)



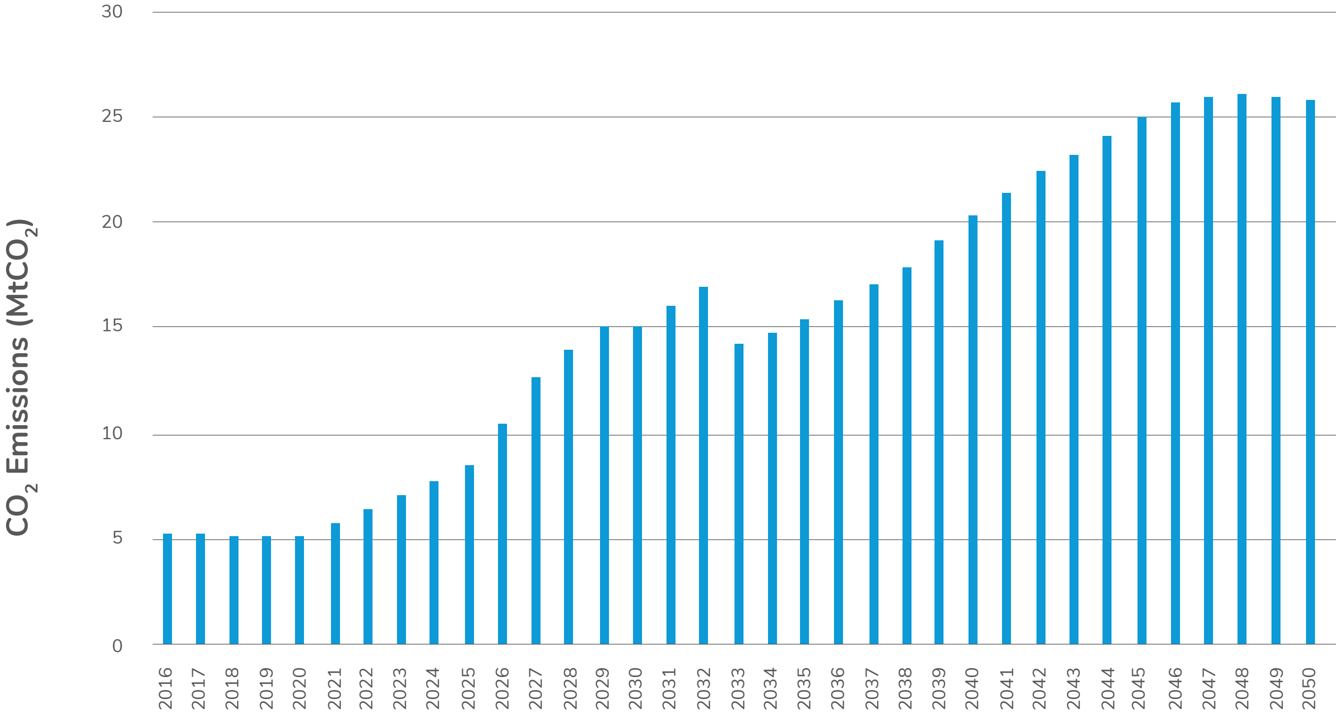
By investing in out of sector carbon reductions, net UK aviation emissions can be reduced to zero by 2050

The period to 2035 is based on how the EU ETS and CORSIA will apply to UK aviation. Beyond 2035 it is assumed there is a gradual transition to achieve net zero emissions by 2050.

6.2 Determining the UK aviation residual emissions to 2050 (continued)

Based on these assumptions the quantity of carbon emissions the UK aviation industry requires to address will change from year to year.

Number of tonnes of carbon assumed to be purchased by UK aviation to achieve net zero emissions by 2050



6.3 Requirements for effective market-based measures

Sustainable Aviation, along with industry, governments and climate science, have consistently advocated for carbon pricing and effective carbon market based measures (MBMs) as an essential element in reducing emissions in the aviation sector. This means mandatory regulation that harnesses the power of markets to seek emission reductions where they can be made most cost-effectively and applied equitably in air transport markets to avoid competitive distortion and carbon leakage.

To achieve the first requirement – environmentally- and cost-effective emissions reduction – the policy measure must allow access to a range of abatement options in multiple sectors and countries. This market-based approach means that the cost of emissions reductions is established by projects that are most able to generate them. This means that airlines and their customers pay no more than necessary for meaningfully achieving carbon targets. However, over time, as global structures to support carbon pricing mature, the cost of carbon can be expected to increase.

The second requirement – equity – is achieved by carefully designing the scope and rules of the policy measure with the objective that all airlines face equal treatment. Market distortion will occur where the cost per tonne of CO_2 of a policy measure is different between different airlines, leading to carbon leakage and potential increase in net emissions. In air transport markets this can affect simple point-to-point markets as well as indirect transfer markets.

The global CORSIA and EU Emissions Trading System (ETS) policy measures both achieve these requirements to a large degree. On the other hand, unilateral ‘eco’ taxes targeted only at air transport and introduced in individual countries don’t achieve either requirement and are therefore a failure environmentally, economically and competitively.

CARBON PRICING THROUGH EFFECTIVE MARKET-BASED MEASURES

CORSIA

CORSIA is a breakthrough global climate agreement to accelerate carbon reductions from aviation and achieve the goal of carbon neutral growth from 2020. From 2021, airlines will be required to pay to reduce CO_2 emissions through qualifying emission reduction projects around the world to meet the requirements of CORSIA. By introducing carbon pricing at a global level, CORSIA achieves the first aviation industry target of carbon neutral growth from 2020 and provides a strong foundation to move towards subsequent targets and measures out to 2050.

To achieve capped growth in emissions at the global level and maintain equity, operators and countries with mature markets will achieve declining net emissions through CORSIA. This is true for the UK and can be seen in the Road-Map diagram by a declining trajectory in net emissions over time as a result of CORSIA.

CORSIA emission reduction units

Under CORSIA, international aircraft operators will collectively be required to purchase independently verified emission units for over 2.5 billion tonnes of CO_2 between 2021 and 2035 representing global funding of over £25 billion in low carbon projects (at an indicative price of £10 per tonne). This means airlines will fund thousands of new carbon reduction projects and programmes that deliver lower carbon emissions.

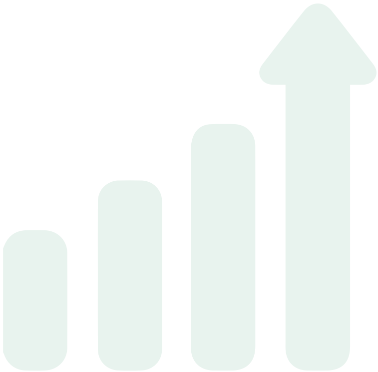
There are many ways to achieve CO_2 reductions that produce emission reduction units, many of which bring other social, environmental or economic benefits relevant to sustainable development. Such offsets can be sourced from various types of project activities, including, for example, wind and solar energy, clean cook stoves, methane capture, forestry and other emissions-reducing projects.

Particularly exciting is the potential for airlines to help move ground energy supplies to better carbon free renewable sources as well as protecting valuable eco-systems by purchasing high quality nature based offsets generated by deforestation prevention or reforestation.

To ensure the environmental integrity of CORSIA, the ICAO Council will adopt a list of emissions units that can be used for compliance. The Council's decision will be informed by a recommendation from a Technical Advisory Body and guided by environmental criteria to guarantee that emissions units deliver real and meaningful CO_2 reductions[112].

The criteria are based on principles commonly applied under existing carbon trading mechanisms and well-accepted carbon offset certification standards, for example:

- A key requirement is that the greenhouse gas reduction or removal projects must be 'additional' to business-as-usual activity. The units must also represent a permanent reduction of emissions that cannot be reversed. Similarly, the activity should not result in unintended increases in emissions elsewhere
- To quantify the greenhouse gas reduction benefits from a project, a baseline is determined to represent what would have happened if the project had not been implemented. Emissions reductions are quantified using accurate measurements, valid protocols, and are audited
- Emissions Units Programs must demonstrate that they have procedures in place to track units and prevent avoidance of 'double counting', i.e. ensuring that emissions reductions are only counted once, across different climate policies and carbon mitigation schemes
- Emissions units programs also need to have safeguards in place to address wider environmental and social risks
- Strict accounting ensures the carbon reduction is achieved, purchased by one airline and 'cancelled' meaning that those reductions are not claimed anywhere else under any other carbon MBM
- UK airlines are clear of the need for high quality carbon offsets to ensure every tonne of emissions reduction paid for genuinely delivers meaningful carbon reductions without unintended consequences or adverse effects



CARBON PRICING THROUGH EFFECTIVE MARKET-BASED MEASURES

Intra-European Policy for Aviation

On average since 2012 when aviation was included in the EU ETS, net emissions on intra-European flights have been reduced by 40%. This is because a finite amount of emissions are allowed for different emitting sectors in the EU ETS and operators must either reduce their emissions or pay to have emissions reduced elsewhere in the system. Since 2012 airlines have funded over 130 million tonnes of CO_2 reduction through the EU Emissions Trading System at a cost of over 1.3 billion Euros. By comparison, it's estimated CORSIA will mitigate 2.5 billion tonnes of CO_2, through ~$25 billion (@ $10 / tonne) of new funds contributed by airlines during the 2021-35 CORSIA period.

During 2020, UK and EU policymakers will consider the next steps for European policy, taking account of the latest developments with CORSIA. We recognise the European political desire to continue with more stringent policy for intra-European flights, and we believe the classical ETS model should transition into a policy that is aligned with the CORSIA framework. We believe it is possible to simultaneously align intra-European climate policy with the CORSIA framework whilst ensuring that intra-European aviation contributes to European climate targets.

Additional positive impacts of effective market-based measures

The benefit of good market-based measures goes beyond the cost-effective emissions reductions that are achieved. By putting a price on carbon emissions, airlines are likely to reflect these costs in air fares, and there is an associated moderation in demand for air travel. The extent of this effect is shown in the first wedge of the Road-Map – "Carbon price impact on demand".

Carbon pricing also provides increased incentive in all other emissions mitigation areas. It increases the focus of airlines on fuel optimising fleet and operations, it enhances the financial case for deployment of sustainable fuels and it positively influences manufacturers to innovate to improve fuel efficiency in future generations of aircraft.

6.4 Assumptions for Effective market-based measures in the Road-Map

The EU Emissions Trading System (ETS) is assumed to apply until 2020. From 2021 CORSIA takes effect. From 021 there is assumed to be UK and EU climate policy for intra-European flights that complements and aligns with the global CORSIA instrument but reflects the need for higher emissions reduction stringency in that region. The European policy is assumed to have a declining cap of 2.2% per annum and be in place until 2035.

We assume that there is no double regulation of emissions, and therefore that emissions reduced through CORSIA are not addressed by the complementary European policy that would apply to intra-European flights.

CORSIA is modelled using best available data and assumptions until 2035 to reflect the design as defined in the ICAO Assembly Resolution of 2016, including a shift from the sector growth method of determining operator obligations to the own-growth method. This causes the net emissions reduction associated with CORSIA to be non-linear up to 2035.

At this point in time the priority is to ensure the successful implementation of CORSIA, but we fully expect that global climate policy will evolve for the period 2035 to 2050 to ensure carbon reduction targets are achieved, incorporating scientific guidance and political considerations of the time. Acceleration of work on long-term targets was agreed at the 2019 ICAO Assembly with the potential for adoption of updated goals as early as 2022, we fully support these measures and the UK government in continuing to do likewise.

For the purposes of this Road-Map we have illustrated the net reduction pathway to achieve either zero net emissions by 2050 or a 50% reduction relative to 2005. To achieve carbon goals, governments through ICAO will need to agree smart policy measures that will apply post-CORSIA.

Cost of carbon

This Road-Map not only incorporates the net emissions outcome from the use of market-based measures but also highlights the effect on demand of carbon pricing. Unit costs of carbon per year are taken from the DfT 2017 Aviation Forecast (see Appendix 2.1). To reflect the expected changing penetration of effective market-based measures over time, we have modelled the effective cost of carbon in each year related to their application. For example, if the EU ETS and CORSIA for a specific year require airlines to pay for emissions reduction units that represent 50% of total emissions, and the cost of units is forecast to be £60, then the effective cost of carbon used to calculate demand moderation in that year is £30.

6.5 Development of emission reduction options

As carbon markets and government policy measures mature, the nature of carbon reduction initiatives is also likely to evolve. Lessons from previous frameworks where some types of emissions reduction units were found to be inappropriate must be learnt. Market forces and policy direction will influence the type and range of options that will become available in the future for generating emission reduction units. Options that could develop as significant areas in future include:

- Natural carbon sinks such as improving soil and peatland CO_2 absorption and reforestation
- Carbon removal technologies such as direct removal of carbon from air and sequestration

We believe there is a lot of potential for negative emissions or Carbon capture and storage (CCS) technologies, but the required investment will be significant, and the potential to accelerate current technologies to meet commercial market demand has yet to be fully assessed. If they are successfully developed, some unproven GGR*(Greenhouse Gas Removal) techniques, such as Bioenergy with Carbon Capture and Storage (BECCS) and direct air capture and carbon storage (DACCS), could be scaled earlier to help meet carbon targets cost-effectively. Whilst these concepts develop, there has been a focus upon Natural Climate Solutions (NCS) such as forestry, peat land, wetland restoration as well as agricultural solutions. This is based on their readiness for implementation and scalability, and the overriding fact that protection and regeneration of the world's nature based assets is key to addressing the climate emergency.

6.6 Opportunities for smart policy mechanisms

Sustainable Aviation recommends the Government work with industry to progress the following issues:

Global leadership in ICAO and UNFCCC: We're clear that concerted, global action on aviation emissions is absolutely essential. We encourage the UK Government to do all it can to drive work through ICAO on setting a clear, long term CO_2 target for aviation compatible with the IPCC 1.5 degree report and 2015 Paris Climate Summit ambition, by no later than 2022. Indeed, COP26 in 2020 at Glasgow presents an ideal opportunity for the UK to show climate change leadership on the global stage by progressing the international framework for aviation emissions to support delivery of the 2050 long-term CO_2 target. To support development of the wider carbon markets, UK government should continue to focus on a successful outcome of UNFCCC negotiations on Article 6 of the Paris agreement.

Align intra-European policy with CORSIA: UK government should transition from the current ETS model into a policy that is aligned with the CORSIA framework.

As ask the UK government to explore the opportunity for UK and other airlines to be allowed to spend some of their CORSIA funds on UK projects as a matter of priority. This will allow UK businesses to support new carbon reduction projects and technologies across the UK, bringing benefits to communities and the economy and ensuring local governance and quality standards are maintained. This should include both nature and technology-based carbon reduction and removal solutions.

IMPROVEMENTS IN AIR TRAFFIC MANAGEMENT AND OPERATIONS

Summary

Air traffic management and operational improvements are likely to reduce CO_2 emissions from UK aviation by around 4.6% by 2050 relative to 2016, with the potential for additional savings from future innovations which we do not at this stage include in our assumptions. This analysis has been updated using the latest DfT traffic forecasts, historical performance data and new analysis looking at the impact of traffic growth on network efficiency. To ensure ongoing improvement in this area Government must continue to support the wholescale modernisation of UK airspace. Without this support the efficiencies already delivered through air traffic management (ATM) and operational improvements could be negated or even deteriorate significantly over the next 10 to 15 years without change, due to increased congestion from expected traffic growth.

IMPROVEMENTS IN AIR TRAFFIC MANAGEMENT AND OPERATIONS

7.1 Introduction

This section sets out our view of the likely improvements to UK aviation's CO_2 emissions arising from improvements to air traffic management, airline operations and airport ground operations.

The range of opportunities from ATM and operational practices can be found in the analysis underpinning the UK aviation 2050 strategy[113], as well as many other sources[114,115,116,117].

The scope of the Road-Map includes airborne and ground based CO_2 emissions from domestic flights within the UK and gate-to-gate emissions from international departures (i.e. from UK airport to non-UK destination airport) and excluding overflights. This approach is consistent with previous Road-Maps and the convention of CO_2 emissions reporting to the UNFCCC.

7.2 Air Traffic Management

7.2.1 Progress to date

Improvements to the efficiency of UK airspace under NATS' control have been driven by performance targets set by the UK aviation regulator (CAA) and NATS' long-term commitment to reduce CO_2 emissions by an average 10% per flight relative to a 2006 baseline. The scope of this 10% commitment includes all traffic within the UK Flight Information Region (FIR) and Shanwick oceanic airspace and aircraft emissions while on the ground (markedly different to the UNFCCC scope used in this Road-Map). Progress against this target, including details of projects and initiatives delivered are outlined in NATS' annual reporting[118].

Previous CO_2 Road-Maps have outlined the opportunities for ATM efficiency. Recent examples of improvements delivered by NATS include:

- Improvements to the structure of airspace, such as minor changes to procedures[119] and airspace redesign[120] to deliver more direct routes and vertically efficient flight profiles
- Improvements to the tactical delivery of flight profiles, e.g. through best practice, training and awareness to increase continuous climbs and descents[121], supporting optimised speed profiles and arrivals holding reduction[122], and through coordination between airspace sectors offering direct routeing or re-routing aircraft through a military training/danger area when the sector is no longer being used actively by the military[123]
- Implementation of controller support tools and concepts of operation, e.g. to optimise the horizontal and vertical trajectories of aircraft[124], avoid holding at airports[125] or to space the arriving aircraft by time rather than by distance[126]

At the time of this publication, NATS has achieved a 7% reduction in CO_2 emissions within airspace it controls, with most of these improvements occurring since 2010. Adjusting for the scope of the Sustainable Aviation Road-Map, this equates to a 1.4% reduction in UK aviation CO_2 emissions since 2010. The original Road-Map expectation was for a higher level of improvement by 2020 corresponding to NATS delivering against its 10% commitment. However, because of increased concerns about the potential for aircraft noise, particularly in the south east of England, as well as changes to Government policy, this plan could not be delivered. These opportunities have now been re-phased within the Road-Map based on NATS' post 2020 plans.

As NATS' data extends only to the edge of UK airspace, the Road-Map is reliant on data from other Air Navigation Service Providers (ANSPs) to indicate their progress at improving efficiency for international departures. We have reviewed historic performance data from Europe and the US, which shows improvements to the structure of airspace. Based on this data and examples of numerous initiatives already implemented we have assumed a further 0.5% improvement in CO_2 emissions since 2010.

IMPROVEMENTS IN AIR TRAFFIC MANAGEMENT AND OPERATIONS

7.2.2 Future ATM improvements

ANSPs (Air navigation service provider) and states across the world continue to progress plans to upgrade how the air traffic system works using satellite-based navigation, increased dynamic sharing of airspace, enhanced data connectivity and new network management, airport surface and controller tools. This opens up opportunities to allow today's modern fleet of aircraft to fly to their full capabilities; climbing and descending more efficiently, operating at their fuel-efficient cruise levels for longer, on their chosen routes and coordinated to arrive at their destination airfields at the optimum times to avoid bunching and therefore reducing the need for airborne orbital holding. Alongside environmental improvements, this will deliver greater capacity and predictability in the choice of routes for airlines.

Airspace modernisation is expected to deliver significant CO_2 savings to aircraft by employing the above solutions. Initiatives at an advanced stage of planning for implementation by NATS from 2020 onwards[127] by NATS include; improvements arising from the systemisation of lower airspace infrastructure (modernisation)[128], Free Route Airspace[129] improvements to Oceanic airspace (ADSB)[130] Automatic dependent surveillance - broadcast, and the expanded use of Intelligent Approach across the UK. Many of these improvements are being replicated across the global air traffic system and are expected to deliver further CO_2 reductions to UK traffic in adjoining airspace (for example Toronto[131] and Amsterdam[132] airports are adopting Intelligent Approach and oceanic ADSB is being implementation in Canadian airspace).

Recent assessments of future ATM efficiency suggest a broad range of attainable performance outcomes versus a 2010 baseline depending on airspace region and current levels of congestion. These typically range from 0 – 8% **(see footnotes 114-116)**.

Our 2020 review also recognises many sources of information suggesting that increased traffic growth can erode or nullify ATM efficiency gains ([118] and [133,134,135]). NATS' recent modelling of future ATM efficiency, based on DfT forecast traffic levels similarly concludes that without change to the ATM system increased traffic congestion will lead to a degradation in efficiency, with the potential to increase holding, increase airspace complexity and the number of interactions between flights to be deconflicted (with associated inefficiency). Without wholescale modernisation of UK airspace this has the potential to increase CO_2 emissions by 8-12% per flight compared to current levels. In addition, recent changes to Government policy have made noise more of a priority below 7,000ft which will likely cause increased fuel burn and CO_2 emissions per flight in built up areas as future airspace change sponsors make use of improved air traffic and aircraft technology to manage noise impacts (e.g. conurbation avoidance, respite and equitable sharing).

The impact of traffic growth and changes to noise policy have led to a reduction in the overall ATM assumptions to 2050 in this Road-Map. Despite this, future Road-Maps should consider future opportunities yet to be identified, performance delivered and updates to traffic forecasts.

7.2.3 Summary

The above discussion is summarised in **Table 7.1**.

ANSP	Timescale	Assumed saving (% of UK aviation CO_2)		
		2019 road-map	2016 road-map	2012 road-map
NATS	Pre 2020	1.4%	2.8	3.0
Other	Pre 2020	0.5%	1.0	1.0
NATS & Other	Post 2020	2.8%	2.5	2.5
Total		4.7%	6.3	6.5

Table 7.1 - assumed scope for reductions in CO_2 emissions from flights which depart from UK airports, arising from anticipated improvements in ATM efficiency

7.3 Aircraft operations

The 2012 Road-Map considered opportunities to reduce UK aviation CO_2 through higher passenger load-factors, better optimisation of fuel-loading and miscellaneous measures such as maintenance of door seals and repairing of dents, regular cleaning of engines and airframes, more efficient flight operational procedures and reducing the on-board weight of aircraft.

Our 2020 review of this area revealed good progress in all three areas, but also in other areas not covered by the original Road-Map. This includes the deployment of reduced engine taxi, optimisation of aircraft speed, in-service modifications to aircraft (e.g. improved turbine blades and winglets) and on-board electronic systems (e.g. taking account of improved wind data and dynamic flight planning to make best use of available airspace and aircraft capability). Following a review of recent airline data, and past Road-Map updates[136,137] showing progress made so far by Sustainable Aviation members we assume that the expected 2.1% improvement has been delivered [see appendix for case studies].

One area of potential improvement that has not been formally included into our assessment is that of electrically aided taxiing, either through the use of electric motors mounted in the aircraft itself or through the use of a dedicated electrically-propelled ground units. The prospects for electric taxiing's deployment at scale are not yet clear. However, we acknowledge the possibility that it may enable a material reduction in global aviation emissions in future years and will monitor its development and deployment.

There is a clear economic imperative on airlines already to deliver operational improvements. Higher fuel prices and emissions trading schemes resulting in CO_2 prices could lead to further initiatives becoming more viable. A greater emphasis on dynamic flight planning before take-off and in-flight, selection of fuel and carbon optimised routes, further weight reduction and in-service technology modifications may lead to Road-Map assumptions being further revised.

7.4 Airport operations

7.4.1 APU Substitution

This improvement relates to airports reducing the use of aircraft auxiliary power units (APUs) while aircraft are on stand and instead providing aircraft with Fixed Electrical Ground Power (FEGP) and Pre-Conditioned Air (PCA) or the provision of more efficient Ground Power Units (GPU), using airport ground infrastructure. We retain the original assumption of a 0.3% saving to UK CO_2 aviation emissions based on information showing increased availability of FEGP/PCA/GPU and airline and airport data showing reductions to CO_2 emissions [see appendix for case studies]. Despite these positive indicators, we recognise that there remain some challenges to full implementation, including; operational constraints, equipment reliability, the need for competitively priced alternatives to APU use and the ability of some aircraft types to utilise this opportunity.

Studies show that there is potential to increase expected improvement levels to above the 0.3% Road-Map goal, with a maximum opportunity of 1.2% based on the 2010 DfT baseline. Future Road-Maps should investigate this potential, particularly in light of further local air quality and noise regulations and expected higher costs associated with fuel burn and associated carbon emissions.

Alongside airport actions to increase FEGP/PCA/GPU availability, industry should also increase monitoring of the actual durations of APU use and ground-based emissions inventories. For the purposes of the current Road-Map it is assumed that the 0.3% improvement will be delivered equally to 2050.

7.5 Supporting products, technologies and research programmes

Additional examples of initiatives offering opportunities for efficiency in ATM and/or aircraft operations include:

- Single European Sky ATM Research (SESAR) continues towards modernising and improving European ATM performance. SESAR contributes to the Single European Sky 10% CO_2 reduction target (against a 2012 baseline). The programme consists of very large demonstrations, including network collaborative management, initial trajectory information sharing, and integrated airport operations. It aims to reduce fuel burn by between 250 and 500kg per flight by 2035[138]. Beyond 2035, continued R&D activities focus on enabling performance-based operations and demonstrating how SESAR Solutions can be deployed in complex environments
- The implementation of Free Route Airspace, which is mandated for implementation across Europe by 2022, will deliver shorter routes and more flexible airspace (civil/military coordination) responding dynamically to traffic flows to improve airspace efficiency and create more choice in routes for airspace users
- NASA's Airspace Operations and Safety Program (AOSP) is working with the FAA to develop the Next Generation Air Transportation System (NextGen) to enhance safety, capacity and efficiency, and like SESAR is expected to result in significant emissions reductions. Part of this is providing advanced automated support to air navigation service providers and aircraft operations and includes several research streams. It also aims to simplify US airspace by implementing Performance Based Navigation, improved surveillance and collaborative ATM technologies
- Manufacturers including, Airbus, Boeing and Rolls-Royce are also investigating and deploying innovations to improve airspace operations. Boeing has the ecoDemonstrator flight test research programme using modified aircraft to develop and test aviation technologies to improve fuel economy and reduce noise. In 2019, investigations began with a Boeing 777 as a flying test bed for 50 projects, including optimised routeing and sharing digital information between ATC, the flight deck and airline operations centres
- Airbus continues to offer new solutions through its NAVBLUE product, a dedicated flight operations and ATM solution software with digital collaboration innovation to enhance safety and efficiency. They are also looking at potential future solutions, including the Automated Formation Flight project that is working to enable aircraft to surf the upwash of air created by another aircraft's aerodynamic vortex. The aim is to demonstrate significant fuel savings in airline operations with test flights expected in mid-2020s
- Rolls-Royce is working to provide data to airlines with Efficiency Insight, Enhanced Efficiency Management and Integrated Efficiency Optimisation to identify emerging patterns in aircraft usage and allow earlier response to trends in performance and operations
- Opportunities to utilise space-based Automatic Dependent Surveillance Broadcast (ADS-B) are also gaining momentum. Aireon, along with ANSPs including NATS, is providing the first ever global air traffic surveillance system using ADS-B. It will provide ANSPs with complete real time air traffic surveillance of all ADS-B aircraft in their airspace which enables improved operational efficiency by optimising en-route oceanic flight paths and improving traffic flow
- More novel propulsion approaches are also been considered, e.g. micro-nuclear, hydrogen and electric

7.6 Potential CO_2 savings from ATM and operations

Table 7.2 summarises the key figures presented in this chapter.

Category	Assumed saving (% of UK aviation CO_2)		
	2019 road-map	2016 road-map	2012 road-map
Efficient air traffic management	4.7	6.3	6.5
Improvements to airport ground operations	0.3	0.3	0.3
Airline operations improvements	2.1	2.1	2.1
Total	7.1	8.7	9.0

Table 7.2 - Potential reductions in CO_2 emissions from UK aviation, due to anticipated improvements in ATM efficiency and operational practices

GLOSSARY

GLOSSARY

Defining aircraft CO_2 emissions

- **Exhaust emissions** = actual CO_2 produced by aircraft flights departing the UK
- **Gross emissions** = exhaust emissions minus CO_2 reductions from use of sustainable aviation fuels
- **Net emissions** = gross emissions minus CO_2 reductions from carbon trading, offsets and removal (CORSIA, EU ETS, CCUS etc.)

ACARE	Advisory Council for Aviation Research and Innovation in Europe
AGP	UK's Aerospace Growth Partnership
ANSP	Air Navigation Service Provider
APU	Aircraft Auxiliary Power Unit
ATI	UK Aerospace Technology Institute
ATM	Air Traffic Management
ATMs	Air Transport Movements (flights)
CAA	UK's Civil Aviation Authority
CCC	UK's Committee on Climate Change
CCUS	Carbon capture, utilisation and storage
CO_2	Carbon Dioxide
CORSIA	Carbon Offset and Reduction Scheme for International Aviation
DfT	UK Government Department for Transport
EU ETS	European Union Emissions Trading System
FEGP	Fixed Electrical Ground Power (for aircraft)

GPU	Ground power unit (for aircraft)
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
MBMs	Market based measures associated with removing carbon emissions
$MtCO_2$	Mega tonne (1,000,000 tonnes) of carbon dioxide
NGO's	Non-governmental organisations
PCA	Pre-conditioned air (for aircraft)
RTFO	UK Renewable Transport Fuel Obligation
SA	Sustainable Aviation
SAF	Sustainable Aviation Fuels
SESAR	Single European Sky ATM Research
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

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[CCC, 2019]	Committee on Climate Change 2019 'Net Zero' – The UK's contribution to stopping global warming
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[ICCT, 2016]	Cost Assessment of Near and Mid-Term Technologies to Improve New Aircraft Fuel Efficiency (International Council on Clean Transportation, 2016)
[IPCC, 2018]	IPCC 2018 Special Report Global Warming of 1.5ºC
[NAP, 2016]	Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions (National Academies Press, 2016, ISBN 978-0-309-44096-7 | DOI: 10.17226/23490)
[SA, 2014a]	Climate Impacts of Aviation's Non-CO_2 Emissions
[SA, 2014b]	Sustainable Fuels UK Road-Map
[SA, 2015]	Sustainable Aviation: a Decade of Progress 2005-2015
[SA, 2016]	UK Aviation Industry Socio-Economic Report
[SA, 2016]	Sustainable Aviation CO_2 Road-Map 2016
[UK GOV, 2017]	UK Aviation Forecast 2017 – Moving Britain Ahead https://www.gov.uk/government/publications/uk-aviation-forecasts-2017
[UK GOV, 2018]	Beyond the horizon - The future of UK aviation - Making best use of existing runways
[UK GOV, 2019]	UK Aviation Strategy
[UK GOV, 2019]	UK Government announcement for UK to go further and faster to tackle climate change
[UK GOV, 2019]	UK Government announcement of UK net zero emissions law
[UNFCCC, 2015]	Paris Climate Agreement

FOOTNOTES

FOOTNOTES

1	IPCC 2018 Special Report Global Warming of 1.5ºC
2	Committee on Climate Change 2019 'Net Zero' – The UK's contribution to stopping global warming
3	UK Government announcement of UK net zero emissions law
4	CCC letter to UK Government on international aviation and shipping
5	UK Government announcement to go further and faster to tackle climate change
6	UK Government Aviation Strategy
7	UK Government 2018 Aviation Strategy - Making best use of existing runways
8	For more information visit here
9	UK Government 2017 Aviation Forecast - sensitivity analysis (table 41)
10	Detailed figures for these calculations are presented in Appendix 2.4
11	It is assumed that the change in passenger demand predicted by the DfT 2017 Aviation Forecast from the removal of carbon price mirrors the change in CO_2 emissions from UK aviation. It is also assumed that the difference between two data points provided by the DfT change in a linear relationship for each year.
12	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/763085/nats-caa-feasibility-airspace-modernisation.pdf
13	Figures will be finalised with the publication of the updated SAF Road Map
14	0.83 (representing a 17% improvement from "known" aircraft types relative to the baseline fleet) multiplied by 0.76 (representing a further 24% improvement from "future" aircraft types) yields approximately 0.63 i.e. a combined improvement of 37%.
15	Source: http://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-fuel.pdf, viewed 15th Oct 2019
16	For example, burning 1kg of fossil-derived jet-fuel produces 3.16 kg of CO_2
17	CORSIA = Carbon Offsetting and Reduction Scheme for International Aviation
18	https://www.iata.org/policy/environment/Pages/corsia.aspx
19	https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx
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21	United Aircraft Corporation
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23	https://www.icao.int/Newsroom/Pages/ICAO-Council-adopts-new-CO2-emissions-standard-for-aircraft.aspx

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24	http://www.acare4europe.org/sria/flightpath-2050-goals/protecting-environment-and-energy-supply-0, viewed 21st Sept 2016
25	ACARE = Advisory Council for Aviation Research and innovation in Europe
26	https://www.theagp.aero/
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39	https://www.virgin.com/news/take-peek-virgin-atlantics-new-airbus-a350, viewed 01 Nov 2019
40	https://www.airbus.com/newsroom/press-releases/en/2019/02/airbus-and-emirates-reach-agreement-on-a380-fleet--sign-new-widebody-orders.html, viewed 18 Nov 2019
41	Analysis of published payload-range charts for the A380 and for the A350 family suggests that, when operating those aircraft at maximum take-off weight on flights between 6600nm and 8500nm, the CO_2 emissions per tonne-kilometre of the A350 aircraft are in the range from approximately 22% (A350-900 at 6600nm) to approximately 34% (A350-1000 at 8500nm) lower than those of the A380 for a flight of the same range. However, A380 operation in UK aviation is primarily on shorter flights, of ranges 3000-6000nm. For the purposes of this Road-Map we take a more conservative view and assume that there is a 15% fuel-efficiency improvement opportunity between the A380 and examples of the latest generation of large twin-engined aircraft such as the A350.
42	https://www.airbus.com/newsroom/press-releases/en/2019/06/jetblue-airways-to-add-a321xlr-and-additional-a220s-to-its-fleet.html, viewed 01 Nov 2019
43	https://boeing.mediaroom.com/2019-10-29-Air-Premia-Announces-Commitment-for-Five-Boeing-787-Dreamliner-Jets, viewed 01 Nov 2019

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44 https://www.airbus.com/content/dam/corporate-topics/publications/backgrounders/A330NEO-INFOGRAPHICS.pdf, viewed 01 Nov 2019

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58 A 14% fuel-efficiency improvement (737-NG to 737 MAX) combined with a further 80% CO_2-reduction due to replacement with “future” all-electric aircraft gives a combined improvement of 82.8%, since 0.86 * 0.2 = 0.172 = 1 - 0.828 = 1 - 82.8%.

59 A 15% fuel-efficiency improvement (A380 to “known” LTA) combined with a further 25% improvement (“known” LTA to “future” LTA) gives a combined improvement of 36.25%, since 0.85 * 0.75 = 0.6375 = 1 - 0.3625 = 1 - 36.25%.

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61 An overall 75% improvement corresponds to a reduction factor of 0.25, while a 15% improvement from ATM/ops corresponds to a reduction factor of 0.85. The reduction factor required from aircraft fuel-efficiency improvements is therefore 0.25/0.85 = 0.294, corresponding to a 70.6% reduction in fuel per passenger kilometre.

62 The RMS approach yields a substantially lower total compared to simply adding the individual technologies’ contributions

63 In alphabetical order: Airbus, The Boeing Company, Dassault Aviation, GE Aviation, Rolls-Royce, Safran, United Technologies Corporation

64 https://www.rolls-royce.com/media/press-releases/2019/18-06-2019-the-sustainability-of-aviation-a-joint-statement-by-seven-of-the-worlds.aspx, viewed 18 Nov 2019

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APPENDICES

Appendices to Chapter 1: Introduction

Appendix 1.1 – Sustainable Aviation – A Cleaner, Quieter, Smarter Future for UK Aviation

Sustainable Aviation is a long term strategy which sets out the collective approach of UK aviation to tackling the challenge of ensuring a cleaner, quieter, smarter future for our industry. Launched in 2005, it is a world first bringing together major UK airlines, airports, manufacturers, air navigation service providers and key business partners.

The industry is committed to delivering a sustainable future, and Sustainable Aviation is critical to delivering that. We are focused on finding collaborative ways of improving our environmental performance and creating a balanced debate to ensure sustainable growth of our industry, which is crucial to the health of the UK's island trading economy. We continue to promote the principles of our strategy both within the UK and internationally.

Sustainable Aviation has set a range of goals and commitments covering climate change, noise and local air quality to deliver a sustainable future for our industry. We regularly report on our progress towards these objectives, monitoring and tracking the practical cooperative work being undertaken by signatories to Sustainable Aviation.

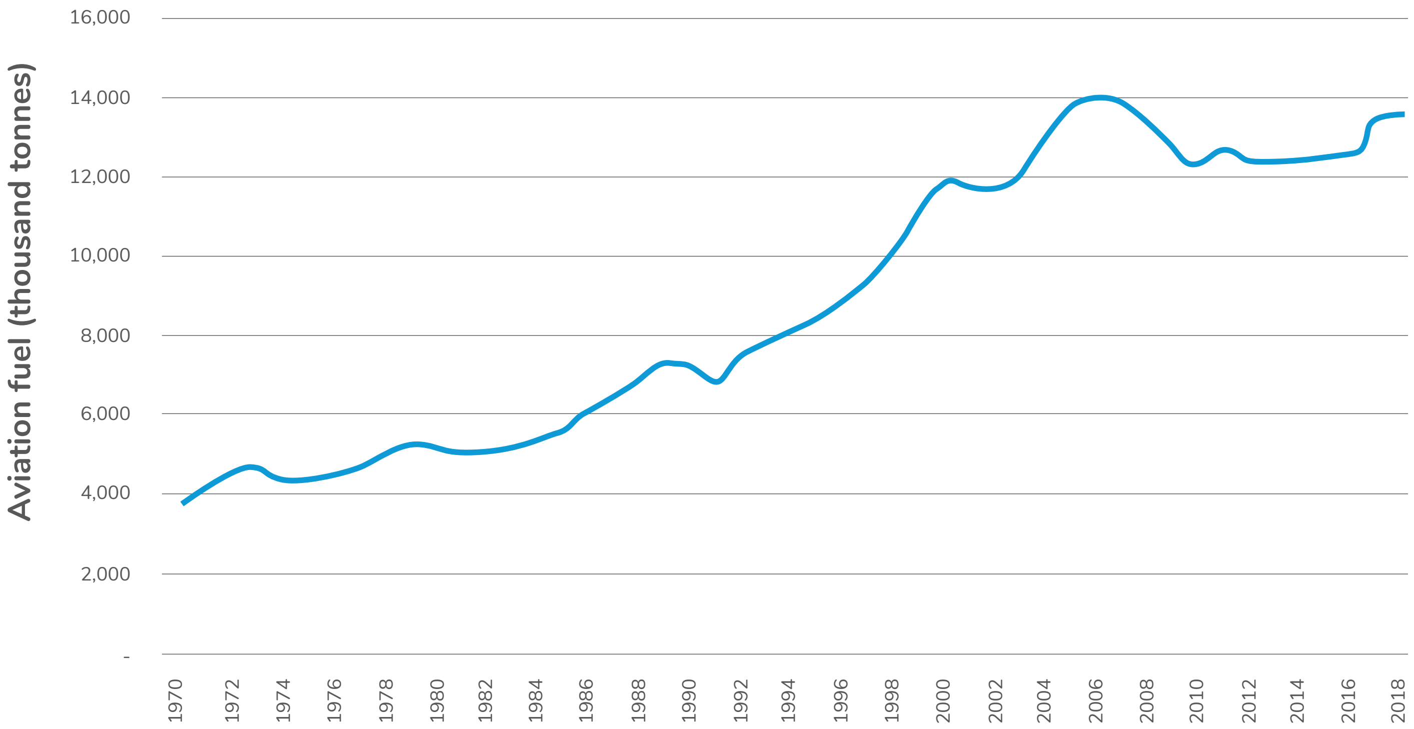
Sustainable Aviation is funded by our members who also provide technical expertise. The number of members continues to grow, with over 90 per cent of UK airlines, airports and air navigation service providers, as well as all major UK aerospace manufacturers and key business partners represented.

Appendix 1.2 – Historic UK Aviation Data

Year	UK airport terminal passengers: arrivals and departures	Index growth	Air transport movements: aircraft landings and take-offs	Index growth	UK Airline Passenger kilometres flown (billion km's)	Index growth	CO$_2$ from departing UK flights (tonnes)	Index growth
2005	226,958,250	1.00	2,266,246	1.00			38,240,502	1.00
2006	234,050,715	1.03	2,313,944	1.02			38,647,059	1.01
2007	239,569,794	1.06	2,345,525	1.03	314.25	1.00	38,344,186	1.00
2008	234,972,281	1.04	2,294,881	1.01	311.49	0.99	37,444,500	0.98
2009	217,738,755	0.96	2,092,276	0.92	296.63	0.94	35,324,937	0.92
2010	210,294,006	0.93	1,972,495	0.87	288.28	0.92	34,091,891	0.89
2011	218,998,803	0.96	2,020,951	0.89	304.44	0.97	35,502,000	0.93
2012	220,428,273	0.97	1,993,711	0.88	308.62	0.98	34,538,637	0.90
2013	228,246,230	1.01	2,012,652	0.89	311.16	0.99	34,833,722	0.91
2014	238,249,686	1.05	2,043,274	0.90	323.87	1.03	34,968,363	0.91
2015	251,329,689	1.11	2,091,774	0.92	332.88	1.06	35,567,256	0.93
2016	268,330,985	1.18	2,178,212	0.96	344.83	1.10	35,804,450	0.94
2017	284,397,095	1.25	2,230,193	0.98	363.21	1.16	37,069,674	0.97
Avg chg p.a.		1.92%		-0.15%		1.45%		-0.23%
Chg 2005 vs 2017		25.31%		-1.59%		N/A		-3.06%
Chg 2017 vs 2016		5.99%		2.39%		5.33%		3.53%
Source:	Dft UK Airport data	Derived	Dft UK Airport data	Derived	Dft UK Airport data	Derived	UK GOV Greenhouse gas emission statistics (international and domestic aviation sources)	Derived

Appendix 1.3 – Historic use of aviation fuel in the UK

Use of Aviation Fuel in the UK



Source: Table 1.1.5 of the Digest of UK Energy Statistics (DUKES) published by UK Government annually
Weblink: https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2019

Appendices to Chapter 2: 2050 Emissions: Hypothetical 'No Improvements' scenario

Appendix 2.1 – Assumed effect of carbon price on UK aviation passenger demand

Year	Carbon price (£ / tCO2)			Passengers mppa				Demand change from central		
	Low	Central	High	Low	Central	High	Zero (£)	Low	High	Zero (£)
2025	£19	£41	£63	297	293	288	300	1%	-2%	3%
2030	£39	£77	£116	321	313	305	328	2%	-3%	5%
2035	£57	£113	£170	346	336	325	357	3%	-3%	6%
2040	£75	£149	£224	373	360	347	390	4%	-3%	8%
2045	£93	£185	£278	403	386	372	424	4%	-4%	10%
2050	£111	£221	£332	432	410	392	453	5%	-4%	11%

All financial figures are in 2016 prices

Table 41: Carbon price assumptions and outputs of sensitivity tests, baseline capacity
Source: DfT 2017 Aviation Forecast

Appendix 2.2 - Analysis of recent aviation passenger and freight growth forecasts

	Airline Passenger Traffic Growth Rate							Freight Traffic Growth Rate							Notes
Data source / Market	Global	Within Europe	Europe - North America	Europe - Middle East	Europe - Asia / China	Europe - Africa	UK	Global	Europe - Asia	Europe - North America	Europe - Latin America	Europe - Africa	Europe - Middle East	Intra Europe	
Boeing	4.6%	3.6%	2.9%	4.3%	5.2%	4.1%		4.2%	4.7%	2.5%	4.0%	3.7%	3.2%	2.3%	Using Current Market Outlook - Pax forecast is 2019-2038, Freight forecast is 2018-2037
Airbus	4.3%	2.3%	2.7%	4.8%	4.3%	3.3%		3.6%	3.8%	3.2%	2.6%	3.7%	3.9%	2.5%	Derived from Global Market Forecast 2019-2038
IATA Air Freight 5yr forecast								4.4%							For period 2019-2024, published by IATA March 2019
UK GOV 2018							1.6%								For 2016-2050
UK GOV 2017							1.4%								For 2016-2050
ICAO Apr 2018	4.1%	2.6%	2.6%	4.0%	5.1%			3.6%					2.5%		For period 2015-2045
Average of available data	**4.3%**	**2.8%**	**2.7%**	**4.4%**	**4.9%**		**1.5%**	**4.0%**					**2.4%**		
SA Base Case							1.5%								SA forecast for 2016-2050
SA No carbon price							1.5%								SA forecast for 2016-2050
SA Realistic effect of carbon price							1.5%								SA forecast for 2016-2050

Note: Grey shaded cells are where no data is available

Appendix 2.3 - Scenarios of annual forecast growth in UK aviation passenger and CO_2 emissions

Year	UK airport terminal passengers			UK departing ATMs	CO_2 emissions from departing UK flights (tonnes)			Notes	Source
	Central carbon price	High carbon price	No carbon price	Central case	Central carbon price	High carbon price	No carbon price		
2005	226,958,250	226,958,250	226,958,250	2,266,246	38,240,502	38,240,502	38,240,502	Historic	UK GOV statistics
2006	234,050,715	234,050,715	234,050,715	2,313,944	38,647,059	38,647,059	38,647,059	Historic	UK GOV statistics
2007	239,569,794	239,569,794	239,569,794	2,345,525	38,344,186	38,344,186	38,344,186	Historic	UK GOV statistics
2008	234,972,281	234,972,281	234,972,281	2,294,881	37,444,500	37,444,500	37,444,500	Historic	UK GOV statistics
2009	217,738,755	217,738,755	217,738,755	2,092,276	35,324,937	35,324,937	35,324,937	Historic	UK GOV statistics
2010	210,294,006	210,294,006	210,294,006	1,972,495	34,091,891	34,091,891	34,091,891	Historic	UK GOV statistics
2011	218,998,803	218,998,803	218,998,803	2,020,951	35,502,000	35,502,000	35,502,000	Historic	UK GOV statistics
2012	220,428,273	220,428,273	220,428,273	1,993,711	34,538,637	34,538,637	34,538,637	Historic	UK GOV statistics
2013	228,246,230	228,246,230	228,246,230	2,012,652	34,833,722	34,833,722	34,833,722	Historic	UK GOV statistics
2014	238,249,686	238,249,686	238,249,686	2,043,274	34,968,363	34,968,363	34,968,363	Historic	UK GOV statistics
2015	251,329,689	251,329,689	251,329,689	2,091,774	35,567,256	35,567,256	35,567,256	Historic	UK GOV statistics
2016	266,630,626	266,630,626	266,630,626	2,119,086	37,343,668	37,343,668	37,343,668	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2017	270,552,049	268,987,725	270,357,619	2,151,151	37,776,263	37,557,842	37,749,115	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2018	272,157,151	271,344,711	274,084,499	2,166,242	38,208,858	38,094,797	38,479,444	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2019	275,669,360	273,701,592	277,811,273	2,175,658	38,641,453	38,365,625	38,941,692	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2020	277,159,589	276,058,423	281,537,995	2,176,528	38,874,109	38,719,661	39,488,220	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA

Appendix 2.3 - Scenarios of annual forecast growth in UK aviation passenger and CO_2 emissions (continued)

Year	UK airport terminal passengers			UK departing ATMs	CO_2 emissions from departing UK flights (tonnes)			Notes	Source
	Central carbon price	High carbon price	No carbon price	Central case	Central carbon price	High carbon price	No carbon price		
2021	277,488,036	278,415,506	285,264,973	2,172,063	38,808,572	38,938,285	39,896,229	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2022	281,574,733	280,772,433	288,991,793	2,199,034	39,104,343	38,992,922	40,134,404	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2023	284,673,197	283,432,902	293,032,434	2,220,135	39,060,150	38,889,968	40,207,124	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2024	288,246,777	285,463,845	296,422,126	2,239,604	39,087,646	38,710,267	40,196,262	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2025	292,547,938	287,842,299	300,171,293	2,257,889	39,027,739	38,399,977	40,044,743	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2026	314,158,991	309,114,015	324,460,125	2,349,733	42,060,523	41,385,087	43,439,669	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2027	325,729,767	320,531,251	338,575,914	2,397,097	43,057,765	42,370,581	44,755,880	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2028	334,079,134	327,501,810	348,065,690	2,436,490	43,603,079	42,744,625	45,428,566	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2029	337,833,823	330,703,173	353,565,670	2,442,245	43,364,830	42,449,530	45,384,193	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2030	341,888,580	333,163,249	358,260,402	2,459,640	43,378,937	42,271,864	45,456,200	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA

Appendix 2.3 - Scenarios of annual forecast growth in UK aviation passenger and CO_2 emissions (continued)

Year	UK airport terminal passengers			UK departing ATMs	CO_2 emissions from departing UK flights (tonnes)			Notes	Source
	Central carbon price	High carbon price	No carbon price	Central case	Central carbon price	High carbon price	No carbon price		
2031	347,268,537	337,530,022	364,674,558	2,479,985	43,395,587	42,178,636	45,570,689	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2032	351,224,152	340,975,820	370,089,780	2,497,401	43,229,338	41,967,954	45,551,356	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2033	354,898,530	345,672,137	376,860,084	2,500,903	43,231,950	42,108,037	45,907,195	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2034	358,822,144	347,779,254	380,799,204	2,515,538	43,163,098	41,834,737	45,806,742	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2035	363,925,368	352,475,396	387,564,946	2,531,507	43,151,074	41,793,436	45,954,047	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2036	368,572,063	357,423,138	394,636,381	2,568,509	43,075,388	41,772,402	46,121,551	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2037	373,298,354	361,671,163	400,933,003	2,592,856	42,887,316	41,551,497	46,062,192	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2038	378,227,054	366,371,286	407,727,534	2,631,005	42,570,100	41,235,713	45,890,429	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2039	383,764,120	371,229,257	414,697,186	2,661,189	42,375,949	40,991,826	45,791,636	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2040	388,818,559	375,480,877	420,987,134	2,700,480	42,428,522	40,973,092	45,938,810	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA

Appendix 2.3 - Scenarios of annual forecast growth in UK aviation passenger and CO_2 emissions (continued)

Year	UK airport terminal passengers			UK departing ATMs	CO_2 emissions from departing UK flights (tonnes)			Notes	Source
	Central carbon price	High carbon price	No carbon price	Central case	Central carbon price	High carbon price	No carbon price		
2041	394,427,238	378,458,531	425,815,541	2,733,058	40,808,156	39,156,005	44,055,646	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2042	400,806,842	386,667,380	436,532,031	2,777,786	40,877,376	39,435,324	44,520,906	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2043	405,281,059	390,132,552	441,897,397	2,813,193	40,720,426	39,198,386	44,399,435	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2044	411,802,242	396,925,260	451,030,566	2,852,282	40,742,531	39,270,645	44,623,669	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2045	418,357,455	402,872,764	459,211,046	2,892,205	40,764,293	39,255,481	44,745,022	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2046	423,875,337	409,338,311	467,960,558	2,937,167	40,825,629	39,425,493	45,071,705	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2047	428,154,208	412,532,132	472,972,712	2,949,540	40,588,461	39,107,509	44,837,197	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2048	433,380,752	416,219,874	478,544,896	2,984,538	40,650,837	39,041,157	44,887,205	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2049	437,840,083	419,398,133	483,525,212	3,015,498	40,676,029	38,962,743	44,920,249	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA
2050	444,183,860	425,402,566	491,765,086	3,043,485	40,786,072	39,061,527	45,155,099	Dft 2018 Making Best use Forecast	Central data published by DfT, rest derived by SA

Appendix 2.4 - SA annual forecast growth in ‘no improvement’ CO_2 emissions from UK aviation depending on carbon price (based on DfT 2018 data)

Year	UK GOV 2018 Making best use forecast (LHR NWR + MBU)						Hypothetical no improvement result				
	DfT Provided Passengers p.a.	DfT Provided ATM's p.a.	DfT provided annual CO_2 (tonnes) including in sector mitigation	DfT Provided Passenger distance flown (km)	Derived Passenger distance flown (million km)	Derived CO_2/PDF (tCO_2 per million km)	UK Gov 2018 MBU - derived CO_2 with central carbon price (tonnes)	Derived change in pax demand zero carbon price vs central case	UK Gov 2018 MBU - derived CO_2 with no carbon price (tonnes)	SA derived CO_2 emissions with modified effect of carbon price (tonnes)	DfT 2017 no improvement CO_2 emissions (central carbon price)
2016	266,630,626	2,119,086	37,343,668	703,087,874,554	703,087.87	53.11	37,343,668	0.00%	37,343,668	37,343,668	37,343,668
2017	270,552,049	2,151,151	37,776,263	711,303,210,172	711,303.21	53.11	37,780,015	0.29%	37,889,403	37,756,596	36,454,563
2018	272,157,151	2,166,242	38,208,858	715,947,101,245	715,947.10	53.37	38,026,670	0.58%	38,246,874	38,259,615	36,899,115
2019	275,669,360	2,175,658	38,641,453	727,168,807,621	727,168.81	53.14	38,622,698	0.87%	38,958,180	38,882,761	37,343,668
2020	277,159,589	2,176,528	38,874,109	731,061,865,087	731,061.87	53.17	38,829,473	1.16%	39,279,178	39,362,759	37,788,220
2021	277,488,036	2,172,063	38,808,572	731,698,209,654	731,698.21	53.04	38,863,271	1.45%	39,425,892	39,791,744	38,232,772
2022	281,574,733	2,199,034	39,104,343	742,225,239,564	742,225.24	52.69	39,422,402	1.74%	40,107,260	40,290,717	38,677,324
2023	284,673,197	2,220,135	39,060,150	749,253,713,655	749,253.71	52.13	39,795,711	2.03%	40,602,279	40,752,245	39,121,877
2024	288,246,777	2,239,604	39,087,646	758,773,214,928	758,773.21	51.51	40,301,328	2.32%	41,234,831	41,217,460	39,566,429
2025	292,547,938	2,257,889	39,027,739	770,749,654,864	770,749.65	50.64	40,937,442	2.61%	42,004,209	41,771,856	40,010,981
2026	314,158,991	2,349,733	42,060,523	843,159,332,036	843,159.33	49.88	44,783,395	3.04%	46,145,888	45,885,934	40,455,533
2027	325,729,767	2,397,097	43,057,765	874,709,069,107	874,709.07	49.23	46,459,121	3.48%	48,075,418	47,751,630	40,900,085
2028	334,079,134	2,436,490	43,603,079	895,444,402,192	895,444.40	48.69	47,560,454	3.92%	49,422,695	48,914,819	41,344,638
2029	337,833,823	2,442,245	43,364,830	904,771,915,336	904,771.92	47.93	48,055,873	4.35%	50,147,305	49,519,014	41,789,190
2030	341,888,580	2,459,640	43,378,937	916,617,333,680	916,617.33	47.33	48,685,028	4.79%	51,016,380	50,210,475	42,233,742
2031	347,268,537	2,479,985	43,395,587	931,928,449,257	931,928.45	46.57	49,498,260	5.13%	52,037,550	51,062,593	42,862,493
2032	351,224,152	2,497,401	43,229,338	943,110,024,947	943,110.02	45.84	50,092,156	5.47%	52,832,935	51,725,703	43,491,244
2033	354,898,530	2,500,903	43,231,950	957,192,333,817	957,192.33	45.17	50,840,121	5.81%	53,795,401	52,950,487	44,119,995
2034	358,822,144	2,515,538	43,163,098	968,871,110,241	968,871.11	44.55	51,460,425	6.15%	54,627,457	53,537,105	44,748,746
2035	363,925,368	2,531,507	43,151,074	984,263,192,175	984,263.19	43.84	52,277,957	6.50%	55,673,787	54,458,883	45,377,497
2036	368,572,063	2,568,509	43,075,388	997,220,842,866	997,220.84	43.20	52,966,187	6.85%	56,595,038	55,296,718	46,006,248
2037	373,298,354	2,592,856	42,887,316	1,012,905,233,125	1,012,905.23	42.34	53,799,244	7.21%	57,676,448	56,192,105	46,634,999
2038	378,227,054	2,631,005	42,570,100	1,027,143,685,427	1,027,143.69	41.45	54,555,503	7.56%	58,681,174	57,023,256	47,263,750
2039	383,764,120	2,661,189	42,375,949	1,044,846,847,072	1,044,846.85	40.56	55,495,785	7.92%	59,889,873	57,948,183	47,892,501
2040	388,818,559	2,700,480	42,428,522	1,059,434,640,447	1,059,434.64	40.05	56,270,598	8.27%	60,926,098	58,694,269	48,521,253

Appendix 2.4 - SA annual forecast growth in ‘no improvement’ CO_2 emissions from UK aviation depending on carbon price (based on DfT 2018 data) (continued)

Year	UK GOV 2018 Making best use forecast (LHR NWR + MBU)						Hypothetical no improvement result				
	DfT Provided Passengers p.a.	DfT Provided ATM's p.a.	DfT provided annual CO_2 (tonnes) including in sector mitigation	DfT Provided Passenger distance flown (km)	Derived Passenger distance flown (million km)	Derived CO_2/PDF (tCO_2 per million km)	UK Gov 2018 MBU - derived CO_2 with central carbon price (tonnes)	Derived change in pax demand zero carbon price vs central case	UK Gov 2018 MBU - derived CO_2 with no carbon price (tonnes)	SA derived CO_2 emissions with modified effect of carbon price (tonnes)	DfT 2017 no improvement CO_2 emissions (central carbon price)
2041	394,427,238	2,733,058	40,808,156	1,077,013,282,576	1,077,013.28	37.89	57,204,266	8.57%	62,107,690	59,380,151	49,239,630
2042	400,806,842	2,777,786	40,877,376	1,095,119,656,999	1,095,119.66	37.33	58,165,965	8.87%	63,325,369	60,502,277	49,958,008
2043	405,281,059	2,813,193	40,720,426	1,107,381,627,465	1,107,381.63	36.77	58,817,245	9.17%	64,209,908	61,101,240	50,676,386
2044	411,802,242	2,852,282	40,742,531	1,126,256,063,515	1,126,256.06	36.18	59,819,738	9.47%	65,482,795	62,143,815	51,394,764
2045	418,357,455	2,892,205	40,764,293	1,145,488,875,647	1,145,488.88	35.59	60,841,265	9.77%	66,782,558	63,143,178	52,113,142
2046	423,875,337	2,937,167	40,825,629	1,159,701,852,433	1,159,701.85	35.20	61,596,171	9.95%	67,727,823	63,987,810	52,831,520
2047	428,154,208	2,949,540	40,588,461	1,170,323,311,316	1,170,323.31	34.68	62,160,317	10.14%	68,465,837	64,521,918	53,549,898
2048	433,380,752	2,984,538	40,650,837	1,182,469,568,872	1,182,469.57	34.38	62,805,450	10.33%	69,295,344	65,163,976	54,268,276
2049	437,840,083	3,015,498	40,676,029	1,193,142,853,745	1,193,142.85	34.09	63,372,349	10.52%	70,040,826	65,772,575	54,986,654
2050	444,183,860	3,043,485	40,786,072	1,208,778,996,624	1,208,779.00	33.74	64,202,844	10.71%	71,080,289	66,734,863	55,705,032
Data Source / Calculation method	Provided by the DfT, based on 2018 Making best use forecast	Provided by the DfT, based on 2018 Making best use forecast	Derived annual figures based on linear change between published data	Provided by the DfT, based on 2018 Making best use forecast	Provided by the DfT, based on 2018 Making best use forecast	Ratio of CO2 to passenger distance flown	Worst case CO2 emissions with no improvement from 2016	Assumes an annual linear change per annum between published data points	DfT 2018 MBU Hypothetical no improvement carbon emissions with central carbon price increased in line with annual change in passenger demand forecast in DfT 2017 Aviation Forecast no carbon price scenario		

Appendix 2.5 – Growth in emissions on Freight-Only Flights

Globally, there is strong evidence that the rate of growth in dedicated freight-only flights is expected to lag behind passenger transport in the years ahead. Furthermore, there is a growing reliance on belly hold freight carried on passenger flights over dedicated freighter-flights.

- Airbus forecasts the passenger aircraft fleet will more than double over the next 20 years, while the freighter fleet will grow by only 55%[139]. Similarly, Boeing forecasts 2018-2038 a doubling in the passenger fleet, with growth in the freighter fleet of nearly 100%[140]
- Boeing forecasts that RPKs will grow at 4.6%p.a. from2019 to 2038, while FTKs will grow by only 4.2%p.a. over the same period[141]
- Airbus forecasts that RPKs will grow at an average of 4.3%p.a. from 2019 to 2038, while FTKs will grow at an average of only 3.6%p.a.[142] over the same period
- Furthermore, Boeing also forecasts for 2015-2035 that belly hold FTKs will grow at a faster rate than total freight FTKs, implying a slower rate of growth for freighter FTKs[143]
- IATA presents data showing that although historically growth in FTKs has matched that in RPKs, over the past few years there has been a significant decoupling of the two, with growth in FTKs being much lower in recent years[144]

In the UK:

- Figures from [CAA] for freight tonnes uplifted from UK airports show that freight carried by dedicated cargo aircraft has declined by 10% between 2005 and 2018, while in the same period, freight carried in the belly hold of passenger aircraft has risen by over 23%, as shown in **Figure 11**. Overall UK air freight volumes have risen by 11% between 2005 and 2018 with most of this growth occurring over the last four years

UK air freight by type of aircraft

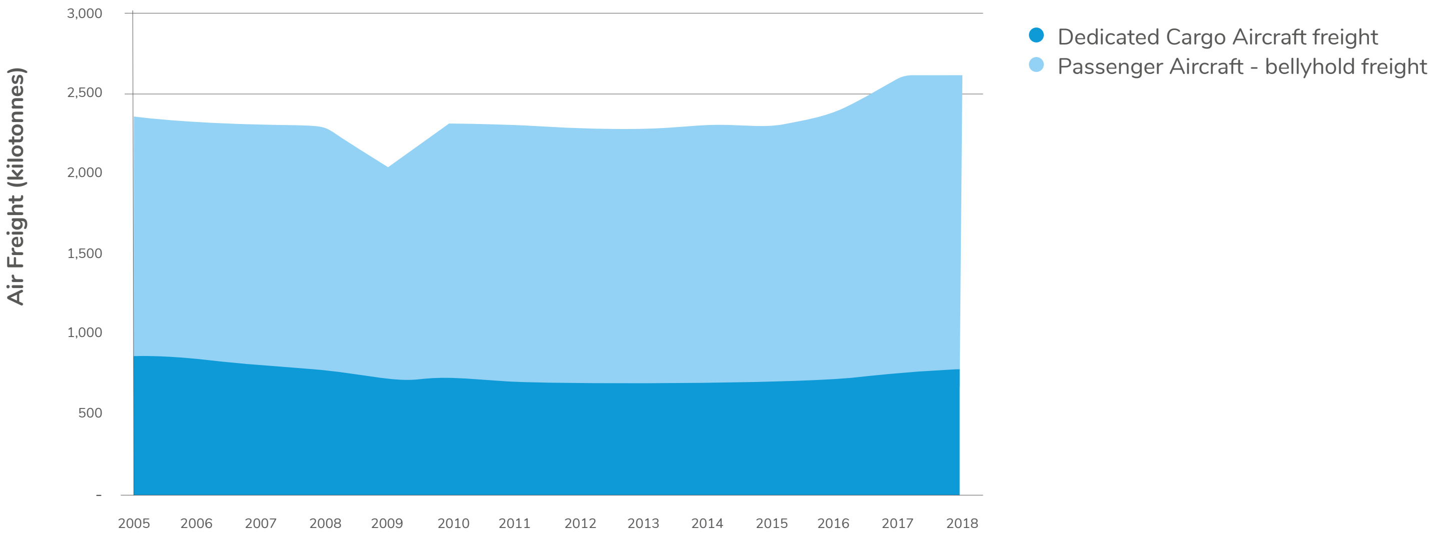


Figure 11 – tonnes of freight uplifted from UK airports. Scope: UK aviation. Data source: [CAA]

Using this information, we are confident that, for the foreseeable future, growth in FTKs on freight-only flights is very unlikely to proceed at a higher rate than that in RPKs on passenger flights. This means that although we do not have access to detailed forecast data for UK freighter activity, we can nonetheless identify an upper bound, representing a growth trajectory which freighter activity is unlikely to exceed. Whilst this is likely to slightly overestimate the actual growth in dedicated freight flight emissions, it represents a safe assumption for this work.

- As a result we make the simplifying assumption that CO_2 from freight-only flights in a hypothetical no-improvements scenario remains at a constant percentage of total UK aviation CO_2, in the same hypothetical no-improvements scenario, over the period 2016-2050. Using table 38 and 69 of the UK Government 2017 Aviation Forecast[145], freighters are shown as 3% of the total CO_2 emissions from UK aviation in 2016 which amounts to 1 $MtCO_2$

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